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2ND SYMPOSIUM
ON SPACE EDUCATIONAL ACTIVITIES

ORGANIZED BY
FEDERATED INNOVATION AND KNOWLEDGE CENTRE OF
BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
HUNGARIAN ASTRONAUTICAL SOCIETY
ESA EDUCATION OFFICE

PROCEEDINGS

esa
EGYESÜLT INNOVÁCIÓS ÉS TUDÁSKÖZPONT
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2ND SYMPOSIUM ON SPACE EDUCATIONAL ACTIVITIES - PROCEEDINGS

Proceedings of the
2nd Symposium on Space Educational Activities

April 11-13, 2018, Budapest, Hungary
at Budapest University of Technology and Economics

Organized by

Federated Innovation and Knowledge Centre of
Budapest University of Technology and Economics

Hungarian Astronautical Society

ESA Education Office

Editor
László Bacsárdi

BME EIT 2018

This proceedings contains the final papers of the symposium as it was submitted by their authors. We have not edited their text or corrected misspellings.

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WELCOME FROM THE ORGANIZING COMMITTEE

Dear Reader,

The 2nd Symposium on Space Educational Activities followed the first symposium held in Padova, Italy in 2015, and continued to be an excellent forum for university students, professors and professionals from all over Europe to present and discuss their educational space-related projects and programs. We had a keynote presentation, six plenary lectures including an astronaut talk, more than 80 oral and poster presentations. Besides providing an opportunity for dissemination of information about educational and research activities, the symposium allowed sharing experience among students and young professionals from different countries and networking with international researchers. The symposium was held on April 11-13, 2018 at the premises of the Budapest University of Technology and Economics. All of our participants were invited to the Welcome reception on Wednesday in Trófea restaurant, a special Yuri's night party on Thursday in the Schönherz Dormitory and a Gala dinner on Friday evening with a 3-hour-long cruise on River Danube on board of the Európa ship.

The symposium was organized by the Federated Innovation and Knowledge Centre (EIT), part of the Faculty of Electrical Engineering and Informatics at the Budapest University of Technology and Economics (BME) – in cooperation with the Hungarian Astronautical Society (MANT), which is the oldest space association in Hungary. The event was carried out under the supervision of European Space Agency's Education Office. Our Technical Program Committee had recognized international members including László Csurgai-Horváth, Lóránt Földváry, Alessandro Francesconi, Sándor Frey, Piero Galeone, Ferenc Horvai, Anton Ivanov, Alexander Kinnaird, Michelle Lavagna, Antonio de Luca, János Lichtenberger, Ali Nasseri and Szabolcs Rózsa. We are grateful for their contributions to the success of the conference. We also thank the hard work of the members of the Organizing Committee with a special thanks to its secretary, Zsuzsanna Hartl-Beck.

We had 206 registered participants from 23 countries including 111 university students, 41 young professional and 54 professional participants.

Keynote and plenary speakers of the symposium were the following (in the order of the talks):

Kai-Uwe Schrogl (*European Space Agency):*
ESA's Education Programme: From inspiration to hands-on experiences
Reinhold Ewald *(European Space Agency):*
ISS - A laboratory in Space
Levente Dudás *(Budapest University of Technology and Economics)*
Educational and research opportunities of picosatellites: the Hungarian SMOG-1 and ATL-1
Zsolt Várhegyi *(C3S Ltd.)*
How to build a DIY new space company
Piero Galeone *(European Space Agency):*
The ESA Academy Programme
Antonio De Luca *(European Space Agency):*
The ESEO Project: history and educational legacy
Titia Skevofilax *(European Space Agency):*
Be a star in ESA's Universe

During the official Opening Ceremony on April 11, the following people welcomed our participants:

Kai-Uwe Schrogl
Chief Strategy Officer, ESA
Hugo Maree
Head of the Education Office, ESA
Reinhold Ewald
ESA Astronaut
András Pócza
Head of Department, Department for ICT Regulation and Management Ministry of National Development
János Józsa
Rector, Budapest University of Technology and Economics
János Solymosi
President of the Hungarian Astronautical Society (MANT)
Kálmán Kovács
Director, BME Federated Innovation and Knowledge Center, Co-chair of the Organizing Committee
László Bacsárdi
Chair of the Organizing Committee, Secretary General of the Hungarian Astronautical Society (MANT)

Speakers of the Closing Ceremony on April 13 were

Piero Galeone
Head of the Tertiary Education, ESA
László Jakab
Dean, Faculty of Electrical Engineering and Informatics (VIK) of Budapest University of Technology and Economics (BME)
László Bacsárdi
Chair of the Organizing Committee, Secretary General of the Hungarian Astronautical Society (MANT)
Kálmán Kovács
Director, BME Federated Innovation and Knowledge Center, Co-chair of the Organizing Committee

We presented five best paper awards based on the author's papers and presentations (either oral or poster).

Christopher Bridges, Peter Bartram, Jonas Holtstiege, Graham Shirvile and David Bowman, *"Lean Qualification of the AMSAT-UK Software Radio Payload"*

Erik de Schrijver, *"ASGARD Balloon and BIFROST Parabolic Flight Programmes: Building Appetite and Nurturing Talent for STEM in Upper Secondary School Students"*

Paolo Marzioli, Alice Pellegrino, Lorenzo Frezza, Federico Curianò, Federica Angeletti, Andrea Gianfermo, Fabrizio Piergentili and Fabio Santoni, *"Lessons learned from STRATONAV on BEXUS 22: Educational activities on stratospheric balloon experiment development"*

Ricard González-Cinca, Natacha Callens and Philip Carvil, *"ESA/ELGRA Gravity-related Research Summer School"*

Lorenzo Olivieri, Matteo Duzzi, Gilberto Grassi, Riccardo Mantellato, Francesco Sansone and Alessandro Francesconi, *"Conjugating educational activities and technology development: the example of TED project"*

Please note that the symposium has three different publications. We have published a printed handbook which provides useful information about the symposium itself. The "Book of abstracts" contains all of the accepted abstracts of oral and poster presentations. This "Proceedings" contains the submitted full papers of the authors.

Following more than a year of thorough planning, we were happy that our participants enjoyed their time during the symposium. We hope that we can welcome you in Budapest again in the future.

Ad Astra!

Dr. László Bacsárdi
chair
Secretary General of MANT

Dr. Kálmán Kovács
co-chair
Director of EIT BME

ORGANIZATIONS BEHIND THE SYMPOSIUM

BME Space Forum
The Federated Innovation and Knowledge Centre (BME EIT) was created at the Faculty of Electrical Engineering and Informatics of Budapest University of Technology and Economics (BME) in 2009 to stimulate the research and development activity and to assist the exploitation of research achievements at the Faculty. Currently, BME EIT operates the BME Space Forum which mission is to harmonize and coordinate the activity of departments at BME participating in space activities by a common vision and strategy, to recognize the joint human and technical resources and amazing achievements, to make internal and external knowledge transfer more efficient, and to utilize opportunities lying in synergies granted by joint capabilities and unified representation. The common aim of BME Space Forum members is to become the bridge between academic research and production, service application, and to participate all phases of research/development/innovation and application processes of space activity. Currently, 12 Departments of 4 BME Faculties participate voluntarily in the activities of Space Forum.
website: eit.bme.hu

ESA Education Office
ESA's Education Office is responsible for the Agency's corporate education programme bringing together young people from many different nations. The aim is to help young Europeans, aged from 6 to 28, to gain and maintain an interest in science and technology, with the long-term objectives of contributing towards the creation of a knowledge-based society and ensuring the existence of a qualified workforce for the Agency that will ensure Europe’s continued leadership in space activities.
website: esa.int/Education

Hungarian Astronautical Society (MANT)
The Hungarian Astronautical Society (MANT in Hungarian) is a civil organization in Hungary that gathers space researchers, users of space technology and everyone who is interested in the interdisciplinary and state-of-the-art uses and research of outer space. The society was established in 1956 in Budapest, and it is the only Hungarian member of the International Astronautical Federation (IFA) since 1959. The aim of MANT is to raise public awareness about space activity and space applications. The society also provides an opportunity for space enthusiasts to meet, exchange ideas and work together. MANT, through its members from various fields of science, organizes conferences, youth forums, summer space camps, issues periodicals, releases media material and holds lectures about space research and connected scientific fields.
website: mant.hu

Our committees

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Chair: *László Bacsárdi*

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Secretary: *Zsuzsanna Hartl-Beck*

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Sándor Frey - Senior scientist, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences

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Ferenc Horvai - Ministry of National Development, Hungary

Anton Ivanov - Senior Scientist, École Polytechnique Fédérale de Lausanne

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János Lichtenberger - Professor, Eötvös Loránd University

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Szabolcs Rózsa - Associate professor, Faculty of Civil Engineering, Budapest University of Technology and Economics

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Extended Abstract ID: SSEA-2018-EA-65

The European Rover Challenge – a giant leap towards a space sector career

Lukasz Wilczynski (1)*

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The project in facts and numbers

The European Rover Challenge (ERC) was created in 2014 by the Polish branch of the Mars Society organization and its spinoff - the European Space Foundation. The idea was to bring the University Rover Challenge project to Europe (which had been organized since 2007 in the Utah desert) but also to expand it with additional sub-events like conference, workshops and a STEM picnic for the public. At the current stage it consists of three parts – the competition that brings together university students from all over the world in a challenge to develop a robotic rover and push their collective engineering potential to the limit; the presentation zone for institutions and companies and a knowledge zone, where workshops and mentoring sessions for the competition teams take place. To date, over 70,000 people had visited the event and over 700 students from 15 countries have participated in the competition [1]. Media from around the world have featured the ERC project in more than 5,000 publications and all of this makes it the biggest open air space and robotics event in Europe [2].

The on-site competition posed teams the challenge of completing five tasks:

- Geological – obtaining samples of "Martian Soil"
- Maintenance – operating electrical rack units where several switches and other electrical components are mounted
- Assistance – performing a delivery task
- Navigation – approaching locations on the field with limited or without supervision
- Presentation – performing a comprehensive project presentation (incl. project management) to the judges.

Career and business oriented goals

The main goal of the ERC project right now is to provide support for the early-stage career development of entry-level professionals representing different disciplines. Students are familiarized with the specifics of space engineering projects, the typical requirements and best practices used in the industry. Since this year's edition, the tasks have been updated on the basis of the roadmaps of the main space agencies such as NASA or ESA so that teams can be brought a little bit closer to the actual demands of the space sector. After four years of running the project we cannot see it as only an event. Our approach to it has evolved and we have begun to see it as what it has actually become - an integrated program towards technological development, specifically in space exploration and utilization. This is the core of the project and the most important thing. The ERC has in its ethos a continuous effort to educate the next generation of multidisciplinary engineers, to boost innovation in research and business and to popularize general knowledge and the latest technology advancements, all of which are to be found in future space exploration. Space exploration and utilization is the leading topic because it represents a new, unknown frontier in both human knowledge and technologies and has a well proven ability to consolidate people's ambitious, sci-fi level goals. Furthermore, career development programs should also adapt to the changing skills needs which are driven by industry. Aspects like rapid decision making, quick learning/adaptation, leadership, VUCA (volatility, uncertainty, complexity and ambiguity) needs to be injected into challenge tasks.

* corresponding author

The ERC project attracts many ambitious, proactive people and is a perfect place for networking. This environment creates a unique community which is working together towards its common interests and visions. The responsibility of the ERC is to maintain this community and its common focus. The project lies midway between academia and industry so it is excellent opportunity to improve cooperation between both. Naturally, the goal for organizers is to boost people engagement and innovation and provide them with the correct environment for new research (new research groups) and business (start-ups) creation. Since 2016, the competition has been followed by workshops for the teams run by experts from different, space-related areas like project management, risk management, new space projects and how to run a startup and get funding.

Our experts come from space agencies, robotics and space companies but also from venture and seed capital firms as we can see two different approaches to a space sector career – which was actually selected by the students themselves when they were asked about their future goals. The first is to simply be hired by a space company or institution so here the most important thing to do is to constantly level up the chosen skills and starting to build a personal brand that may be noticed by potential employers. The second approach is to give them knowledge about entrepreneurship and how to build a business based on skills, competences and sometimes even products (like ready-to-be-commercialized parts of the rovers). The ERC project can already boast several success stories from its alumni including those who have been selected for ESA or NASA internship programs. Some went even higher, starting PhD projects, but there are also some young startups founded by the previous ERC teams and utilizing theirs skills to build inspection robots, education robots for STEM activity as well as developing the concept of an intelligent solar sail which was awarded by Airbus and Merck in the latest Space Exploration Masters 2017 competition [3].

Furthermore, as the project represents continuous activity with annual trials, it is well suited for the validation of concepts and benchmarking of local, national and international roadmaps especially in terms of early professional development, various technologies and operations aspects. That is why with this year's edition we have launched a PRO formula for more advanced teams. The goal here is match the best student concepts that are already too advanced for the regular STUDENT version, with some more sophisticated rovers even coming from real research groups. In this way, we can allow our alumni to make the next step and still be a part of the European Rover Challenge program.

Promoting STEM fields

As mentioned above, ERC is also an excellent tool for STEM popularization stimulating creativity, imagination and courage towards solving most complex challenges of humanity. The second part of ERC event is a science and technology picnic organized in the form of an open exhibition of space related companies and institutions. This formula attracts whole families and space sector enthusiasts and facilitates the transmission of massive amounts of knowledge and inspiration to the next generation of space workers. Since the last edition, we had also seen rising level of inquires from schools and youth robotics teams to participate in the competition. Thus this was also the inspiration to open up the regular formula to youth teams as well so that we could give the opportunity for the next Elon Musk.

Partnerships and new ideas

The ERC is constantly evolving, powered by the ambition of its community and recent trends. It should always present challenges of two levels: one, suited with current market needs, showing the possibilities to enter markets and career paths in the near future (e.g. elements of already planned missions), and the second, presenting bold concepts towards non-existing markets and technologies, boosting imagination and extreme innovation (e.g. space mining). We have also formed many alliances with space organizations (like the Austrian Space Forum OEWF or Mars Planet from Italy)

* corresponding author

and companies to gather additional experts for our event and to open it for additional sub-events or connect it to other space projects (like the AMADEE Mars simulation mission organized by OEWF on the Arabian Peninsula which will host a winning rover of the European Rover Challenge 2018 in its next edition intwo years). We have also started to be asked by companies for ordered competition tasks that will fulfill its agendas and some of the smaller projects. And here is the whole new space for the development of our event as we are very open to any interesting idea that can be implemented into the ERC.

Keywords: space, robotics, education, competition, STEM

[1] ERC webpage, http://roverchallenge.eu (Last retrieved: Mar 10, 2018)

[2]OEWF webpage, http://oewf.org/en/2015/09/european-rover-challenge-2015-the-biggest-open-air-space-event-in-europe/ (Last retrieved: Mar 10, 2018)

[3] Space Exploration Master webpage, https://www.space-exploration-masters.com/winner/golden-fleece-metallic-coatings-for-intelligent-solar-sails-from-in-situ-resources/ (Last retrieved: Mar 10, 2018)

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Extended Abstract ID: SSEA-2018-EA-96

EXO-RO: Involving High-schoolers in Robotics and Astrobiology by Means of a Rover Competition

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Abstract— **The European Space Education Resource Office Romania (ESERO Romania), in synergy with the Romanian Space Agency (ROSA) organize a national rovers competition aimed at youngsters of highschool age - now on its second edition. Mixed (boys and girls) teams of maximum four kids build and control a rover that navigate a terrain analogous to an extraterrestrial planet looking for signs of life and determining the suitability of the environment for human life. In the ESERO tradition, outer space is being used as an exciting context and entry point for STEM, kids having to develop and use skills in robotics, programming, biology, chemistry and other fields. In 2015, the Exo-Ro inaugural edition took place at the "Muddy Volcanoes" site in the Buzau County, while 2017 sees the competition taking place underground, at the Targu Ocna salt mine.**

Keywords— Robotics, STEM, Education, Astrobiology

I. INTRODUCTION

Exo-Ro is the Romanian national exoplanetary rover competition dedicated to secondary school pupils. This event, organized by the Romanian Space Agency (ROSA) [1] in synergy with the European Space Education Resource Office – Romania (ESERO Romania) [2] and local partners [3], is aimed at promoting the knowledge of space sciences – especially astrobiology and robotics among the Romanian youth, to raise the quality of education and to encourage the youngsters towards a scientific career.

The Romanian Space Agency is the national coordinator of the Romanian space activities, whereas ESERO Romania is a collaboration between the European Space Agency and the Romanian Space Agency. The ESERO project is ESA's main means of supporting the primary and secondary education community in Europe, using space related themes and the genuine fascination felt by youngsters for space to enhance school pupils' literacy and competence in STEM-related subjects.

II. THE COMPETITION

A. The Mission

The competition setting scenario is the remote control of a rover on an exoplanet and the analysis of environmental parameters, determining whether the site is suitable to human life.

The main scientific mission - mandatory for each team - consists in moving the rover by remote-control to a fixed point notwithstanding the time lag that would exist in reality between the explored location and the control center, the measurement of some parameters (atmospheric pressure and temperature of the environment) and the broadcast of images.

The secondary mission is chosen by each team, be it collecting scientific samples and using sensors on board the rover to measure other local parameters (e.g. atmospheric composition, light level, humidity) in order to determine the human habitability of the site as well as the possibility of life existence (methane analysis, moisture, pH, radiation etc.) using sensors of their own choice.

B. The phases

The completion follows the organisation of the CanSat competition with preliminary reporting, testing and competing. The language for the reports and presentations is English, in order to increase the literacy among the young aspiring scientists.

By attending Exo-Ro, the participants have the opportunity to manage all the stages of an engineering project, from the selection of objectives, the design and integration of the components, to the system testing in the end. As a consequence, the participants learn practically and familiarize themselves with the scientific research methods and acquire new concept, improve their technology and programming skills, learn the importance of coordination and team work and, last but not least, improve their communication skills.

Prior to the finals, the jury scores reports such as critical design reviews (CDR). The finals have a theoretical and a practical component, both the completion of the primary and secondary missions as well as the data analysis and the presentations done in front of the jury and the public counting towards the final score.

C. The Participants

The competition is opened to mixed (boys and girls) teams of three or four 14-19 year old highschool students hailing from the same institution coordinated by a science teacher.

The number of teams participating in the finals is limited to nine. The teams are selected based on the quality of their submission, having in mind as well an even geographical distribution across the country.

D. The Jury

The competitors are assessed by a competent and diverse team hailing from the academia, ESERO Romania / ROSA and from the secondary schools community. The language of the competition is English.

E. Support

The teams are provided complimentary board, lodging and local transportation during the finals, whereas the transportation to the location and the construction of the rover is at their own expense.

Although participation of the coordinating teachers in previous ESERO Romania trainings is not a prerequisite for entering the Exo-Ro competition, ESERO Romania does offer such trainings in the relevant fields. We thus organized two editions of an introductory course in astrobiology and space technologies for biology, chemistry and physics teachers (in the summers of 2015 and 2017), as well as courses for CanSat coordinating teachers whereby the Arduino and, lately, the Astro-Pi platforms are being introduced (every winter since 2015). The knowledge and skills thus acquired are proving very useful in the Exo-Ro competition, although not designed specifically for it.

F. Location

As Exo-Ro is an event involving student-built models of exoplanetary rovers, the competition takes place in areas resembling, at least physically, alien environments (terrestrial analogue sites).

In 2015 (September 11-13), the first edition of the competition took place in the eerie environment of the “Muddy Volcanoes” [4] in the Buzău county. A protected area of national interest, the “Pâclele Mici” zone is situated at a height of 341 meters and is spread over 16.5 hectares.

In 2017 (October 24-26), the second edition of Exo-Ro took place underground, being hosted by the Târgu-Ocna salt mine in the Bacău county [5]. The teams traveled to a depth of 240 metres to a series of communicating chambers whereby salt had been mined in the past decades, this environment simulating a lava tube on an exoplanet.

III. The Road Ahead

Exo-Ro has proven very popular with Romanian science teachers and their students. Every passing year, the quality of the submissions increases, as well as the degree of difficulty of the challenge. While the Romanian CanSat event is a qualifier segment of the European CanSat competition, there is no such international competition at high-school level – the European Rover Challenge [6] being directed at university students. The “Hungarians on Mars” simulated Mars rover competition taking place every year in Hungary is, like Exo-Ro, a national competition. It may be time to consider whether opening up the Romanian competition to foreign participants might deserve merit.

References

[1] http://www.rosa.ro

[2] http://www.esero.ro

[3] Such as the Bacău County Council, the Târgu Ocna City Council and the Târgu Ocna Salt Mine in 2017

[4] https://en.wikipedia.org/wiki/Berca_Mud_Volcanoes

[5] http://www.salina.ro

[6] http://roverchallenge.eu

Full papers

SPRING DRIVEN EXPANDABLE REFLECTOR FOR DEPLOYABLE ANTENNAS

Cristian Ambrosini[1]*, Alessandra Bellina[2], Loris Bogo[3]*, Stefano Di Marco[4]*, Filippo Marconi[5]*, Vittorio Netti[6], Denis Soso[7], Giorgio Tesser[8]*

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ABSTRACT

Solid dish antennas are a widespread technology nowadays, employed in many communication systems. Despite this, the mass and volume of this type of antenna are sometimes not compatible with the characteristics of space systems and their operating environment. This prevents their use in many more applications in which, actually, solid dish antennas could be very useful. Deployable antenna structures seem to offer a promising solution to this problem by combining an optimized structure with the same features of a solid dish.

This paper presents a new design for a parabolic reflector, able to extend its surface through a radial opening, umbrella-like mechanism. The light structure and the compact initial configuration of the reflector make this device a great option for those applications in which the physical constraints are a particular issue. The deployment is initiated by a single actuation system which releases the arms, making the reflector to expand its surface by nine times, compared to the stowed configuration. Furthermore, this design is characterized by an innovative system that exploits a central fixed parabola[1]. This guarantees operativeness also in the event of unexpected behaviour of the deployment system, overcoming the need for other antennas for redundancy, otherwise required to assure that the correct functionality of the system is not compromised.

This kind of technology could be used, for instance, to implement an aerial stratospheric telecommunication system, composed of high-data-rate microwave radio link, or for interception of communications and radar signals, for military and intelligence, for Earth observation in low and midrange-frequency radar, deep space observation and remote sensing. This paper presents a detailed 3D prototype design and experimental test results. In addition, the major reliability parameters of parabolic reflectors, namely surface accuracy, stiffness of the dish and deployment actuation, will be analyzed and discussed in order to highlight their potentialities for future space and planetary missions.

The potential of this new concept was recognized by SNSB/DLR/ESA who selected it for a flight experiment on its REXUS/BEXUS project[2].

I. INTRODUCTION

A parabolic reflector, frequently referred to as "dish", collects an incoming parallel beam of radio waves and concentrates them into its focal point, also called focus, where the actual antenna is placed. This part is sometimes referred to as the antenna feed. To achieve the maximum gain, it is necessary that the shape of the dish is accurate within a small fraction of a wavelength, this to ensure that the waves headed from different parts of the antenna reach the focal point in phase[3].

The aim of this experiment is to develop a deployable reflector, assess its mechanical functionality and map the accuracy of its surface during the flight[4]. In this project, the antenna feed is not considered, as the test requires operating conditions that cannot be recreated on the balloon (for example the distance between testing emitter and receiver should be higher than the Fraunhofer distance, that in this case exceeds the spatial dimensions of the balloon). The reflector characterisation is valuable regardless the used wavelength and without considering all the factors that affect the efficiency of the feed itself. Investigations on a matched feed may be carried out as an advancement of this work.

II. EXPERIMENT CONCEPT

A picture of the whole system is shown in Fig. 1. The expansion of the useful surface is possible thanks to the Deployment subsystem, composed of six folding arms. Each one is made of a primary rib, a secondary rib and a rocker. These arms are connected in a loop by four joints forming the simplest movable closed chain linkage, called "Four-bar linkage". The Actuation subsystem initiates the expansion phases, freeing the arms that are able to rotate, dragging and unfolding the membrane. The membrane is composed by twelve quadrangular, doubly-curved surfaces, clamped together with the ribs. Three inspection cameras, two of which are mounted on the top profile of the gondola and one on the

TABLE I. MAIN CHARACTERISTICS OF DREX

	Optics Geometry
Configuration	Prime focus, front feed, parabolic
Projected aperture	0.96 m, hexagonal
Dish dimensions	0.36 m in compact configuration 0.96 m in deployed configuration
Focal lenght	0.3375 m
	Dimensions and mass of the reflector in launch configuration
Diameter/Length	0.36 m / 0.11 m

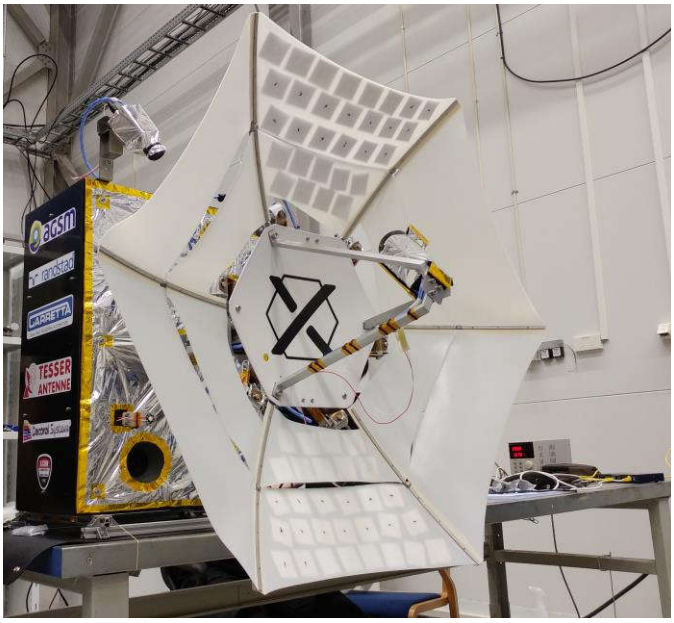

Figure 1: Deployable Reflector Experiment

parabola focal point, record the deployment for further post-flight kinematic analysis. The Frame subsystem represents the backbone of the entire structure. It connects the Reflector, the external portion of the experiment, with the Case, the internal part that contains all the electronics and the stereo vision subsystem. Table 1 shows the most important characteristics of the system.

The deployment procedure consists of three stages, shown in Fig. 2, each characterised by a specific configuration of the reflector elements:

- The reflector covers one ninth of the totally deployed dish extension and it is fixed to the case. The primary ribs are linked to the vertices of the central hexagon frame by hinges, featuring preloaded springs for the deployment actuation. A set of six secondary ribs, linked to the primary ribs, allows a wider aperture. In this configuration, the membrane is folded, and each primary rib is collapsed behind the central hexagon with the secondary rib overlapping (Fig. 2/A).
- The deployment is initiated by a thermal cutter process. The actuation mechanism is based on a single actuation. A precise amount of current flows into a resistive wire which heats up and cuts a cable that is responsible of keeping the mechanisms locked. Each circular membrane is unfolded and moved to acquire the nominal parabolic shape. The deployment rate is controlled by rotary dampers coupled to the hinges, that act against the springs to maintain a constant rate of movement and ensure a smooth deployment (Fig. 2/B).
- The ribs are aligned to the diagonals of the central hexagon and the membrane is maintained in tensioned condition. The reflector reaches an operative reflective surface of 0.658 m^2 (Fig. 2/C).

An inaccurate shape of the dish degrades the signal strength. Distortion of the deployed antenna dish may cause the reflected signal beams to focus off-centre of the focal point. Poor focus of these reflected signals reduces the quality of signal transmission, making the dish ineffective. This represents a critical point of the overall design of the antenna dish, as a failure concerning the membrane would defeat the primary purpose of the entire project.

Inaccuracies in the shape of the dish may be caused, among all, by factors like thermal expansion/contraction of materials, inaccurate manufacturing of components, poor assembly of the antenna unit, or by an unequal force distribution between different ribs.

Two stereo vision systems were meant to be used to precisely acquire data on the membrane shape. The stereo vision is a process that allows to transform a pair of images, captured by two different cameras, into a cloud of points with depth value information associated. This cloud of points, called depth map, is obtained by applying geometry laws to the distance between the same physical point captured by the two pictures, called disparity. In this way, a precise 3D image of the membrane can be built, and it is possible to calculate an efficiency index using a finite elements simulator.

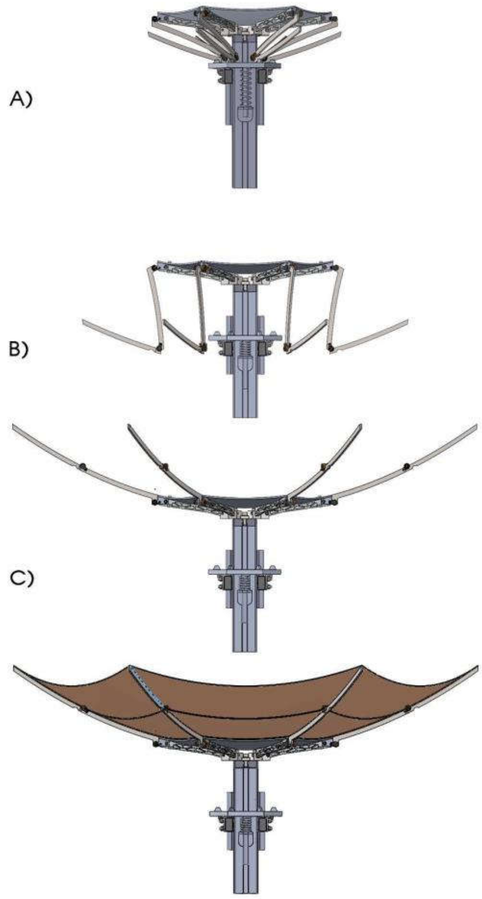

Figure 2: Deployment sequence, A, B, C not representative of the membrane.

III. EXPERIMENT MILESTONES

DREX was selected for the 10th cycle of the REXUS/BEXUS programme and scheduled to fly with the BEXUS-24 platform. In this section, the main stages of its development, from the initial idea to the manufacturing and assembly, are described. Each stage is thought to represent a milestone of a typical space mission, from design phases to reviews by experts from the major aerospace agencies in Europe[5].

A. Early design (September 2016 – December 2016)

The first concept of DREX, illustrated in the proposal form, was already comprehensive of the two main systems, that are the Reflector and the Case.

The overall configuration was close to the definitive one, except for some aspects:

- the strut profile mounted on the Reflector was meant to host two RF transmitters to test the reflectivity of the membrane;
- the Reflector was mounted close to the case to minimize the momentum due to the gravity acceleration;
- the axes of the hinges were designed to be parallel to the axis of the parabola, in this way the ribs in stored configuration lie along the sides of the fixed central hexagon, as shown in Fig.3.

This step was the first level of evaluation of the participants to this educational programme. The experiment was pre-selected, and the team was invited to ESTEC, ESA's European Space Research and Technology Centre in the Netherlands, to present a more detailed version of the experiment concept.

The mechanical design had some major adjunction and the team started to study elements of the deployment and actuation subsystem. A spring-damper mechanism was studied in order to obtain a controlled deployment and a burn-wire mechanism to actuate the deployment. The RF transmitter was removed due to unfeasibility of the test and it was replaced with an inspection system, composed of three cameras seeing different parts of the Reflector.

The process flow and the data utilization were established, along with a first mass and link budget

B. Preliminary Design Review (Febraury 2017)

After the Selection workshop the team was selected for the REXUS/BEXUS programme. As first task, the commission asked the team to provide its first version of the SED, the Student Experiment Documentation, a document descriptive of the experiment in all its aspects.

The first review of the experiment, the Preliminary Design Review, was held at the DLR GSOC site in Oberpfaffenhofen,

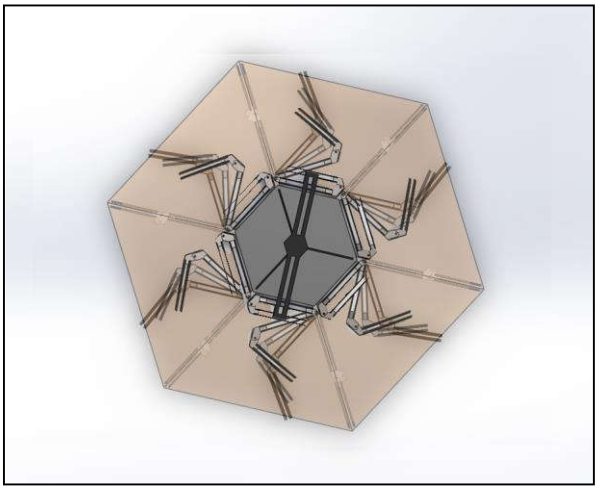

Figure 3: DREX deployment early configuration.

in Germany. At this stage, several changes to the design were applied:

- the objectives and the requirements of the experiment were defined;
- the axes of the hinges were rotated, causing the membrane to fold under the fixed central hexagon and not along its sides, reducing the footprint of the folded configuration and relaxing the requirements on the membrane;
- preliminary deployment analyses were performed to study the behaviour of the overdamped spring-driven mechanism and the membrane. Kapton and Silicone Film were selected as the two best possibilities for the membrane material;
- a preliminary electrical design was studied, mostly involving COTS component;
- the software was in an early design phase, with a higher-level block scheme and divided into processes;
- cameras of the stereo vision systems were selected and the relative distance between the Reflector and the Case was adjusted to ensure the best optical configuration for the triangulation.

C. Critical Design Review (May 2017)

The second review of the experiment took place at ESTEC, in the Netherlands. It was meant to evaluate the final design of the whole experiment, which could not be modified anymore.

The mechanical design was completed and defined in every critical point. The actuation (Fig, 4) and the deployment (Fig. 5) mechanism were finalised and advanced numerical model of the deployment were performed, along with FEM analysis of the Case and of the Reflector. The final configuration of the spring-driven deployable mechanism involved one clock spring and one rotary damper for each joint. These springs exploit a constant torque in time. Reducers provide the damping required to control the deployment speed of the spring driven mechanism. This practically means that a constant and controlled rate of deployment can be achieved. The speed, when reaching the extended configuration, can be calculated and controlled.

The team had to design a custom version of constant torque spring to fulfil the requirement (2,2Nm) varying the width, the thickness and the distance between storage and torque spool, as well as the length to obtain a 180° degrees rotation. The actuation is triggered by the Thermal Cutter. It is a Hold Down Release Actuator that secures the deployable appendages during launch and releases them when needed.

The thermal cutter system is also based on redundancy and reliability. The nichrome burn wire release mechanism uses a nichrome burn wire that, when the mechanism is activated, heats up and cuts a Vectran cable allowing the deployment to actuate. To activate the nichrome wire, a constant current of 1.60 Amps is necessary to ensure a successful and reliable cut. A specific version of the mechanism was designed and tested for the experiment. A Vectran cable is used as a pulley, connecting locker slab to the fixed structure. As the locker slab tries to descend, the cable tenses and prevents an unforeseen deployment[6].

Silicon rubber was chosen as the material for the membrane, thanks to its stretch capability, and its final shape was established. The design of the stereo vision subsystems was completed, defining the application of AR markers to the backside of the membrane to create contrast points to be detected by the software. These points would have then been triangulated with the double point of view system to create a 3D map of the membrane during the flight.

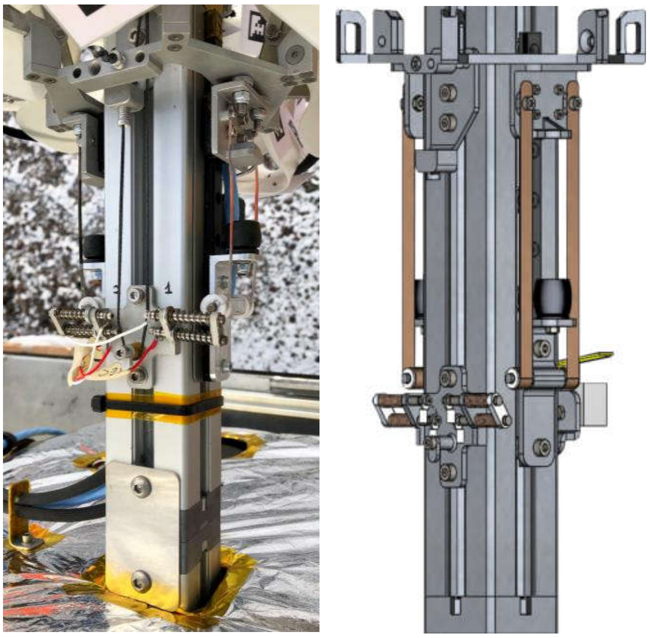

Figure 4: CDR design and final configuration of the actuation subsystem.

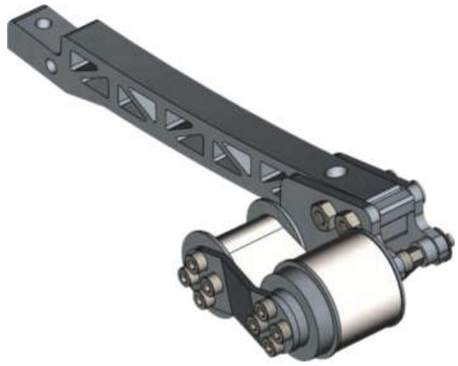

Figure 5: View of the deployment subsystem.

D. Last phases (June 2017 – September 2017)

During this period, the last two reviews took place: the Integration Progress Review (IPR), in July, and the Experiment Acceptance Review (EAR), in September, both hosted by the laboratory of the Industrial Engineering department, at the University of Padova. In both cases, experts from ESA and SSC evaluated positively the status of the experiment. The launch campaign readiness was confirmed soon after.

Regarding the completion of the experiment, the team faced funding issues and deliveries delays of some components, but the whole system was assembled in all its subsystems before the departure towards Esrange Space Centre, in Sweden, where the launch campaign took place.

IV. Flight Data

DREX flew successfully with BEXUS-24 platform in October 2018. However, due to electrical issues occurred during the Late Access manoeuvres on the ground, the actuation subsystem was damaged, and the deployment could not be performed during the flight. Nevertheless, the experiment was functional for almost four hours from the launch event and several data could be acquired. The temperature probes provided a thermal profile of several components (Fig. 6).

Furthermore, a set of images from the stereo vision cameras and few videos from the inspection cameras were acquired. An example of an image from the stereo vision cameras is shown in Fig. 7. The structure of the whole experiment was recovered in good conditions, as it perfectly withstood the landing.

The Case structure and the Reflector were intact and showed no signs of yielding. A post-flight deployment was then performed. The damaged components were replaced, and the system overall conditions were tested.

All the mechanisms were perfectly functional: springs were loaded in stowed configuration without any loss of pre-load angles, the damper performed nominally during the post flight test as well as the thermal cutter and the actuation mechanisms.

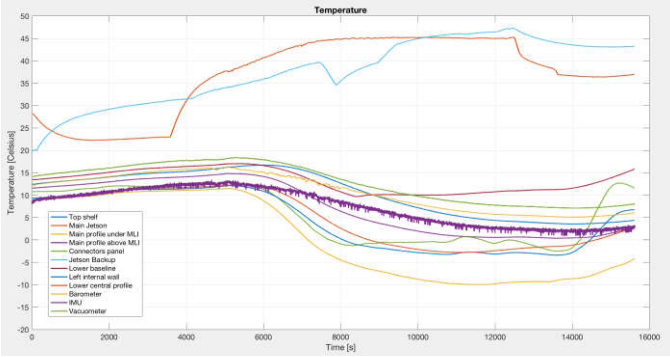

Figure 6: Temperature profiles of several components during BEXUS-24 flight.

V. Lessons learned and Conclusions

The REXUS/BEXUS programme gives to students the opportunity to participate to a real space mission. The programme requires the teams to meet deadlines, prepare scientific documentation and expose their work to a group of experts from international space agencies and companies.

The teams have to put effort in fund-raising and money management as well as public relationship and outreach activities. The programme is challenging but rewarding as well. Students have to learn how to realize their idea by themselves, developing engineering and team work skills that cannot be learned only with a purely academic formation.

The team faced some problems regarding:

- delivery on time of some mechanical components;
- development of the new technologies for the membrane;
- finding of the shelf components for the deployment subsystem;
- electrical issues during the Late Access procedures, just before the launch.

The most important lessons learned as results of the issues encountered were:

- keep in close contact with the manufacturing companies, especially if the material is sponsored and programme some spare time to forecast unexpected problems;
- start the characterisation of new technologies early in the project and never underestimate the time necessary to develop them. In a prototype approach, further tests are required to characterise the performance of the system;
- to reduce the overall complexity and cost of an experiment, it is critical to evaluate the available components in the design phase. The team was not able to find springs and dampers that could match the requirement and certificated to withstand the stratosphere environment, thus a custom set of springs was designed, and a test campaign was conducted to assess the performance of the dampers;
- never underestimate the integration between systems of different nature, like mechanical and electrical, because it can be critical in specific conditions. Indeed, the malfunction of the deployment during the flight can be related to an issue of this nature.

In conclusion, despite the electrical problem that occurred on the ground, the experiment was able to withstand the stratosphere environment, the deployable mechanism performed well in the post-flight test, the electronics and the stereo vision subsystem performed nominally during flight. The developed know-how about the deployable mechanism as well as stereovision techniques will be a useful asset for future projects involving expandable antennas.

Acknowledgment

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Special thanks also go to ESA, DLR, SNSB, the University of Padova, the Department of Industrial Engineering and CISAS.

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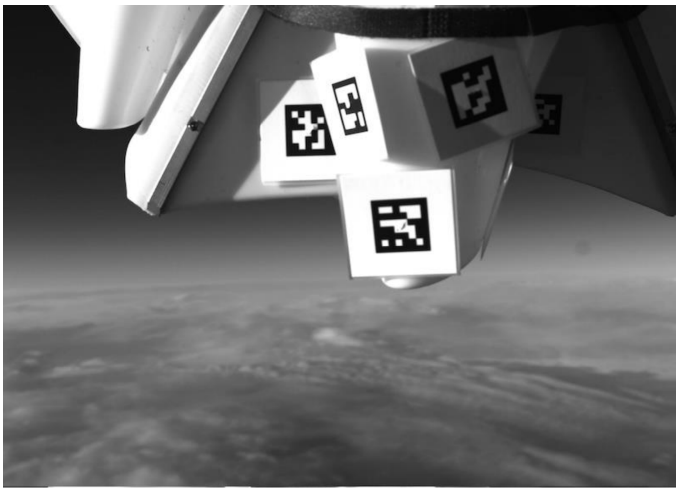

Figure 7: Image taken by stereo vision camera during BEXUS-24 flight.

The ESEO Project: history and educational legacy

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***Abstract*—The ESEO Project is one of the hands-on programmes of the ESA Academy. As all other ESA Academy's initiatives, it aims to improve students' skills, boosting their motivation to be engaged in the space domain, and to create special opportunities enabling them to be directly involved in experiences that can help to bridge the gap between university studies and professional life. The origins of the project are dated back to beginning 2000s.**

At that time, the project was called SSETI-ESEO, and it was coordinated by an association of students, as part of the Student Space Exploration and Technology Initiative (SSETI). Since then, several changes were introduced in the project: a few affected the project organisation, others the configuration of the satellite, and the mission profile. However, consisting with the ESEO Project's name ("European Student Earth Orbiter") the key common aspect remained the commitment to involve students from several ESA Member States, and to engage them in a common space programme developing the mission of a satellite in Low Earth Orbit. Many students got the opportunity to prepare their Master thesis related to the ESEO project, and several others based theirs PhD studies on different aspects of the project.

On a few specific occasions, many training sessions were organised for the participating students.

Since the outset of the ESEO project, more than 500 European students and about 30 academic staff participated in different phases of the project, with many of them involved in the mission definition and in the early design definition activities, as well as in the manufacturing and testing of the flight hardware. For many of them this hands-on space project experience, constitutes an highly valuable asset, important to pursue a job position in the European aerospace industry, in Academia, or in space agencies.

Keywords— European Space Agency, ESEO, Education, Hands-on programmes

I. INTRODUCTION

ESEO is a project of the ESA Education Office, consisting in the development of a micro-satellite, primarily with educational objectives. It is developed as part of ESA Education's hands-on programmes, carried-out with the purpose to offer university students the opportunity to acquire important hands-on experience of a space project, across all space disciplines, thus contributing to prepare a well-qualified technical workforce for ESA's Member State. Students have been strongly involved during all project phase. Since the beginning, ESEO involved many university student teams either belonging to ESA member states or belonging to PECS states (i.e. European states which stipulated cooperation agreements with the European Space Agency).

The mission of ESEO is based on using a Sun Synchronous Orbit (SSO). The nominal mission duration is 6 months, with the possibility of one additional year extension. Its nominal attitude will be nadir pointing, and its configuration is characterized by the presence of three body-mounted solar panels and a radiator positioned on the face of the satellite that a the on-board attitude control system keeps always in the shadow, oriented towards deep space. Fig. 1 shows an artist's impression of the spacecraft in its final configuration.

Fig. 1 Artist's impression of ESEO in orbit

The mission objectives of ESEO are the following:

- take pictures of the Earth and/or other celestial bodies from low Earth orbit for educational outreach purposes;
- provide radiation dosimetry and space plasma measurement in low Earth orbit and its effects on satellite components;
- test technologies for future education satellite missions.

In addition, ESEO will also offer in orbit demonstration (IOD) of a new type of innovative Integrated Current Limiters (ICL).

The ESEO operations will be managed from Forlí (Italy) by the Operations Centre carried out by the University of Bologna, while the downlinking of the scientific data will be performed by the S-band ground station based at the Technische Universität of Münich.

II. THE HISTORY

A. SSETI ESEO origins, 2000-2006

The ESA Education Office started the Student Space Exploration and Technology Initiative (SSETI) in 2000. The main objective of the SSETI initiative consisted in creating a network of students, educational institutions and organizations on the Internet, which together would own the capability and the means to design, build and launch a micro-satellite. Since the beginning of the SSETI initiative, students from around 20 different universities throughout all Europe engaged in the development of the very first SSETI microsatellite, named as the 'European Student Earth Orbiter (ESEO). At that time, the launch date was set by end 2004, as an Ariane 5 piggyback. Table 1 reports the universities that were originally involved together with their relevant areas of responsibility within the project.

Subsystem	University	Country
Structures & Configuration	University of Porto University of Bilbao	Portugal Spain
Power	Naples University	Italy
Attitude Determination & Control	Instituto Superior Técnico	Portugal
Onboard Data-Handling System	Lulea University Newcastle University Ollscoil Atha Cliath	Sweden United Kingdom Ireland
Thermal Control System	Manchester University	United Kingdom
Propulsion	Stuttgart University	Germany
Communications System	Wroclaw University University of Calabria	Poland Italy
Mechanisms	Swiss Federal Institute of Technology	Switzerland
RadFET	Lulea University	Sweden
Narrow-Angle Camera	Umea University	Sweden
Ground Segment	Instituto Superior Técnico Wroclaw University Universidad Complutense de Madrid Universidad Politécnica de Madrid	Portugal Poland Spain
Simulations	Escuela Técnica Superior de Ingenieros Aeronauticos	Spain
Mission Analysis	University of Zaragoza	Spain
Risk Assessment	University of Pisa	Italy
Public Relations	Hochschule für Druck und Medien	Germany
SSETI Design Model	Swiss Federal Institute of Technology	Switzerland
Legal Matters	University of Paris	France

Table 1: SSETI's Universities

B. *SSETI-ESEO early study phases till phase B1, 2006 – 2008*

After the launch of SSETI Express in 2005, ESEO became the second ESA student satellite, and it was meant to be the technical precursor of the SSETI European Student Moon Orbiter (ESMO). Fig. 2 shows the configuration initially defined for SSETI ESEO.

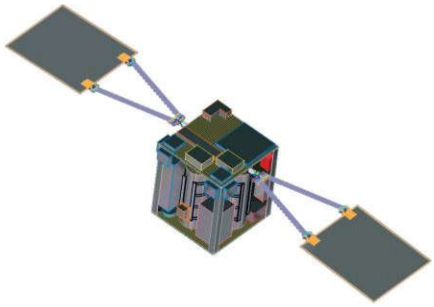

Fig. 2 SSETI ESEO configuration

Several student teams were dedicated to the development of the different subsystems and payload complements, and the launch was at that time planned in 2008, with Soyuz or Ariane 5.

During this project phase, the mission objectives were defined as:

1. Take pictures of Earth and other celestial bodies: three **Cameras** on-board (Narrow Angle Camera, micro camera, star tracker).
2. Measurement of radiation levels: **TriTel** instrument on board
3. Measurement of plasma flow: **Langmuir** probe on-board
4. Test bed for advanced technologies: small high gain antenna, large inflatable antenna, orbit control thrusters.
5. Involvement of radio-amateur community in the downlink of telemetries (housekeeping and scientific data).

Table 2 reports the technical facts characterising ESEO at the end of phase B1of the project.

Dimensions	600 x 600 x 700 mm
Mass	120 kg
Lifetime	Minimum 1 month
Attitude Determination	Sun sensors, horizon sensor, magnetometers, star tracker
Attitude Control	Momentum wheel, cold gas attitude thrusters
Orbit control	Cold gas main thruster
OBDH	CAN Bus, RS-232, RS-242
TT&C	S-band, 9.6 kb/s or 128 kb/s
Power	Deployable solar array, 150 – 300 W
Batteries	Li-Ion, 300 Wh
Power Bus	15-25V Unregulated
Propulsion	18 litres tank, 300 bar Nitrogen cold gas
Thermal	Active

Table 2: SSETI ESEO technical facts

The SSETI-ESEO team tried a few times to achieve the Preliminary Design Review, but unsuccessfully.

This led to the need for ESA Education to reconsider the project organization.

C. ESEO Phase B2, 2009 – 2011

The ESA Education Office decided to continue offering the experience to the students, but under the coordination of a System Prime. This ESA released a competitive Invitation To Tender for Phase B2, to involve an industrial partner as Prime Contractor and System Integrator. As result of the tender, Carlo Gavazzi Space S.p.A (currently OHB Italia S.p.A.) was selected.

The group of participating universities had some changes; some universities confirmed their participation in the programme, others decided to leave, and a few others joined the group.

Table 3 reports the list of university teams participating in Phase B2:

Subsystem	**University**	**Country**
Micro Camera	Danmarks Tekniske Universitet University of Vigo Lulea University	Denmark Spain Sweden
Mission Analysis	University of Zaragoza	Spain
Star Tracker	Institut supérieur de l'aéronautique et de l'espace	France
Power system and Langmuir Probe	Budapest University of Technology and Economics	Hungary
TriTel instrument	Hungarian Academy of Science	Hungary
Thermal control and satellite integration	Politecnico of Milano	Italy
Telecommunications	Universitá del Sannio	Italy
Attitude Control System	Instituto Superior Técnico	Portugal
Configuration, On Board Data Handling, Operations	Warsaw University	Poland
Telemetries and Telecommands	Wroclaw University	Poland
Structure	Politehnica University Bucharest	Romania
Mission Exploration	Glasgow University	UK
AMSAT Payload	Surrey University	UK

Table 3: Universities involved in Phase B2

Under the supervision of the Carlo Gavazzi Space the project achieved the following reviews:

- Mission Definition Review (MDR), in Feb/Mar 2009
- System Requirements Review (SRR), in July-Aug 2009
- Preliminary Design Review (PDR), in February 2011.

In conclusion of Phase B2, a new configuration of the satellite was defined (Fig. 3), consisting of a spacecraft utilizing deployable solar panels, with a total mass of about 120 kg.

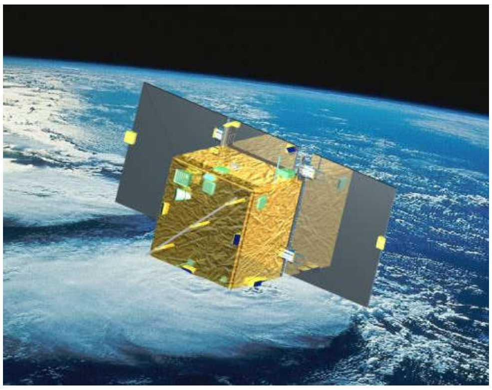

Fig. 3 Phase B2 ESEO configuration

After PDR, mostly because of financial issues, the Education Office decided to change approach, readdressing the project towards a smaller baseline.

D. ESEO Phase B2/C/D, 2013 – 2018

By end 2012, as a result of a competitive Invitation To Tender for Phase C/D/E1, a new System Prime was selected, and ALMASpace S.r.l, a spin-off company of the University of Bologna, awarded the contract to redefine the ESEO baseline, and to coordinate and supervise the ESEO students teams. The following milestones have been achieved, and the satellite reached its final configuration and mission profile:

- June – Nov. 2013: Preliminary Design Consolidation Review (meant to bring the redefined spacecraft design baseline up to the maturity level of a PDR).
- February 2014: Instruments Preliminary Design Review
    - DTU Copenhagen (uCam payload) leaves the ESEO University Network
- June 2014: Tartu Observatory (Digital Camera) joins the ESEO University Network
- July 2014 – May 2015: CDR Process for Platform Subsystems, Payloads, Space and Ground segments.
- Dec 2014: ALMASpace S.R.L. incorporated in SITAEL S.p.A., that becomes the new System Prime
- 2016: Satellite design modifications according to CDR outcome, Payloads EBB testing.
- 2017: Platform S/S and payloads PFMs testing and delivery.
- March/April 2018: Start of PFM integration

The launch is currently planned between last quarter 2018 and first half 2019.

Table 4 provides the list of universities currently participating in the ESEO Phase C/D/E.

Subsystem	University	Country
Micro Camera	Tartu Observatory	Estonia
De-orbiting Mechanism	Cranfield University	UK
Power distribution and Langmuir Probe	Budapest University of Technology and Economics	Hungary
TriTel instrument	Hungarian Academy of Science	Hungary
S-band transmitter	Wroclaw University	Poland
AMSAT Payload	Surrey University	UK
GPS receiver	University of Bologna	Italy
Ground Operations	University of Bologna	Italy
S-band ground station	TU Münich	Germany
UHF Secondary Ground station	University of Vigo	Spain
Attitude Determination Experiment	TU Delft	Netherlands

Table 4: List of the universities participating in the ESEO Phase C/D/E

III. THE EDUCATIONAL LEGACY

When the new Industrial System Prime was selected, contractual agreements were defined in order to organise lectures dedicated to the students participating in the ESEO project and involving ESA, Industry specialists, and University of Bologna. In particular, 3 editions of Lecture courses and internships took place between September 2013 and September 2014 at the conference centre of the University of Bologna in Bertinoro. Each edition was composed of two weeks courses: one week with lectures related to space disciplines, and the second week concentrating on ESEO related subjects. These two initial training weeks were followed by a third one in the form of an internship at ALMASpace premises. University Credits were recognised to all the participants, pending the successful result of a final exam conducted at the end of the internship. About 60 students from the network of ESEO university teams were selected to participate in these training opportunities. In addition, 20 students external to the ESEO project were also offered the opportunity to participate in the ESEO Lecture courses.

Students have also been involved in interface tests of their equipment with the ESEO spacecraft platform, at the System Integrator premises and they are currently involved in the overall satellite integration and validation test campaign, at least for the parts relevant to their instrumentation.

In addition, training Sessions at the ESA Academy's Training and Learning Centre at ESEC (Redu, Belgium), are being organised, aiming at offering a more complete preparation in satellite telecommunications and operations, especially oriented to those that will be involved in the spacecraft operations.

Based on the records and lists of names received from the participating university teams during all these years, more than 500 students have been involved in the ESEO project. ESA Education Office made an effort to keep track of (hopefully) all those that participated in different forms and periods, with the help of the universities. The overall numbers of the students that participated in the ESEO project are reported in Table 5.

DK	Danmarks Tekniske Universitet	7
ES	Universidad de Saragoza	8
FR	Institut supérieur de l'aéronautique et de l'espace	11
HU	Budapest University of Technology and Economics	50
IT	Politecnico di Milano	2
IT	Università Del Sannio	2
PT	Instituto Superior Técnico of Universidade Técnica de Lisboa	18
PL	Warsaw University of Technology	42
PL	Wroclaw University of Technology	280
RO	Politechnica University Bucharest	4
UK	University of Surrey	7
EE	Observatory of Tartu	15
EE	University of Life Sciences	1
EE	Tallinn University of Technology	1
FI	Tampere University of Technology	1
SE	Luela University of Technology	1
UK	Cranfield University	16
IT	University of Bologna	31
DE	TU Münich	16
ES	University of Vigo	4
HU	Hungarian Academy of Sciences	13
NL	TU Delft	13
	TOTAL	**543**

Table 5: Students involved in the ESEO project

Among all participating students, more than 70, prepared their master thesis on subjects related to ESEO (Table 6).

HU	Budapest University of Technology and Economics	8
PL	Wroclaw University of Technology	40
UK	University of Surrey	2
UK	Cranfield University	12
IT	University of Bologna	9
HU	Hungarian Academy of Sciences	2
NL	TU Delft	4
	TOTAL	**77**

Table 6: Master theses developed within the ESEO project

Finally, at least 12 students utilized ESEO as subject for their PhD studies (Table 7).

PL	Wroclaw University of Technology	4
EE	Observatory of Tartu	1
UK	Cranfield University	1
IT	University of Bologna	2
HU	Hungarian Academy of Sciences	4
	TOTAL	**12**

Table 7: PhD theses developed within the ESEO project

During all these years, at the universities which are still participating in ESEO, at least 30 academic staff were involved as coordinators of the activities of their students. Table 8 resumes their participation according to their university affiliation.

HU	Budapest University of Technology and Economics	9
PL	Wroclaw University of Technology	5
UK	University of Surrey	1
EE	Observatory of Tartu	1
UK	Cranfield University	3
IT	University of Bologna	5
HU	Hungarian Academy of Sciences	5
NL	TU Delft	2
	TOTAL	**31**

Table 8: Academic Staff involved in the ESEO project

The data on the numbers of participating students summarized in all these tables show how ESEO played an important role to contribute creating a generation of aerospace engineers, physicists, scientists, or specialists in various space disciplines. For many of them, the hands-on experience offered by ESEO was beneficial for their professional careers in both industry, academia, and space agencies.

IV. Conclusions

This paper summarises the history of the ESEO project, an educational satellite developed by the ESA Education Office. During the whole lifetime of the project, since the initial definition of its preliminary concepts, until the assembly integration and testing of the flight unit, ESEO involved many hundreds students from ESA Member and Cooperating states, coming from many different Universities. In many cases students were offered dedicated training and learning courses/opportunities, and students had a key role during all project development phases. Feed backs received by ESA Education from students say that for many of them the participation in ESEO was instrumental to help them to achieve better perspectives for their professional careers.

Acknowledgments

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A sincere appreciation is also dedicated to the personnel and the management of the industrial System Prime/System Integrators: OHB Italia S.p.A. for Phase B2, and especially ALMASpace S.R.L./SITAEL S.p.A., which is dedicating substantial efforts to achieve ESEO readiness for launch.

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Increasing public participation in exoplanetary research through Citizen Science and user-friendly tools

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Abstract— **Previous research on Citizen Science (CS) projects agree that it can serve as a way of both increasing levels of public understanding of science and public participation in scientific research. Historically, the concept of CS is not new, it dates back to the 20th century, when citizens where making skilled observations, particularly in archaeology, ecology, and astronomy. Citizen Science benefits a variety of communities, such as scientific researchers, volunteers and STEM educators [1]. Participating in CS projects is not only engaging the volunteers with the research goals of a science team, but is also helping them learning more about specialised scientific topics. In the case of astronomy, typical examples of CS projects are gathering observational data or/and analysing them. Recently, the idea of CS has been improved due to technological progress and the arrival of Internet. The phrase "astronomy from the chair" that is being used in the literature highlights the extent of the convenience for analysing observational data [2]. A significant factor of a CS project is the meticulous development of dedicated tools [3]. In this direction, the Holomon Photometric Software (HOPS) is a user-friendly photometric software for exoplanets, where graphical representations, statistics and models are brought together into a single package. HOPS can be used as part of a CS project in analysing transiting exoplanets and producing light-curves. In this way, it could contribute to the scientific data analysis but it could be used also as an educational tool for learning and visualizing photometry analyses of transiting exoplanets, where the public can engage with exoplanetary research and data analysis. For the past year, we have been applying the project in collaboration with experienced amateur astronomers and the University of Thessaloniki. Following this first stage, we aim to approach additional audiences, such as amateur astronomy clubs and schools, in order to expand the number of participants and increase diversity and inclusiveness. In this context, we are developing an online platform where everyone can interact with the scientific community, get involved in exoplanetary research and get information. A key element of the platform is educational video and audio material with the aim of familiarising and training the inexperienced users.**

Keywords—citizen science; exoplanets; public participation; user-friendly tools

I. Introduction

Currently the number of exoplanets is rapidly growing, with over 3500 planets discovered. This number is expected to grow even more in the future with dedicated missions that are expected to find additional planets [4]. While discovering new exoplanets is still important, we have now entered a new era, where the better characterisation of these planets and their host stars is of extreme importance.

Understanding worlds beyond the Earth is a key issue for humanity and concerns everyone, not only the scientific communities. We strongly believe that research and science is an effort that everyone can take part. For this reason, in the context of our project, we are willing to collaborate with members of the public including also students of schools and universities and help towards answering fundamental questions of science and society: Are there other planets like the Earth? Could they host life? Is there any other type of life?

Today, the general public can get involved in the effort of answering the above questions through citizen science projects. Such projects have demonstrated their usefulness for research and education, given that in the contemporary world it is much easier for everyone to participate [1]. In the case of a project on characterising exoplanets, long-term continuous monitoring of targets is necessary. This is a process that members of the public can contribute by obtaining or analysing data from small ground-based telescopes.

We present here the first Citizen Science project on planetary sciences organized in Greece and the first of its kind in Europe, entitled *ExoWorlds Spies*[1] (Fig. 1.). The main idea of the project is to observe stars hosting exoplanets with the aim of improving their parameters and their ephemerides. We especially designed this project to ensure high data quality, reliability in the scientific results but also to ensure participants' interest and continuous participation in the project [5]. The project is designed in a way to involve the users in depth and promote critical thinking.

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[1] *http://www.astro.auth.gr/n/?p=exoworlds_spies_(english)*

Fig. 1. ExoWorlds Spies logo

II. Aims Of The Project

A. Exoplanet Reseach Scope

ExoWorlds Spies is a project aiming to monitor exoplanets through regular observations and finally help the effort of characterising these unknown worlds.

Today, despite the large number of discovered exoplanets, we know very little about them. For instance, we do not know if they are surrounded by atmospheres or what they are made of. These are important elements which will help us better understand their nature. A technique that is being used to probe the atmosphere of an exoplanet is transit spectroscopy [6]. During a transit, the stellar and the planetary discs overlap, and while a part of the stellar light is blocked by the core of the planet, another, smaller, part is filtered through its atmosphere. Future space missions like the James Web Space Telescope (NASA) and ARIEL [7] (ESA candidate) will try to characterise as many exoplanets as possible [8]. However, to make these missions as efficient as possible and to organise large-scale surveys, we need to have a good knowledge of the orbital parameters of the planets observed, especially of the expected transit time. To achieve that we need to monitor the transits of the exoplanets for long periods of time. This is where small and medium-scale telescopes and the public can contribute significantly and make a difference, especially when observing time in large telescopes is limited.

B. Citizen Science Scope

The advantage of Citizen Science is that the users not only get information but they are actively involved in real scientific research. In this way, a Citizen Science project focused on exoplanets can be a vehicle to engage the public with different aspects of planetary science and, ultimately, improve the relationship between science and society. Citizen Science can be an effective practise to reach various audiences – not only amateur astronomers – and bring them closer to scientific research. We aim to evaluate our work and identify the best practises in Citizen Science projects. The feedback from this evaluation will be guidance for improvements on this project, as well as future Citizen Science projects.

C. Space And Astronomy Education Scope

In the context of the presenting project, our team is collaborating with members of the public in order to produce scientific results. The public can play a significant role and help obtaining and analysing such data using the equipment of the Holomon Astronomical Station and other observatories. The interdisciplinary nature of Citizen Science projects can positively affect a variety of communities. Not only the scientific community is getting support by the public for carrying out the research, but also the participants are benefitted to a great extent. For members taking part in the project, it is a great chance to develop new skills and get specialised knowledge in planetary sciences in an appealing way.

The acquired skills include: using astronomical equipment, analysing scientific data (photometry and model fitting), using academic literature, and getting familiar with computers and software. Especially young people such as students will have the opportunity to experience research in practice, which will help them orient their professional careers. In the context of the modern society, science and technology are interconnected and an ever-increasing percentage of the modern job market benefits and requires scientific reasoning as well as computational skills.

By participating in this project the audience will also learn about the research in the field of extrasolar planets. At an initial stage, the participants will become more familiar with our Solar System, the difference between a star and a planet, and the different categories of planets. Furthermore, they will learn about a wide range of different aspects concerning exoplanets, such as: detecting and re-observing exoplanets through the transit phenomenon, atmospheric studies of exoplanets through transit spectroscopy, formation, evolution and chemistry of exoplanets.

In addition, through *ExoWorlds Spies* we will try to change people's attitudes towards science, by introducing the following aspects:

- Science can be done outside academia.
- Science is a collaborative effort.
- Students should not consider science as a difficult and distant task.

Finally, we believe that today there is a number of concepts around exoplanets that need to be clarified:

- Habitability does not mean existence of life; we need to understand the conditions on exoplanets via atmospheric studies.
- Planets can be much different from the Earth, even if they have the same size.
- We cannot travel to exoplanets, so we need to preserve our own planet.

III. METHODOLOGY

The methodology we follow is briefly described below:

- Obtain data of stars known to host exoplanets with small/medium scale ground telescopes. Specifically, we take photos during an exoplanet transit.
- Analyse the data: at this stage, we use the photometric software designed by our team to measure the light coming from the target compared to other stars on the field of view.
- Interpret the data: at the final phase of the process we are doing the model fitting of the transiting exoplanet and we produce the light-curve. The drop of the target star's light can provide more information about the exoplanet: its size, its orbit and its transit timing.

The above process is repeated on a regular basis, with the aim of tracking any changes in the long term.

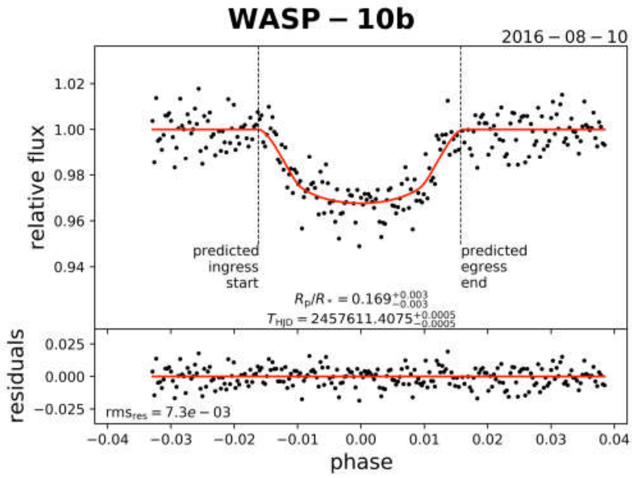

Fig. 2. The transit of WASP-10 b, as observed from the Holomon Astronomical Station, and analysed by one of our participants.

IV. TOOLS AND EDUCATIONAL MATERIAL

A. *The HOlomon Photometric Sofware (HOPS)*

The Holomon Photometric Software [9] (HOPS) is especially designed by our team for data analysis and light-curve extraction. In an effort to increase public participation in a Citizen Science project, it is significant to design the tools by using specific characteristics [3]. Following this pattern and other successful Citizen Science projects, we designed the software in a user friendly way. The main features of the software are presented below: interactive, with user interfaces, geospatial and free for everyone to download and install.

B. *Website and Audiovisual Material*

We have recently developed a dedicated website for the project in order to disseminate the material and the tools to as many people as possible. The website includes audiovisual material, information on the project, the photometric software, instructions, observational data and graphics. All sources are online, free, and available for everyone both in Greek and English. In order to approach various audiences from the public and more effectively communicate with them, we created also a social media platform (a Facebook page) and an E-mail account. Several people from different places and backgrounds have already contacted us to express their interest to participate in the team. Social media can play a significant role in popularising scientific ideas but also in informing the participants for updates related to the project.

V. FIRST SCIENTIFIC RESULTS

We have conducted a number of observations using the equipment at two observatories in Greece: the Holomon Astronomical Station and Nunki Observatory [10].

A representative example of a transit light-curve that we've produced and was analysed by a participant of the project is presented in Fig. 2.

VI. IMPACT FOR ASTRONOMY AND SPACE EDUCATION

The tools and the material described above are now available online and a small number of participants has already started training on real data. At the same time, *ExoWorlds Spies* can be used as a vehicle to educate students of different levels and engage them with exoplanet research. Until today, we have used these tools to train astronomy undergraduate and masters students in Greece and in the UK. We aim to extend this effort, evaluate its effectiveness and identify the best strategies. Finally, this will enable us to produce some general results with regards to Citizen Science and Space/Astronomy Education using as a case study the project *ExoWorlds Spies*.

VII. FUTURE WORK

In the near future, we will organise meetings and workshops for people and students who want to get trained and start analysing data. We will also carry out more observations using the equipment of the observatories we collaborate in Greece. We are open for contributions in our project either on the observation part or the data analysis. Our ultimate goal is to create a collective list of observations from transiting exoplanets to better identify their ephemerides and characteristics. At the same time, such an effort would contribute to future space missions dedicated on exoplanet research.

Acknowledgments

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Research-based education at BME

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***Abstract*— Budapest University of Technology and Economics (BME) is the leader in Hungarian technical higher education. At the more than two centuries old BME, several researchers and development engineers pursued their education or work who attained world-class achievements in the area of modern space research. By 2012, numerous Departments and research groups have been performing space research, implementation and education activities at BME, therefore a Space Forum was established at BME to coordinate all activities in this field along a jointly worked out strategy. This coordination creates the basis of building-up a common research-based education system at BME. We identified and evaluated our current educational capacities and conditions, and we are preparing to work out a space engineering specialization at BME. In this paper we report our first steps in this process.**

***Keywords*— space education; research-based education; Space Forum; space engineering**

I. Introduction

BME is the leader in Hungarian technical higher education. On the international level, BME is a renowned university of the Central and Eastern European Region. Its diplomas are recognized throughout the world. From among its excellent students, three were awarded Nobel Prize: György Oláh (1994), Dénes Gábor (1971) and Jenő Wigner (1963).

II. Outstanding Record of BME in Space Activity

A. World-class achievements in space research

At the more than two centuries old Technical University, several researchers and development engineers pursued their education or work who attained world-class achievements in the area of modern space research.

A few outstanding personalities from the long list: Tódor Kármán - known in the world as the father of rocket technology - obtained his mechanical engineering diploma in 1902 and lectured for years at the Royal Joseph University - entitled to issue doctoral degree in engineering - as it was called then.

Zoltán Bay, leader of the 1946 ground-breaking Moon radar experiment, established and headed the Department of Atomic Physics at the Technical University.

Ferenc Pavlics, who received his diploma in mechanical engineering in 1950, became famous for being the development engineer of the first extra-terrestrial vehicle, the Moon rover used in the Apollo program.

Gyula Tófalvi, who in 1958 won the Grand Prize of the Brussels World Fair with his ionospheric research equipment, was among the first to obtain electrical engineering diploma at the University.

Antal Bejczy, developer of the remote-control engineering for the Mars Pathfinder, studied at the Faculty of Electrical Engineering until 1956.

Ákos Detrekői, the internationally renowned expert of geoinformatics and remote sensing, remained with the Technical University from receiving his civil engineering diploma through his entire professional career.

The first Hungarian astronaut Bertalan Farkas has close ties to the Technical University: researchers graduating from or working at BME participated the preparations of several experiments developed by Hungarians on the Salyut-6 space station (1980), and he obtained his diploma in engineering at the Faculty of Transportation Engineering of BME.

The second Hungarian to enter space, Charles Simony, living in the USA, also has connections to BME: his father, Károly Simonyi was an outstanding lecturer of BME VIK (Faculty of Electric Engineering and Informatics), and Charles established radio contact with BME during his space flights (2007 and 2009), and later visited the Masat-1 development team at BME.

B. BME building blocks of Hungarian space successes

In 1961, organized by Csaba Ferencz, a third year BME electrical engineering student, the Rocketry Student Scientific Circle started its operation at BME, which became BME Space Research Group in 1965. In 1966 – first in Central Europe and with their own developed equipment - they received images of weather satellites.

András Gschwindt graduated from BME as electrical engineer in 1965, has been very successfully heading the Space Research Group since 1970. A Soviet satellite took one of their own equipment, a power supply unit to space already in 1973. Up to date, they have manufactured equipment for fifteen satellites, two comet probes (Vega and Rosetta), and the Mir space station. None of these equipment was faulty. In 2009, under his professional guidance, the construction of the first Hungarian satellite, Masat-1 commenced.

István Apáthy also graduated from BME as electrical engineer (1969), familiarized with space research and soon started working at the Research Centre for Nuclear Energy of Hungarian Academy of Science. The further development of the most successful Hungarian space device, the Pille dosimeter, is connected to his name. The first Pille instrument was used by Bertalan Farkas on-board the Salyut 6 space station in 1980. Later versions of Pille were taken aboard US space shuttles, the Russian MIR space station and the International Space Station. The second Hungarian astronaut, Charles Simonyi also used it.

János Solymosi worked as development engineer from 1983 in the Space Research Group of Department of Microwave Infocommunications of BME. He participated the development of several on-board satellite space devices, among them the historic VEGA program. He is the founder and leader of Hungary's largest space industry firm, Bonn Hungary. Their equipment is present on the International Space Station and a number of satellites, what's more, they participate India's Mars program, as well.

III. BME Space Forum

At the Faculties of BME, numerous Departments and research groups perform space research, implementation and education activities, from theory research through the practical manufacture of diverse devices and services, to undergraduate and graduate level education. Recognizing the lucrative opportunities in harmonizing the work of the numerous individually operating research groups, a few years ago three departments undertaking space activities established the BME Space Forum and offered participation in the Forum's work (joining) for all organizations and research groups of the Technical University.

BME Space Forum operation and management is performed by the Federated Innovation and Knowledge Centre of BME (BME EIT). Head (president) of Space Forum is Dr. Kálmán Kovács, director of BME EIT; deputy head is Dr. László Bacsárdi.

BME EIT was created at the Faculty of Electrical Engineering and Informatics of BME in 2009 to stimulate the research and development activity and the utilization of the research results at the Faculty and to be able to do the same at the university level. BME EIT operates as a R&D service center. Its major tasks are research coordination and project management. Since 2010, BME EIT has managed 28 projects in the value of 27 M EURO and employed about 2,200 persons in 5,500 contracts. One of the most significant topics coordinated by BME EIT is the space activity (research, application and education) of BME.

IV. Research-Based Education

There is a long tradition of research-based education in space science at BME. It supports not only several successful personal careers but ensures remarkable contributions to the build-up of institutional and business entities of Hungarian space research and technology.

Currently, 73 Departments of the 8 Faculties encompass the research & education activities of BME. From among these, 12 Departments of 4 Faculties are members the Space Forum. Participants of Space Forum joined voluntarily. It is their common objective that the various space activities performed at BME should not be dissipated, but all activities in this field should be coordinated along a jointly worked out strategy.

Space Forum represents its member organizations in a uniform manner towards BME's current and future partners, and initiates cooperations that may significantly contribute to the more efficient utilization of the University research and educational capacities.

BME is a research university by mission, and its primary task remains the provision of high-level training of mechanical, IT and natural science engineers as well as economic, business and management professionals. As we detailed above, the education of technical and scientific fundamentals of space activity has been a considerable part of the curriculum for decades at various Faculties of BME.

V. BME Space Forum Members and their Research and Educational Activities

Currently, there are about 20 courses at 4 faculties in this area on undergraduate (BSc and MSc) level, coordinated by BME Space Forum. Moreover, the members of the BME Space Forum offer participation in ESA educational experimental programs and NASA student exchange programs, as well.

A. Faculty of Civil Engineering

BME Space Forum has two participating departments from the Faculty of Civil Engineering.

1) Department of Geodesy and Surveying

BME Space Forum representative is Dr. Szabolcs Rózsa, associate professor, the head of the Department.

Space activity of the Department is marked by satellite positioning system theory and the research of its application for Earth observation, navigation and the maintenance of geodetic reference frames. The Department has been operating a continuously running GNSS (Global Navigation Satellite Systems) reference station since 2000, which observes GPS, GLONASS, Galileo and EGNOS satellites.

Further key topics include modelling Earth's gravity field with space gravimetry and space gradiometry, and the examination of recent crustal motion and deformations with satellite navigation systems.

The Department offers three subjects: “Satellite positioning” for BSc students, “Satellite geodesy” and “Global navigation satellite systems (GNSS) theory and applications” for MSc students. Practices in the Department's Open source GIS software systems laboratory supplement the curriculum.

2) Department of Photogrammetry and Geoinformatics

BME Space Forum representative is Dr. Árpád Barsi professor, the head of the Department.

The Department has been actively using and researching the cartographic and other engineering application of remotely sensed images since the 1970's. For GIS system applications, these images can be regarded as essential sources of information both for altitude conditions of the Earth surface and land cover analysis. It comes from the above that space remote sensing, processing of satellite images are an integral part of the Department's teaching and research work.

In education, they perform the theoretical and practical presentation of remote sensing methodologies and applications on BSc and MSc level, and the recent questions of environment and remote sensing in MSc level and in PhD doctoral school. Their curriculums include practices in Photogrammetry Lab in the field of remote sensing, GIS, photogrammetry, Earth observation, intelligent transport systems, etc.

B. Faculty of Electrical Engineering and Informatics

The BME Space Forum has the most significant ratio of participating Departments from the Faculty of Electrical Engineering and Informatics (VIK).

1) Department of Broadband Infocommunications and Electromagnetic Theory

BME Space Forum representatives are Dr. Lajos Nagy associate professor, the head of the Department and Dr. László Csurgai-Horváth associate professor.

Space research and education of the Department has a history of 40 years that saw equipment developed here entering space in more than 20 space missions. Major research-development directions: power supply/distribution systems of space vehicles, on-board telemetry transmitters and receivers, measurement-data collection, ground service equipment, ground receiver and control stations, space technology construction and thermic problems, and testing of millimeter wavelength radio wave propagation and application for communications.

Connecting to ESA's educational programs, their students can take part in a number of space research programs that include high altitude rocket and balloon experiments, and the development of on-board systems and experiment instrumentation of educational satellites.

Following the recent successful completion of the Rosetta comet research program, the Department currently participates a wave propagation and a communication experiment in the ESA Alphasat program, and - also in the coordination of ESA, as well as ALMASpace - the development of the power distribution unit and a plasma diagnostic instrument of the ESEO small satellite. In a cooperation project, our Department takes part in the radar image processing of the ESA Sentinel-1 space probes.

In undergraduate level they offer two subjects: "Space technology theory and practice" for BSc students, and "Space technology practice and lab" for MSc students. And they efficiently manage the participations of their fellows in ESA educational programs, too.

2) Department of Electron Devices

BME Space Forum representative is Dr. András Poppe associate professor, the head of the Department.

As a unique range in Hungarian education-research, the activity of the Department covers areas from semiconductors through nanotechnology tools to the theory and practice of encapsulated systems, all these supported by computerized design systems. In the area of space activities, the superior proportion of participation in the manufacturing of Masat-1, the first Hungarian produced satellite, is an outstanding achievement of the Department.

Following the success of Masat-1, the Department is engaged in continuing the Masat program, not only by building and testing (e.g. heat load) satellite subsystems, but by offering subjects with topics "Thermal analysis tools" and "Control electronics technologies", and practices at Thermal analysis and tests Laboratory.

3) Department of Electronics Technology

BME Space Forum representative is Dr. Tamás Hurtony assistant professor.

The Department's space activities primarily encompass the areas of micro- and nano-electronic technologies and thermal analysis.

They have achieved successes in several ESA educational programs and projects (BEXUS, ESEO, REXUS) and have efficient cooperation with ESA Education Office. They also offer opportunity to their students to get involved and to have practice in their spin-off company, EFI Services Ltd.

4) Department of Networked Systems and Services

BME Space Forum representative is Dr. László Bacsárdi associate professor.

The education and research topics of the Department include fixed and mobile communications, as well as quantum computing and communication.

Space related research includes high-reliability measurement sensors moving autonomously on remote celestial body surface, under extreme conditions, with scarce power resources and lack of maintenance, as well as secure quantum-based satellite communication.

They offer subject at MSc level in Quantum communications, and practices at their Mobile Communications and Quantum Technologies Laboratory.

5) Department of Measurement and Information Systems

BME Space Forum representative is Dr. Ákos Horváth associate professor.

The Department participates space activities primarily via software technologies and secure systems operation areas. The subjects offered in space related technology are "Critical embedded systems" and "Cyberphysical systems", both for MSc students.

6) Department of Telecommunications and Media Informatics

BME Space Forum representative is Dr. Klára Vicsi scientific advisor.

The Department is involved in the research of convergent telecommunications, information and media technologies. In the area of space research, the most significant activity is performed by the Speech Acoustics Group of the Department in the COALA program. The Department performs psychological status monitoring by computerized analysis of language phenomena.

In education, the subjects “Data mining and media content recognition” and “Speech technology and media content recognition” offer space application content.

C. Faculty of Mechanical Engineering

BME Space Forum has two active members from the Faculty of Mechanical Engineering.

1) Department of Mechatronics, Optics and Engineering Informatics

BME Space Forum representative is Dr. Krisztián Samu associate professor, deputy head of Department.

Key education and research areas of the Department are mechatronics, optics (with related human sight and imaging systems), and the technology of robotics, remote control and submicron measurements.

Space activities have increased at the Department in recent years, mainly in the field of joint development and manufacturing of space quality optical imaging tools – in cooperation with the German Max Planck Institute –, and in the area of development of NIR spectroscopic tools and electromechanical devices. They offer “Optical systems design” studies for BSc students.

2) Department of Applied Mechanics

BME Space Forum representative is Dr. Gábor Stépán professor, member of Hungarian Academic of Science, the head of the Department.

The Department performs space research activities in the following areas: space vehicle navigation and orientation control (gyroscopic control), development of special robotic systems and special need mechanisms, planning of reconnaissance and landing units and planetary surface vehicles (rovers).

Parallel with their research activities, they recommend their MSc students special courses as “Design and manufacture of autonomous surface explorer robots” and “Small satellites directional stabilization”. The Department has an outstanding machine tools vibrations and vibration measurement Lab.

D. Faculty of Transportation Engineering and Vehicle Engineering

The Faculty of Transportation Engineering and Vehicle Engineering is also represented in BME Space Forum by two Departments.

1) Department of Control for Transportation and Vehicle Systems

BME Space Forum representative is Dr. Péter Gáspár professor, the head of the Department, member of Hungarian Academic of Science.

Space competences at the Department currently include GNSS systems appearing in the areas of education and research, but their experiences cover applied missile control theory implementation, as well.

They offer curriculum in automatic on-board control systems theory and applications in MSc level.

2) Department of Aeronautics, Naval Architecture and Railway Vehicles.

BME Space Forum representative is Dr. Dániel Rohács associate professor, the head of the Department.

For decades, the education of space dynamics has been successfully conducted in the area of space research, but research in the areas of propulsion and flight dynamics, as well as autonomous aircraft are also significant.

The Department is very active in education. They have three courses: “Special Propulsion (Rockets, Ramjets, Scramjets)” for BSc students, “Aerodynamics and Flight Mechanics” for MSc students and “Space Dynamics” in both levels. The curriculums contain measurements and practices in laboratories as Aero-thermodynamics Lab and Flight Simulator Laboratory.

VI. New Generations of Professionals

BME is a research university by mission, and its primary task remains the provision of high-level training of mechanical, IT and natural science engineers as well as economic, business and management professionals. As we detailed above, the education of technical and scientific fundamentals of space activity has been a considerable part of the curriculum for decades at various Faculties of BME.

Currently, there are about 20 courses at 4 faculties in this area on undergraduate (BSc and MSc) level, coordinated by BME Space Forum. Moreover, the members of the BME Space Forum offer participation in ESA educational experimental programs and NASA student exchange programs, as well.

Space research and space industry (including space services) require qualification not only for the professional staff; it is necessary for the utilization for society that knowledge is built in primary and secondary education, as well. The first steps have been taken in recent years. Space activity, beyond the above, requires special training, as well, in Hungary, as an ESA Member State.

In the future, BME Space Forum could assume significant part in the above educational, training tasks. However, the establishment of the laboratory infrastructure of BME necessary to the education, training aligned to ESA engineer/researcher requirements (ESA qualification, space qualification, AS-9100 quality assurance) is yet needed. It is an encouraging result in the area of young researchers that the number of students selecting space research courses has increased at BME.

Year to year several space and space related research topics – e.g. satellite positioning systems, satellite orbit modelling, space dynamics and space communication, as well as Earth observation, climate, precision agriculture, future mobility, smart city services, model-driven engineering, etc. - have PhD students, what's more, the majority of them are involved in space research projects.

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Towards a new Horizon for Planetary Observation in Education

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"Man must rise above the Earth – to the top of the atmosphere and beyond – for only thus will he fully understand the world in which he lives". The famous quote by the Greek philosopher Socrates anticipates the importance of space travels and earth observation techniques for the research of coupled human-environment systems. The projects "Columbus Eye - Live-Imagery from the ISS in school lessons" and its follow-up project "KEPLER ISS" bring the view of astronauts on our Earth into classrooms using NASA HDEV Experiment video material to teach students about STEM topics in an interactive, intermedial and interdisciplinary approach. The next step is widening the horizon towards the Earth-Moon system and beyond, teaching the students about geographic information systems and their use in exploring not only our own planet, but others as well.

Keywords—earth observation, ISS, horizons, school contest, augmented reality

I. Introduction

Capturing pupil's attention for natural sciences is a difficult task due to the high complexity of the material and the high degree of abstraction in natural sciences. However, humans have a deeply curious nature, especially when they are young [1], and (manned) spaceflight has a high potential to evoke fascination for the involved sciences. The projects Columbus Eye and KEPLER ISS use the view of Earth from space and the International Space Station (ISS) to keep the pupils curious in order to foster methodological competences, mainly in secondary school lessons [2]. The material is also popular with university students in their Remote Sensing (RS) beginner's courses and is used to catch up on the mathematical and physical basics of satellite image analysis.

So far, the data basis of the learning materials are videos from the NASA High Definition Earth Viewing (HDEV) Experiment that is used to provide teachers, pupils and anyone interested with free, accessible, fascinating videos of the Earth and easy-to-use software [3,4,5]. Propaedeutic learning happens on the fly while the pupils find out more about the interconnections between human activity and various Earth ecosystems, resulting in a deeper understanding of coupled human-environment systems as well as scientific methods [6].

The following paper describes how HDEV video material is currently used to create school materials, how data from other earth observation sensors aboard the ISS will be used in future lessons, the technical and didactical background of the material, and the development of the new Augmented Reality (AR) app that introduces the pupils to our Moon.

II. ISS-borne Sensors in Education

A. HDEV – High Definition Earth Viewing Videos

The NASA HDEV Experiment started in 2014 when four commercial off-the-shelf cameras were installed at the Columbus External Payload Adapter of the ESA Columbus module to determine how well they could withstand the harsh conditions in space [3]. They continuously record the Earth from space at three different viewing angles (fore, nadir, aft) with a spatial resolution of about 500 m (in nadir, depending on ISS orbit parameters). However, due to the static zoom, lens and light sensitivity settings of the cameras, night-time recordings only show black and the lenses are not fit to directly face the sun, which occurs to the fore and aft cameras when the beta angle of the ISS is below 32 degrees. The cameras are operated in an automatic camera cycle, allowing only for one camera to record data at a time. This cycle can be modified to track objects or events on the ground through the different angles of the cameras [4], which the Columbus Eye project is allowed to do.

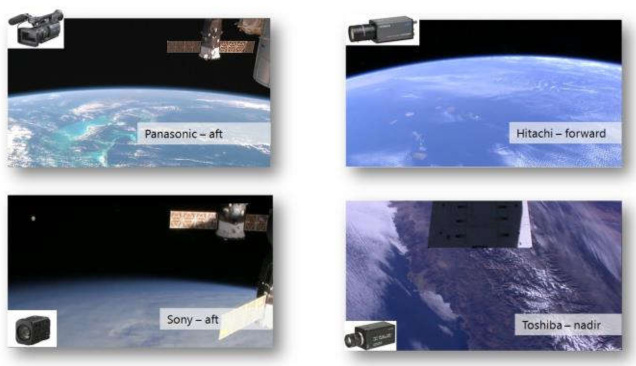

Fig. 1. View from the cameras of the HDEV Experiment (Source: NASA)

Transferring the continuous data stream from the ISS to the Columbus Eye servers, where they are stored exclusively, works via NASA's Tracking and Data Relay Satellite System (TDRS) and the Telescience Resource Kit (TReK) [7]. The original videos are divided into 1-hour segments for easier handling and pre-processed in MATLAB to reduce Mie and Rayleigh scattering. An atmospheric correction is not possible due to the availability of bands: The commercial off-the-shelf cameras only provide red, green and blue channels, no IR or UV. More than 200 highlight videos, 2 AR apps, 6 work sheets and 4 digital observatory lessons based on this data are provided on the website (http://columbuseye.uni-bonn.de/).

While night-time videos are not possible with HDEV, the Japanese project Meteor (operational, launched in March 2016) uses an ultra-sensitive CMOS colour high-resolution camera to detect meteors on the dark side of the Earth. Just like HDEV, Meteor uses consumer products. However, it does not stream its videos continuously, as the data transmitting capacity is not sufficient. Only videos containing meteors are transmitted to Earth [8] and can be turned into learning materials.

B. *ISS Earth observation sensors*

Besides HDEV, there are and were many Earth RS missions based on the ISS, some of which provide their data online for free. Three sensors were identified which are especially suited to create learning materials from. Data from these sensors will be processed into Mini-MOOCs aimed at pupils in secondary and tertiary education as well as decision makers in governmental institutions.

The Hyperspectral Imager for the Coastal Ocean (HICO) provided Hyperspectral data to perform scientific research not only in coastal marine environments, but also around inland lakes, rivers, and estuaries. The main goals however were to analyse coastal water clarity, bottom types, bathymetry and on-shore vegetation maps [9]. The sensor was active between September 2009 and September 2014, when a solar storm damaged the sensor too severely to resume operations. Over 10,000 images were taken during that time, some of which are suited to demonstrate coastal pollution, weather phenomena and harmful algae blooms to our target groups.

The Cloud-Aerosol Transport System (CATS) investigation used a LiDAR instrument to provide range-resolved profile measurements of atmospheric aerosols and clouds [10]. The sensor was active since January 2015 but had to cease operations in October 2017 due to technical issues with the payload system. Highlights of the data are provided with background information on the sensor's website. This data will be used to visualise anthropogenic and natural atmospheric pollution in our Mini-MOOCs.

The Rapid Scatterometer (ISS-Rapid Scat) was a radar instrument used to measure near-surface wind speed and direction over the ocean [11] and acted as a quick and cost-effective replacement for NASA's QuickScat. It was launched in September 2014 but suffered a critical power failure in August 2016. Its data will be implemented into our Mini-MOOCs about RS methods and about ocean processes.

III. Educational Principles

RS of the Earth's surface as a tool in school lessons has only rarely been used in the past although teaching pupils to interpret and analyse such imagery is requested by international education standards [12, 13]. Pupils are expected to benefit from the use of air- and spaceborne sensors' imagery due to the excellent visualization of various topics and the increase of important competences, such as spatial orientation, scientific workflow, literacy, responsibility and decision-making [14].

Columbus Eye's and KEPLER ISS' learning materials aim to do just that. The didactical concept of the projects' learning materials is based on interdisciplinarity, interactivity and intermediality, combining them in a moderate constructivist approach [14, 15]. The pupils' abilities to transfer knowledge and solve problems autonomously are improved when learning with the material: They are given a topic and a problem, the necessary interactive tools to analyse it and have to find their solution themselves [7].

Each of the learning modules comes with a work sheet for the pupils as well as sample solutions and a didactic commentary for the teachers, giving them background information and help with the implementation of the material into their lessons. The learning material is based on ISS- and satellite-borne RS data and thus is strongly associated with Geography lessons. However, other STEM subjects like mathematics, physics, biology, and computer science contain necessary background knowledge to understand the possibilities and methods of RS [17] and are included in the material subsequently.

E-learning techniques are unavoidable when teaching about methods in RS. Thus, online tools were programmed specifically with the intention of conveying RS methodology basics to pupils in an approachable way, compared to professional RS software that requires expensive hardware, often is expensive itself, and needs to be taught to the teachers extensively. These interactive tools are a highly specialized alternative for the given tasks, ensuring quick and easy comprehension of the application for teachers and pupils alike. Teachers receive additional material explaining the tools as well as background information about the methods, topics, objectives, and sample solutions to ensure easy integration into their curricula and individual lessons.

Mobile learning (M-learning) takes this one step further, taking advantage of the anywhere, anytime availability of smartphones and other mobile devices by focusing on the mobility of the learner and their interaction with learning environments. AR apps are an important part of this as they enhance real surroundings with virtual context, adding information in the form of images, videos, maps and more [16]. Educational AR apps and research have become more prevalent only in the past few years [18], since mobile devices like smartphones and tablets are available to everyone [19]. STEM AR apps are especially popular due to their positive effects for the pupils. Capturing their attention becomes easier due to their enjoyment and interest for the topic rising. Additional benefits are enhanced learning efficiency, cognitive skills, attention, confidence and social interaction between the pupils [18].

All of these benefits come with very little expenditure, time, and effort for the schools. Compared to many STEM experiments, AR apps need hardly any space and even less equipment – only technology that most pupils already have access to and use on an everyday basis [19]. While a class trip to space is not practicable for the foreseeable future, an AR app to watch and analyse videos of Earth from space is just a download away.

IV. Technical Implementation

A. Digital Learning Modules

Both the observatory and the downloadable learning modules are based on Flash technology. The observatory consists of images extracted from HDEV material, embedded in a slider window with a zoom function. Landmarks and other interesting objects in the images (whether they are directly visible in the resolution or not) are marked in the image. Clicking on the markers reveals images and additional information about the phenomena. Pupils create a map from the image by adding a new surface type, then define it through areas of interest and a colour and text description. The map is created from several of these areas of interests with a Minimum Distance Classification. No pre-defined solution is provided; each pupil receives a different result based on their classification parameters.

The downloadable learning modules contain work sheets, teacher materials and HDEV videos. The “Stereoscopy” module provides additional images to experiment on colour channels and create anaglyph images using complementary colours and the free software GIMP. The “Scattering and Colours in the Atmosphere” module contains a Flash-based swipe-tool to compare the unprocessed HDEV material with the same video processed to reduce Rayleigh and Mie scattering. The “Calculating the Mean” module contains a complete lesson as a Flash module that teaches about calculating the arithmetic mean and the method’s uses in RS. Images from HDEV are filtered in the tool by the pupils, compared in a swipe tool, and their pixel values displayed. The lesson module also contains quizzes and background information.

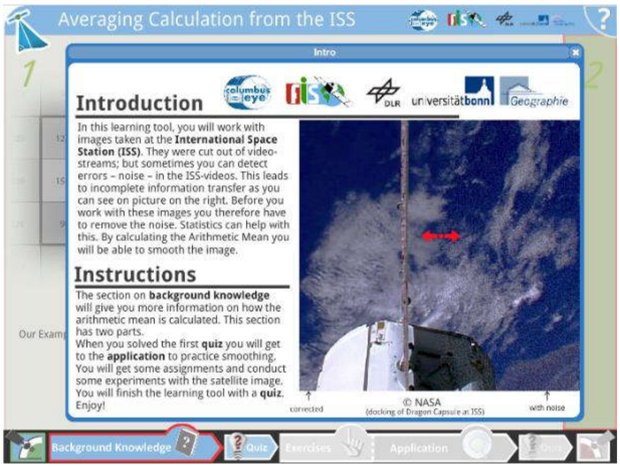

Fig. 2. Mathematical thinking and remote sensing methods in the module “Calculating the Mean”. The filtered image is on the right, the original image on the left side of the image.

Due to the end of Flash development and support by the developer Adobe, the modules will be transferred into the successor software, HTML5/JavaScript.

B. Augmented Reality Applications

The AR apps are created with Unity 5.6 with the Vuforia extensions, allowing building Android and iOS apps [20]. The apps work only in combination with their corresponding work sheets as these include geometrical markers. These are detected via the built-in cameras of smartphones. The quality of the marker’s print, including whether it is printed in monochrome or colour, the final size on the sheet, or even whether it appears on another device or projection, does not matter for the apps to work. The marker detection works via edge detection, making the only requirement for the marker images a high number and an equal distribution of sharp edges.

When the marker is detected by the app, a video incorporated in the app is triggered. Image extent and position of the marker are passed on to the video handler. On their smartphone screen, the pupils see most of the work sheet the same way it appears to their eyes, but the geometrical marker – usually part of the info material – is replaced by the video material and animations. Working with different layers, the ISS videos can be annotated with additional information used for the tasks in the work sheets. Analogous and digital information are combined.

There are two AR apps published so far: “The Eye of the Cyclone” that features an HDEV video of Typhoon Maysak, annotated with air pressure data, and “Aralkum – A Lake disappears” that features an HDEV video of the Aral Sea and an animated time series created from Landsat data spanning the years 2000-2016. Both apps come complete with worksheets for the students as well as a didactic commentary and example solutions for the teachers. The Cyclone package can be found at columbuseye.uni-bonn.de/English/. The Aralkum package is only available in German at the moment but will be translated into English in the near future.

V. From the Earth to the Moon and Back

The new AR app “From the Earth to the Moon and Back – Gravity in the Earth-Moon System” and its corresponding worksheet will teach pupils about the effects of gravity on Earth. It is aimed at advanced physics lessons in the latter high school years and covers parts of the German curricula on gravity and Kepler’s laws of planetary motion. The effects are demonstrated by their influence on the Earth’s surface, connecting Physics and Mathematics with Geography. An image of the Earth, hanging in space, works as a marker. To improve image detection, additional objects with a high amount of sharp edges are included, like serif-rich text and a scale. The app overlays the detected Earth image with a low-resolution three-dimensional model of the planet on the screen. Using a standard directional light asset representing the Sun, a Moon placeholder and the marker, an eclipse is simulated or misses the Earth, depending on the angle and distance between the device and the marker.

The distance between the device's camera and the Earth marker is also used to demonstrate the gravitational effects of the Moon on the tides. The device in the hand of the pupil represents the Moon and the distance is calculated relative to the size of the printed Earth marker, meaning it is always true to scale, even when projected on a wall. In standard DIN A4 print, the scale is a practicable 1:100,000,000. Depending on the distance to the marker sheet, a UI layer shows the high and low tides on Earth, exemplarily using a section of the German Bight. The data basis is a Digital Elevation Model (DEM), combined from ASTER GDEM [21] and Bathymetry data of the North Sea [22] and Baltic Sea [23]. While Unity is not predestined to process geodata, the elevation information can be extracted via grayscale and used to display ocean extent depending on the distance of the 'Moon'. However, exact tide modelling is not within the means of the programme, nor is it necessary for the objective. The process is thus simplified, depicting the sea level at high and low tide under the influence of a closer or further Moon.

The pupils are to observe the tide differences and identify the cubic dependency between the distance between the two masses and the gravitational force, resulting in a similar dependence of the maximum tide difference. They are also to discuss other factors that have an influence on the tides, beginning at the other components of the gravitational force and including, but not stopping at, density differences in the affected materials, and local topography.

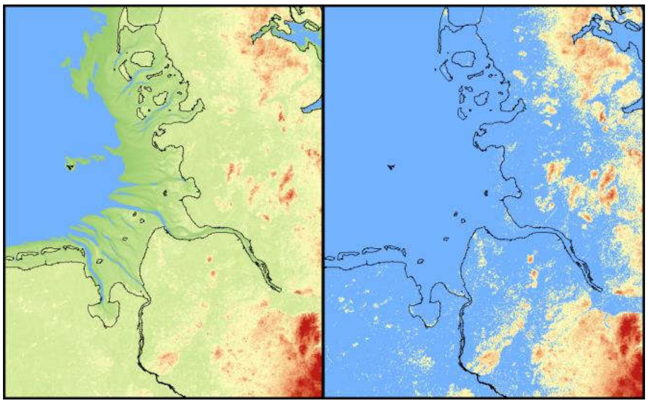

Fig. 3: Preview of images in the new "From the Earth to the Moon and Back" app. Depicted is the approximate sea level at low (left) and high (right) tide in the North Sea at an Earth-Moon distance of 100,000 km.

The app and work sheet will further the pupils' understanding of physical and mathematical principles of everyday phenomena, encourage them to observe, deduce and test their theories, perform thought experiments, and use modern technology in an educational context. On top of facilitating scientific thinking, the pupils' attention should be increased by the interactive, interdisciplinary and intermedial lessons.

VI. Conclusion and Outlook

Theoretical and practical knowledge of the natural sciences is important for pupils to learn, but it is more effective to teach it in a way that fascinates them and sparks their interest enough for them to consider careers in STEM. Earth Observation from manned space flight like the ISS combines a wide variety of STEM fields with inherent fascination and curiosity in many pupils and teaches them about the interconnection of earth's various ecosystems and the effect of human activity on them in the process.

The Columbus Eye and KEPLER ISS projects provide easy-to-use learning materials on the website (columbuseye.uni-bonn.de/) in German and English language. A great number of teachers and pupils can access the learning materials easily due to the distribution via new media, the use of widely available software and technology as well the absence of charges. This allows for efficient and inexpensive experiments that the whole class can conduct simultaneously and autonomously, enhancing learning efficiency, cognitive and social skills of the pupils. Using new technology like AR additionally improves the pupils' interest and attention in the given topics.

New materials will use additional sensors aboard the ISS and widen the horizon from observation of the Earth, to the Earth-Moon system and beyond. A future extension of the Moon lesson in the form of a digital learning module will focus on the use of GIS in Space Exploration: A DEM of the Moon will be combined with spectral data to determine possible locations for lunar stations. The pupils will assume the roles of space exploration researchers and will be confronted with the challenges and determination process currently under way [24] to help them understand how the scientists involved come to their conclusions and show them possible careers in Space Exploration.

Acknowledgment

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MATRIOCHKA, Adventure and Achievement of a two-stage rocket made by French students from ESTACA

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Abstract*—Matriochka is a rocket built by a student team from ESTACA, a leading French school in space engineering. This project was a challenge because the rocket was designed and built by ourselves in our free time. Matriochka has two main specificities: two stages (Stimulus & Reflex) and a reusable stage. The rocket was launched during the C'Space, the French launch campaign for amateurs. Clubs from all over the world come each year to launch rockets, cansats and balloons. This main event is organised by CNES, the French space agency and Planète Sciences. Matriochka was an atypical project for the C'Space because since 1997, 10 two-stage rockets were designed for this campaign but only 5 were launched and only 2 were allowed to ignite the second stage (the first one was a Japanese rocket in 1997). Therefore Matriochka was the third one with a second stage ignited and the first one with all securities compliant to CNES requirements. Then, Matriochka was also unusual because of fins configurations: profiled fins for Stimulus (1st stage) and circular fins for Reflex (2nd stage). Unfortunately the software used by the CNES was not able to validate these concepts. We had to create new validation methods and test extensively to convince them. Moreover, Stimulus was designed as a reusable stage: robust structure, limitation of the consumable products, and maintenance minimisation between two launches... In fact Reflex was a rocket itself and we would like to offer Stimulus to embed rockets from other clubs as 2nd stage! That is why Stimulus was made flexible. We can adapt the fins (size and position) for the stability and we designed standard interfaces between both stages. Last particularity was the context. Actually engineering work and 90% of the rocket was performed by the team (carbon composite, aluminium manufacturing, nosecone customization, assembling...) and 10% provided by sponsors and crowd funding. Matriochka was launched successfully in Tarbes (France) on the 23/07/2017 and all data (measurements and videos) validated the concept: stages' separation, recovery systems, flight sequential with safety conditions and stability of both stages. Finally, everyone learnt so much in technics, management, system engineering, manufacturing, outreach... For us the project was an adventure and the result was a reward from all of efforts provided! Now we are ready to use these results, maintain the launcher and launch again. To summarize Matriochka was a mix of challenge, humility, work and fun!

Keywords*—*amateurs rockets, two-stage rocket, innovative project, challenges, C'Space

I. Introduction: First active two-stage reusable rocket of our organization

Matriochka is a rocket built by a student team from ESTACA, a leading French school in space engineering. This student project, which was started in 2015 and launched in 2018 (successful flight), is a two-stage reusable rocket close to 3-meters long and whose 2nd stage is a mini-rocket. Matriochka is defined as an « active » two-stage rocket: meaning that the mini-rocket has a loaded engine which is ignited at separation time (2nd stage is not inert).

2nd stage separation was based on a concept of « hot separation » : the mini-rocket was ejected only using its engine's thrust (Cariacou engine, average thrust of 150N and burning time close to 1s). This configuration of « hot separation » has never been tested on former two-stage projects from our student organization, Matriochka was the first to choose it and use it with full success.

We wanted the launcher to be simple, in order to be consistent with our reusability objective and to minimize phases of maintenance. Moreover, the "heat jettisoning" gets as main advantage the limitation of failure modes which are specific to ejection (mini-rocket is ejected as soon as its engine is ignited, there are no complementary systems as an actuator or a spring for example). For safety reasons (protection of public and ground operators), it is necessary to set safeties up on electronic card which commands fire ignition of 2nd stage engine. This electronic card, connected to the 2nd stage engine, was subjected to strict qualifying requirements from French Space Agency (CNES) who is in charge of safety during the one-week launch campaign. In a few words, after RAMS trade-off, 4 safeties were implemented on electronic card which ignites 2nd stage engine: time window for stage separation, detection of thrust ending for the 1rst stage, hatch contactor in order to detect an untimely opening of hatch for recovery stage, and finally attitude control of launcher with an inertial measurement unit.

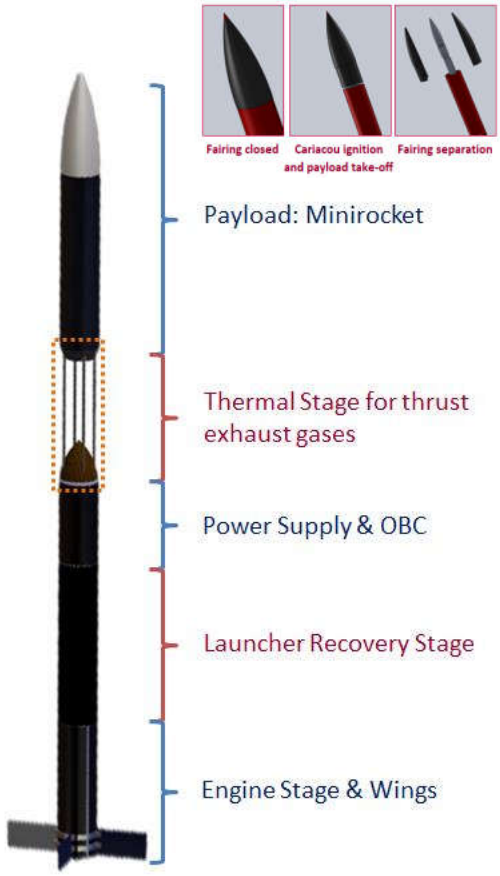

Figure 1: global view of Matriochka's architecture

An open architecture was chosen to make the exhaust of hot gases easier. The ignition of a Cariacou engine is indeed powerful (hot temperature close to 3000K).

Faced with this extreme temperature, several precautions were taken: a thermal protection made of cork was placed inside the carbon tube containing the payload, a wooden deflector was used as a consumable thermal protection for lower module, launcher paintings were all resistant to high temperatures, and a lithium grease was spread before flight on all launcher parts potentially affected by engine's flame.

II. C'SPACE PRESENTATION

"C'Space" is the French national campaign dedicated to experimental rocket launches (student projects). This event gathers close to 200 students each year. These students have various education levels (secondary school, students in engineering …) and most of them come from France, but the event also attracts student teams from Russia, Austria, Japan or Peru. The C'Space is supervised both by French national space agency (CNES, supplier of solid propellers and in charge of launches safety) and scientific organization Planète Sciences (coordination, projects follow-up, rockets quality control). The first C'Space edition took place in 1965. During this one-week event, experimental rockets (around 25), mini-rockets (around 30), CanSat (around 10) and stratospheric balloons take off from a launch area under French army control.

III. WHAT MAKES MATRIOCHKA UNUSUAL AT C'SPACE

Matriochka's team was built among enthusiastic participants of the C'Space launch. The team was therefore aware of how often and how smartly people already failed at realising two-stage rockets. The following conclusion was drawn: a two-stage rocket includes more sophisticated subsystems than a classic rocket. Consequently, the fundamental ground for Matriochka was to find a more rustic approach. All the game was not to create heavier problems while stepping out of the common paths… This provoked a few noticeably unusual characteristics.

Considering that an experimental rocket is an achievement only doable when given the appropriate resources and more demanding than small rockets, our secondary objective was to come up with a reusable first stage. The idea was to flight-prove it first hand with one of our own small rockets and then to offer other teams to fly their small rockets. They would then be able to put their small rocket to the constraints of an experimental rocket, thus learning at a cheaper cost how to realise reliable experimental rockets. Thus our concept needed to be both reusable and flexible.

To start with, C'Space is the only opportunity to launch experimental rockets in France, meaning that there are numerous other campaigns throughout the year launching smaller rockets. The most famous example is the international competition Rocketry Challenge with about 70 launches per year. Hence, attending the C'Space is not that common for French rocketeers. Moreover, even at C'Space two thirds of the launches actually are small rockets. So that launching an experimental rocket is an even less common achievement. Among these projects, two-stage rockets are even less common: from 1997 to 2017, 17 two-stage projects were conducted by different student teams – including one Japanese project. Unfortunately, an estimated 38% of them do not make it to the flight itself and some of them do not even manage to take part in the launch campaign at all. In addition, most of the projects that did fly were actually inactive: the second stage's engine was empty and not to be ignited. This launch was therefore only flight-proving technologies in the vision of a potential active flight. This inactive flight is part of the approval procedure to fly an active two-stage rocket but is also quite a hazard since close to 20% of the inactive flight outcome was one or both stages being destroyed on impact. All these factors lead to the fact that Matriochka only is the 3rd active two-stage rocket launched in France since 1990.

Classic staging consists in using the first stage as a booster with respect to the global launcher. Quite inappropriately, experimental rockets are slenderer than full size launchers. So that such an architecture applied on experimental rockets' diameter implies important dynamic loads on the inter-stage. This delicate subsystem often fails to maintain satisfyingly the overall rocket rigidness.

Figure 3: Classic design of a two-stage rocket (left) vs Matriochka (right)

Observing how difficult it was to solve this problem thanks to feedback from others projects, the Matriochka team decided to fully integrate the second stage inside the first one. On the other hand it implied to open the fairing of the first stage to let the second one to get out… Thanks to a deep understanding of fairing opening earned on previous projects the team was able to realise a reliable passive system, that was ground tested prior to the launch.

Early design phases lead to another break in the habits of two-stage rockets. The corner stone of Matriochka certainly was the safety analysis that began at system level as soon as the team was created. It was unanimously considered that a system was needed to achieve the separation of the stages, right before igniting the second stage’s engine. Considering the potential weight of such a system and the high complexity of realisation and operation it was decided to use the existing thrusting system of the second stage instead. Therefore, the second stage’s engine was put in charge of jettisoning the second stage as well as its primary role of thruster. This “heat jettisoning” concept made Matriochka unusual on a technical level but also regulatory: the inactive flight, intended to “flight-prove” the separation system and observe the impact on trajectory was pointless… Matriochka was then the first two-stage rocket to fly straight with an active second stage’s engine since the late 1980’s.

This heat jettisoning system also had a visual consequence. Since one of our secondary objectives was to minimize maintenance between two launches, the heat jettisoning was not to irremediably damage the first stage. The most reliable solution was to open up the volume where the second stage’s engine would ignite itself so that no damage was to be feared. As a consequence Matriochka flew with an open architecture between its lower part and the second stage’s volume.

Last but not least the fins configuration of both stages could not be validated using the standard validation tools. These tools are based on the Barrowman method, thus limited to flat two-dimensional fins. Consistently with our reusability and payload adaptability objectives, the first stage’s fins were profiled. This was part of an aerodynamic optimisation aiming at reducing their size; which allows to adapt their position along the launcher axis to keep it stable with a variety of second stages without disassembling the first stage’s fins.

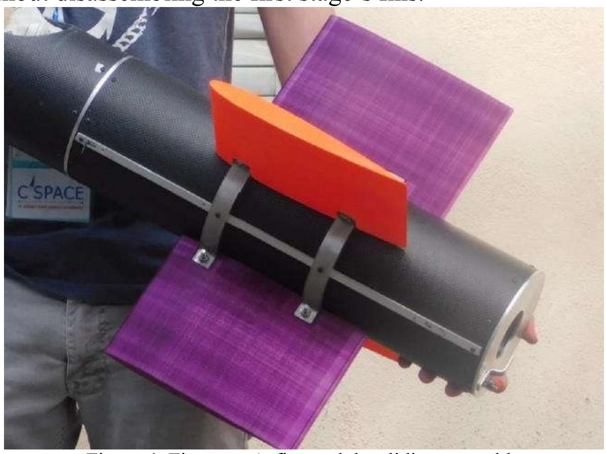

Figure 4: First stage's fins and the sliding assembly

Regarding the second stage’s fins the small half-span available was only creating a tenth of the mandatory lift gradient. Thus a solution came up as cylindrically-shaped fins allowing a greater fin area to fit inside the limited effective half-span.

The only limitation to the range of payloads that can be embarked on Matriochka’s first stage stands in the diameter of the second stage. It naturally depends of the first stage nominal diameter in relationship with the ability to design aerodynamically stable fins for the second stage. This max diameter was estimated to be 85mm.

IV. A VALUABLE EXPERIENCE FOR ALL THE “MATRIOCHKINS”

Designing and realising Matriochka enabled us to learn a lot. First of all, it was an impressive technical experience because at ESO (ESTACA Space Odyssey), the aim is to build by ourselves most of the subsystems. Then the early phases (phases 0 & A) of design represented the opportunity for everyone to give ideas and to elaborate concepts for the different sub-systems; a manner for each of us to lead our ideas from the concept to the results. Finally we used the ECSS basis to manage the project, another manner to learn how to lead a project through the European standards to be ready to join the space industry as engineers!

A. *Technical knowledge*

First of all, even if we developed Matriochka as engineer students, we did not stop the work with a fancy concept but we also built all the sub-systems, performed the integration, the assembly and then the tests. On this project we were the head but also the hands. Indeed this philosophy changed a lot the perspective of technical solutions because facing technical limits enabled us to criticize our early choices. Creating an impressive CAD is quite easy but there is a gap to achieve development of the functional system. Being an engineer and an operator at the same time enabled us to learn humility and concrete know-how. We made by ourselves for example: the carbon composite of the structure, the machining of aluminium parts (Two companies supported us for some aluminium parts because of the tolerances required), the electronics, the improvement of the nosecone with glass fibre, the footprint of the second stage inside the first stage's nosecone…

Moreover, all members were encouraged to give ideas during the preliminary phase without discarding any of them. Then we organized a meeting which lasted 2 days to present all ideas and to perform the first trade-off for the high level sub-systems. According to the first choices, the teams were created according to their skills and motivation. This method enabled to have on Matriochka a lot of ideas from all the members of the project by encouraging creativity first and by trading-off feasibility and challenge.

Finally we were introduced to flight safety and regulations. The design of most students' rockets in France is not affected by the regulations but two-stage rockets are. This kind of projects are quite rare that is why the risk is important: high altitude, high ground range, ignition of a second stage, dangerous or unpredictable attitude of the second stage… The regulations forced us to reconsider the electronics several times to comply with the last requirements (which arrived only in 2017, a few months before the launch). An experience teaching us to be reactive and flexible!

B. System engineering training

It was decided at the beginning of the project (in 2015) to use the European standard ECSS as a baseline to lead Matriochka. This method helped us to manage the project and to be trained to this famous standard.

Furthermore, we encountered some drawbacks to lead such a big group: how to communicate effectively? How to store information? How to share data and work all together? It was a good introduction to use and create tools to share planning, progress status, schedule, data… Even a database and technical notes were created to improve communication and knowledge transmission. Indeed, it was decided to write technical notes especially for specific operations and processes as if the entire team of the project would be replaced. The aim was to write theses notes for a hypothetic new team who would like to pursue our objectives. This reasoning made us aware of knowledge management priority and we are trying to transmit this method to our association ESO.

Then we used previous experiences and feedbacks from formers ESO members and projects. Learning from the past and from more experienced people is always valuable and we were really open-minded to pieces of advice. In addition, previous projects reports helped us especially to lead the trade-offs.

Finally we also had to face some planning and resources difficulties: because of academic or professional constraints, most of us had to leave France during a few months: Canada, Luxemburg, Holland, French Guyana, Sweden … In that context, everyone had to be aware of the importance of communication and information sharing especially when facing difficulties.

C. Matriochka is in the air!

Matriochka lifted-off on the 19/07/2018 in Tarbes! This flight validated the "heat jettisoning" and several other sub-systems. Both Stimulus (the first stage) and Reflex (the second stage) performed well.

The "heat jettisoning" was validated by the observation through 3 cameras integrated on Stimulus (one oriented upwards the jettisoning, one oriented downwards the fins and the last one inside Reflex's nosecone). Moreover, an inertial measurements unit collected all Stimulus data. These data were analysed and proved that the behaviour of Stimulus was safe and as expected by the simulations. This inertial unit validated the good functioning of all the safety barriers implemented in the electronics: Pro 54 burn-out detection, double timer, Stimulus attitude and recovery hatch closure checking. Other sub-systems were validated: adjustable fins, 3D-printed fins, cylindrical fins of Reflex, recovery of both Reflex and Stimulus (two different systems) and the ejection of Reflex.

Finally, a maintenance phase has been performed in order to prove the feasibility of re-configuration of Matriochka in a few weeks. The only tasks performed were: buying a new spring (lost during the fairing ejection), cleaning the rocket because of lithium grease used to protect the carbon fibre from the fire and adding a patch on carbon fibre near the recovery hatch (1cm).

D. Direct educationnal content

Matriochka was the topic of some integrated projects of the academic track of the ESTACA: firstly a final year project allowed 3 students to work on aerodynamics, structures and thermodynamics. This led to design and size the overall rocket, especially regarding the warm gases exhaust. Two third-year projects of integrated engineering process were conducted (TRL, weight budget and cost estimation of a jettisoning system for the first group and of the recovery system for the second group), as well as a safety and dependability project (RAMS analysis) embracing all systems during the whole lifespan.

As usual in our student society, Matriochka was a strong opportunity to practice project management in every aspect: team management, budget and resources planning… Rocketry skills were practiced by the team: fin stability, trajectory, sizing of critical subsystems such as parachutes and actuators (springs, magnetic locks and cylinders, but also commanding breadboards using transistors or integrated micro-computers. Last but not least, some sensors were used, as simple as switches checking discrete states and as sophisticated as a full IMU reconstructing the trajectory onboard the launcher in real time.

The typical know-hows of our student society were mastered: carbon and glass fiber tubes molding, aluminum and steel machining, assembling processes, breadboard manufacturing, carpentry (box containing the rocket during the transport)…

Finally some rather uncommon know-hows were applied: fairing opening elaboration, pneumatic system, pyrotechnic regulations…

NOTA: project full documentation can be distributed by contacting us on our emails or on Facebook and all photos and videos can be found here: https://www.facebook.com/matriochka.eso/

CONCLUSION

The flight of Matriochka was a full success and it enabled our association ESO to fly its first active two-stage rocket, a big challenge finally accomplished!

Energy, dynamism, pugnacity, team spirit, passion and fun were the keys of this great adventure. We learnt so much during these three years particularly that transparency and humility are keys to success, two last qualities that enabled us to keep questioning ourselves and putting things into perspectives.

Finally a wonderful adventure and an accomplished challenge together!

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NanoStar University Network: Hands-on higher Aerospace Education through Nanosatellite Student Challenges

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***Abstract*—NanoStar is a new network of universities and institutions that aims to provide students with a practical, hands-on experience in the development of nanosatellites. It does so by, first, establishing a catalogue of shared resources among the partners; second, by deploying the necessary computer infrastructure for collaborative engineering; and third, by developing a robust work methodology for the design, construction, and testing of nanosatellites. With these three elements operational, NanoStar will perform a first test-run of the concept with a series of student design challenges around a moon fly-by CubeSat mission.**

Keywords—nanosatellites, cubesats, university networks, student design challenges, concurrent engineering, space systems engineering

I. Introduction

Higher education in Space Engineering and related areas can largely benefit from a more hands-on approach, where students participate in real space projects. Practical experience is essential in the learning process for subjects such as project management, systems engineering, analysis and design of spacecraft subsystems, and testing, verification and validation. Additionally, group projects allow students to develop and hone their soft-skills for their professional careers.

Due to their affordable cost, availability of information and resources, and the non-negligible opportunities for an actual launch, nanosatellite projects are an ideal educational platform for universities to realize all the above. These projects can be used to motivate, attract, and retain the best talent to aerospace-related studies. Nanosatellites based on the CubeSat standard have also become a platform of choice for small-scale research, technology demonstration, and business demonstration projects. For these reasons, many universities are embarking on the design, construction, testing and launch of nanosatellites, and their number has increased in the last years. As of January 1 2018, a total of 877 Nanosats have been launched, of which 811 are CubeSats [1].

In this spirit, the NanoStar university network has been created to provide a useful framework for the collaborative development of student nanosatellite missions. The initial development of this network for the years 2018-2020 is funded by the EU INTERREG-SUDOE V-B program and aims to establish the nuclear structure of the network, plus the resources, computer infrastructure, and work methodology to develop nanosatellite missions with university students.

This communication presents the NanoStar network and its goals, the initial NanoStar partners, and the 2018-2020 work program, covering the project schedule, expected results, and the plans for the extension and perennization of the Network after the conclusion of the project.

II. The NanoStar network

The initial NanoStar Network, a consortium of 7 universities of southern France, Spain, and Portugal, plus two aerospace clusters, has the main goal of developing a nanosatellite-based education methodology to train the future generation of aerospace leaders. This will be implemented by, firstly, creating a catalogue of shared of the resources from the different partners; secondly, defining a common set of tools and software, and thirdly, by defining a robust work methodology for the design, development, construction, testing, launch and operation of nanosatellite missions. The educational program will be structured around competitive/collaborative student design challenges, where students will take the lead in the development of nanosatellites under the guidance and advice of the universities staff. The first edition of the student challenges will take place in 2018-2020, around the common topic of a nanosat fly-by mission to the Moon. The initial NanoStar Network project for this period is funded by the EU INTERREG-SUDOE program.

The NanoStar network also aims to maintain close and healthy communication with the space industry and the entrepreneurial ecosystem in the represented countries, offering opportunities to collaborate with and to sponsor some of the student challenges. After the initial development period of the NanoStar network, its expansion to include other universities and other countries is planned. Likewise, due to its open structure and ample educational goals, there exist many potential synergies between NanoStar and ESA Academy or other like-minded initiatives in Europe that must be studied.

III. NanoStar partners

This section briefly introduces the partners of the NanoStar network (see Table 1) and their complementary strengths. Together with these partners, ESA-Bic Sud-France, ESA-Bic Portugal, and Madri+d act as associates for the project.

TABLE I. NanoStar partners

Partner
1. Aerospace Valley (FR)
2. Institut Polytechnique de Bordeaux (FR)
3. Institut Supérieur de l'Aéronautique et de l'Espace (FR)
4. Université de Montpellier (FR)
5. Madrid Plataforma Aeronáutica y del Espacio (ES)
6. Universidad Politécnica de Madrid (ES)
7. Universidad Carlos III de Madrid (ES)
8. Universidade da Beira Interior (PT)
9. Instituto Superior Técnico (PT)

A. *Aerospace Valley*

Aerospace Valley is the coordinator of the NanoStar project. Aerospace Valley is a global competitivity cluster with more than 800 members in the aeronautic, aerospace, and embedded system sectors. Among its members there is the French space agency (CNES), and several companies that strongly support the NanoStar project.

The Aerospace Valley cluster exists since 2005 and has been awarded the Gold Label for its proficiency in project management. It is also a lead actor in France regarding public dissemination, with more than 100 events per year.

B. *Institut Polytechnique de Bordeaux*

The engineering school ENSEIRB-MATMECA of Bordeaux INP has more than 1200 students and concentrates all the necessary engineering capabilities to design a nanosatellite. The school has 4 departments in electronic, telecommunications, computer science and mathematics & mechanics. Previous experience includes the design of two GNSS and TMTC cards for nanosatellites. The team is part of the H2020 FabSpace 2.0 project for the innovation based on geo-data, and a member of the Copernicus Academy.

Together with UC3M, Bordeaux INP is co-responsible of the definition and management of the student design challenges in the NanoStar project.

C. *Institut Supérieur de l'Aéronautique et de l'Espace*

ISAE-SUPAERO (Institut Supérieur de l'Aéronautique et de l'Espace) is a university dedicated to the education of engineers and researchers capable of designing, developing and operating complex systems, in the fields of aeronautics and aerospace. The skillset and research activities of ISAE-SUPAERO cover systems engineering, simulation, validation, and all specialties, scientific or technical, involved in aerospace systems. ISAE-SUPAERO is familiar with software related to aerospace field, whether in terms of use or development.

ISAE-SUPAERO also uses CNES software solutions, notably in their courses and nanosatellite projects, in cooperation with the University Space Center of Toulouse. ISAE-SUPAERO will oversee the development of the concurrent engineering software suite of the NanoStar project, in close collaboration with Lisbon IST.

D. *Université de Montpellier*

Montpellier university was the first French university to launch two nanosatellites: ROBUSTA-1A in 2012 in a Vega launcher, and ROBUSTA-1B in 2017 in a PSLV. The

University took part in the FEDER SOLARIUM project that consisted in the adquisition of the thermal and radiation test facilities for nanosatellites. University Montpellier is developing a 1U cubesat project called MTCube for ESA. The university participated in the Fly Your Satellite first edition with the ROBUSTA-1B and second edition with CELESTA.

U. Montpellier is in charge of the NanoStar work package for the establishment of the shared-resource agreement between the partners.

E. Madrid Plataforma Aeronáutica y del Espacio

The Madrid PAE cluster manages cooperation projects between companies, universities, and research centers, at a regional, national and international level. It has extended knowledge in space-related project management.

Madrid PAE cluster is experienced in the communication and dissemination of European projects, using communication platforms and dissemination networks, as well as social networks. It also has its own internal distribution networks with the research centers and universities. It has produced logos, messages, and communication and dissemination projects for European project results in H2020.

F. Universidad Politécnica de Madrid

The Ignacio da Riva Institute (IDR) at UPM has proven capabilities in the design, manufacturing and operation of a full space system. In the framework of the NanoStar project, the two most relevant capabilities of UPM are the design of spacecraft thermal control and structural subsystems, and the assembly-integration-testing of spacecraft components.

IDR is a research institute dedicated to education and R+D activities in the field of aerospace science and engineering.

UPM is responsible of the work methodology work package in NanoStar.

G. Universidad Carlos III de Madrid

UC3M combines the leading research group in electric space propulsion in Spain (aerospace department), and a large experience in photonics and laser technologies (electronics technology department). All science engineering departments at UC3M (aerospace, electronics technology, telecommunications, mechanics, robotics, structures, physics, materials, mathematics) are hosted in the same campus and interact tightly with each other, providing a truly multidisciplinary environment for the development of complex systems like nanosatellites. UC3M has recently prepared a massive online open course (MOOC) on space systems engineering and the history of the conquest of space [2].

The electric propulsion group has advanced simulation codes to model the plasma-spacecraft interaction problem, mission analysis, and proven experience in the design of space systems in phase A (e.g. FP7 LEOSWEEP project). Its laboratories have a large vacuum chamber for plasma thruster development and testing.

The optoelectronic instrumentation team has design and development capabilities for photonic subsystems, optical systems and fiber optic sensors, with application to communications and on-board monitoring, for space communications, scientific experiments and technological demonstrators. It has a laboratory for optoelectronic instrumentation and laser technologies.

UC3M is in charge, together with Bordeaux INP, of the student design challenge work package in NanoStar.

H. Universidade da Beira Interior

The UBI is a rather new Portuguese university with currently 7000 students. UBI has participated in more than 300 European, national and privately-funded projects. The UBI Engineering College with 1700 students offers one of the two courses in the domain of Aerospace Engineering in Portugal. With more than 100 PhDs, the engineering faculty includes the C-MAST Center for Mechanical and Aerospace Science and Technologies. C-MAST has a vast scientific production and experience in participation in research and educational projects in the field of space, including some projects of CubeSat development, being therefore able to collaborate in developing the robust work methodology for the design, construction, and testing of nanosatellites.

UBI will implement the state-of-the-art models of collaborative engineering in NanoStar.

I. Instituto Superior Técnico

The Lisbon IST is the largest and oldest engineering school of Portugal. Founded in 1910, IST has around 10000 students, 800 professors, and 600 civil workers. The aerospace engineering diploma was created in 1991 as an interdepartmental course between the mechanic and electric engineering departments.

The Aerospace Science and Technology center has 40 years of experience, with more than 30 projects funded by ESA and the EU. The telecommunications institute of IST has direct contracts with ESA in two antenna projects.

IST will oversee the development of the collaboration software suite together with ISAE-SUPAERO.

IV. NanoStar Work Program

The 2018-2020 NanoStar project is structured in 5 work packages, which are overviewed next.

1. *Agreement for sharing resources among the consortium partners*. Developing a spacecraft, even if it is nano-sized, is a multidisciplinary effort that requires experts from different engineering areas, and advanced testing facilities. Each partner has its own resources and capacities, and establishing a catalogue of resources is a first goal of the NanoStar project.
2. *Connected, concurrent engineering platform development.* The objective of this work package is to configure a suite of software dedicated to the engineering of nanosatellites, and a concurrent design facility (CDF) at each partner premises. This will cover collaborative concurrent engineering, with a model-based system engineering approach. This work will

rely on existing CNES nanosatellite design software and acquired experience.

3. *Nanosatellite development methodology.* The availability of resources (personnel experience, facilities, codes) and a concurrent design environment does not guarantee the success of a nanosatellite design project. This work package will provide students with a clear and robust methodology to achieve that. This will be implemented, at least partially, in the form of live documentation (wiki, videos, tutorials, etc.).

4. *Student design challenges.* To validate the operation of the NanoStar network and improve on the results of previous work packages, a first set of student challenges will be prepared. The challenges will be articulated around a CubeSat flyby mission to the Moon, which permits introducing advanced aspects such as propulsion, mission autonomy, and three-body mission analysis. More information on the challenges is provided in Section VI.

5. *Future work plan preparation.* As the 2018-2020 NanoStar project is intended to kick-start a network of universities enduring and expanding in time, this work package will consolidate the results obtained in the project and identify mechanisms to continue with the operation of the network. As part of this effort, the development of a space for the creation of nanosatellite-based start-ups is planned.

V. Work Schedule

The work schedule for the 2018-2020 NanoStar project is shown in Fig. 1. The total duration of the project is 30 months. Work starts with work packages 1 to 3 to prepare the network of resources, the concurrent design facilities and software, and the work methodology. Student challenges (WP4) begin with the academic year 2018-2019 and run for the reminder of the project. In the last year, the perennization activities (WP5) will take place.

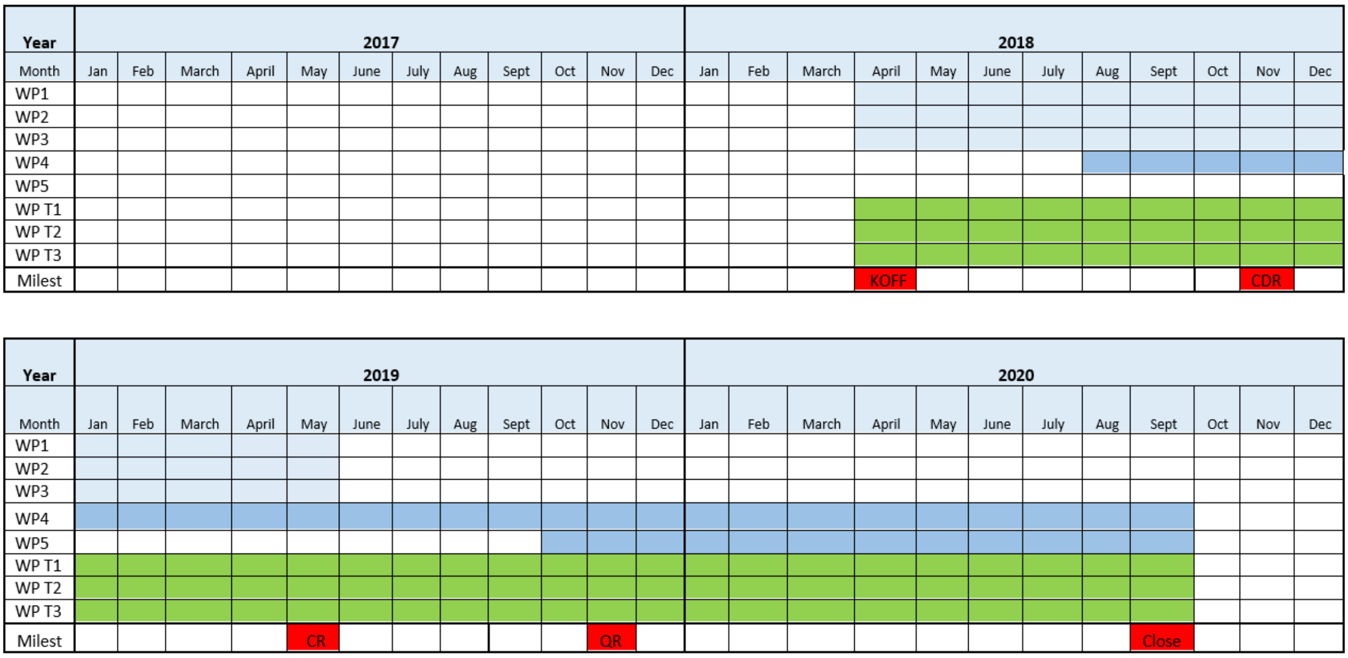

Figure 1: Schedule for the NanoStar project for the period 2018-2020. The beginning of the project was delayed from the initial February 2018 to April 2018.

VI. Student Design Challenges

The main objective of NanoStar is to grant the students with an opportunity for a hands-on, practical education in the development of nanosatellites. In the first edition of the student challenges, a CubeSat mission to perform a flyby around the Moon has been selected as the common theme. The complexity and richness of the mission, compared to a simpler LEO observation CubeSat for example, allows educating the first cohort of students not only on the fundamentals of nanosatellite design, manufacturing, and testing, but also on advanced topics such as three-body orbital mechanics and propulsion systems.

The student challenges are articulated around a competition-collaboration axis: students need to collaborate in teams, which will be multidisciplinary and international (with members from various NanoStar institutions), but at the same time they will need to compete with other teams. The winning teams will receive a diploma and an award as a means of motivation. The university staff from the NanoStar network will provide guidance and advice to the student teams throughout the challenges.

A near-complete engineering model of a nanosatellite will be the outcome of the challenges project. The manufacturing of a flight model and the launch and operation of the system will be part of the activities left for the continuation of the NanoStar network after the conclusion of the 2018-2020 project.

Project-wise, the challenges are structured in two phases as follows:

1. A one-semester first phase where a student competition for preliminary mission designs will be called. After this period, a jury composed by staff members from the NanoStar institutions will convene to select the winning proposal. The chosen design will serve as the baseline to the rest of the student challenges in the next phase
2. A second phase with detailed design, manufacturing, and testing challenges. In this phase, students will approach specific aspects of the nanosatellite mission, such as the detailed design and construction of the AOCS subsystem, the thermal design, the preparation of a test bed to verify and validate the nanosatellite model, the integration and testing of the system, or the preparation of a ground segment.

This first experience with student challenges will allow the consortium to evaluate the operation of the network, and to perform improvements for the future.

VII. Concluding Remarks

The NanoStar network is a new educational initiative by 7 universities across the Southwest of Europe and 2 aerospace clusters, which aims to provide students with an opportunity for hands-on practice in the aerospace sector with the design and development of nanosatellites.

The network will be structured around a catalogue of shared resources, a common collaborative computer infrastructure for concurrent engineering, and a student work methodology. The participation of the students will be implemented through student challenges, i.e., competitions among international and multidisciplinary teams of students from the partner universities, guided by their staff members.

A first period for the NanoStar is just started for 2018-2020 thanks to the INTERREG-SUDOE funding. The goal of this first project is to establish all the critical elements of the network and perform a first test-run of its operation with a set of student challenges articulated around a CubeSat flyby mission around the Moon. The communication, dissemination of the outcomes of the network is planned, as well as the study of its continuation, the possible synergies with other initiatives in Europe, and its extension after the conclusion of this first 30-month period.

Acknowledgments

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LEDSAT: educational LED-based small SATellite for testing new techniques based on passive optical methods with a co-operative target

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***Abstract* — LEDSAT (LED-based small SATellite) is an educational spacecraft currently under development at Sapienza – University of Rome, Italy. This 1U CubeSat has been selected to be part of the 2nd edition of the Fly Your Satellite! (FYS!)Programme, managed and organized by the European Space Agency (ESA) Education Office. Within the end of 2019, LEDSAT will be deployed in orbit from the International Space Station (ISS). The project is part of the Sapienza Space Systems and Space Surveillance Laboratory (S5Lab) hands-on educational activities and it will be carried on also by students involved in the Post-graduate Course in "Space Mission Design and Management" at Sapienza – University of Rome. The LEDSAT core idea has been conceived by the S5Lab research team, with the support of the Italian Space Agency (ASI) and the Astronomy Department of the University of Michigan, USA. The CubeSat mission aims at the in-orbit testing of Light Emitting Diodes (LEDs) used to autonomously illuminate the spacecraft with both pre-determined and ground-commanded flashing sequences. In particular, the primary mission objective is the detection, identification and orbit determination of LEDSAT by means of the optical data acquired by a network of six observatories involved in the project. The secondary mission goal is to verify the possibility to get information about the CubeSat attitude main parameters through specific flashing sequences. Indeed, a different pattern for each CubeSat face could allow the reconstruction of the spacecraft tumbling motion through the analysis of the light curves obtained by the gathered optical data. Finally, LEDSAT will test a light-based communication method that could be implemented as back-up for the radio-frequency standard transmission, in case of a critical failure of the communication subsystem. Finally, the LEDSAT project is offering a unique chance for the involved students to take part at each phase of a CubeSat Mission, from concept to disposal.**

LEDSAT can be considered a "calibration target" for the current methodologies of spacecraft optical tracking, since it will offer the unique opportunity to compare the obtainable optical data to the real ones provided by the instrumentation. Moreover, the satellite could demonstrate the capabilities of LED panels for CubeSat identification, tracking and back-up communications.

Keywords — educational university CubeSat; LEDs; cooperative target; optical observatory.

I. INTRODUCTION

The launch of the Russian Sputnik-1, the first artificial Earth satellite, on Oct. 4, 1957, marked the start of the Space Age [1]. In this occasion, the last stage of the rocket that bore Sputnik-1 into Space was left behind becoming the first real man-made space debris in the Earth Orbit.

Space junk includes both natural and man-made particles. While natural space debris such as meteors or their fragments are generally orbiting around the Sun, the artificial ones are closer to the Earth [2]. The amount of mission-related debris and fragmentation debris in Earth orbit has grown steadily since 1957. Currently, over 15,000 distinct objects have been tracked by the U.S. Department of Defense's Joint Space Operations Center (JSpOC) [3], but statistical models estimated a total of around 29000 objects bigger than 10 cm and 750000 objects with a dimension included between 1 and 10 cm [4].

Space junk represents a real threat to operative spacecraft and space systems. The survey asset developed on-ground and in-orbit for their monitoring permits to control their status and trajectories in order to avoid possible impacts with cooperative objects by defining proper collision-avoidance manoeuvres, when needed. The most common and standard techniques used to this purpose are based on optical, radar and laser ranging measurements.

Over the last decades, space industry experienced an increased interest towards smaller missions and smaller satellites due to recent advances in the components miniaturization and reliability [5]. Thousands of nanosatellites have been recently launched in the Low Earth Orbit (LEO), between 200 and 2000 km of altitude, for scientific and technological purposes. In the next future, the LEO ring will become even more and more crowded [6]. The emerging plans for large constellations in this region will have an important influence on the evolution of the space debris environment, as stated by the Inter-Agency Debris Coordination Committee (IADC) [7]. To face these unique tracking and identification challenges, new methods for improving space debris tracking performances and the possibility to distinguish and uniquely identify a certain spacecraft once deployed in orbit are needed.

In this context, the LEDSAT (LED-based small SATellite) mission has been conceived by the Sapienza - Space Systems and Space Surveillance Laboratory (S5Lab) research team in collaboration with the University of Michigan ([8]–[10]). By merging the S5ab research team expertise in the university CubeSat design and development ([11]–[14]) with the activity performed in the framework of the space debris monitoring ([15]–[17]), the LEDSAT project came out as a follow-up to the Light Emitting Diodes (LEDs) technology tested on-board the Japanese FITSAT-1 small satellite, deployed by the ISS on October 5, 2012 ([18]). LEDs located on the external surfaces of an orbiting spacecraft emitting light in different wavelengths can be detected by ground-based telescopes also when the satellite is not illuminated by the Sun, during the spacecraft orbital eclipse period (more details are provided in Paragraph II). The analysis of the optical data that will be acquired during the LEDSAT mission lifetime will allow the S5Lab research team to investigate new techniques and possible improvements offered by the chance of observing a cooperative payload, also tunable depending on the mission objective to be investigated. The LEDSAT design was performed in late 2016 through a Concurrent Engineering Activity (CEA) in the framework of the Space Engineering MSc course of “Spacecraft Design” at Sapienza – University of Rome [14]. Then, after consolidating the CubeSat design, the student team decided to apply for the second edition of the ESA Fly Your Satellite (FYS!) Programme. The project was proposed in March 2017 and accepted in May 2017.

LEDSAT is the third university nanosatellite project carried out by the S5Lab research team. The laboratory activity in this field started with the 3U CubeSat URSA MAIOR (University of Rome la Sapienza Micro Attitude In Orbit testing), launched in June 2017 in the framework of the QB50 project [19]. In 2017, the 1KUNS-PF (1st Kenyan University Nano-Satellite – ProtoFlight model) has been successfully developed and integrated in the framework of the S5Lab collaboration with the University of Nairobi (Kenya), in response to the Announcement of Opportunities in the framework of the United Nations/Japan Cooperation Programme on CubeSat Deployment from ISS Japanese Experiment Module (Kibo) “KiboCUBE”. Since September 2014, the activity carried out at S5Lab has been focused on offering to students different educational hands-on activities and opportunities related to the space field where their training has been considered also more important than the nominal mission itself. The development of a University CubeSat is a perfect opportunity for involving students in a real space project, allowing them to learn how to face all the related difficulties, how to manage the available resources (such as time, budget, mass and power) and how to work as a team for accomplishing the success of the mission.

In paragraph II, the LEDSAT mission is described in detail, including its main objectives. Paragraph III offers a complete overview about the project System Architecture and main segments. To conclude, Paragraph IV presents the status of the projects and it briefly summarizes both educational and scientific expected outcomes.

II. LEDSAT MISSION

As part of Track B of the ESA FYS! Educational programme, LEDSAT will be deployed from the ISS within the end of the 2019 and the beginning of 2020. The target orbit altitude is between 410 and 420 km, at an inclination of 51-52 degrees and the expected mission lifetime is one year in total.

A. Main Mission Objectives

A LED-based payload able to autonomously illuminate the spacecraft can lead to an extension of its time of detectability to the whole orbital eclipse period [10]. In fact, the embedding of such a system on a satellite could, in principle, guarantee the target observability regardless of the phase angle (i.e. the angle between sun, target and Earth-based observer) which defines the two naturally accessible time windows for the usual optical observation (Fig. 1).

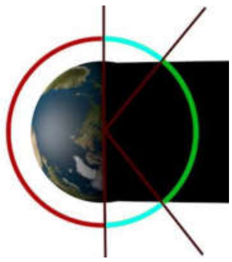

Fig. 1. Total observing window of LEDSAT composed by: two semi circular cyan sections representing the standard passive illumination observational opportunities, the central green region representing the extension of such window thanks to the active illumination system.

The main scientific goal of the LEDSAT mission is related to the possible improvements achievable for the orbit determination accuracy. Advances are connected to the design and development of an on-board active-illuminating system able to autonomously flash with different patters (Fig. 2) to serve as an identification target for optical observations in LEO. LEDSAT system may allow a comparison and validation of optical tracking data to radio telemetry, the information of the on-board GPS and possible laser ranging measurements.

Considering that star catalogues are provided with a precision on the objects celestial coordinates of few milli-arcseconds [20], a sidereal tracking of the active illuminated target may let to promising angular accuracy, resulting in a higher precision in the orbital determination procedure based on such kind of measures. Moreover, self-illumination could allow distinguishing satellites when launched, as usual, in large

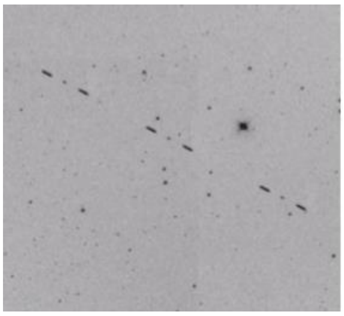

Fig. 3. Simulated LEDSAT Flashing Patterns visible in optical acquired data.

clusters, to be compliant with the required standards [21]. This will be possible by letting the satellites flash with different pre-programmed patterns with different colours of LEDs. immediately after their in-orbit deployment.

A further prospect is the attitude determination through simultaneous observations of the tumbling target with different filters from ground. Indeed, the use of a cooperative target, emitting light in three different colours (red, green and blue) will enhance the capability of reconstructing the satellite attitude and recognizing the different CubeSat's faces from the light curves observation. This task will be approached also by exploiting different flashing patterns, possibly decoupling those flashing sequences from the satellite rotational frequency. In both cases, the use of a virtual model to generate simulated light curves to fit on the real measured one will be of fundamental importance [17]. Indeed, the defined LEDSAT payload allows to a spacecraft tracking without filters, observing the satellite tracklet, or with the adoption of wide filters, in order to distinguish the different satellite faces.

In addition, the spacecraft LEDs will also test an innovative method to communicate with ground, that will allow to down-link of basic scientific or housekeeping data or dummy messages even in case of an on-board transceiver failure. Generally, approximately 20% of all the CubeSat mission failures are caused by a Telemetry, Tracking and Control (TT&C) system malfunctioning or failure [22]. Single LED panels to be used as back-up communication system for future CubeSat and orbital platforms could significantly increase the reliability of these systems data-link. In fact, by considering the ground-based equipment and the satellite angular velocity it should be possible to adjust the flash timing (i.e. the bit rate) and transmit to ground simple information, such as telemetry, battery status, etc.

The LEDSAT mission also aims to include amateurs and simple ground-based systems in the observing community by placing the absolute timing of the LED flashes on the spacecraft itself and resolving the need for high timing precision of the Ground Station (GS). Finally, the educational purpose shall be mentioned because the opportunity to take part at each phase of a real spacecraft mission, from concept to disposal, is a unique chance for students interested in working in the space field.

III. SYSTEM ARCHITECTURE

The main elements of the LEDSAT mission are the Space, the Ground and the User Segment, totally under the student team responsibility. The Launch Segment is provided by the ESA in the framework of the FYS! Educational Programme. A detailed description of the complete system architecture is given in the next four sub-paragraphs (from A to D).

A. Space Segment

The LEDSAT *Space Segment* consists in a 1-Unit CubeSat (100 x 100 x 113.5 mm and 1.3 kg of mass). The spacecraft will mount LED panels of three different colours (red, green and blue) on all its six faces, with the same diodes colour on opposite faces. The LEDs configuration has been designed in order to ensure the spacecraft detectability from each observing station (value of Signal to Noise Ratio of 10 and minimum apparent magnitude of 13, [23]).

The satellite will be mainly composed of COTS components for the bus sub-systems and bespoke Printed Circuit Boards (PCB) for the payload. A satellite exploded view drawing is presented in Fig. 3.

The satellite will be capable of managing the LED operations both automatically and by ground command. In order to allow the activation of the LEDs with a significant duty cycle when in eclipse, six Li-Ion cells are included, for a total energy storage of 58 Wh. The LED tasks are commanded by the On-Board Data Handling (OBDH) and managed by a dedicated set of electronic components. A precise oscillator will assure a high precision in timing accuracy and synchronization to the GPS UTC time, in order to improve the traceability of the LEDs from ground. Orbital and attitude sensors will allow comparing the data acquired with the satellite observations to real data in order to achieve the mission objectives. Retroreflectors will be

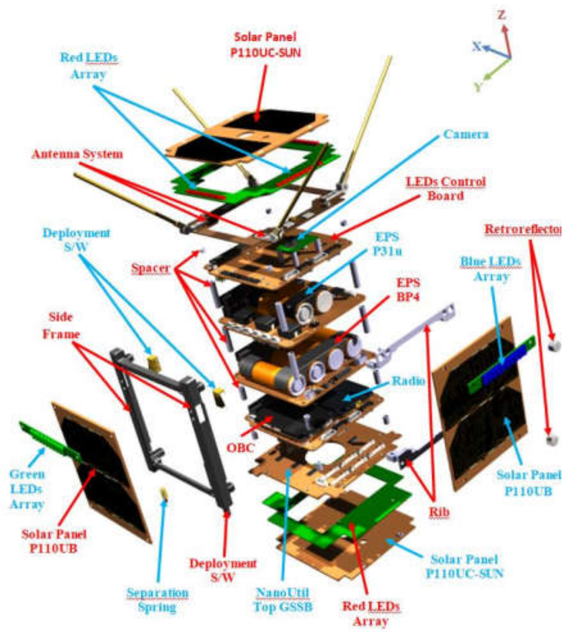

Fig. 2. LEDSAT 1-U CubeSat exploded view.

located on the external faces of the CubeSat to allow laser ranging measurements of the spacecraft during its mission lifetime.

B. Ground Segment

The *Ground Segment* is composed by three different networks of GSs. The observing campaigns will be carried out by the Optical GSs network, composed by six observatories, located in Michigan (USA), Chile, Kenya, Switzerland, and Italy.
The communication link in the UHF (Ultra-High Frequency) band (around 435 MHz) with the small satellite will be ensured by the Radio Frequency (RF) GSs network, composed by three stations, located in Ann Arbor (Michigan – USA), in Nairobi (Kenya) and in Rome (Italy). The third GSs network is based of two Laser Ranging stations located in Matera (Italy) and in Bern (Switzerland) to reconstruct the CubeSat orbit through laser ranging measurements. All the GSs previously mentioned will ensure all the operations needed for observing, communicating and ranging the CubeSat. Their distribution around the globe permits to maximize the overall visibility time and number of passes, with a maximum average interval equal to 5 minutes per pass over a GS. The Ground Segment Overview is shown in Fig. 4.

Fig. 4. Ground Segment main GSs.

C. User Segment

An important role in the LEDSAT mission will be played by the *User Segment*. This consists in an Internet platform dedicated to the astrophiles and astronomers interested in tracking LEDSAT. Indeed, while the Two-Line Elements (TLEs) of the spacecraft will be always made available in the website header, a dedicated form will allow the users to submit their telescope pictures of the satellite flashes, whose timing and pattern schedule will be available on the website. This mission feature will improve the amount of data to integrate for determining the spacecraft orbit and attitude, and it will help to verify the methodologies for optical data fusion and filtering for the orbit determination of uncooperative objects in space.

D. Launch Segment

The *Launch Segment* is offered by ESA in the framework of the FYS! Educational Programme. Indeed, LEDSAT will be deployed by the International Space Station (ISS) between the end of 2019 and the beginning of 2020 with the other two European university CubeSat selected for the 2nd edition of the Programme.

IV. CURRENT STATUS & EDUCATIONAL RETURN

A. Current Status and next steps

The project is currently at the end of the Critical Design Review phase, which aims at defining an acceptable CubeSat design to be realized during the satellite integration. Once the CDR is passed, the satellite is under configuration control, thus ensuring that each possible design change is clearly justified by the University team and approved by ESA.

Critical aspects of LEDSAT mission are related to unexpected degradation of the diodes in the space environment, i.e. a gradual lowering of light output and loss of efficiency or a shift in the bandwidth of the dominant wavelength. A complete radiometric and environmental characterization of the devices, including Thermal-Vacuum (T-VAC), Ultra-Violet (U-V) and gamma-ray radiation, have been performed between October and December 2017. Replicas of the LED boards have been manufactured and tested. Optical verification and characterization of the models has been assessed by measurements of the total irradiance and the peak wavelength. Moreover, UV tests have been performed at Sapienza's available facility. The main criticality has been related to the silicone lens covering each LED. It has been observed that the degradation of the silicone could cause bandwidth shifting. Therefore, the LEDs test boards have undergone a representative dose of UV radiation without any a significant change of the radiometric characteristic. A Total Ionizing Dose (TID) test was performed at the Co60 facility of ESA ESTEC in Noordwijk, The Netherlands. As main result, no degradation in the electrical parameters (current and voltage) or in the light emission performances (irradiance, flux and peak wavelength) up to a TID of 34 krad (Si) was detected.

The satellite integration is already on-going, while the software production will start between March and April 2018. The satellite will be fully integrated and ready for the ambient test campaign in Fall 2018, while an environmental testing campaign is currently scheduled for the first half of 2019, in order to qualify and accept the CubeSat for the space flight.

B. Educational Return

The FYS! Programme offers to University students a chance to follow the development cycle of a CubeSat mission, from concept to in-orbit operations. The first year of CubeSat project, from the preparation of the proposal to the Flight Model integration early phases, has led students to face a multiplicity of technical challenges. Every minor change on the design requires a complete update of the whole satellite design, and this inter-dependency among the sub-systems has helped to strengthen the teamwork capabilities of all the team members. Currently, the team is still learning to cope with many aspects of a space project not usually covered by the University courses, such as product assurance and configuration management. Last but not least, all the hands-on activities already performed or planned for the next phases are representing a unique chance to gain the so-called *soft skills* on a space project production.

V. CONCLUSIONS

Since September 2016, the S5Lab research group focused on photometric and astrometric studies to develop a payload configuration able to be tracked in LEO even by amateur telescopes. The LEDSAT mission aims to validate in-orbit a standard and compact system based on LEDs to enhance the visibility time window of the satellite and to improve the orbit determination accuracy. The same system will be qualified also for the reconstruction of the spacecraft attitude by exploiting different flashing patterns and LED colours together with the use of colour filters. Always adopting the on-board LED system, the possibility to communicate information to the RF GSs will be proven in the framework of an educational university project carried out by a student team.

The mission concept and feasibility and the preliminary design were performed at Sapienza – University of Rome through a Concurrent Engineering Activity. The principal driver for the on-board configuration design were a limited power budget and mass constraints. The optical instrumentation capabilities of the ground segment have driven the choice of the colour and number of LEDs. Consequently, COTS high-powered LEDs have been selected and the final flight configuration has been defined after proving its detectability by the six observatories belonging to the observing network by means of apparent magnitude and signal to noise ratio analyses of the luminous flux.

In May 2017, LEDSAT has been selected as one of the six European CubeSats part of the ESA's FYS! Educational programme. In December 2017, the LEDSAT team faced the project CDR and the main design details of the spacecraft have been consolidated. LEDSAT will be deployed in orbit between the end of 2019 and the beginning of 2020 from the ISS.

ACKNOWLEDGMENT

It is worth mentioning that the LEDSAT project is one of the six CubeSat currently under development due to the selection for the 2nd edition of the Fly Your Satellite! Programme managed by the ESA Education Office. Within the Programme, students design and build their satellite at their universities and benefit from direct knowledge transfer of ESA technical and managerial expertise, as well as access to facilities. The activities presented in this paper is supported by the Italian Space Agency (ASI) and Sapienza's Department of Mechanical and Aerospace Engineering (DIMA). During the mission lifetime, the observing and laser ranging measurement campaigns will be performed from network of observatories and laser-ranging stations managed by S5Lab, the Astronomy Department of University of Michigan (U-M, USA), the Astronomical Institute of the University of Bern (AIUB, Switzerland) and the ASI's Center of Space Geodesy in Matera (CGS, Italy). Finally, the radiometric testing campaign for the characterization of the LEDSAT on-board payload was supported by the Italian company Profilocolore Srl.

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Pyroless Recovery System

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***Abstract*—The Pyroless Recovery System (PRS) is designed to store pressurized gas and release it at a certain time. As the name already suggests this system works without pyrotechnics. The PRS has two pistons, a forward and tail piston. The forward piston has a bigger diameter than the tail piston. Different areas of the pistons and constant pressure lead to different forces. The Pyroless Recovery Mechanism (PRM) restrains the piston from moving. If the PRM is in released position the piston moves, the chamber opens and sets the stored gas free.**

Keywords—sounding rocket, recovery, release mechanism

I. Introduction

The Pyroless Recovery System (PRS) is designed to store pressurized gas (e.g. CO_2, air) and release it at a certain time. As the name already suggests this systems works without pyrotechnics. This makes it safer in terms of fire, however one still needs to be wary of the high pressure.

The motivation of the TU Wien Space Team [1] to develop such a system was the launch event C'Space in Tarbes, France. Planéte Sciences [3] organizes this event annually and the TU Wien Space Team has been participating in it since 2011. Usually the TU Wien Space Team uses pyrotechnics for the recovery, but the regulations from Planéte Sciences do not allow any pyrotechnical equipment.

Last year the TU Wien Space Team used its new self-developed Pyroless Recovery System to separate the rocket at apogee. After the PRS releases the pressurized gas expands inside the rocket and the overpressure pushes the rocket apart. This event is called separation. The impulse of the separation then pulls the drogue out of the tube.

The PRS from the TU Wien Space Team (Fig. 1, left) is an adapted version from the design of Troy Prideaux [2].

A. Common separation methods

Beside the PRS there are a few other commercial options to separate a rocket, some of these methods are listed below.

- Spring released by a mechanism
  - Axial
  - Side door
- CO_2 capsule and valve
- Pyrotechnical
- Motor ejection

B. Comparison with valve design

The release delay between the valve design and the PRS is equal. A fast gas release is desirable however a slow gas release can prevent a safe separation.

Advantage:

- Low release force/moment
- Adjustable restraining force during design
- Faster release of the gas tank
- Big opening area
- Smaller gas volume is needed (factor 2-3)

Disadvantage:

- Higher system weight
- More difficult to manufacture
- More parts (more complex)
- Filling process
- Unstable release → friction moment from gear or servo is needed to keep it close
- More costs

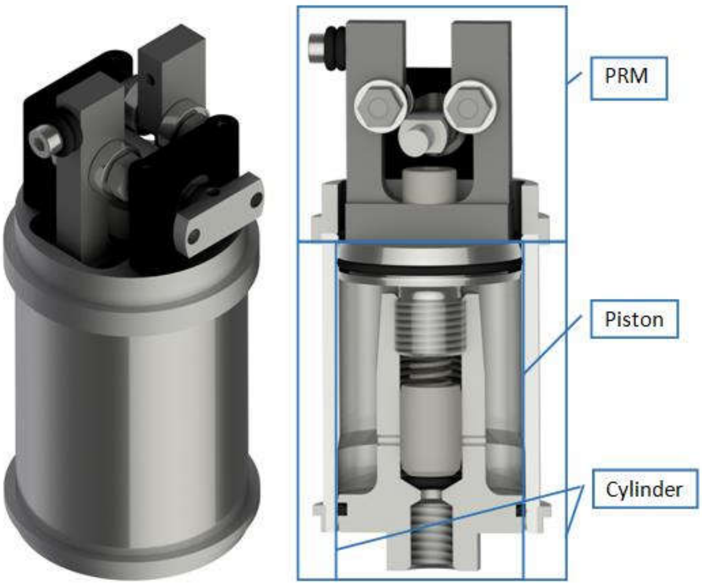

Fig. 1: PRS overview (left), cross section of the PRS (right)

II. PRS COMPONTENT OVERVIEW

This chapter gives an overview of the components and how they are named. This convention will be used in the whole paper.

The Pyroless Recovery System (PRS) consists of four subassemblies (Fig. 1, right):

1. Piston (Fig. 2)
2. Cylinder (Fig. 3)
3. Pyroless Recovery Mechanism (Fig. 4)
4. Other operating parts (Fig. 5)

A. Piston

1. Forward piston
2. Tail piston
3. Check valve
4. Spring
5. O-ring (3x)

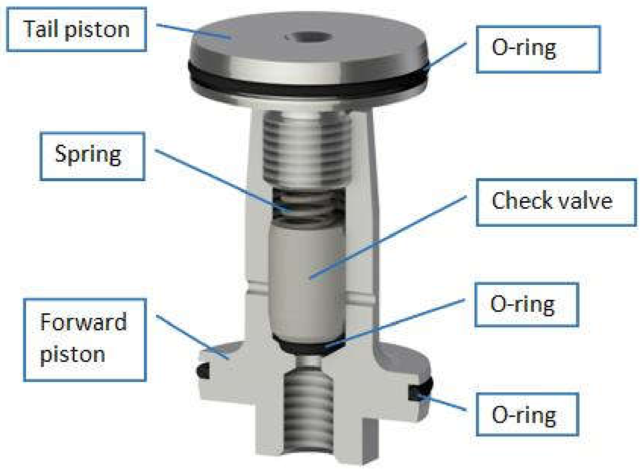

Fig. 2: Piston

B. Cylinder

1. Cylinder
2. Mounting support

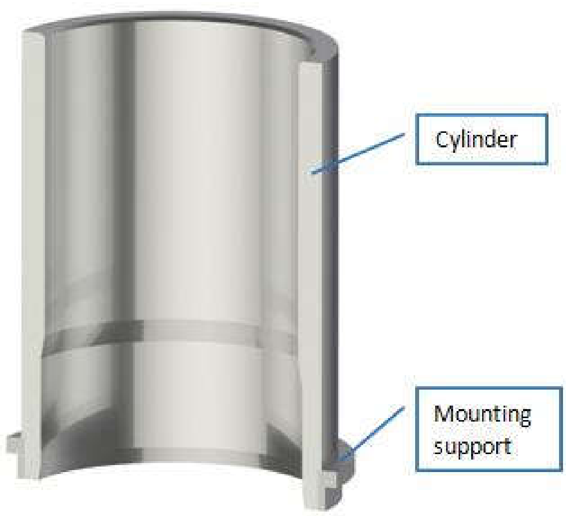

Fig. 3: Cylinder

C. Pyroless Recovery Mechanism (PRM)

1. Base plate
2. Bearing
3. Camshaft
4. Screw
5. O-ring
6. Bearing retainer
7. Bearing
8. Thread bar
9. Nut
10. Washer
11. Screw
12. Mechanism support

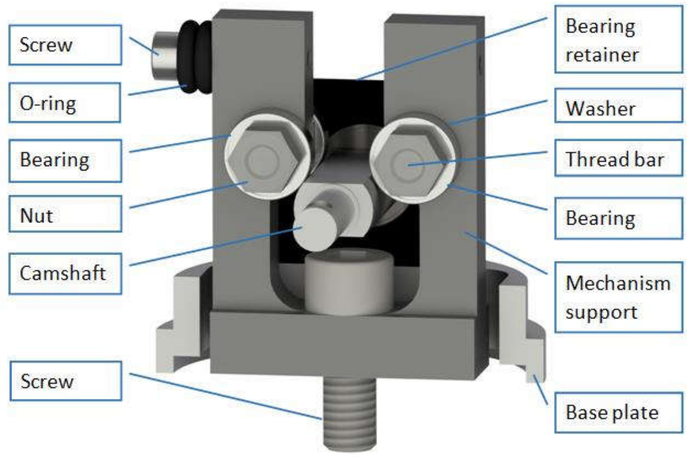

Fig. 4: Pyroless Recovery Mechanism (PRM)

D. Other operating parts

These parts are needed during the filling and operate the PRS. The parts needed for filling will be removed afterwards and are not part of the flight configuration (Fig. 5).

1. Spike
2. O-ring
3. CO_2 Capsule

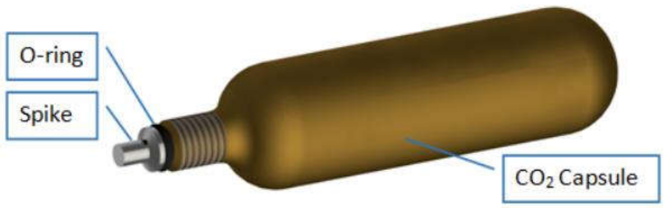

Fig. 5: Other operating parts

III. FUNCTION

A. Filling

Fig. 6 left shows the filling of the PRS. The PRM is in the closed position. During the screw in of the capsule, the spike makes a hole in the capsule and opens the valve. CO_2 can flow into the cylinder.

If you remove the capsule, the check valve will close itself. Do not forget to remove the spike and the O-ring.

B. Closed and armed

Fig. 6 middle shows the filled PRS. The valve and the PRM are closed. In this mode the PRS is ready for flight and can be installed in the rocket.

C. Open

Fig. 6 right shows the open/ released PRS. The camshaft of the PRM rotates 90°, the piston moves down and the gas will be released.

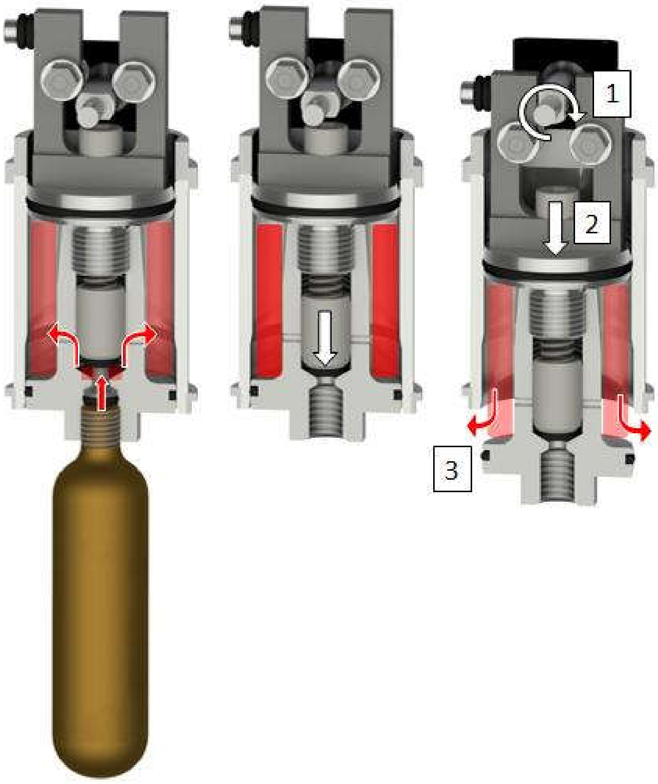

Fig. 6: Filling; closing and armed; open (from left to right)

IV. FUNDAMENTALS

A. Self opening constraint

The PRS has two pistons, a forward and tail piston (Fig. 7). The forward piston has a bigger diameter than the tail piston.

$$d_{p,forward} > d_{p,tail} \tag{1}$$

From this it follows that also the area of the forward piston is bigger.

$$A_{p,forward} = \frac{d_{p,forward}^{2} \cdot \pi}{4} > A_{p,tail} = \frac{d_{p,tail}^{2} \cdot \pi}{4} \tag{2}$$

The gas pressure (p_G) increases with gas temperature (T_G) and gas density (ρ_G), the relation is shown in Fig. 8. At the certain temperature and density the pressure in the cylinder is in equilibrium.

$$p_G(T_G, \rho_G) = const \tag{3}$$

Different areas of the pistons and constant pressure lead to different forces. This differential force (ΔF) can be calculated.

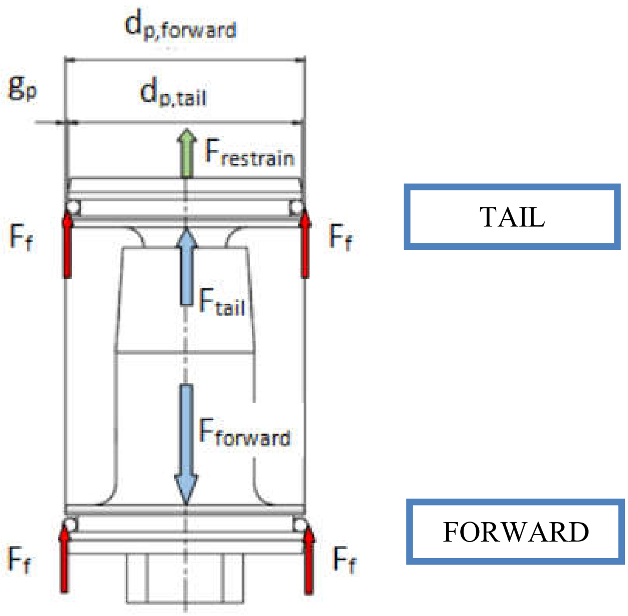

Fig. 7: Sketch of the two pistons

$$\Delta F(T_G, \rho_G) = F_{forward} - F_{tail} \tag{4}$$

$$\Delta F(T_G, \rho_G) = \left(d_{p,forward}^{2} - d_{p,tail}^{2}\right) \cdot \frac{\pi}{4} \cdot p_G(T_G, \rho_G) \tag{5}$$

Due to O-ring friction forces (F_f) between the cylinder and the piston, the restraining force ($F_{restrain}$) is smaller than the differential force (ΔF). $F_{restrain}$ is the restrain force, needed to avoid the piston from opening.

$$F_f = F_{f,forward} + F_{f,tail} \tag{6}$$

$$F_{restrain} = \Delta F(T_G, \rho_G) - F_f \tag{7}$$

The O-ring friction force increases with:

- Gas pressure (↑)
- Cord strength (↑)
- O-ring diameter (↑)
- Surface roughness (↑)
- Materials (↕)
- Lubrication (↓)
- Tolerances (↕)
- Notch dimensions (↕)

PRS self opening constraint:

$$F_{restrain} > 0 \tag{8}$$

B. Diameter differential

The diameter differential (g_p) is essential for the self opening PRS and is derived below. The piston gap (g_p) is shown in Fig. 7.

$$d_{p,forward} = d_{p,tail} + 2 \cdot g_p \tag{9}$$

$$d_{p,forward}^{2} = d_{p,tail}^{2} + 4 \cdot d_{p,tail} \cdot g_p + 4 \cdot g_p^{2} \tag{10}$$

The piston gap (g_p) is very small compared to the diameter.

$$g_p << d_{p,tail} \tag{11}$$

$$\Rightarrow d_{p,forward}{}^2 \approx d_{p,tail}{}^2 + 4 \cdot d_{p,tail} \cdot g_p \tag{12}$$

Considering equation (5) and (12) the following expression for small parameter g_p can be written

$$\Delta F \approx \left(d_{p,tail}{}^2 + 4 \cdot d_{p,tail} \cdot g_p - d_{p,tail}{}^2\right) \cdot \frac{\pi}{4} \cdot p_G(T_G, \rho_G) \tag{13}$$

$$\Delta F \approx d_{p,tail} \cdot g_p \cdot \pi \cdot p_G(T_G, \rho_G) \tag{14}$$

At a given temperature, density, diameter and needed differential force, piston gap (g_p) can be computed with the following equation:

$$g_p \approx \frac{\Delta F_{needed}}{d_{p,tail} \cdot \pi \cdot p_G(T_G, \rho_G)} \tag{15}$$

This part wants to always move in the direction of the larger piston. To avoid the system from opening, the PRM has to restrain the piston. This restraining force can be adjusted in the construction. The greater the difference of the piston area and the gas pressure, the greater the differential force.

The restraining force is smaller than the differential forces, because of the friction between the seal and the cylinder.

C. Determine critical design parameters

The PRS is designed to be filled with carbon dioxide. The CO_2 inside the capsule is a supercritical condition and cannot be calculated with the ideal gas equation. The critical parameter is the pressure at a given maximal density and at the highest allowed temperature.

1) Density

First we have to calculate the density. The mass of carbon dioxide and the volume of the CO_2 capsule should be evaluated from the specification of the capsule manufacturer.

The needed mass of CO_2 depends on the dimensions of the recovery compartment and the volume of the PRS is the design parameter. In the following equation the volumes of the capsule and the PRS are connected without any leakage. The new density after the filling can be calculated as follows.

$$\rho_{filling} = \frac{m_{air} + m_{CO_2}}{V_{PRS} + V_{Capsule}} \tag{16}$$

Enough time for thermal equilibrium is assumed. After connecting the two volumes the gas expands and cools down. The gas pressure decreases due to lower density and lower temperature. After a while the temperature returns to ambient and the pressure increases slightly, but below initial pressure (Fig. 8).

The mass of the air inside the PRS (m_{air}) is very small compare to the mass of carbon dioxide and can be neglected. Equation (16) can be rewritten as

$$\rho_{filling} = \frac{m_{CO_2,Capsule}}{V_{PRS} + V_{Capsule}} \tag{17}$$

The filling density is an important design parameter in Fig. 8. The next thing which is important is how much mass of CO_2 is stored inside the PRS.

$$m_{CO_2,PRS} = V_{PRS} \cdot \rho_{filling} \tag{18}$$

Equation (17) and (18):

$$m_{CO_2,PRS} = m_{CO_2,Capsule} \cdot \frac{V_{PRS}}{V_{PRS} + V_{Capsule}} \tag{19}$$

or

$$V_{PRS} = V_{Capsule} \cdot \frac{m_{CO_2,PRS}}{m_{CO_2,Capsule} - m_{CO_2,PRS}} \tag{20}$$

2) Temperature

The design temperature (T_d) is the maximum temperature during operation and has to be chosen carefully. Worst case: Hot summer day on the launch pad waiting for confirmation.

Temperature has a big influence on the pressure. If you have already temperature values inside the rocket from previous launches take the highest one and add a safety margin. You can also put a thermometer inside your rocket and put it into direct sunlight during a hot summer day and wait for a while.

Depending where you launch your rocket the design temperature should be at least 60°C.

Do not forget that the restraining force also depends on the temperature and should also work during cold conditions (launch in winter).

3) Determine design pressure

As mentioned earlier the carbon dioxide is in a supercritical condition, so the determination of the design pressure can be done as follows.

With the filling density and the design temperature the design pressure can be read from the diagram [4] in Fig. 8.

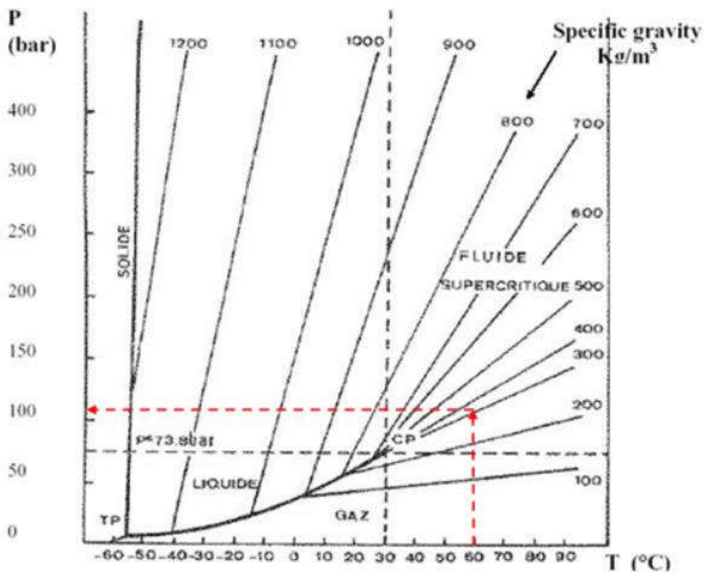

Fig. 8: p,T,ρ -diagram of carbon dioxide [4]

Example:

In the example we use a capsule with 15,6g of CO_2 and 21ml volume. The PRS has a volume of 25ml and is operating at maximal 60°C.

Determine the design pressure and the maximal stored CO_2 mass.

$$\rho_{filling} = \frac{m_{CO_2}}{V_{PRS} + V_{Capsule}} = \frac{15{,}6[g]}{25[ml] + 21[ml]} \approx 339\left[\frac{kg}{m^3}\right] \quad (21)$$

$$T_d = 60[°C] \quad (22)$$

From diagram in Fig. 8 (red dash line):

$$p_d(T_d, \rho_{filling}) = 110[bar] \quad (23)$$

$$m_{CO_2,PRS} = m_{CO_2} \cdot \frac{V_{PRS}}{V_{PRS} + V_{Capsule}} = 15{,}6 \cdot \frac{25}{25+21} \approx 8{,}5[g] \quad (24)$$

4) Needed amount of CO_2

The amount of CO_2 depends on the volume of the recovery compartment (V_{rec}). The bigger the volume of the recovery compartment the more gas is needed.

The factor k describes the pressure increase inside the recovery compartment and should have a value between 1.0 and 1.3.

Due to the fact that pressurized CO_2 cools down during expansion, a $v_{gy,CO2}$ of 0.541 l/g is recommended (see Table 1, at 15°C / 1 bar).

$$m_{CO_2} = k \cdot \frac{V_{rec}}{v_{gy,CO_2}} \quad (25)$$

Table I shows the expanded volume per mass ($v_{gy,CO2}$) for CO_2 at different temperatures.

Fig. 9: STR-06 "Watney" launch at C'Space 2016

TABLE I: EXPANDED VOLUME [5]

at 30°C / 1 bar	0.570 l/g
at 15°C / 1 bar	0.541 l/g
at 0°C / 1 bar	0.513 l/g
at -15°C / 1 bar	0.484 l/g

If you compare the needed mass of CO_2 (25) in a PRS with Black Powder (m_{BP}) the factor is around 4. So if you have used Black Powder in the past, equation (26) should be a good estimation for the needed mass of CO_2 in a PRS.

$$m_{CO_2} \approx 4 \cdot m_{BP} \quad (26)$$

V. TEST FLIGHTS

As mentioned in the introduction the current PRS version was developed for the launch event C'Space 2016 (Fig. 9). The flight of the STR-06 "Watney" was fully nominal.

Four weeks later the TU Wien Space Team participated at another launch event in Manching (Germany). This time the Team decided to test the PRS again in the upper stage of the STR-06A two stage rocket (Fig. 10).

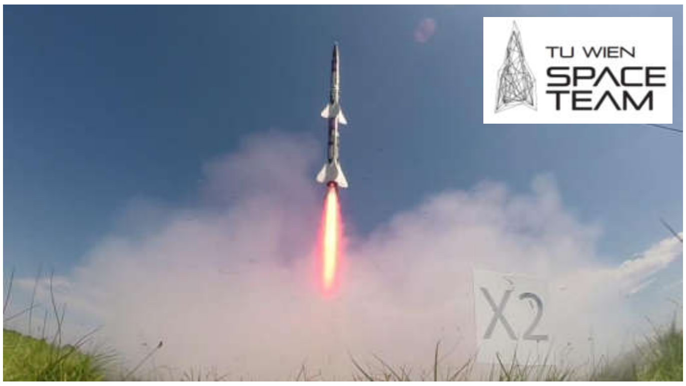

Fig. 10: STR-06A "Watney" launch in Manching 2016 (GER)

VI. EDUCATIONAL CONTENT

At university students mainly gets a theoretical knowledge in their field of study. Practical skills and working on a project as an interdisciplinary team are underrepresented in the curriculum.

To accomplish this project physicists, mechanical engineers, electronics engineers and computer scientists were involved. Training social and communication skills cannot be started as early as possible. In the framework of student projects creative solutions can be realized without being afraid of making mistakes.

Acknowledgment

I would like to thank the club "TU Wien Space Team" and all sponsors for their support to accomplish this project. Especially "iSi Components GmbH" and "Amari Austria GmbH" contributed significantly to this project. All sponsors of the "TU Wien Space Team" are shown on the website [1].

I would also like to thank Troy Prideaux [2] for his inspiring design and informative conversations.

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Asgard Balloon and Bifrost Parabolic Flight Programmes: Building appetite and nurturing talent for STEM in upper Secondary School Students

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***Abstract*—Initiated in 2011, the Asgard high altitude balloon programme has been targeted at upper secondary schools from its inception, offering flight opportunities 'to the edge of space' to motivated teams of students with an interest in STEM (Science-Technology-Engineering-Mathematics). The technicalities of an Asgard balloon flight are treated. The Asgard programme is discussed, including the calendar involved and the learning opportunities provided, both in preparation of the experiments and during the launch campaign itself. Progress made by secondary schools through recurrent participation in the Asgard programme and derived projects is illustrated. Bifrost parabolic flights are covered in similar fashion, with attention to the duration of the microgravity phase, the quality of the microgravity environment, etc. The flight capabilities of the Cessna Citation II used in the Bifrost Programme are covered.**

Keywords—parabolic flight, high altitude balloon, secondary education, microgravity,

I. Introduction

Generally speaking, hands-on space education projects offered at secondary school level tend to use space as context or reference frame while the students' experiments themselves only get to fly on drones or 'cansats', usually to altitudes on the order of a few tens of meters, up to about 1000m. Furthermore, these projects tend to be modeled after sports competitions, with a 'winner' being declared after the flight and following closing presentations, more than after genuine space projects.

This approach has the combined advantages of low technological threshold, low cost and wide accessibility. This makes it particularly well suited to the massive secondary school population of over 42 million students in ESA member states alone. However, experience with the Asgard high altitude balloon programme (flying annually since 2011) has shown that numerous upper high school students, their teachers and their schools, benefit little in the long run from the competitive nature of such programmes, and far more from a recurrent hands-on project organised along the lines of actual space projects, as has been the norm for hands-on space education at tertiary level for many years.

Furthermore, such realistic simulations are far more effective at wetting a student's appetite for an engineering or research career and are therefore far more likely to guide a student's tertairy education choices towards STEM (Science, Technology, Engineering and/or Mathematics) [1].

II. Asgard High Altitude Balloon Flights

The balloons flown in the Asgard programme are the same ones used routinely by the Belgian Royal Meteorological Institute for its thrice a week soundings. In the early years of the Asgard programme, these were 1500 gram latex balloons, now 1200 grams. With hydrogen as lifting gas (far cheaper than helium) this allows an Asgard balloon to carry a 300 gram gondola with a >1600 gram payload to a burst altitude of about 30km – a region known as 'near space' - in about 2 - 2,5 hours (Fig.1.).

The payload comes down under parachute at approximately twice the ascent velocity, bringing the total mission duration to about 3 to 4 hours. That allows the payload, launched at about 11am, to be down by mid-afternoon and recovered by late afternoon. This is considered very desirable, because there is no data downlink, so the teams need their hardware in order to prepare their 'first results' presentations for the day after launch.

Fig. 1. The English Channel seen from an Asgard balloon over Belgium.

A. The Asgard Programme

The Asgard programme is open for participation to secondary schools worldwide. Emphasis is on 11th and 12th grade students. While team size at the school itself is not regulated, the team participating in the flight campaign is limited to 5 students and a teacher. Some slack is given when needed, e.g. when some foreign schools require two teachers to be present at all times during trips abroad. The language of the project is English.

B. Calendar

Taking genuine space projects as a role model for the Asgard programme, the first step is the call for proposals, which is issued early september, at the start of the new school year. Deadline for submission of proposals is November 11th. A jury of organizers, chaired by Viscount Dirk Frimout, Ph.D., Belgium's first astronaut (and for years professionally engaged in the design of instruments for high altitude atmospheric research) then selects a suitable number of proposals in the categories 'beginners' and 'advanced'. A school is considered 'advanced' if it has experience with two Asgard campaigns or equivalent (Cansat, Bifrost). School teams are notified of the jury's decision regarding their proposal by mid-december so they can get to work when Christmas exams are over. By the end of January a first progress report is due, showing work has started and is progressing. Any issues can thus be identified early and experiment design adjusted accordingly. By March a second report is due showing actual construction has started and appropriate testing is planned. By April the final design and operation documents are due, together with the hardware. Integration takes place (as of this year) two weeks prior to the launch campaign, preferably in the presence of one or two team members.

The launch campaign usually falls in the second half of April, preferably two weeks after the Easter holidays. As the Royal Meteorological Institute always flies its sounding balloons on mondays, wednesdays and fridays, Asgard balloons always fly on a thursday (Fig.2.).

Fig.2. Asgard balloon flights (single or dual) fly from the site of the Royal Meteorological Institute, Ukkel, Belgium.

The campaign therefore starts on a wednesday morning in the Planetarium's auditorium with a welcome address and an opening lecture by an invited speaker (usually a space scientist). Then the participating teams give a 10 minute presentation each, explaining their experiment, its setup and any issues encountered in its preparation. Coffee breaks and lunch are offered to all participants. After the presentations, the integrated gondolas are shown to the teams and startup procedures are rehearsed. Any last-minute issues are dealt with. On thursday morning the teams meet at the site of the Royal Meteorological Institute. After a welcome address the teams are given their instructions for the remainder of the day, as different teams will get different workshops/guided tours and/or presentations. Team captains are convened for a final experiment check and then a group picture is taken before the countdown and balloon launch. While most teams stay on site for their scientific afternoon, about 20 students and teachers set out for the Museum of Natural History, while a few others go on a balloon chase. While this is mostly an organizer's affair, it happens that time-critical biology experiments require a team member to be on the recovery team to put samples in confined conditions (be they sterile, cold or dry) as soon as possible.

If and when the gondola (which carries both GPS and a mobile tracker) is recovered, it is returned to the hotel where the students reside, so they can recover their experiments, start processing the data and preparing their 'first results' presentation of the next morning.

On friday all team reconvene at the Planetarium for final presentations and conclusions. A new round of pictures concludes the official part of the campaign (Fig.3.). As a final social event, pizzas are offered to all participants while in the background, pictures taken during the campaign bring back fresh and warm memories. Teams then head back home, ready to start work on the scientific poster they are to produce by the end of May.

Fig.3. The Asgard-VII teams and organizers in front of the Brussels' Planetarium at the end of the campaign.

C. Partners

The Asgard programme is built on the contribution in kind made by several partners. Sint-Pieterscollege of Jette provides technical support to the participating teams, keeps the Asgard User's Guide up to date and has overall responsibility. The Euro Space Society brings in the professional experience and notoriety of its President, Viscount Dirk Frimout, who chairs the jury. The Royal Meteorological Institute offers the balloon flight, lifting gas, and personnel needed for launch. The Brussel's Planetarium offers its infrastructure for presentations and payload integration. The Royal Observatory of Belgium, the Belgian Institute for Space Aeronomy, the Solar Terrestrial Center of Excellence and the Royal Meteorological Institute offer guided tours, presentations and/or workshops given by their scientific staff. As of this year, the Royal Institute for Natural Sciences will do the same, offering a unique view on its first class collection of meteors and unique set of exquisitely preserved dynosaurs. Here too, the guided tours include an exceptional 'behind the scenes' visit.

D. Cost

Participation in Asgard is free of charge, and the project is open to secondary schools worldwide. The student teams are responsible for all expenses involved in the design, building and testing of their experiment. Travel expenses are also covered by the participants. Hotel costs and catering are covered by the European Space Agency. All costs related to the flight, the guided tours, presentations and workshops given by the scientists are graciously covered by the Asgard partners.

E. Learning opportunities and educational aspects

Among the various competences students need to develop in Asgard are cooperation, planning, communication and respect for deadlines. This requires a level of teamwork seldom reached in normal school activities both in intensity and in duration.

Furthermore, as most experiments require at least some electronics, circuit design, power and storage capacity management enter the equation, as does programming (in either C++, Python or other language). Using electronics also involves learning about technical specifications, as temperature variations can affect component performance and cause power issues (batteries)(Figs.4.&5.).

Fig.4. A 12th grade student's project: 3 Geiger counters with coincidence circuits to investigate the angular distribution of atmospheric gamma radiation.

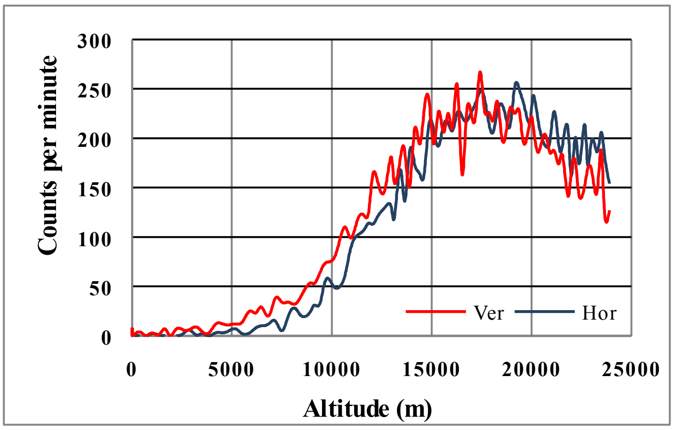

Fig.5. Results of the '3 Geiger counters' experiment, showing slightly higher radiation levels in the vertical direction below the Pfotzer maximum at 18km. The lower vertical radiation levels at higher altitudes are within the statistical error margin.

Thermal control becomes an item because under low pressure conditions radiative cooling takes precedence over the more effective convective cooling relied upon at sea level. Testing is another important element in flight qualification, and is often overlooked or underestimated by unexperienced students.

Designing, building, testing and flying experiments are but part of the Asgard project. The collected data need processing and interpreting for conclusions to be drawn. Presenting (both the project's goals and its achieved results) is equally important (Fig.6.). That is why on the first day of the launch campaign, student teams give presentations to each other about their mission and the issues it faced during development. It helps students realise setbacks are an integral part of any project, and fosters cooperation and mutual assistance.

International contacts are a bonus, and encourage students to build an network of friends and acquaintances that can help them in later years. On the last day of the campaign, teams give another presentation, this one on their preliminary results. While some data processing take longer than can be expected to be performed by students on a single evening, a first look is often enough to determine whether an experiment performed as expected or not, and in the latter case, to identify the possible cause(s). This again helps students to accept that failure can happen, and to identify the steps needed to avoid such problems in future educational as well as professional projects.

Fig.6. Students presenting their project, issues encountered, and solutions implemented on the first day of the Asgard-VII launch campaign.

On launch day, when the recovery team is on its way chasing the balloon, teams are offered guided tours, workshops and presentations by professional scientists working at scientific institutes. This helps the students get a realistic picture of what a scientist's professional life looks like, and helps them understand the workings of scientific research institutes. This is very useful information for them, as most students are in either 11th or 12th grade, and tertiary education choices are fast approaching.

F. Derived projects

The knowhow acquired over a number of participations in Asgard campaigns - or similar such as Bifrost or Cansat - allows ambitious schools to set their sights higher and accomplish projects that fall outside the scope of either Asgard, Bifrost or Cansat. In 2014, a magnetometer experiment was run on Belgium's Antarctic base at the Utsteinen nunatak in Queen Maudland (Fig.7).

In 2016, three schools organized a joint expedition to Longyearbyen, Svalbard to fly latex balloons at very high latitudes (78°N) (Fig.8.). The experiments were designed to take advantage of the launch site's unique location: experiments based on TV communications (heavily regulated in more densely populated western Europe) and studies of Earth's magnetic field and atmospheric gamma radiation [2].

Fig.7. Student magnetometer at the Belgian antarctic base in Utsteinen.

Fig.8. Radiation experiment on a balloon flown from Kjell Henriksen Observatory, Longyearbyen, Svalbard.

While long duration balloon flight is usually inaccessible to secondary schools, Sint-Pieterscollege qualified for HASP2018 (High Altitude Student Platform), a cooperation between the Louisiana Space Consortium and NASA. A package of radiation experiments called STRAINS (Stratospheric Radiation Instruments) is being developed within the 'small payloads' constraints: 15x15x30cm for a maximum mass of 3 kg, max 0,5A@30VDC. In this case a team of students will have the opportunity to travel to Fort Sumner, New-Mexico in September and fly their experiments to an altitude of 40km for a total of 5-20hours (depending on wind speeds) (Figs. 9&10).

Figs.9&10. HASP offers long duration, high altitudes and more payload mass than latex (weather) balloons could. On the right, the STRAINS experiment setup under construction in March 2018.

III. Bifrost Parabolic Flights

The Bifrost programme offers secondary school students the opportunity to perform experiments under microgravity conditions and feel its effects in person. The flights are performed with the flying laboratory of the Technical University of Delft (The Netherlands) (Fig.11). A converted business jet, this plane is capable of flying parabolas offering up to 12-15 seconds of microgravity (<0,03g)(Fig.12), or slightly longer parabolas offering Lunar or Martian gravity levels. Longer periods of 2g hypergravity are also possible. In the Bifrost programme, each flight lasts about one hour during which approximately 12 parabolas are flown.

Fig.11. TUDelft's Cessna Citation II flying laboratory used for Bifrost parabolic flight.

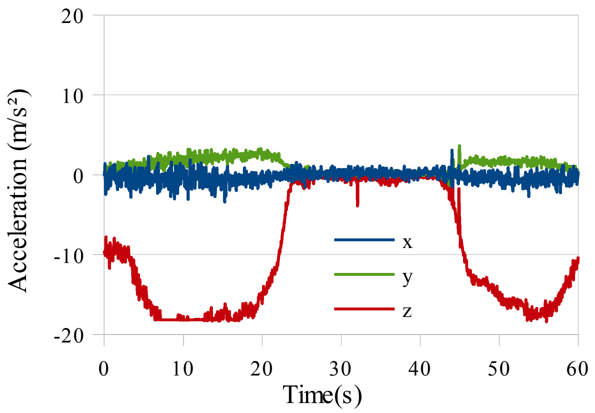

Fig.12. A student designed Inertial Measurement Unit (IMU) assessed the duration and quality of the microgravity offered, as well as the variability in direction of the pseudogravity felt during Bifrost parabolic flight.

A. The Bifrost Programme

The Bifrost programme is open to final year students from secondary schools in the Brussels Capital Region. While team size at the school itself is not regulated, the team participating in the flight campaign is limited to 5 students and a teacher. The language of the project is English.

B. Calendar

The Bifrost 2017 campaign started with an 'announcement of opportunity' communicated to the schools of the Brussels Capital Region in June 2016, followed by a call for proposals in September. Deadline for the submission of proposals was October 2016. Of the 18 proposals received, 12 were selected by a jury of microgravity and space professionals for the second round. The 12 team teachers were given a workshop on parabolic flight and the technical constraints their experiment would have to meet. These constraints dealt with matters of size and mass, but also the issues involved in the use of high voltages, chemicals, pyrotechnics, pressure vessels, lasers, batteries etc. A manual was compiled and put at the disposal of the teams to help them get started. A visit to each school was planned over the course of the next few months to answer students' questions and help avoid problems during preflight safety briefings and/or in-flight. Two intermediate progress reports were delivered to the jury. In March, all teams gathered at the Planetarium for presentations to the jury and each other, followed by another selection round in which the jury selected four teams for actual parabolic flight (experiment + team members), and four teams that would fly their experiment but no students. The flights took place in The Netherlands.

C. Cost

Participation in Bifrost is free of charge, but the project was open only to schools in the Capital Region of Brussels (2017). The organizers cover student teams' expenses on their experiment up to €500. All other costs, the plane, fuel, take-off and landing taxes, insurance, travel, hotel costs and catering are covered by the organizers.

D. Learning opportunities and educational aspects

While all learning opportunities mentioned earlier for Asgard equally apply to Bifrost, parabolic flight has its own advantages. The bigger volume (0,25 m³) and mass limits (10 kg) imposed on the experiments, the presence of experimenters that can adjust parameters between paraboles, and the presence of experimenters on whose bodies (noninvasive) experiments can be performed significantly broaden the scope of scientific inquiry that is accessible. Geology, physiology and fluid physics are but a few examples.

E. Tertiary Education

It should be noted that the Bifrost format could be used to offer parabolic flights to science and engineering students at a reasonable cost, making it accessible to universities or similarly-sized organisations with an interest in hands-on space education.

Conclusions

Since the dawn of the 21st century technology has become available that allows secondary schools to engage in challenging hands-on space related education projects. With today's ease of communication, these projects can just as easily be made international in character, encouraging students to see the entire world as their home and workplace, not their school, town or country. Furthermore, by modeling hands-on space education projects on real space exploration missions, the professional life of the scientist or engineer is brought closer to the students, encouraging them to pursue careers in STEM faculties. By making such projects recurrent, knowhow and competences are built in the teachers too, encouraging them to engage annually in similar projects, to the greater benefit of students and schools alike. Some schools grow beyond these projects and can engage in exciting endeavours until recently accessible only to universities or professionals.

Acknowledgment

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Achieving Successful Satellite Engineering with an Undergraduate Project-Based Team

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Abstract— **The University of Warwick's Satellite Engineering Team (WUSAT) is currently in its twelfth year of operation. This paper highlights the remarkable story of a Final Year Master of Engineering undergraduate project. Borne out of an engineering department that does not include Aerospace Engineering as one its specialisms, the development and achievements of the WUSAT programme demonstrates the ability of high-quality students, who have studied classical engineering subjects, to successfully apply their knowledge to any specific engineering application.**

In its explanation of how this has been achieved, this paper describes the origins of WUSAT and how, despite having no previous Space experience at the outset, the team has managed to work on ESA supported projects for eight of its twelve years. It shows how, despite having minimum funding, an extensive partnership support group, based on the principle of mutual benefit, has allowed the team to function successfully. The structure of the team, its philosophy, and the wider WUSAT Programme of operation is also discussed. The use of Systems Engineering, and particularly the application of Concurrent Engineering principles, are shown to be a key feature in producing good working practice within the team structure and in the handover between successive teams.

Detail of each of the four WUSAT missions to date is given. These highlight the operating principles of the project-learning philosophy, and indicate the enormous experience received by WUSAT team members prior to their graduation.

Extended benefits of the WUSAT programme include its significant outreach capability, its proud record of supporting women in engineering, and its ability to provide high-level promotion of our students, our department, our university, and an extensive range of collaborative partners.

A discussion on potential future developments to the WUSAT Programme is also given. This explores possible ways of improving continuity between teams, improving funding income, and increasing the mutual benefit between WUSAT and its extensive range of partners.

Keywords— CubeSat Engineering, Project-based Learning, Concurrent Engineering.

I. BACKGROUND

The School of Engineering at the University of Warwick offers engineering degree programmes in the classic engineering degree subjects [1]. These can be studied over a period of 3 years for a BEng degree, or 4 years for an MEng degree. The philosophy of the engineering approach at Warwick is that 'real world' engineering requires engineers of different disciplines to have a good understanding of the work that all engineers do. The ability of engineers in multidisciplinary project teams to effectively communicate with each other at an appropriate technical level is key to all successful engineering project work. Engineering students at Warwick study elements of all engineering disciplines before specialising in their chosen programme of study. MEng students are placed into a significant group project in Year 4 of their MEng programme, and the multi-disciplinary profile of each team is designed to meet the needs of the project requirement they are selected for.

Hence a typical WUSAT team would contain in number, one to three of each of the following engineering types, depending on the stage of development of the satellite and its support systems – Systems, Mechanical, Electronic, Manufacturing, and Computer Systems Engineering. In order to meet both their course objectives and launch programme (e.g. ESA) objectives, WUSAT teams must be extremely effective in the organisation and implementation of their team management, systems engineering and general planning and control procedures. As the period of a typical WUSAT mission would be from two to six years, the subject of Knowledge Management in relation to 'handover' between teams is also a crucial factor.

II. WUSAT MISSIONS

ESMO (2006 – 2012)

The first WUSAT team was formed in 2006, initially with the intention of forming a joint sub-system team with the Aeronautics and Astronautics Group headed by Prof. Steve Gabriel at the University of Southampton [2]. The initial intention was that we would design and build the electrical supply to power Southampton's electric propulsion system. However, we subsequently became the primary team for the entire electrical supply system on ESMO. These six years taught us a great deal about

- How to operate as a team
- How to work with ESA and other subsystem teams
- How to attract and retain important collaborations with supporting companies and other organisations

WUSAT-1 (2012-2013)

This was our first 'solo' incursion into the world of CubeSats. The team designed and built a 1-Unit CubeSat that was launched by a helium balloon from a CAA approved site in Wales. Carrying a range of cameras and a tracking device, WUSAT-1 reached an altitude of approximately 30km, took some excellent video/images, and landed by parachute at a site in Warwickshire within 100m of the team's predicted landing site! WUSAT-1 taught us that we were capable of developing our own modest satellites.

WUSAT-2 (2013-2015)

Launched in March 2015 through an ESA supported REXUS programme. WUSAT-2 was a 1-Unit CubeSat that carried a light spectrometer payload to an altitude of approximately 90km where it was ejected from the Orion sounding rocket (REXUS 17) [3] [4]. WUSAT-2 descended through the atmosphere recording light frequencies, estimating the density of elements such as sodium and O^2 over a range of altitudes and transmitting the data to our ground station. We were informed at the time that WUSAT-2 was the first ejected experiment in seventeen launches that successfully operated and transmitted its data to ground! WUSAT-2 taught us that

- We were capable of meeting the requirements of an ESA-type launch programme
- Our knowledge management systems could cope with the handover between successive teams and still meet launch programme requirements.

WUSAT-3 (2015 – present)

Following the success of WUSAT-2, our firm goal was for WUSAT-3 to be a Low Earth Orbit satellite, deployed from the International Space Station (ISS) via ESA's 'Fly Your Satellite' programme [6] [7]. To this end, WUSAT-3 is being designed as a 3-Unit CubeSat, capable of meeting the requirements of NanoRacks deployment from the ISS. Following discussion with one of our collaborative Partners, Roke Manor Research [5], it was determined that the payload would be a signal direction-finding system capable of locating the type of signal transmitted by radio tags used for monitoring wildlife. This payload concept also led to the exciting prospect of linking to the Max Planck Institute for Ornithology [6] whose ICARUS system will be fitted to the ISS for implementation during 2018. The ICARUS system will aim to upload data from tags that carry GPS information, whereas WUSAT-3 will calculate the tag location via a camera and four-arm antenna system. Both systems are 'proof of concept' experiments and the mutual corroboration of results will benefit all parties. To date, WUSAT-3 has taught us

- That we can develop more advanced satellites including e.g. ADCS orientation control systems, deployable antenna designs, PV panel electrical generating circuitry, LEO-to-ground RT communications capability, etc.
- That we can employ Concurrent Engineering techniques in order to establish and maintain suitable control over all design decisions in a more complex space technology project.
- That we can use ESA-style change control documentation in order to establish efficient knowledge management throughout the life cycle of the mission, and particularly to cope with our team handover requirement.
- That we can extend the scope of our project to include non-engineering partners, e.g. wildlife monitoring tag developing companies.
- That we can use WUSAT to excite and motivate young potential engineers to want to undertake a career in Space engineering.

III. WUSAT Partnership Support Group

The 'team' ethic within the WUSAT programme is extremely strong. Apart from being very supportive of all individuals in any current WUSAT MEng team, we have a philosophy of trying to make all our extended support network feel part of our 'team' and able to share in our achievements. This includes;

- Our many collaborative partners work with us in a variety of ways [8]. We have worked with over 40 such partners in the twelve years we have been in operation, though – of course – current partners vary dependent upon the requirements of each particular mission. It is important for us to think "What can we do for them?", rather than just ask them to do things for us. They tend to supply funding (very limited), components, software licences, training, technical advice, etc. We offer promotion of their name/logo on all our promotional outlets (logos on WUSAT polo shirts, posters, website, outreach presentations, etc). In some cases – for the company's own internal/external outlets – we provide articles/case studies highlighting the company's involvement with WUSAT. We also hold a 'Sponsor's Day' towards the end of each academic year. All of our collaborative partners are invited to visit us for the day. The Project Directors will give a presentation on the current status of the WUSAT programme & current mission, whilst the team will give a technical presentation of their year's work. This helps to
  - make the partners feel part of the team,
  - enables further discussion on potential collaboration,
  - provides expert feedback on the team's presentation prior to them giving it to a more formal assessment panel as part of their MEng assessment schedule.
- A number of PhD students who are ex-WUSAT, and have progressed to study a PhD within Warwick Engineering (not necessarily WUSAT), but who continue to support the WUSAT team when they can.

- Our excellent departmental engineering technician workforce who do wonderful work, both in terms of finished product and in terms of their assistance and advice to team members.
- The School of Engineering staff at the University of Warwick who, in some way, all contribute to the development of the students that arrive in our WUSAT lab for the 4th Year of their MEng programme.
- Our 'WUSAT Watchers' group of individuals who, from a variety of backgrounds, have learned about our WUSAT missions and are keen to continue to receive news of our progress.

Apart from the usual website, Facebook, Twitter feeds, we produce a regular WUSAT Newsletter that is circulated by email to all of the above. There are many occasions in which we have been able to offer something in return to the 'partners' listed above in recognition of their work with WUSAT. Whether it may be in the form of job application references, articles, submissions for awards, attending their promotional events, or even access to articles through Warwick's library, we never stop thinking of ways in which we can make our arrangements with them more mutual.

IV. WUSAT Team Organisation

A typical WUSAT team consists of six to eight final year MEng students. The mix of engineering disciplines in, e.g. a team of seven, might be two Electronic Engineers, two Mechanical Engineers, two Systems Engineers, and one Mechanical/Manufacturing Engineer. The WUSAT Programme is defined and managed by two Project Directors. These are;

- Dr Bill Crofts - the originator of the WUSAT programme who has twelve years of experience in working with ESA and managing such programmes.
- Prof. Julia Hunter-Anderson – is a Space Systems engineer with thirty years of experience in the Space Industry.

Additional assistance is provided, typically, by two to three ex-WUSAT postgraduate students who are studying PhD programmes within the School of Engineering but under non-WUSAT supervisors.

Team Selection – All final year MEng students are placed into a multi-disciplinary project team (of which WUSAT is one). Therefore, there cannot be an 'open' choice for the students. The Project Directors must present their proposed project, outline the project requirements, and stipulate their desired team profile considered capable of meeting these requirements. It is the job of the module management to then 'best fit' the final year MEng cohort into the various project teams in order to provide the most appropriate teams for each group project. In this sense, this part of the group project experience is also 'real world'. It is emulating the scenario where a client with a project requirement approaches a company to undertake and complete that project. In this scenario the company, having won the contract, would select its best team for the job in hand.

However, all of the students do have an opportunity to make a case to be selected for a certain type of role, and possibly even to be selected for one of their preferred options of project. They are invited to submit a statement of their interests, skills and experience, which the module management can take into account when selecting who will go into which group project team. Students who demonstrate a strong desire to work on the WUSAT project can enhance their case by e.g.

- Being an active member of Warwick Aerospace Society [9]
- Applying to attend Space technology courses, ESA or similar, the details of which are circulated to them by the WUSAT Directors.
- Attending conferences, etc, related to Space technology.
- Applying for internships at Space technology related companies.

Team Organisation – The incoming team will take part in handover activities with the outgoing team. The outgoing WUSAT team will be heavily involved in deciding what form that handover activity will take.
Once in place, the new team will receive from the Project Directors;

- Instruction on the heritage and working practices of WUSAT and its previous missions.
- Instruction on the requirements for weekly progress meetings, agenda/minute conventions, additional administrative/organisational roles to be undertaken by team members.
- Instruction on the requirement to set up a rota for minute-taking/meeting Chairing, in order to ensure that administrative duties are shared equitably.
- Instruction on the necessity of accurate, well-maintained, well-managed documentation.
- Instruction on the importance of efficient, secure document filing and archiving.
- A lecture on Space Systems, and instruction on the typical phases of satellite system development and the requirements that need to be met to successfully complete these phases.
- Instruction on the relationships with our various collaborative partners, and how these should be fostered and maintained.

Technical Progression – Once the working year is underway for the incoming WUSAT team, they will have access to all documentation produced by previous teams that have worked on the same mission. Team members are able to look for additional guidance on how they will progress current designs via discussion with;

- The Project Directors.
- Contacts at our collaborative partner institutions.

- ESA mentors, when on an ESA launch programme.

However, it should be clearly stated that, in the main, the direction of technical development of any given sub-system is largely at the discretion of the student(s), how much time they are willing to give, how much they can attempt within the limits of their knowledge and abilities. – notwithstanding any requirement for change imposed by e.g an ESA review panel.

V. Systems Engineering / Concurrent Engineering

MEng student projects at Warwick are often conceived around complex systems – e.g. automotive, submarine, rail, biomedical – in order to best represent a complex real-world project experience. In principle any student could achieve the same educational experience on any of the projects.

Each project requires a degree of systems engineering. Although there are not sufficient systems engineering students to satisfy all projects, the complexity of the WUSAT project generally ensures that there is at least one. WUSAT-3 is also unique across the MEng Projects in that one of the Project Directors is a professional Systems Engineer, with 30 years' experience working in the Space domain across all project phases and with all stakeholders. A series of initial working seminars and ongoing support throughout the year helps each successive student team to get up to speed as quickly as possible, especially important considering the multi-year project timescale:

Technical Leadership and Critique – despite the students driving the direction of their project, the Project Directors act both as the Customer and technical leadership at a systems level. The aim is to ensure that appropriate processes are followed in order to support rigorous design decisions.

Space Systems Primer - bringing the team up to speed as quickly as possible on the peculiarities of the Space environment, the requirements and constraints imposed by a launch, particularly via the ISS, the standard breakdown of a space system (including space, ground and user segment and launcher) and its operation up to end-of-life.

Use of Standards - bringing the team up to speed on the essentials of industry standard engineering, product assurance and technical management approaches and tools. This aims to ensure that the knowledge of design decisions, hardware and documentation of each team are effectively captured and can be handed-over to successive teams. With the expectation of applying to ESA's FYS! Programme, focus is given to using the ECSS standards, tailored as appropriate to the small satellite environment. This tailoring is achieved in collaboration with the student team and in consultation with our Collaborators in industry and academia.

Systems Engineering Methods – all team members are expected to support a Systems Engineering approach, as per the Standards. The Systems Engineering students drive this approach and are guided in practicing the skills and using the knowledge gained in their studies to date, including:

- *Requirements Engineering* - the student team is required to consider the positive (and negative) impact of their project/design when defining or evolving the technical requirements. Where possible they are encouraged to liaise with the End-User community. For example, for WUSAT-3 one systems engineer (and Project Director) attended a Bio-Logging Symposium (BLS-6) in order to understand the End-Users' needs and the current technical offering. The team also considers the possible verification and validation methods, matching testing requirements with the facilities available at the University and the facilities of our collaborative partners' network.
- *Concurrent Engineering (CE)* - the team is strongly encouraged to use a CE approach for design development, driven by the Systems Engineers. CE is dependent upon processes and tools/facilities as well as the time and dedication to co-working sessions. It is the latter aspect which has proved to be the most difficult to implement, due to the different lecture timetables of each student, putting more emphasis on remote and partial co-working sessions than in-situ sessions. Nevertheless, the team have implemented a simple Concurrent Design Facility (CDF) concept based on their experiences from attending ESA Academy's CE Challenge and Training courses. We have also started a collaboration with one of the industry leaders in CE software/training, Rhea Group, and expect to include their CDP4 software and processes for use by future teams. This experience will feed back to Rhea for product improvement.
- *Budget Management* – e.g. mass, power, pointing and link budgets are actively maintained

There has been increasing interest from other complex MEng projects, in the WUSAT systems engineering approach and the rigour afforded by the Space industry standards.

VI. Extended Benefits

Outreach – Space Technology is always highly attractive to young people. Hence the WUSAT Programme and its various missions have always had enormous appeal for budding engineers. WUSAT Project Directors and teams consider that we have a duty to act as an important outreach showpiece on behalf of all our stakeholders. These include;

- The European Space Agency
- The UK Space Agency
- All our partner companies and institutions
- The University of Warwick
- The School of Engineering
- The City of Coventry.

We deliver our outreach message through a number of mediums including;

- University Open Days
- Local School Open Days
- Presentations to local groups of various types

- Local radio interviews
- Attendance at Space Conferences
- Supplying articles/material to our collaborative partners which they then use in their outreach activities.

We have a finite amount of budget and time for these activities, but we invariable make the effort where we can as we consider it to be high priority for the WUSAT programme.

Women in Engineering – WUSAT is very proud of its record in supporting women engineers. In our twelve years of existence, we have seen a higher percentage of women engineers working on WUSAT missions than the national average of women in engineering. Statistics [10] show that, at March 2016, only 9% of the UK engineering workforce was female. Whereas, to date, 23 of the 93 engineers that have worked on WUSAT have been female (i.e. approximately 25%). This is a significant achievement for the WUSAT programme and a major feature of engineering at the University of Warwick.

Enhanced Attraction of WUSAT Graduates to Employers – We have had extensive feedback from ex-WUSAT students who have told us that their time with WUSAT played a significant part in subsequent job interviews. It is clear from their response that important features of WUSAT operation such as;

- Time management
- Multi-discipline team management
- Development of a complex system
- Systems Engineering, etc

are of great interest to employers. They clearly place considerable significance on the skills developed through the WUSAT programme. For this reason, we have no doubt that WUSAT graduates are highly employable

VII. Future Developments

WUSAT Research Group – Funding is always an issue for WUSAT. Not being a postgraduate research group means that we do not attract research funding in the conventional sense. One potential solution to this problem is the development of a WUSAT Research Group. Initial work has been undertaken to establish a database of all Warwick Engineering Academics whose research could also be applicable to Space Technology applications (e.g. Thermal Modelling, Additive Layer Manufacturing, etc) [11]. The concept is that PhD students could carry out Space-related research within the WUSAT environment, but supervised primarily by a non-WUSAT academic within Warwick Engineering. This has a number of potential advantages. It could;

- help to develop a portfolio of research, attributable to WUSAT, that could then be used to develop a submission for an Impact Case Award (i.e. A funding award for generating research that has had an impact in actual applications).
- provide enhanced links with companies interested in e.g. Industrial Case Award funding for academic/industrial jointly supervised PhDs.
- generate greater engagement of non-WUSAT academics with the WUSAT programme.
- provide an increased capability for the WUSAT team in having more long-term PhD students working in the WUSAT lab.
- further enhance WUSAT's profile in the wider Space education community.

VIII. Conclusions

The WUSAT programme has made remarkable achievements in its twelve-year history. It continues to remain ambitious for both the level of missions to which it can aspire and the enormous opportunity it offers MEng and PhD students. It offers a first-class window on opportunities in the Space industry, and promotes employment in Space Agencies and Space Technology Companies to a wide range of potential students. It also continues to inspire young women to seriously consider engineering, especially Space engineering as a career with great prospects.

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Conjugating educational activities and technology development: the example of TED project

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***Abstract*— *TED (Tethered Electromagnetic Docking) is a system proposed by a group of researchers and students of the University of Padova for close rendezvous and docking between spacecraft. It consists in a small tethered probe ejected by the chaser, reaching the proximity of the target with a controlled deployment, and then magnetically guided by a receiving electromagnet mounted on it. Because of the generated magnetic field, alignment and mating are possible; then, as the tether is rewound, the chaser is able to dock with the target. To perform a preliminary verification of TED, three groups of students have been involved in the project and contributed to the evaluation of its critical technologies in reduced gravity: in the framework of ESA "Drop your Thesis!" 2014 and 2016 campaigns the experiments FELDs and STAR focused on the test of the tether deployment and control, while PACMAN, in the framework of ESA "Fly Your Thesis! 2017" parabolic flights campaign, tested proximity operations by means of electromagnetic interactions. In this paper, a description of TED concept and its development roadmap is presented, introducing the critical technologies tested by FELDs, STAR and PACMAN experiments. The second part of the paper focuses on the educational outcomes of the three experiments, introducing statistics on (1) students participation, (2) scientific publication production, and (3) influence of the educational programs on the students' career.*

Keywords*— *Tethered electromagnetic docking; Microgravity; "Drop your Thesis!"; "Fly your Thesis!"

I. Introduction

Since the beginning of the space era, the procedures for cooperative rendezvous and mating of large manned and autonomous spacecraft have been deeply investigated [1], while research on small satellite docking and uncooperative bodies capture is still under development. In fact, close approach and joining phases require complex GNC (Guidance, Navigation and Control), precise position sensors, significant propellant consumption, and dedicated mating interfaces.

With regard to small satellites, the research is mostly focusing on the enabling technologies (from miniaturized docking mechanisms [2][3] to navigation sensors [4] and strategies [5]); few space demonstration of small satellites RV/D are currently under development [6][7]. Similarly, in the field of uncooperative bodies capture, no in-orbit demonstration has been performed yet. The growing interest on ADR (Active Debris Removal) missions is however encouraging the development and the ground test of novel capture systems [8] as well as the relative GNC technologies (e.g. [9][10]).

The employment of tethered systems for close approach and docking/capture phases has been proposed to simplify or integrate the procedures currently under investigation; interesting contribution have been proposed by the Polytechnic of Milano [11-15] and the University of Padova [16-18]. Such systems allow to create low-stiffness connections between the involved bodies, reducing the risk of undesired collision by allowing safe-distance operations; furthermore, under certain well described conditions, the dynamics of tethered system is stable [19], allowing slow and safe proximity operations.

A. TED concept and advantages

On these considerations, the Tethered Electromagnetic Docking (TED) procedure is proposed for close rendezvous

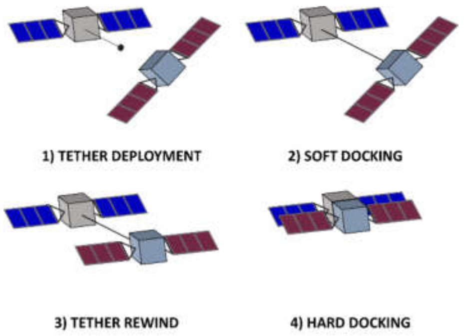

Figure 1: Tethered Electromagnetic Docking procedure concept

and joining. Thanks to the use of a small tethered probe, ejected by the chaser and captured by the target by means of electromagnetic interactions, a low stiffness connection between the vehicles can be provided; the joining manoeuvre between the two bodies can therefore be realized simply rewinding the tether, avoiding any propellant consumption.

Fig. 1 depicts TED procedure; first (1) the tethered probe is launched thanks to a propulsive mechanism, able to monitor and control the tether motion with a brake system. When the probe reaches the sphere of influence of the electromagnetic interface mounted on the target (i.e. the volume in which the target-generated electromagnetic field is greater than the Earth magnetic field), it aligns and self-guides to mate with it (2); an active probe can be also employed to increase the working range, or in case of passive ferromagnetic interfaces on the target. After the achievement of soft docking, the tether provides the low stiffness connection between the two spacecraft; finally, after (3) the two-body dynamics has been stabilized, (4) the tether allows to safely join chaser and target by rewinding it.

TED concept aims to be a competitive solution to standard close-range rendezvous and mating operations, allowing the reduction of proximity navigation and guidance requirements between chaser and target spacecraft. The advantages of this method could contribute to enable a large number of future on-orbit servicing missions; in particular, it will be possible to execute joining operations even between small satellites, despite of their limited resources, as TED is not requiring propulsion capabilities and extremely precise attitude and position determination and control to perform the close rendezvous and soft docking manoeuvres [18][20].

It is worth to point out that the benefits of this novel docking strategy with respect to the standard docking procedures are not limited to fuel savings and GNC accuracy [17][19]: first, a remarkable advantage can be envisaged in the negligible impulsive force transmitted by the small probe to the target during the soft docking connection; second, TED would increase the docking manoeuvre reliability allowing the tether retrieval in case of unsuccessful deployment and subsequent docking attempts [20].

TED demonstration is subjected to the development of some critical technologies and their verification in relevant environment. For this reason, reduced-gravity experiments have been designed and realized by our students in the framework of TED development plan, as depicted in Fig. 2, with the goal of an in-space demonstration (TED-Sat). The critical technologies for launch and passive proximity guide and for tether deployment and retrieval have been demonstrated in two test campaigns: FELDs (Flexible Electromagnetic Leash Docking system) [21] and STAR (Space Tether Automatic Retrieval) [22] were selected for ESA Education Office's "Drop Your Thesis!" program [23], that, through the use of ZARM Drop tower [24], gives university students the opportunity to perform scientific or technological research in microgravity conditions. Similarly, PACMAN (Position and Attitude Control with MAgnetic Navigation), in the framework of ESA Education Office's "Fly Your Thesis!" program [23], tested active magnetic proximity operations during a campaign of parabolic flights. Next paragraphs will introduce TED technologies verification, while section III will describe students participation and educational outputs of the whole project.

II. TED CRITICAL TECHNOLOGIES VERIFICATION

Few technologies required investigation and verification during the development of TED; tests were performed on (1) the tethered probe launch system, (2) the tether controlled deploy and retrieval, and (3) the electromagnetic proximity navigation (both passive and active).

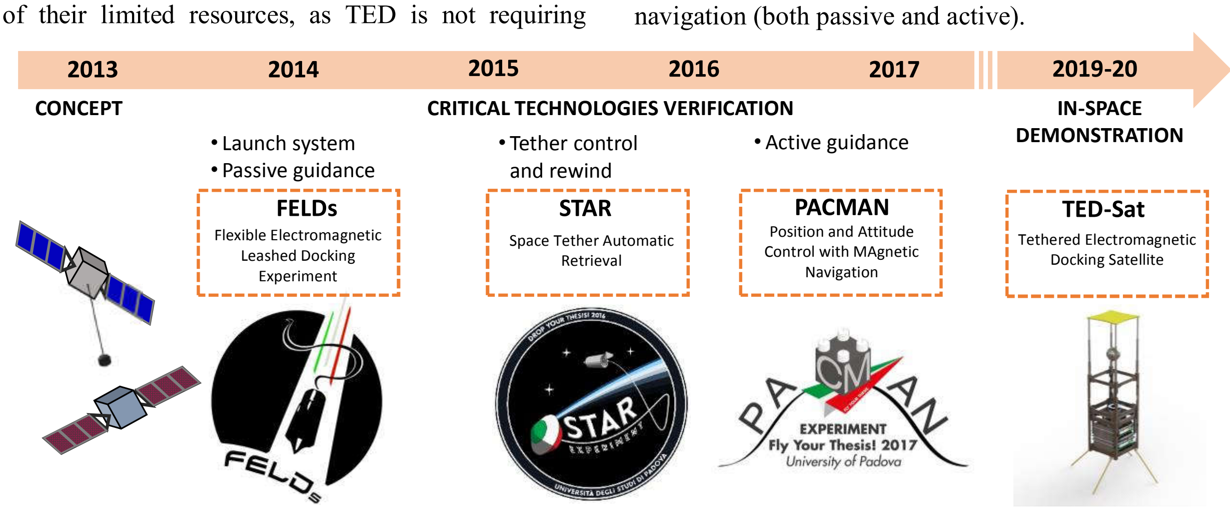

Figure 2: Tethered Docking procedure concept (left) and development plan (right), with technologies verification and the expected in-space demonstration

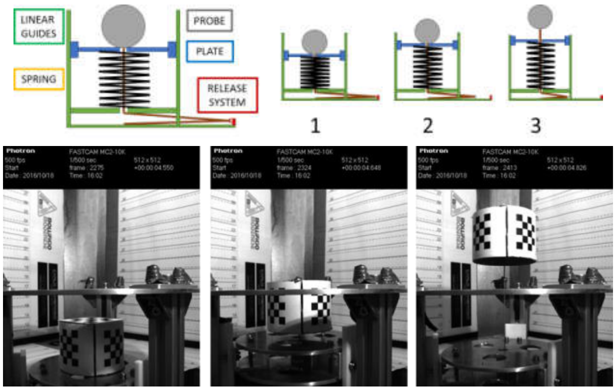

Figure 3: FELDs launch system (up) and upgraded STAR mechanism (down). In FELDs, after tether release (1), the plate is pushed by the spring driving the probe (2) until it reaches the linear guides end (3). In STAR, the tethered probe before release (left), the launch phase (centre) and the probe after separation from the plate (right).

A. Launch system

TED launch system objective is to release the tethered probe towards the target with a desired initial velocity. In-space tethered deployments have been performed mainly using two technologies: propelled probes (e.g. TSS-1 [25]) or spring-based systems (e.g. SEDS, YES [25]). Considering TED operations, a spring-based system was chosen, since it is easily settable to give a specific speed to the probe, it is easily reloaded trough recompression and, finally, it can be used for many launch attempts without consuming propellant.

The launch system working principle is reported in Fig. 3 (up): it is composed by a release system, a spring, three linear guides and the tethered probe. The probe is supported by an interface disk, able to glide on the three vertical guides. As the release system frees the tether (1), the plate is free to move, pushed by the spring (2), and driving the probe until the end of the guides (3). The first prototype of this concept employs for simplicity a single-shot actuator for the release system instead of a reusable mechanism. The launch system was tested in the FELDs experiment; the microgravity verification consisted in five drop tests at ZARM Drop Tower; three were completely successful, while the last two drops failed due to malfunctions during the release, which caused the tether to snag into the internal mechanism, increasing friction and slowing the probe. An updated mechanism, using electromagnetic release instead of the single shot actuator was employed in the STAR experiment; this solution allows launch repeatability. For all the five tests the launch system worked nominally, releasing the tethered probe with the expected initial velocity (Fig. 3, down). After the end of the STAR experiment, it can be stated that the launch system TRL is 6, having demonstrated the critical functions in the microgravity environment of ZARM drop tower in Bremen.

B. Tether controlled deploy and retrieval

The demonstration of the capability of controlled deployment and retrieval of the tethered probe is fundamental in TED development.

Over the past years, an impressive number of contributions and deep insights have been made to widen understanding of tether dynamic behaviour in space, making the physics at the basis of such systems well-known. However, the deployment of a space tether has always been a critical issue in the past space tether missions. In fact, what emerges from literature and heritage in this field is that a successful employment of space tether requires extremely good mechanical design of deployers and brakes, as well as highly robust and adaptive control strategies [26-28]. At present, both space agencies and aerospace industries are interested in the tether related technology to enable various mission concepts (e.g. [29] [30]). In this context, due to the lack of available technologies for both tether deploy and retrieval, a novel mechanism had to be developed and tested for TED application, with the desired characteristics of (1) low inertia and low friction on the reel, (2) tether retrieval capability and (3) deployment / retrieval control. In Fig. 4 a sketch of the developed mechanism is reported. The deployment is meant to be initiated by the aforementioned spring-based launch device. The deployer has a dedicated active brake mechanism, whose aim is to control the tether tension during the deployment, whilst an electric motor has the task to retrieve the tip mass once the deployed tether has been engaged by a dedicated locking mechanism (bail). More specifically, the tether prior to deployment is wound up around a fixed spool, and it is free to flow out from the spool with minimal inertia (without trailing rotating parts). In this way, there is negligible resistance to the tether exit motion (the mere tether inertia). The tip mass is driven along the desired path by means of the tether tension, that is controlled by the brake mechanism.

The tether reel system was tested by the STAR experiment; the tested hardware is reported in Fig. 4 (down, left) and was subjected to 5 tests in the drop tower. In Fig 4, down on the right, are reported three pictures from a microgravity test. It is possible to see that the system was able to deploy the probe and retrieve it to the original launch position. All the five tests were successful, with only minor off-nominal behaviours due to the necessity to tune the brake and the reel control systems. Test analysis confirmed that the experiment was successful and the deployer was substantially functional. At the end of STAR project, the tether deployment and retrieval reached a TRL of 6.

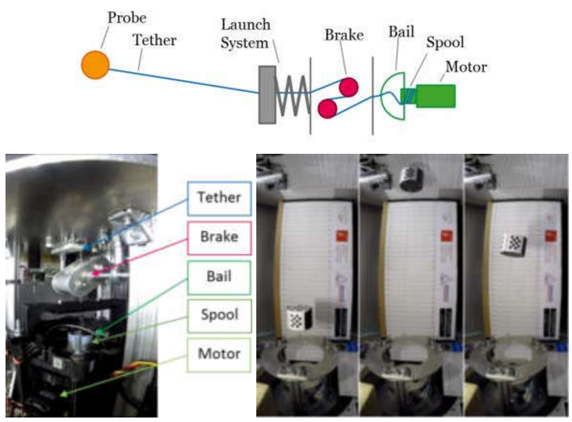

Figure 4: TED proposed tether controlled deploy and retrieval system schematics (up) and STAR configuration (down, left) and operations during drop test (down, right)

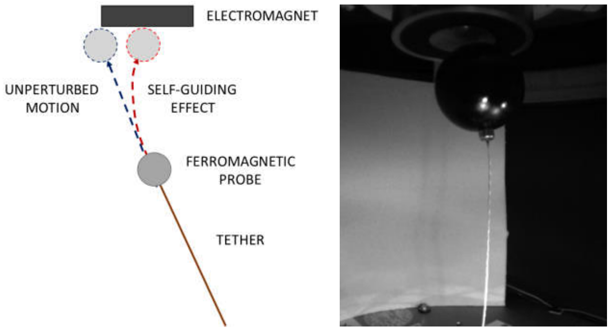

Figure 5: simplified investigated scenario for evaluating the self-guiding effect on TED probe (left) and its test by the FELDs experiment (right)

C. *Magnetic passive and active self-guide*

The objectives of the tether launch and deployment systems are to place the TED probe in proximity of the target, i.e. into the volume of influence of the electromagnetic field generated by the target and/or the probe itself; proximity operations by means of electromagnetic interactions are therefore foreseen to complete the rendezvous and docking.

A relevant work on proximity electromagnetic navigation is represented by the RINGS (Resonant Inductive Near-field Generation System) project in the framework of MIT SPHERES program. In the on-orbit tests on the ISS, the SPHERES vehicles were equipped with large coils, in order to generate electromagnetic coupling actions for both power transfer and relative navigation [31]. In parallel, a simpler technology was designed and tested in ground laboratories by Underwood and Pellegrino [32] on low friction tables, in the framework of the AAREST program for in-orbit assembly of a space telescope.

In the TED case, the self-guidance effect is fundamental to complete the soft-docking manoeuvre by moving the probe to contact the target. First, a simplified scenario was investigated, employing a ferromagnetic tethered probe and a fixed electromagnetic target, as reported in Fig. 5. The proposed layout also allows to investigate the momentum and energy transfer due to the probe impact on the target. Three successful drop tests performed by FELDs experiment allowed the verification of the self-guiding effect on the ferromagnetic probe. When the probe enters the electromagnet sphere of influence (about 10 cm for the FELDs configuration), there is a clear variation on its motion due to the magnetic force acting on it. The working range of the self-guiding clearly depends from the probe geometry and the electromagnet power; scaling to operational conditions, the sphere of influence size can vary from about 20 cm (CubeSat-sized spacecraft) to up to 1 m (100 kg class satellites). The microgravity verification of the uncontrolled magnetic self-guide gave this technology a readiness level of 5.

The complete assessment of active electromagnetic proximity operations, in the framework of PACMAN project, was performed during the test campaign of "Fly your Thesis! 2017" program. During the parabolic flights of December 2017, the two modules (Fig. 6) were launched and the active one manoeuvred to align and perform soft docking. A closed-loop GNC system was designed to compute the desired control

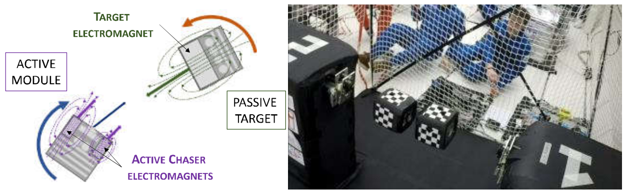

Figure 6: PACMAN working principle (up) and test in microgravity (down). The two modules are free to float during the low-gravity parabolas, and the active module manoeuvre to rendezvous, align and soft dock with the passive target.

torques considering the relative position/attitude information the magnetic field model. Data analysis is still under completion, but after preliminary assessments a TRL of 5-6 can be expected from PACMAN tests.

III. TED SPACE DEMONSTRATION

TED-Sat, the space demonstration of TED technologies, is expected to kick-off in early 2019, depending on funding availability, and to be based on student activities, following the path of the three previous experiments. While its main scientific goal will be to test the TED principle and the developed technologies in relevant environment on board a 2U CubeSat, the educational objectives are wider and involve both the realization of the first CubeSat of the University of Padova and the creation of a small satellites development group based on active participation of students.

IV. SCIENTIFIC AND EDUCATIONAL OUTCOMES

The cornerstone of TED development is its educational framework: the whole project has been based on the participation of students team, dedicated to the verification in relevant environment of the critical technologies. Up to date, the three teams have been composed mostly by Aerospace Engineering students; only about 40% of the members came form from the Information Engineering field, generally recruited after the FELDs, STAR and PACMAN teams were selected by ESA Education Office.

A. *Scientific production*

In addition to the design and experimental activities, the student teams dedicated time and resources to results presentation and dissemination. Up to date, the scientific production consists in 12 conference papers, 1 paper published in a scientific journal, 1 patent (STAR deployer), and about 10 presentations to the public. FELDs and STAR papers at the 66th and 68th International Astronautical Congresses were awarded with the "*Hans Von Moldau best student team paper*" award, indicating the quality of the proposed work.

B. *Students survey*

A survey was submitted to the students involved in TED, to assess the status, satisfaction and key issues of the project. Part of the results are reported in Fig. 7. In particular it can be noted that the students satisfaction is really high, oscillating between good (20%) and very good (80%). The participation to the experiments caused delays in studies always lower than 1 year. Last, among the critical issues the students dealt with, the bureaucracy and the procurement were the most incisive.

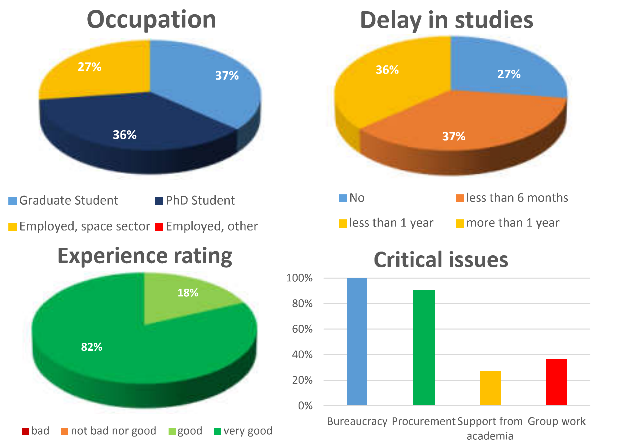

Figure 7: from top-left, clockwise: students occupation after the experiments, delay in studies due to the activity, critical issues and satisfaction from the experience.

V. Conclusions

This paper presented the development plan for the Tethered Electromagnetic Docking system. The innovative mating system uses a tethered magnetic probe that is able to self-align and soft dock with a target interface. The proposed procedure implies (1) a reduction of chaser-to-target relative navigation and guidance requirements during rendezvous, (2) high propellant saving, and (3) a decrease of transmitted forces and attitude disturbances between the vehicles during docking.

Through test in the microgravity environment of ZARM Drop Tower in Bremen, the critical technologies of (1) the probe launch system, (2) the tether controlled deployment and retrieval, and (3) the magnetic self-guidance were proved, reaching Technology Readiness Levels respectively of 6, 6 and 5. Similarly, parabolic flight tests allowed the verification of active magnetic guide, reaching a TRL of 5-6.

The three experiments involved in TED development had been performed by student teams in the framework of ESA Education Office programs. In addition to the scientific production, the students gained experience in the design and realization of complex experiments, and acquired important and appreciated competences for both their academic and professional careers.

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STAR: a University Students Drop Tower Experiment

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Abstract—The use of tethers in space has been proposed to carry out several different tasks, including, for instance, electrodynamic drag devices, spacecraft tugging, novel docking systems. Tether deployers developed and flown so far demonstrated lack of engineering knowledge during tether operations; in particular, a tether retrieval has never been performed by small automated spacecraft. In this context, Space Tether Automatic Retrieval (STAR) is an experiment carried out by five engineering students from the University of Padua, whose main objective was to design, build and test in microgravity a novel concept of space tether deployer with retrieval capability. The experiment has been selected by the Education Office of the European Space Agency for the 2016 edition of the Drop Your Thesis! educational programme. The Drop Your Thesis! programme offers university students the unique opportunity to perform scientific experiments in microgravity conditions using the Bremen Drop Tower facility operated by ZARM. To demonstrate the functioning of the deployer, a braided line has been successfully deployed and retrieved in each of the five tests that were conducted in microgravity conditions. The prototype of the deployer is inspired to passive deployers already developed for past space missions, such as SEDS-I and SEDS-II, integrated with an innovative reeling device to enable the tether retrieval capability. More specifically, the experimental setup was composed by four main subsystems: a spring-based launch device to start the deployment phase; a length and length rate measurement system to measure the amount of deployed tether by means of optical sensors; a dedicated active braking mechanism to control the tether deployment velocity by means of a feedback control on length-vs.-time reference trajectory; and a retrieval system to eventually rewind the tether around the spool and reset the system to the initial state. This paper presents motivation, conception and microgravity testing of the Space Tether Automatic Retrieval Experiment, and describes the educational return of the project.

Keywords—space tether; tether retrieval; 'Drop Your Thesis!', drop tower; university students

I. Introduction

STAR (Space Tether Automatic Retrieval) is a scientific experiment that has been carried out by a team of engineering M.Sc. students of the University of Padua that has been selected for the 'Drop Your Thesis!' (DYT) 2016 educational programme, organized and promoted by the Education Office of the European Space Agency within the 'ESA Academy' context. The goal of STAR was to develop a simple and reliable deployment mechanism for space tethers with retrieval capability, adapting the well-established fixed-spool-fishing reel technology to obtain an autonomous system.

The participation to the DYT programme has been seeked for its indisputable educational aspect. By participating to this "hands-on"-activity, the students had the opportunity to gain a valuable practical training that complemented the more theoretical studies conducted at the University. The DYT programme has offered to the students the opportunity to test the prototype of the mechanism in microgravity conditions by means of the ZARM Drop Tower facility in Bremen, performing a series of functional tests in relevant environmental conditions in order to validate the deployer concept.

The importance of developing such a technology is remarkable. At present, both Space Agencies and industries are investigating the use of space tethers for various applications (e.g., tethered space tug [1] and electrodynamic drag devices [2] for active debris removal missions, environmental research [3]), for which a reliable tether deployer with retrieval capability would be a key subsystem.

Even if STAR Experiment can be considered as a self-consistent research with its own relevance as a stand-alone experiment, its needing has originally shown up as part of a

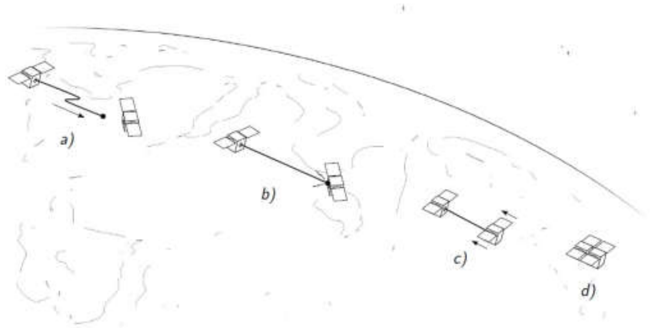

Fig. 1: Tethered Electromagnetic Docking (TED) concept. a) The chaser spacecraft deploys a tethered probe, which performs a b) electromagnetic soft-docking to the target spacecraft; the tether is then c) rewinded and d) eventually the two spacecraft hard dock to each other.

wider technology investigation initiative of the Space Systems Group (SSG) of the University of Padua (UniPD). This research enterprise aims at investigating the application of the TED concept (Tethered Electromagnetic Docking, cf. section II of this paper) to a small satellite mission [4]. In this context, and with the cornerstone goal of enhancing the educational return of the Aerospace Engineering degree course offered by the University of Padua, research initiatives have been encouraged by the group, leading to three reduced-gravity-experiments designed and realized by engineering students: STAR itself, FELDs [5] and PACMAN [6]. FELDs and STAR participated respectively to the 2014 and 2016 editions of ‘Drop Your Thesis!’, whilst PACMAN was part of the ‘Fly Your Thesis!’ 2017 campaign, a further “hands-on”-activity offered by the ESA Education Office as part of ESA Academy.

II. Background

TED (Tethered Electromagnetic Docking) is a novel technological concept proposed by a group of researchers and students of the University of Padua for close rendezvous and docking between spacecraft [4]. It consists in a small tethered probe ejected by the chaser, reaching the proximity of the target with a controlled deployment, and then magnetically guided by a receiving electromagnet mounted on it. Because of the generated magnetic field, alignment and mating are possible; then, as the tether is rewound, the chaser is able to dock with the target (Fig. 1). Throughout this investigation, a specific research on the tether deployment and retrieval actuation technology, consisting in the STAR Experiment, was conducted.

In the past, different tether deployer devices were developed for spaceflight. Tether deployment can use passive (non-motorized) or active (motorized) deployers. Active deployers are used for tethered systems that need to be retrieved (e.g., the TSS missions [7]) or for systems in which the tether length must be varied throughout the mission. Active deployer usually utilized a drum around which the tether is reeled up, and the drum rotates as the tether is unwound. If neither retrieval nor length control are involved, a passive deployer is normally well suited for deploying the tether. Passive deployers typically utilized a stationary spool whereby the tether unravels from the spool by pulling it out along its axis (e.g., OEDIPUS missions [9]), as displayed in Fig. 2. The

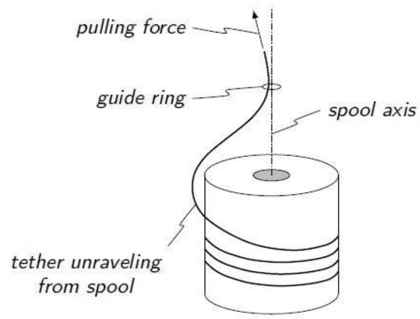

Fig. 2: Passive deployer working principle. Redrawn from [8].

passive deployer is often flanked by an active braking mechanism, whose scope is to increase the tether tension in order to control the deployment (e.g., PMG [10] and SEDS [11] missions).

Despite the fact that different tether deployment devices were actually developed and flown in space, the deployment of a space tether has always been a critical issue for the past space tether missions. An acknowledged lesson learned from these is that a successful employment of space tether requires extremely good mechanical design of deployers and brakes, as well as highly robust and adaptive control strategies. For example, the NASA-ASI TSS-1 deployment failed due to a blockage in the tether leveling system of the deployer [7], and the tether was eventually retrieved. This is, at the time of writing, the sole known mission where a successful (partial) tether retrieval was performed. The deployment hardware was, in that case, extremely massive and complex and cannot be applied to smaller-scale missions. Instead, an example of control system malfunction was in the ESA YES2 mission. In that occasion a 32-km tether was successfully deployed but the control dynamics was off nominal [12]. Against this, however, a reliable spooling mechanism was designed for YES2 deployment, based on the same working principle of the PMG and SEDS deployers, which behaved successfully .

In the recent years, several space tether experiments were performed on different orbital platforms. Regretfully, the majority of them experienced failures, underlining again the persistent difficulties inherent to the practical implementation of the space tether concepts, even if the mission targets were less ambitious if compared to the above-presented-major missions. An up to date list of space tether flights is available in [13].

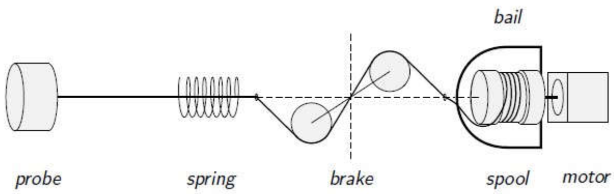

Fig. 3: STAR deployer concept.

III. The STAR deployer concept

The STAR deployer concept is described in the following paragraph. With reference to Fig. 3, the tether deployment is initiated by a spring-based launch device. This is a classical solution in thrustless systems (i.e., systems in which the deployment is not aided by thrusters), such as SEDS and YES2, and was also implied in a similar experiment tested at the ZARM Drop Tower facility for the FELDs Experiment [5], in which behaved successfully. Hence, for simplicity, the same design of the launch mechanism used by FELDs was adapted to the STAR deployer, implying, conversely from FELDs, three COTS electromagnets to release the tethered probe.

In order to control the deployment, STAR has a dedicated active brake mechanism, whose aim is to control the tether tension during the deployment, whilst an electric micromotor has the task to retrieve the tip mass once the deployed tether has been engaged by a dedicated locking mechanism (the bail, playing the role of a “clutch”). More specifically, the tether prior to deployment is wound up around a fixed spool, and is free to unravel from the spool with minimal inertia, without trailing rotating parts. In this way, there is negligible opposition to the tether exit motion, that is the mere tether inertia. The tip mass is driven along the desired path by means of the tether tension, that was controlled by the brake mechanism. Since the deployment of short tethers does not require high control authority [14], a simple roller-based brake design was chosen, which being simpler to implement and actuate, given also the educational nature and the limited resources of a student experiment.

During the retrieval phase, the tether is first engaged by the bail, so that the tether is no longer free to exit the deployer. The functionality of the bail mechanism is inspired to the same device used in many fixed-spool-fishing reel devices of the fishing poles. Again, for simplicity reasons, a COTS bail was procured and adapted to the STAR design. This adaptation included the replacement of the torsion spring that closes the bail before the fishing line retrieval with a cam mechanism, which performs the same task but in a controlled fashion. In fact, having the bail mechanically coupled with the shaft of an electric micromotor, the actuation of the motor closes the bail thanks to the cam mechanism and the tether is engaged.

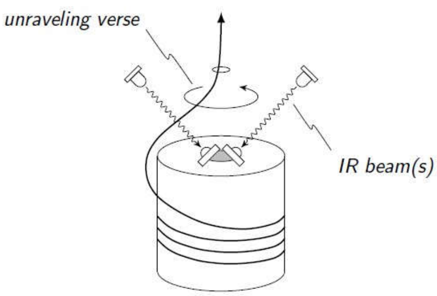

Fig. 4: Principle of length registration by interruption of infrared beams during deployment. In this picture, IR emitters are located on the spool canister whereas receivers are inside the spool, as in YES2 and SEDS missions. Only two emitter-receiver pairs are portrayed.

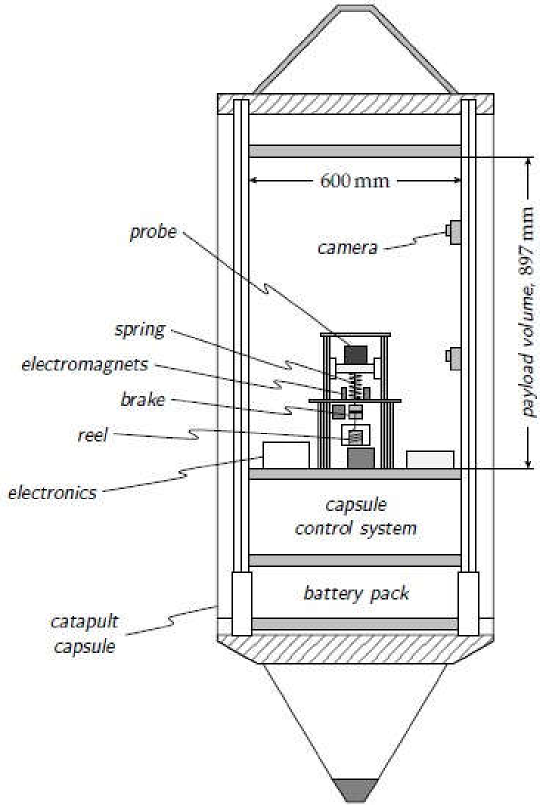

Fig. 5: Schematic drawing of STAR Experiment integrated in the catapult capsule.

Once closed, the bail continues to revolve (thanks to the motor) around the spool and reels in the tether, which is eventually wound up around the spool. Deployment control is carried out by means of a Proportional-Derivative (PD) feedback control law, whose control variables are the instantaneous tether length and length rate. This control technique is the same, as mentioned, used in the SEDS-2 and YES2 missions. The deployed length is measured by an optical device (SLODES) whose working principle is explained by Fig. 4: when deploying, the tether performs a circular movement around the spool axis, interrupting sequentially a certain number (eight, in the case of the SLODES) of infrared beams. Each pulse stands for a portion of deployed loop, thus to a certain increment in the deployed length, from which the total length of unwound tether and its deployment rate can be derived. The demonstrated effectiveness of this mechanically simple technique induced the STAR experimenters to build on the same basic concept for conceiving the mechanism.

The STAR concept exploits therefore the advantages of a passive deployer in terms of mechanical simplicity and reliability during deployment, but the possibility of performing a retrieval gives STAR the capabilities of an active deployer.

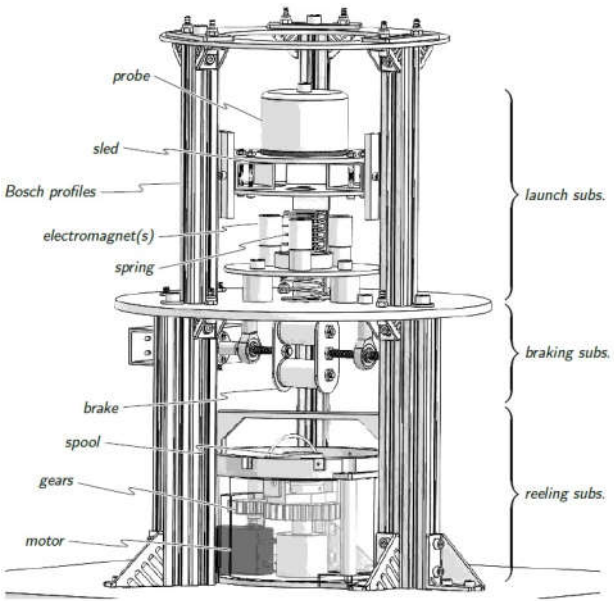

Fig. 6: Schematic drawing of STAR Experiment integrated in the catapult capsule.

For this reason, we can classify the STAR deployer as a hybrid between the passive and the active deployers.

The setup has been integrated in the catapult capsule as portrayed in Fig. 5, while a more detailed schematics of the experiment setup is available in Fig. 6.

IV. MICROGRAVITY TESTS AND RESULTS

The Experiment has been tested by means of the catapult mode of the ZARM Drop Tower. In general, a drop tower (or drop tube) is an elongated vertical structure used to generate periods of controlled weightlessness for scientific research purposes. Weightlessness is achieved by injecting the capsule containing the experiment setup in a steep parabolic trajectory with respect to the Earth's centre; this is done on the majority of the drop towers by releasing the capsule from the top of the

Fig. 7: Frames of launch 2. Left: tether and probe during deployment, right: braking mechanism and reeling mechanism during retrieval.

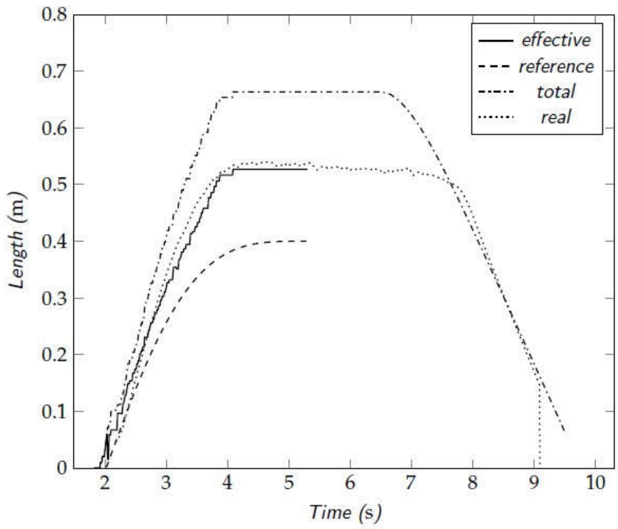

Fig. 8: Launch 2 length measurements.

tube and having it fall to the ground. In the ZARM Drop Tower, instead, the experiment capsule can be shot upwards from ground level by means of a worldwide unique catapult system, in a way that the parabolic trajectory is treaded for twice the height of the drop tube, allowing for a total weightlessness time of approximately 9.3 s.

In each of the five performed microgravity tests, the probe's motion was recorded during the weightlessness timeframe by means of two high frame rate video cameras (60 FPS each) mounted along two orthogonal directions. Graduated scales on the capsule walls promptly allowed a rough estimation of the tethered probe trajectory. In addition, the probe was equipped with markers (checkerboards) that have been used to track its trajectory with a computational vision technique, after the tests were completed. A photo of the deploying area of the experiment capsule is reported in Fig. 7, left. In the background the graduated scale used to perform a first rough tracking of the probe's motion can be noticed. A second scale is on the right (not visible) seen by a second high-frame-rate camera (located on the left). The projection of the probe's contour on the scale allowed to esteem the tether length that exited the deployer. On the right is reported a picture of the deployment mechanism during the second microgravity test.

The outcomes of the post-processing analysis were compared with the controller output, as shown in Fig. 8. Plotted is the total tether length profile measured by the SLODES device, the effective deployed tether length which is derived from the total, the reference length profile fed to the controller and the real length profile computed through computational vision. As can be seen, the latter closely matches the effective length profile, with an error in the order of the centimetre. In Fig. 9 the reader can instead observe the detections of the tether passes by the single emitter-receiver pairs for the same launch of Fig. 8.

V. EDUCATIONAL RETURN OF THE EXPERIMENT

The participation to 'Drop Your Thesis!' resulted for the team members an invaluable educational opportunity. This high-calibre programme allows University students to perform

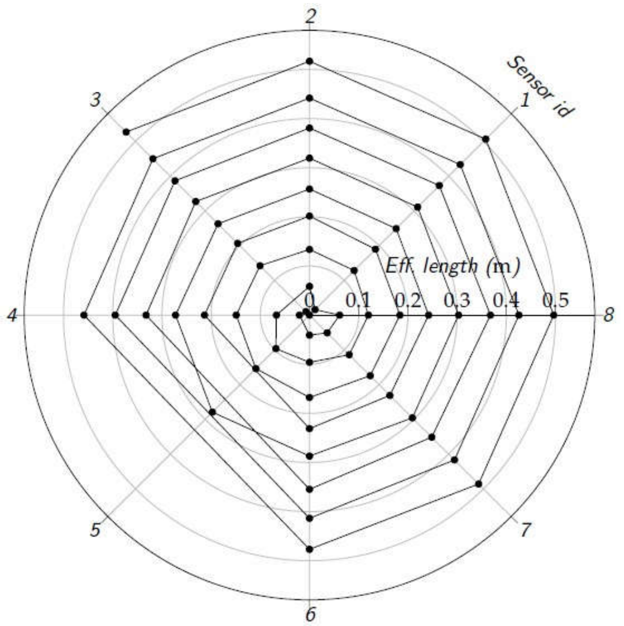

Fig. 9: SLODES readings for launch 2.

scientific research in a facility usually exploited only by professionals and researches.

Through this experiment, the students themselves were operating in a privileged position, being exposed to the standards of the top-class research facility and the working practice of the European Space Agency. By means of this experience, the students could train both their hard and soft skills, complementarily to the training that is usually gained in a University degree course. For example, soft skills like teamwork have been extremely enhanced; the students are also exposed to an international environment and have to interface with the industry for the procurement and manufacturing of the experiment setup. Hard skills that the students developed within the STAR project were, amongst the other, hands-on-skills like soldering, mechanical design, electronics design, computational vision.

The students had also the opportunity to present their result to the scientific community, opportunity usually not available below Ph.D. level. The scientific production related to STAR counts so far six conference papers, several presentations to the public, a Master's thesis and a registered patent.

VI. CONCLUSIONS

This paper presents design and test of a novel concept of space tether deployer called STAR, conducted by a team of engineering students of the University of Padua within the framework of the 'Drop Your Thesis!' educational programme. The device is inspired to passive deployers used in past space tether missions, such as SEDS and YES2, but is integrated with an active device that gives this deployer the retrieval capability which classifies this deployer as a hybrid between the passive and the active space tether deployers. The device's functionality has been demonstrated through a series of five microgravity tests at the ZARM Drop Tower facility in Bremen. The educational return of the STAR project is also presented.

ACKNOWLEDGMENTS

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DISCLAIMER

The affiliation of the main author, G. Grassi, at the time of conducting the experiment was Department of Industrial Engineering, University of Padua. In publishing this paper, the author does not represent in any way its current affiliation, the European Space Agency, and its work.

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Space Universities Network - supporting Space Science and Engineering Higher Education Community in the UK

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***Abstract*—The world space economy is expected to grow to $400 billion by 2030. In 2015 the UK had 38500 directly employed with a further 70000 jobs dependent on the space sector. By 2030 the UK aims to have a further 100000 new people employed within the sector. Training space engineers and scientists is critical to fulfilling this aim. The UK-based "Space Universities Network" (SUN) was formed in 2016 with the aim of enhancing the quality of learning and teaching by providing support and resources to the space science and engineering higher education community. SUN's objectives are to facilitate the creation of a skilled workforce of graduates who can meet the challenges of future scientific and commercial exploitation of space. The network addresses this need by helping to inspire students to join the space sector and ensuring they are well equipped at University to contribute. SUN enables the developing, sharing and promotion of effective practice and innovation in the delivery of university-level space science and engineering curricula. It does this through workshops, offering opportunities for networking to support the space teaching community and a web-based repository of resources. This paper describes the process that led to the foundation of SUN, its objectives, modes of operation, prime activities, evaluation and future projects. Once firmly established, it is hoped to expand the network through partnerships with similar organisations in other countries.**

Keywords—higher education; community; network; resources;

I. Introduction

The world space economy is expected to grow to $400 billion by 2030 and the UK has ambitious plans to secure 10% of the global market, growing the space workforce by a further 100000 jobs. Training new space engineers and scientists is therefore critical. In the UK, accepted University undergraduate places have increased from 271000 in 1994 to 535000 in 2016 [1]. This has meant that some science and engineering departments have struggled to maintain the level of laboratory participation and build and test projects for their students. It is recognized that there is a shortfall in Science, Technology Engineering, and Maths (STEM) graduates. A report by the industry body 'Engineering UK' suggests that this is as much as 20000 graduates a year [2]. A UK accreditation body called the 'Institute of Engineering and Technology' has produced a report on skills, based on surveys of employers. These surveys established that 62% of UK engineering employers are concerned about graduate skills, and of those, 59% say that is because Engineering and technology degrees do not develop sufficient practical skills. 68% of employers are concerned that the education system will struggle to keep up with the skills required for technological change [3]. Against this backdrop, the UK-based "Space Universities Network" (SUN) was formed in 2016, with the aim of enhancing the quality of learning and teaching in Space Science and Engineering. SUN members wish to enable the development, sharing and promotion of effective practice and innovation in the delivery of university-level space science and engineering curricula.

II. Aims and Objectives

The value of the Space Universities Network comes from the collective intention to advance learning in Space Higher Education, with a particular focus on space science & engineering. Eventually, the experiences and learning of the community will develop into a shared repertoire of case studies, contacts, questions, equipment, concepts and perspectives.

The objectives of SUN are to:

- Improve the competitiveness of the UK's future Space workforce and address the shortage of skilled Science Technology Engineering and Maths (STEM) graduates.
- Share space teaching ideas, providing new ideas, broadening topics covered and enriching curricula.
- Liaise with industry on graduate requirements to meet the increasing demand for professional scientists and engineers, and to promote subsequent career development.
- Encourage increased reflection in space education practice and material.
- Provide a coherent approach to trialing and evaluating new pedagogical methods across multiple institutes and a wider student base.
- Provide awareness of space degrees and space employment market, with commensurate increase in student numbers.
- Provide opportunities for networking and collaboration in teaching and research.
- Provide access to resources, facilities, equipment and specialist expertise.
- Influence policy on the teaching of space science and engineering to produce graduates prepared for tomorrow's industry and research.

III. Evolution of the Network

The community was started by 3 members of the Space Engineering community who met to discuss ideas for teaching and learning in 2015. It has then spread by open invitation to UK Higher Education institutions. The first workshop was held in June 2016 with 25 members present. A debate was held to discuss the necessity and UK strategic context for the community. Key issues to be addressed by the community were identified during the workshop. All participants wrote down their own issues and challenges that they faced in their everyday experience of teaching and learning space science and engineering. Then together they formulated some ideas and solutions which could help with some of these challenges. A list of potential useful resources, tools and methods were discussed (see section V. Methods). Next the necessary infrastructure of the community was suggested to consist of a website, an academic listserve email list and networking workshops. After this event, the next step was to apply to a competitive funding call and to be awarded funding by the UK Space Agency. This paid for the commissioning of the database-backed website which would host many of the resources and for the launch of the organization at the UK Space Conference in Manchester in May 2017 (Fig.1). Establishing a core group who would drive forward the community was key. This group is called the SUN working group and holds regular meetings (aimed roughly at the solstices and equinoxes!) Subgroups were formed later to look at various work streams, proposing ideas for events, driving the collection of resources, looking for funding and liaising with industry and media.

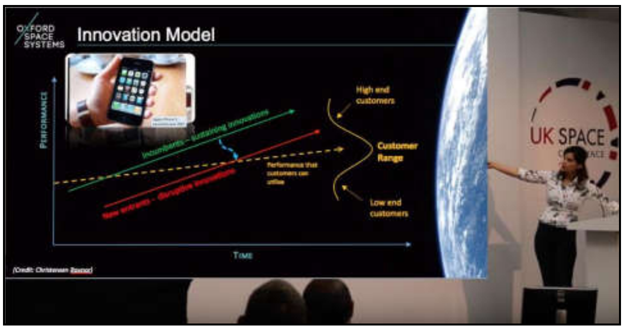

Fig. 1: "What does the Space Industry want from graduates?" Shefali Sharma from Oxford Space Systems at the SUN workshop in May 2017

A set of Terms of Reference and a Strategy document were written jointly by the group and these have helped focus efforts. Celebrating the successes of the members and the network is done regularly via the medium of an email newsletter.

IV. Membership

The membership of the network has grown from 3 to 52 over the past 2 years. These members come from 28 different Higher Education Institutions in the UK (as at Feb. 2018). A list of current members can be found at: https://spaceuniversitiesnetwork.ac.uk/members.
All Institutions of Higher Education interested in Space in the UK are invited to join. The majority of members are in Engineering departments, but at a recent meeting, the community wished to emphasise the welcome to space scientists and Earth observation scientists as well. SUN works hand in hand with partner organizations including the student organization: Students for the Exploration and Development of Space (SEDS), the Satellite Applications Catapult (a government innovation hub), the Space Action Network (a network focused on research) and ESERO-UK (European Space Education Resource Office) and others.

V. Methods

The aim of SUN is to support the Space HE community in the UK by sharing and encouraging effective practices in space teaching and learning across the UK University sector. The main method of communication between members is the email list, through which members put out notices of events that they are running (either for students or for staff), posts that they are advertising, outreach events, collaborations they are seeking etc. The newsletter is also used to draw members' attention to joint events, new website resources initiatives and there is an interview with a different member each month. Annual workshops have centered on topics of interest to members, who are always striving to provide the best learning experience for their students by keeping themselves up to date with emerging technologies and new themes in the space business. One of the goals of SUN has been to liaise with industry about curricula and skills, so the theme of the 2017 workshop was proposed to be: "What does the Space industry want from graduates?" Leaders of successful space companies, agencies and accreditation institutions were invited to give talks to SUN members about the qualities and skills they were looking for in University graduates. The main messages of the industry leaders were summarized in an article on the event by a student careers organization here: https://spacecareers.uk/ ?p=article_public&id=224.

The talks were filmed and are available on the SUN YouTube Channel here: https://www.youtube.com/channel/UC0jythXs3CuC-Ld2i-qVDpg/videos (see also Fig. 2). SUN Workshops are also about understanding new developments in the space sector. For example, in 2018 members have chosen to learn about new uses of space data and will be attending a workshop on downstream applications of satellite services. Ordinarily, SUN members might only attend a workshop centered on their research domain, so these workshops will broaden their knowledge and keep them up-to-date with developments outside of their specialist areas. This in turn will be of benefit to their students. Short courses on specialist subjects open to students have also been organized by individual members. These have been arranged in tandem with the student organization UKSEDS, who promoted them. For example, the University of Leicester has provided a course on orbital mechanics and Kingston University London a course on rocketry.
One of the other key attractions of SUN is the curated web-based repository of resources to support teaching and learning which has been created. This is being built up by members of SUN who can log on to the website themselves and view, upload and download resources. These resources are visible (but not downloadable) at:

https://www.spaceuniversitiesnetwork.ac.uk/resource-bank.

The resource bank (Fig. 2) contains:

a. Case studies of practical teaching ideas - satellites built in soda cans, water-powered rockets, incident investigation reports for space mission failures.
b. Class resources – videos clips, icebreakers, useful articles on scholarship of teaching and learning
c. Question bank of questions on specific space topics with topic tagging for search purposes
d. Database of guest lecturers and topics
e. Database of external examiners
f. Database of laboratory and test facilities including specialist equipment for satellite testing
g. Links to our partner space careers website: spacecareers.uk and ESA UK outreach website ESERO UK.

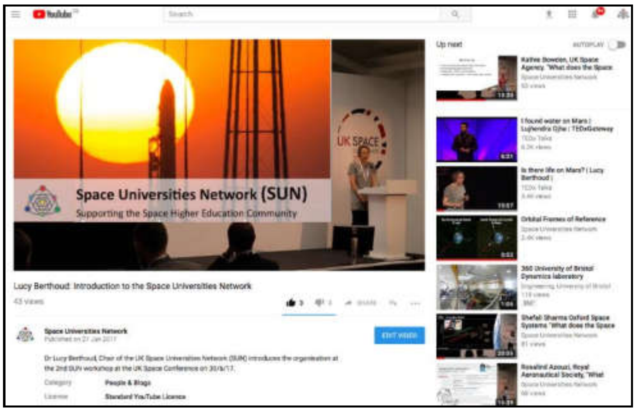

Figure 2: SUN YouTube channel shares workshops and videos publicly

VI. Evaluation

It is challenging to evaluate a network such as this. Some of the benefits are difficult to measure, for instance the evolution of connections among practitioners, relationships based on trust, and a language and context shared by community members. The joint projects coming from the community are also evidence of success of that community. Evidence to date includes: members being invited to other institutions to give guest workshops on teaching ideas that they have developed, members being invited to be external examiners at other institutions, the highlighting of academic facilities to potential UK users, for example specialized laboratories at Kingston University London and the University of Birmingham, new ways to introduce younger colleagues to other experienced academics in space, sources of enriching/ enhancing ideas for courses, e.g. inter-university competitions to build rockets and CanSats or microsatellites.

An anonymous electronic survey of all SUN members was performed in November 2017, and 13 members responded. The results from the survey indicated that 30% of responders had attended both workshops, 69% had met someone new at the workshops, 92% read the SUN emails, 61% had passed along a piece of information or request from SUN, 85% had gained a useful piece of information from SUN, 62% had learned about something new and 31% had implemented a new teaching idea and 15% had tried a new suggestion.

Answers to the survey question: "what, if anything, have you gained from SUN?" included:

- *So far, it's early days, but I think it's helpful to build a network of practice in Space-related teaching.*
- *Developed links for outreach activities and potential extra-curricular competition development*
- *Didn't know about GMAT orbit modelling software before*
- *Access to high quality teaching material, for example course on use of orbit modelling*
- *Being part of a supportive like-minded community.*

Answers to "how can SUN improve?" included:

- *More website resources*
- *Links to other equivalent networks in other countries might be useful - both for training (placements, internships, exchanges) and/or for resources.*
- *Having a regular meeting to allow academics to meet, at a site where space science and engineering activities are taking place, to share best practice, brainstorm and address strategic challenges facing the space and higher education community in the UK*

VII. Future work

Whilst value to some of its members has been established, it is harder at this stage to measure the impact on the students, who are also stakeholders. Resources have been uploaded to the website from which students can directly benefit if they are taught by SUN members. Further work continues to build up the teaching resources on the website, including a series of case studies which will be produced in the next year.

Currently further funding is being sought in order to expand the network to space science, as well as engineering. Also, modes of continuing the dialogue with industry will shortly be established, as industry have shown a great interest in working with the network. They cite the ease of access to the community as their interest.

VIII. Conclusions

The Space Universities Network (SUN) is a community of space science and engineering Higher Education staff at UK Universities. The members are interested in developing their teaching and learning skills. This work has described the evolution of the network, the membership, the methods, the way the network has been evaluated and some ideas for future work. This work demonstrates the value of such a community to its members and other stakeholders even in the first years of its inception.

Acknowledgements

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Fig. 3. Space Universities Network website resource bank.

Lessons Learned from STRATONAV on BEXUS 22: Educational activities on stratospheric balloon experiment development

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Abstract*— STRATONAV (STRATOspheric NAVigation) is a scientific project conceived by a team of Italian students from Sapienza – University of Rome. It was proposed for the ninth cycle of the REXUS/BEXUS Programme (Rocket- and Balloon-borne Experiments for University Students). The project started in 2015 in the framework of the educational activities of the Sapienza Space Systems and Space Surveillance Laboratory (S5Lab). The experiment was focused on the performance verification of the VHF Omnidirectional Range (VOR) radio-navigation system on-board a stratospheric balloon, in order to evaluate its compliance with the future stratospheric aviation navigation systems. The experiment development, started after a Selection Workshop held in December 2015, has been supported by several reviews organized by the REXUS/BEXUS Programme organizing space agencies. The first reviews (Preliminary and Critical Design Reviews, PDR and CDR) were aimed at evaluating the experiment design, by verifying its compliance with the BEXUS bus, with the payload vehicle structure and with the requirements aimed at safely launching the experiment. The main criticalities of this phase were related to improvements needed to finalize the design process and to the teamwork attitude of the team members. The experiment manufacturing was completed between June and September 2016. The most important challenges connected to this phase were related to the preparation of the selected components for the balloon flight, such as the modification of the VOR receiver in order to permit its remote control. The integration was evaluated through two further technical reviews. STRATONAV was then successfully launched on 5th October 2016 from the Esrange Space Center in Kiruna, Sweden, on-board the BEXUS 22 stratospheric balloon. The experiment managed to fulfill all the mission objectives during the five hours of stratospheric flight. This paper describes the STRATONAV development cycle, by focusing on the practical experience gained by the students. After a brief presentation of the project, the experiment development cycle is described. For each project phase, the main completed activities are reported and the most important lessons learned are presented.

Keywords— VOR, Navigation, stratosphere, BEXUS, hands-on activities

I. Introduction

STRATONAV (STRATOspheric NAVigation) is a stratospheric balloon project carried out between October 2015 and January 2017 by a team of students of Aerospace Engineering from both Sapienza – University of Rome and Alma Mater Studiorum – University of Bologna. The project was aimed at assessing the accuracy of the VHF Omni-directional Range (VOR) radio-navigation system above its Standard Service Volume (SSV) limit height of 18 km, in order to verify its applicability to future stratospheric vehicles ([1]–[4]). The idea was conceived in the framework of the Sapienza Space Systems and Space Surveillance Laboratory (S5Lab) hands-on activities offered to the BSc and MSc students of Aerospace Engineering [5].

The experiment was proposed and accepted in December 2015 for the ninth cycle of the REXUS/BEXUS (Rocket- and Balloon-borne Experiments for University Students) Programme and accommodated on BEXUS 22 stratospheric balloon. After a cycle of reviews, organized by the Space Agencies supporting the Programme (Preliminary and Critical Design Reviews, PDR and CDR, Integration Process Review, IPR, Experiment Acceptance Review, EAR), the experiment was launched on-board BEXUS 22 on October 5th, 2016, from the Esrange Space Center in Kiruna, Sweden. STRATONAV managed to acquire data for the whole balloon flight duration (approximately 5 hours), achieving all its mission objectives and being able to measure a radio-navigation system precision higher than expected ([1], [2]).

All the Programme phases, from concept and preparation of the proposal to the in-flight operations and post-flight data analysis have offered to the involved students a great opportunity to improve their hands-on skills and technical know-how on the production of space systems. The core team involved in the STRATONAV experiment is currently taking advantage of all the lessons learned for their participation in the ESA Fly Your Satellite! (FYS) Programme, within the

LEDSAT project ([6], [7]). This paper presents three of the major technical difficulties faced by the team members within the experiment development and how these issues turned into useful advises for the current team members projects. The gained experience is related to the design finalization in PDR and CDR phase, to the system verification prior to launch, and to the philosophy adopted for defining the data collection processes. The lessons learned are presented in Section III after a brief description of the mission concept and experiment architecture, contained in Section II. After each lesson learned, the educational return of the experience is exposed in detail.

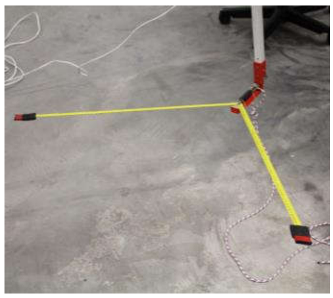
II. STRATONAV MISSION CONCEPT AND EXPERIMENT ARCHITECTURE

As described in Section I, STRATONAV aimed at investigating the applicability of the VOR Navigational Aid (NavAid) to future stratospheric aviation. The VOR system is a mature and reliable Radio-Frequency (RF) system used to compute the civil aircraft routes since the 1940s. The NavAid takes advantage of ground-based stations, transmitting a Very High Frequency (VHF) signal in the dedicated bandwidth from 108 to 118 MHz, that are spread all-over the world, with a consequent coverage on almost all the land areas on Earth. An airborne VOR receiver is capable of processing the signal to extract the radial, equal to the angle between the Magnetic North direction (with respect to the ground-based station) and the bearing angle of the station, with respect to the station position [3]. The NavAid SSV dimensions are defined, in terms of power density, by the International Civil Aviation Organization (ICAO, [8]), and, for high power stations, are usually set to 185 km in range and 18 km in height. However, link budget calculations, based on the radiated power of each station, indicate how the limit height could be extended beyond the stratosphere [4]. While several high altitude air-breathing fixed wing vehicles, such as the Concorde or the NASA ER-2 [9], have flown nearby 18 km of altitude, the in-flight verification of the VOR precision rates are performed on-board aircraft that are not capable of overcoming 10-12 km of altitude [10]. Therefore, an assessment on the VOR radial accuracy in stratosphere could lead to a significant leap forward in the definition of future stratospheric aviation navigation systems. The BEXUS flight opportunities were identified by the STRATONAV team members as a perfect chance to perform this investigation. Indeed, the BEXUS balloon provides the possibility to operate at altitude higher than the VOR SSV limit (usually between 25 and 32 km), for an extended flight time (between 2 and 5 hours), with the payload recovery after the flight. Moreover, the launch area (Esrange Space Center, Kiruna, Sweden) is served by a large number of VOR stations, thus with the chance to acquire a large amount of data from the balloon flight.

STRATONAV was designed in two units (depicted in Fig. 1), an aluminium box of 340 x 340 x 550 mm, placed on one corner of the BEXUS 22 gondola, and an antenna unit, composed by a V-shaped bespoke antenna, replicating the design of usual civil aircraft navigational systems, mechanically fastened to a 1200 mm pole, attached to the gondola corner. In order to maximize the received signal power and to minimize the interference caused by the metallic BEXUS gondola, the distance between the antenna plane and the gondola floor plane was fixed to 800 mm, as suggested by a Numerical Electro-Magnetic Code (NEC) analysis ([3], [4]). The experiment box was divided in two stages, with the ground plane hosting the RF receiving system and the Power Control Unit (PCU), and a *mezzanine* (upper stage) dedicated to the two On-Board Computer (OBC) cores, a Global Positioning System (GPS) receiver as reference for the acquired radials, attitude, temperature and pressure sensors. The VOR radials were acquired by two independent RF receivers. A Commercial-Off-The-Shelf (COTS) VOR portable receiver was modified by the team members in order to be connected to a signal port of the primary OBC core. This was provided with the capability to down link scientific and housekeeping data to the experiment ground station. On the other hand, a Software-Defined Radio (SDR) recorded the VOR signals, acquiring more than 350 GB of raw data, that were processed after the experiment recovery.

As reported in Section I, the experiment flew on-board BEXUS 22 stratospheric balloon, on October 5th 2016. The balloon reached the floating altitude of 32.2 km and flew eastwards for approximately 250 km, until being parachuted, after balloon cut-down, in the Finnish taiga. Part of the flight has been performed in day-time and part in night-time. Despite the extreme environmental conditions in terms of air pressure and temperature, the experiment was perfectly functional during the whole balloon flight, achieving all its objectives.

a)



b)

Fig. 1: STRATONAV Experiment Box (a) and VHF antenna (b).

III. MAIN LESSONS LEARNED FROM THE PROJECT

A. A good experiment design greatly depends on a good team communication

Each new REXUS/BEXUS cycle starts with the preliminary design of the experiment, that shall be delivered in the first documentation pack (the Student Experiment Documentation, SED) version. The preliminary design is the first team *rendez-vous*, after the selection, with practical problems connected to the design of real objects. This means that, in addition to traditional issues that a common student may have already coped with in the University courses exercises, a great number of pitfalls threaten the integrity of a real experiment design.

In the STRATONAV case, a lot of major issues came out from the preliminary design description just two days before the first SED delivery deadline, when a reasonable timeline should allow only a fine document polishing and graphic layout re-styling. The main reasons of this situation were a lack of communication among team members, as well as the unfamiliarity to cope with subsystem interfaces. Indeed, before selection, the team was organised by assigning a sub-system to each team member. This sub-system-oriented team break-down was applied also to the SED chapters division: each sub-system chapter was univocally assigned to the team member responsible for that experiment segment. The lack of experience among team members did not suggest to establish some *monitoring and support team members*, in order to encourage a cross-check of the design details for each sub-system and to identify the possible discrepancies in advance. As first lesson learned (and possible suggestion for new teams in the next cycles), it is important to remark how the higher is the number of people with a system-level awareness of the design, the lower is the risk for similar major problems to occur.

Another remarkable problem was offered, in the days prior to the first SED delivery, to the dimensions and interfaces of the components. As said before, interface definition among components is often an underestimated task. Indeed, as it could be appear obvious and boring, many of the major problems in the very first definition of a space system are hidden inside this (relatively) simple operation. In particular, two discrepancies emerged in the days before the SED v1.0 delivery. With reference to the two most likely COTS receiver models:

- One of the identified models size was slightly smaller than the experiment ground plane. However, the team members did not take into account that the RF connectors had to be connected on the rear side of the transceiver, thus exceeding the dimensions of the experiment;
- Regarding the other model, there was no clear information on the remote controllability capabilities, on the needed software requirements for the connected OBC, on the parameters that may be remotely managed.

While the first issue was solved before the documentation delivery, yet forcing all the team members to dramatically increase their workload for the remaining days, the remote control issue was re-encountered at CDR phase. Indeed, even if it was possible to connect the transceiver to a computer, this functionality was only related to the possibility to change the device frequency memory storage, without any chances to control it or to automatically acquire VOR radials. This problem was solved, prior to CDR, with the choice to modify the receiver by directly soldering wires (connectible to the signal ports of the newly selected OBDH) into the signal vias of the COTS transceiver PCBs. However, this new design choice significantly increased the risks of the project, and forced the team members to purchase three transceivers instead of only one. In particular, one was broken shortly prior to experiment acceptance, the other two were purchased as primary and as back-up components for the launch campaign. The lesson learned associated to these events are thus related to the need for a reliable, regular and strong communication link among all the team members. A better communication in the very first experiment development phases would have probably caused a significant saving in the project budget and in the team members time and energies dedicated to the project.

B. Major issues are sometimes caused by simple components failures

The multiplicity of issues caused by the various COTS transceiver modifications let the team members understand how that component was representing the project main criticality. Even if following the test plan produced prior to every hands-on activity (and updated at each development phase), the focus of the team members responsible for sub-units testing and system verification was always centered on the COTS receiver performances in terms of remote controllability and data acquisition from the OBC. Moreover, the peculiar shape of the VOR SSV and the distance of the University laboratory from the nearest VOR station did not allow the team members to perform daily tests on the effectiveness of the communication system RF chain. For example, after characterizing the antenna VHF band pattern with multiple tests ([4]), there were no activities dedicated to a quantitative assessment on the antenna performances before and after each further test on system-level, or before and after each experiment or sub-system transport. The antenna and RF chain was simply supposed as a "go" for the launch, without any practical proof. Indeed, approximately 18 hours before lift-off, the team members chose to perform a meticulous verification of all the key experiment features before mounting the experiment on the BEXUS 22 gondola for an actual launch attempt. After passing each check on the receivers and OBC cores functionalities, the team started to test the SDR performances in receiving and recording a dummy VHF signal (in AM/FM band). The measured received power was astonishingly lower than expected. In the first days of launch campaign, no verification was possible on the reception of an actual VOR signal, due to the position of the Space Center with respect to the two nearest VOR ground stations. With few hours left before launching the experiment, the team members started a hurried check on the electrical contact between the single components of the RF chain, which consisted of the V-shaped antenna, of a VHF band-pass filter, of a 3dB splitter (used to convoy the signal from the single antenna to two separate receivers) and of several meters of coaxial wire. With the exception of the cables, all the components of the RF chain were in-house developed: the antenna was manufactured by adapting a measuring tape and a soldering N-type connector, the filter connectors had been soldered by the team members, the 3dB splitter had been entirely manufactured by the team (in collaboration with Rome's Amateur Radio Association). While the 3dB splitter and the filter assured a perfect contact between input and output pins, the antenna check revealed a component malfunctioning. The signal pin (output of the N-type connector) showed a bad electrical contact, discontinuous and with a great attenuation, with the antenna metallic branches, probably caused by a small damage occurred during the transport to Kiruna. Without particular effort, the N-type connector pin was adjusted and a perfect contact with the corresponding RF chain wire was restored. The connector pin is depicted in Fig. 2. The antenna worked perfectly during the whole flight, since the VOR signal was received (with high Signal-to-Noise Ratio, SNR) from few seconds after lift-off (when in line of sight with the nearby stations) to a couple of minutes before landing and experiment shut down.

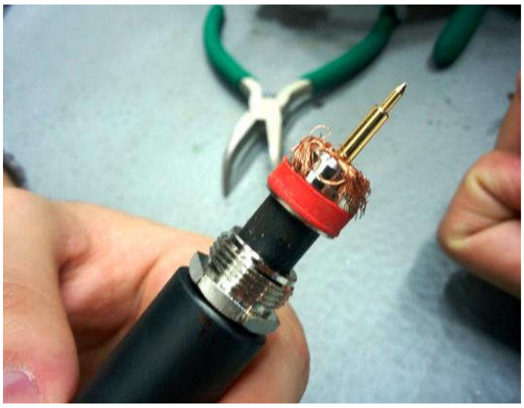


Fig. 2: Antenna N-type connector pin after pre-flight modification.

This experience shows how often major issue could be caused by simple failures, that might not include the most critical and delicate components or tasks of the project. This lesson learned flourished, in the following projects involving the team members, in a series of practical applications that allowed improving the results accuracy in all the performed tests. For example, when designing the LEDSAT 1-U CubeSat, the team members involved in the Light Emitting Diodes (LEDs, the payload of the spacecraft, [6]) needed to perform some irradiance measures on the LEDs in order to verify their nominal performances. The first measure attempts with a portable irradiance probe showed an incredibly low irradiance value. Before proceeding to any design changes, a simple test showed how the irradiance probe saturated the measures at low distances. As for the presented experience, a simple detail in the test procedure could cause severe problems to the continuation of a project. It is important to proceed at higher level of complexity when assessing a malfunctioning or a failure. Jumping to conclusions can amplify the effect of a simple failure into a major *show stopper* or towards significant delays for a project.

C. *Sometimes data usefulness is almost unpredictable prior to flight*

During the software architecture definition, the team members wanted to keep the data collecting processes as simple and safe as possible, in order to prevent any possible software glitches or lock-ups, that are obviously representing a major issue if recursively occurring during a balloon flight. Even if this design driver is, in principle, preserving the operations safety, a wide data collection shall be maintained among all the instrumentation available on-board, to maximize the scientific results of the experiment.

STRATONAV had to measure the balloon altitude in order to associate the measured VOR radial precision to altitude data, as referred in Section I and II. On this purpose, the experiment took advantage of a GPS receiver and of a barometer. The latter was added shortly prior to the CDR, in order to provide redundancy to the GPS altitude measure for shutting down the experiment, after balloon cut-down, slightly before the gondola landing. The selected barometer was flight proven on-board a general aviation plane, but a successful pressure altitude indication was not guaranteed by the manufacturer if flying above 10 km. However, the experiment vacuum test proved that the barometer worked until “saturating” its measure at 25500 m of pressure altitude (according to the International Standard Atmosphere [11] model). Even after the vacuum test, the team members did not implement any storage of the pressure altitude data, since, at that time, the risk to cause a software lock-up (when receiving an error message after polling the barometer measure) appeared higher than the effective usefulness of storing the altitude data twice. Moreover, the selected GPS receiver, whose model had already been tested on a stratospheric balloon, appeared more reliable in a continuous activation in stratosphere, and less prone to return errors when being polled. Unexpectedly, part of the balloon flight was performed during night time, with environmental temperature conditions that became harsher than expected for approximately half of the flight time. The experiment GPS antenna was located on the upper edge of the BEXUS 22 gondola, being exposed to the outer environmental conditions and not protected by the experiment box insulating material. For a small flight portion nearby balloon cut-down (approximately 15 minutes), the GPS antenna failed to acquire signal, with a consequent loss of positioning data for the very last section of flight. This issue was easily solved by interfacing the OBC clock data, associated to each data packet, to the last decoded GPS timestamp, and to the official BEXUS EBASS (Balloon Service System, the electronic unit used by the BEXUS pilot to monitor the balloon data and to control its trajectory), during the post-flight data analysis.

However, the described experience introduces an important lesson learned for this typology of projects: it is very difficult to determine the effective usefulness of data prior to the data analysis phase. Therefore, a good software design driver is to acquire as many data as possible. All the collected data may be used in a totally different way, with reference to events occurred during the balloon flight. To provide a further example, the experiment box temperature was acquired during the whole flight along with VOR data, in order to ensure that no components were working outside their acceptable temperature ranges, and to ease a failure analysis after the flight, in case of malfunctioning or total loss of one or more components. After the flight, all the temperature data were used to associate a very small bias on the acquired VOR radials to the experiment box inner temperature. This error was effectively caused by the variation of the main oscillator of the COTS receiver, which reacted to high temperature changes with a slight frequency shift on the VOR signal de-modulation. Such kind of error was not easily predictable prior to flight, and the temperature data, which were supposed not to be considered at all in case of mission success, turned to be extremely useful to correlate the VOR bias to the environmental conditions of the on-board receivers.

IV. Conclusion

The lessons learned presented in this paper are related to the STRATONAV Experiment, launched on-board BEXUS 22 stratospheric balloon on October 5th, 2016, from Esrange Space Center in Kiruna, Sweden. The project was selected for the ninth cycle of the REXUS/BEXUS Programme in December 2015. The experiment aimed at verifying the accuracy of the VOR radio-navigational system in stratosphere, and it successfully managed in all its mission objectives. One of the most important outcomes of the project is represented by the experience gained by the team members, successfully applied, in 2017, for ESA Fly Your Satellite! Programme, with project LEDSAT.

The presented experiences cover different phases of the experiment development cycle. The first presented experience is related to the team communication and interface definition during the design phase (Phases A, B and C [12]). The second lessons learned are linked to the need for a thorough verification, even on the simplest components (and related to Phase D). Finally, the last events described are dealing with the data acquisition processes definition, when it is not easy to predict the future usage of the collected data (Phase D and E).

Some of the team members are currently planning to submit new experiments for the REXUS/BEXUS Programme, since research on-board stratospheric balloons and sounding rockets represents a unique chance for doing scientific research, along with training students to real space projects and offering them unique hands-on activities related to space and near-space vehicles launches. All the team members have recognized the educational return offered by the participation in the Programme in the last University MSc course phases, including their Master Theses, and in the early stages of their professional careers as aerospace engineers.

Acknowledgement

STRATONAV is a REXUS/BEXUS Programme project, carried out between October 2015 and January 2017 by the Students of Sapienza – University of Rome and Alma Mater Studiorum – University of Bologna. The REXUS/BEXUS programme is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through the collaboration with the European Space Agency (ESA). Experts from SSC (Swedish Space Corporation) and ZARM (German Center of Applied Space Technology and Microgravity) provide technical support to the student teams throughout the project. EuroLaunch, the cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaigns management and operations of the launch vehicles.

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Teaching Astronomy with *ESASky*

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***Abstract*—*ESASky* is a science-driven discovery portal providing simplified access to astronomical data. It allows users to quickly visualise data from all European Space Agency (ESA) missions and from the missions of other agencies. Science-ready data are easily retrieved from the corresponding mission archives without assuming any prior knowledge of the mission and/or data characteristics. The tool's advanced visualisation capabilities and its ease-of-use make it very appropriate for Astronomy students of all levels. We describe the main functionalities of version 2.1 of the tool and present some educational activities that make use of *ESASky*, which have been developed in collaboration with the CESAR initiative at ESA's European Space Astronomy Centre.**

Keywords—Astronomy and Astrophysics; multi-wavelength Astronomy; astronomical data; Primary; Secondary; University

I. Introduction

One of the most important goals of science education is that students understand how science works. To achieve this, students' work should resemble, as much as possible, that of real scientists – allowing them to put the scientific method into practice. Yet this is not always easy in fields such as Astronomy where the requirements (in terms of equipment and working conditions) make it complicated to translate real-science activities into classroom activities.

Fortunately, in the last decades, technological developments have greatly simplified this task: Computers (or tablets) are now a common sight in many classroom landscapes, and software tools have been developed that enable students to work with astronomical data in a similar (but simplified) way to professional astronomers. They can even perform real-time observations from their classrooms using robotic telescopes that may be located on the other side of the world. All this effort has contributed to make Astronomy education easier and more enjoyable, as well as reach younger students.

However, the use of professional data, especially from space missions, in Astronomy education is still very limited, and is often restricted to the most advanced (college-level) students. There are three main reasons for this: i) the difficulty in finding and retrieving data usually kept in archives and databases with not very intuitive access interfaces; ii) the variety of data products available, which makes it difficult for a non-expert user to identify the most suitable product for their specific needs; and iii) the need, in many cases, to process the data prior to their scientific use. This requires good knowledge of the data and their acquisition process, a step that most students and their teachers are not prepared to carry out.

The same problems are faced by professional astronomers when they want to use data from an unfamiliar telescope, instrument or wavelength range. This is a serious caveat in a time when astronomical research has become increasingly multi-wavelength. In addition, while the utility life of the data products from a given mission may extend long beyond the operational life of that mission, memory of the mission's characteristics and peculiarities is more quickly forgotten by the community. Therefore, in the last decade, all major astronomical data providers have devoted efforts to develop tools that ease the task of searching and retrieving data from their archives to users of all levels of expertise. It is now

Fig. 1. The *ESASky* interface, showing the Skies functionality during the activity *Exploring the Interstellar Medium*. The image displayed corresponds to the Horsehead Nebula as seen by the Herschel Infrared Observatory.

standard practice that observing facilities and space missions provide pipelines for quick and efficient data processing, and/or science-ready products that match the requirements of most users. It has also become customary that these data are served online through customisable archive interfaces.

Within this context the ESAC Science Data Centre (ESDC) has developed *ESASky* (http://sky.esa.int, a science-driven discovery portal providing simplified access to astronomical data from space missions. This web-based tool allows users to quickly visualise data from all ESA missions and missions from other agencies. It makes it easy to retrieve science-ready data from the mission archives, without assuming any prior knowledge of the mission and/or data characteristics. While originally designed with the professional user in mind, *ESASky*'s advanced visualisation capabilities and its ease-of-use also make it suitable for Astronomy students of all levels.

In this contribution, we describe the *ESASky* application, focusing on those functionalities that may be of the highest interest to educators, and present some educational activities that have been developed in collaboration with the CESAR education initiative at the European Space Astronomy Centre (ESAC) of the European Space Agency (ESA). We also take the opportunity to provide a summary of other educational activities delivered by the CESAR team.

II. The ESASky Application

ESASky is accessed by loading the following URL in any standard internet browser:

http://sky.esa.int

No registration is needed, because all products served by the application are public. Since its version 2.1, released in February 2018, *ESASky* can also be accessed from mobile devices, with certain limitations.

When the application loads, the user is presented with a region of the sky as imaged by a particular mission and wavelength range, and a pop-up window with a description of the object visualised. Users can randomly view more objects by clicking on the Dice button in the left hand menu. If they want to view a particular object or region, they just have to type the name or coordinates in the search box in the top right hand corner, and *ESASky* will display it as seen in the current sky – that is, the currently selected mission and wavelength.

As a matter of fact, what is displayed is not a single telescope image, but an all-sky panorama –we call it simply “a sky”– built by combining all the images taken by that particular space mission at that particular wavelength. This allows users – astronomers or students– to explore the entire sky by zooming in and out and panning around. The application includes a large number of such *skies* displaying all the observations carried out by ESA’s major astronomy missions across the spectrum, as well as observations by missions and ground-based telescopes from other data providers (CDS, NASA, JAXA…). Thus, it is now possible, with just a quick glance, to know if a given astronomical object has been observed by a given mission, and what it looks like in a particular wavelength range.

Users can access the Skies menu by clicking on the colourful button in the left hand menu, and create a stack of these panoramas to seamlessly switch between them, either by hand or by using the video-style buttons (Fig. 1). This way,

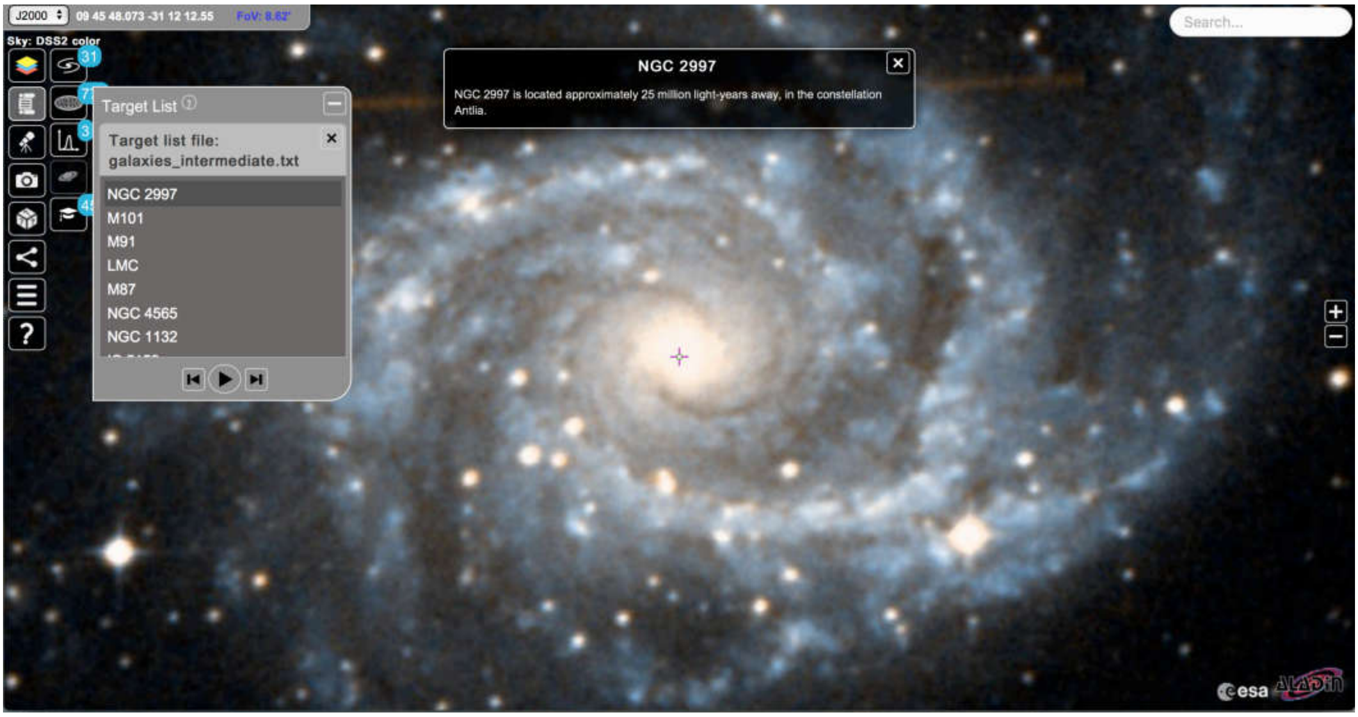

Fig. 2. The Target List functionality of *ESASky*, ready to start the activity *The secrets of Galaxies*. Displayed is galaxy NGC 2997 as observed in visible light by the Digital Sky Survey (DSS).

students can see how an object's appearance changes across the entire electromagnetic spectrum. They can explore and compare astronomical images in all wavelength ranges and make conclusions from the appearance and colours of the objects, without having to download or process anything. They can also take snapshots of the sky regions being visualised so that they can add the images to their school reports, web pages, or blogs.

Students can also take a tour of a pre-defined list of objects by clicking on the Parchment button that opens the Target List functionality. Selecting one of the available lists, displays a sample of astronomical objects of different types (galaxies, planetary nebulae, supernova remnants, etc.). It is possible to move from one object in the list to another manually, or using the video-style buttons (Fig. 2). Teachers can create their own lists of objects following the instructions in the *ESASky* documentation pages.[1]

More advanced students can download the images to carry out measurements and data analysis locally in their computers. This is done by clicking in the appropriate button to bring up the imaging data menu, which opens a chart of information about all the images available in the area of the sky being viewed. The information is grouped by mission and wavelength range. By clicking on one of the boxes in the chart, a table is opened summarising the information about those data (central coordinates, filter, duration, etc.), and, at the same time, the contours or *footprints* of the images are displayed on top of the displayed sky. It is possible to sort the table columns and to filter the data to display only the information about the images that fulfil certain conditions. Therefore, it is possible to select and download only the images that are really wanted.

It is not only images that are available: *ESASky* also provides catalogue data and spectra. All data are science-ready (fully processed and calibrated), and are retrieved directly from the scientific archives. For the most advanced students, the tool is compliant with Virtual Observatory (VO) standards and protocols, so they can send data directly to their favourite VO application.[2]

Another functionality with high potential in education is the possibility to search for Solar System objects (currently, only comets, planets and their satellites). When the name of a Solar System object is entered into the search box, the application provides information about all the imaging observations available that intersect (in space and time) the orbit of that object in the sky (Fig. 3). This is a fast and visual way of identifying observations of a particular object in the mission archive, but also to see how it has moved in the sky – providing, for example, a nice visual example of prograde and retrograde motion. Students may even find images that have serendipitously observed their target, just because it happened to be in the field of view, which may yield to exciting discoveries.

A complete description of the application, including some video tutorials, can be found in the *ESASky* documentation pages,[3] and in several publications [1, 2, 3, 4, 5].

[1] https://www.cosmos.esa.int/web/esdc/esasky-target-lists

[2] For more information on the Virtual Observatory, visit: http://www.ivoa.net

[3] https://www.cosmos.esa.int/web/esdc/esasky-how-to

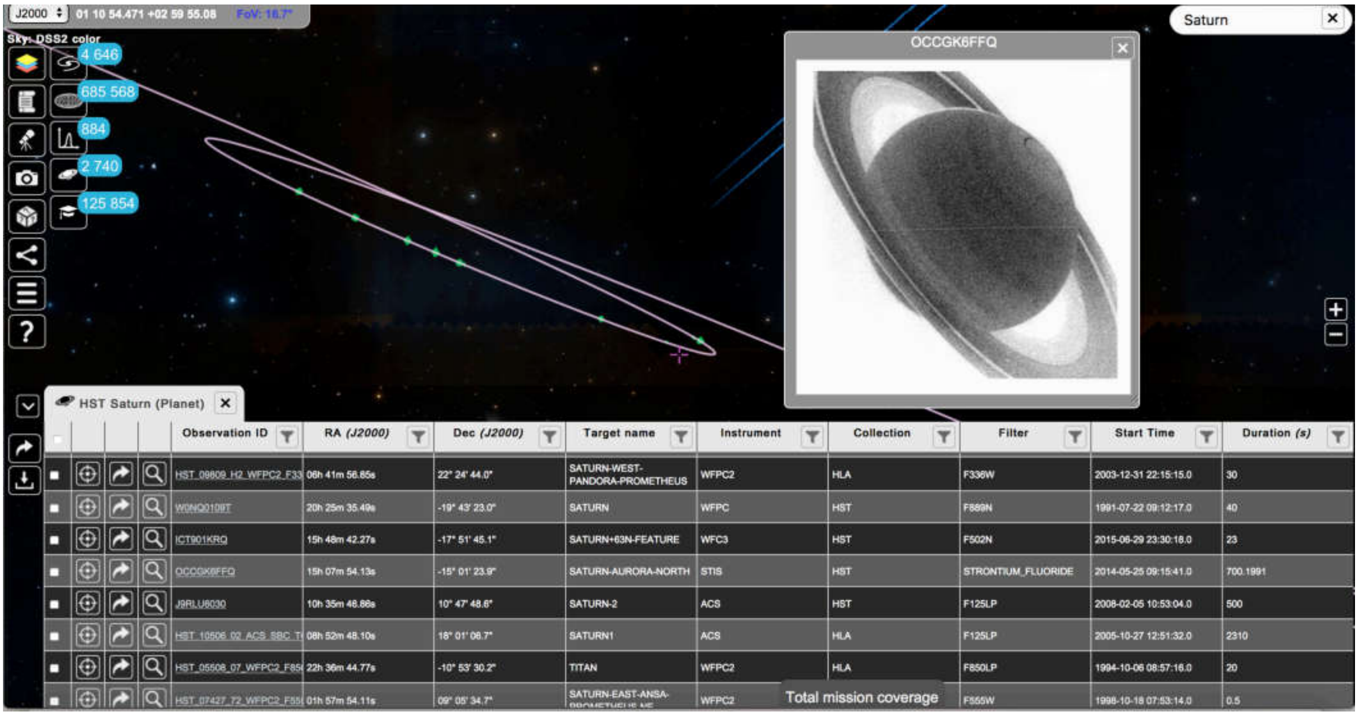

Fig. 3. The Solar System Object functionality of *ESASky*. The orbit of Saturn and a summary table of all the observations of the planet performed by the Hubble Space Telescope are displayed, as well as a preview or *postcard* of one of the images. The contours or *footprints* of the HST observations are shown in green on top of the orbital path.

III. THE CESAR INITIATIVE

CESAR (*Cooperation through Education in Science and Astronomy Research*) is an educational initiative developed by ESA at ESAC, in cooperation with the Spanish Institute for Aerospace Engineering (INTA) and the Spanish public company *Ingeniería de Sistemas para la Defensa de Espa*ña (ISDEFE). Its main goal is to provide students from European schools and universities with hands-on experience in Astronomy and Space Science research.

CESAR offers the following activities to schools and teachers:

- *Space Science Experience:* Students from local schools visit ESAC to undertake a hands-on science activity together with some ESA space experts. They have to prepare for the activity in advance with the help of their teacher. A videoconference with a CESAR team member is also held to answer any questions that may arise during the preparation phase. Once at ESAC, students have to 'accomplish a mission' (e.g., prepare a trip to the Moon, study the Sun's rotation…). After the visit, they can write an abstract explaining what they have learned during the activity; the two best abstracts of the class are selected to participate in the 'SSE awards'. A list of the activities currently offered (in English and Spanish), designed for students aged 8-16 years old, can be found in the CESAR webpages.
- *Interactive Science Cases:* Free online interactive activities, either guided investigations or laboratories, on science and Astronomy topics. They are intended to make science more accessible and appealing, and to help students develop scientific reasoning and critical thinking skills. The Science Cases cover all levels from Primary school to University. They are available in English from the CESAR website.
- *CESAR telescopes:* The CESAR Solar Observatory (CESO) at ESAC provides images of the Sun every minute to be used by students with online interactive educational software. In addition, CESAR is now adapting the 15m VIL-1 satellite antenna at ESAC to be used as an educational radiotelescope. Two robotic optical telescopes of diameters of 50 and 30cm are installed near Madrid at the ESA Deep Communication Station in Cebreros, and NASA Madrid Deep Space Communication Complex in Robledo de Chavela, respectively. The CESAR team is currently working toward making these telescopes fully operational for schools to perform observations remotely via the Internet.
- *Teacher training:* In collaboration with the *Centro Territorial de Innovación y Formación* (CTIF) of the Regional Ministry for Education of the Madrid region, CESAR organises training workshops in Astronomy and Space Science for local Primary and Secondary school teachers. We also take part in the teacher training workshops organised by ESA's Education Office.

For more information about these activities, visit the CESAR website.[4]

IV. CESAR/ESASky Educational Activities

With such an exciting tool as *ESASky* and an active educational project like CESAR being developed next door to each other, it was natural that both eventually converged to create some educational activities. They take the form of CESAR Science Cases, where students use *ESASky* to study the properties of some astronomical objects and try to figure out their properties under the guidance of their teacher.

The first two activities, described below, are already available from the CESAR website. They are conceived as guided investigations, that is, students are expected to extract conclusions from the images, in a similar way as real scientists do.

A. The Secrets of Galaxies[5]

In this activity, students view a list of galaxies with *ESASky*, and have to classify them morphologically according to the Hubble Tuning Fork scheme (spirals, barred spirals, ellipticals and irregulars). They compare the properties of the different types of galaxies based on their optical (visible) colours and how they look like in different wavelength ranges. As an extension, students can discuss whether the Hubble Tuning Fork represents an evolutionary sequence for galaxies, as well as the interaction of galaxies.

The activity was initially prepared for students of Secondary school level and above, but a version for younger students is also provided, where students are only expected to be somewhat familiar with the idea of a galaxy. In the advanced levels, students must also have some basic knowledge of the properties of stars of different ages, and of the relation between the interstellar medium and young stars. The activity may also be of interest for Introductory Astronomy courses at the university level.

B. Exploring the Interstellar Medium[6]

This activity is an introduction to the interstellar medium (ISM) for Secondary school and higher levels, including university courses. Students have to view a list of regions in different wavelengths, (optical, near-infrared and far-infrared), and study how the presence of gas and dust is responsible for the effects they see and for the differences between images of the same region. As extension, they can study the relation between the ISM and the formation of stars.

To successfully carry out the activity, students have to be familiar with the basic ideas of the electromagnetic spectrum and blackbody radiation.

C. Future activities

These two activities use two key functionalities of *ESASky*: visualisation of a target list, and visualisation of the sky in different wavelength ranges. In the near future, other activities will be offered, some of them making use of other functionalities, such as data inspection and download or visualisation of Solar System Objects.

Future activities will cover topics such as: stellar evolution, multi-wavelength Astronomy, stellar clusters and moving groups, galaxy clusters, planet formation, asteroid hunting, and more.

V. Conclusions

We have presented *ESASky*, an online discovery portal for Space Astronomy data with advanced visualisation capabilities and a user-friendly interface. At the ESDC we are greatly convinced of the possibilities that this application opens for Astronomy education, and we have started a collaboration with the CESAR project at ESAC to develop educational activities that teach Astronomy using real data.

The activities currently available use the skies visualisation feature of *ESASky* in a guided investigation for students to discover the properties of galaxies and of the interstellar medium. We plan to keep offering more activities in the near future, adapted to different student levels, and some of them making use of other tool functionalities.

To conclude this contribution, we want to invite educators to try the *ESASky* educational activities and provide us feedback through the CESAR contact page.[7] We also encourage them to develop their own activities with the application. If you do so, we also kindly ask you to provide feedback to the *ESASky* development team on the issues you may find while working with the tool, and about the features you would like us to improve/add to make it a better tool for education. You can contact the team through the *ESASky* user forum.[8]

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Astronomy and Planetary Science educational activities at the Aula EspaZio Gela

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***Abstract*—We introduce the Aula EspaZio Gela [1], a facility at the Bilbao School of Engineering, University of the Basque Country (Spain), dedicated to teaching Space Science and Technology and Astronomy and Astrophysics at Master and Doctorate level and to promoting the development of these fields in both public and private sectors [2]. We present some simple practices and observations with small telescopes that have lead to contributions to the scientific literature co-authored by the students**

Keywords— Planetary Sciences; Astronomy

I. INTRODUCTION

The Aula EspaZio Gela was founded in December 2008 and its teaching activities in Space Science and Technology started shortly after in 2009 [1-2]. The facility consists of a lecture room (with a maximum capacity for 25-30 students) and an astronomical observatory, where a variety of small telescopes and cameras are used to perform practices in astronomy, astrophysics, planetary sciences and orbital mechanics, and at the same time, scientific research. Up to now, about 110 students have obtained the Master Degree in Space Sciences and Technology. Fourteen of them have obtained or are pursuing a PhD degree in Science or in Space Technology, and most others are employed in companies of the space segment or close to it.

We describe in this paper some of the activities, practices and scientific research carried out using the small telescopes at the Aula Espazio Observatory, which had lead to publications in refereed journals with the participation of the students. In this way, students are encouraged to pursue a scientific career and acquire the required methodological background.

II. ACTIVITIIES AT THE AULA ESPAZIO GELA

A. Main Activities

The main activity in the Aula is the teaching of the one-year master course "Master in Space Science and Technology". We also participate in the PhD Physics program on the same subject. Moreover, we train students in ground-based astronomical observations and in space projects, and promote their relationships with companies and organizations in the space sector. In addition, we organize specific meetings, seminars and public outreach conferences. We also support professional initiatives of the students and organize visits to companies and research centers, where students complete some practices.

Fig. 1. The Aula EspaZio Gela and two of the telescopes (diameters 50 cm and 36 cm) from its Astronomical Observatory.

B. The Master in Space Science and Technology

The master's degree is a one-year course and it is open to graduates having completed four or five years in Engineering or Physics. It includes of 8 core subjects and 7 electives to be chosen out of 14, leading to two possible itineraries: science or technology-engineering. The Master ends with a Master's thesis [2].

III. PRACTICES WITH SMALL TELESCOPES

All through the master's history, students have conducted a series of practical observations and studies on astrophysics and planetary sciences using telescopes with different diameters in the range 28-50 cm [3-8]. We use simple CCD or CMOS fast cameras to get images at selected wavelengths and free available software for their processing [3-4, 9]. Observations with these telescopes can be explored online on the Aula Espazio observatory website [1].

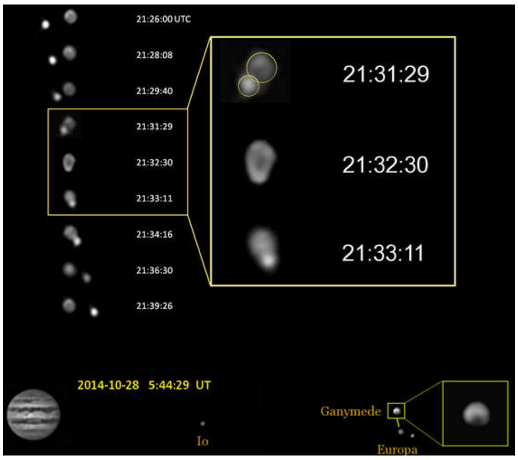

Fig. 2. Jupiter satellites Europa and Ganymede mutual eclipse (PHEMU event) captured with a 28-cm telescope from Aula EspaZio Gela (from reference [6].

A. Orbital Dynamics

We have used images of the four Galilean satellites of Jupiter, obtained with a 28-cm telescope and a camera, to study the satellites' orbits applying techniques learned in the core subject "Astrodynamics". In a first study we used measurements of the parallax, the latitude of the shadows projected by the satellites on the Jovian disk and orbital positions to retrieve their orbital parameters [4]. In a second study, we measured the orbital longitudes and mean motions of the satellites to retrieve the Lagrange resonance between Io, Europa and Ganymede and the quasi-commensurability of the orbital periods of Ganymede and Callisto [5]. Finally, we have used the mutual occultation and eclipses between satellites during the so-called PHEMU in 2014 and 2015 to fix their size and orbital parameters, exploring a technique with applications to the characterization of extrasolar planets [6].

These techniques have been also applied to the satellites of Saturn, Uranus and Neptune and are pending to be published.

B. Interferometry

Interferometry is a powerful high precision technique in astronomy to accurately measure the coordinates of celestial bodies and the size of distant sources. We have developed a simple laboratory experiment that reproduces the operation of the Michelson stellar interferometer. In this experiment, the laser light emerging from the circular end-faces of one or two polymer optical fibers is used to simulate the stellar emission [7-8]. The images of the interference patterns are acquired with a CCD camera coupled to a small telescope masked by a double aperture lid. The measurement of the fringe visibilities allows us to determine the diameters of the "fiber stars", the separation between them and their relative orientation (See Fig. 3) [8]. The experiment can be performed both outdoors in the daytime and indoors, and angular sizes of around 2″ can be resolved with relative errors less than 16%. Besides, we have performed interferometric observations on real bright stars to study the interference patterns, which are pending of analysis)

C. Planetary Atmospheres Studies

The reflectivity of the disk of a planet at selected wavelengths (using filters when taking images) can be used study the upper clouds and their surface properties [9]. Radiative transfer methods can then be used to retrieve these properties [10]. We have employed such techniques to study the basic properties of Jupiter's upper clouds from images obtained with a 0.5m telescope from the ultraviolet to the near infrared, including methane absorption bands, and offered a number of tools to the education community [3].

Importantly, because of their high dynamical behavior, planetary atmospheres are a subject where small telescopes make significant science contributions [9], and in section III, we present specific contributions of the telescopes of the Aula Espazio Gela.

D. Other Activities with the Aula Telescopes

There are a number unpublished works, most of them resulting in Master Theses: (a) Spectroscopy: Acquisition and analysis of stellar spectra to build our own spectral library; Acquisition and analysis of planetary spectra; Use of the Doppler shift on the absorption lines of the spectrum to measure the rotation rate of Saturn and its rings. Students have also worked on the identification of the absorption band by

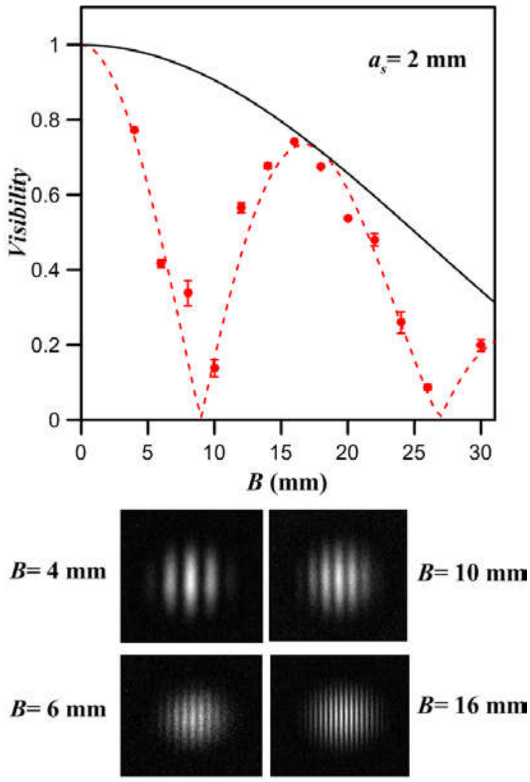

Fig. 3. Top: Visibility curve as a function of the pinhole separation obtained for a binary circular source of the same diameter separated by 2 mm placed at 54 m. The solid circles are experimental points and the dashed line is the theoretical fitting. Bottom: Interference patterns obtained with four pinhole separations: B= 4 mm, B= 6 mm, B= 10 mm, and B = 16 mm.

ammonia and methane gases. (b) Solar activity: We make regular observations of the Sun activity using apochromatic refractive telescopes (12 and 15 cm in diameter) and working at three different wavelengths (Ca-K line, visible and Hα), studying sunspots, active regions and the chromospheric activity. (c) In spite of the low-mid aperture of our telescopes and the difficulties arising from a urban observatory, we have been able to measure the changing level of light arriving from stars undergoing transits by known exoplanets around them. (d) We have performed astrometric studies of binary systems (Sirius A-B) and extensive imaging of galaxies, nebulae and stellar cluster at selected wavelengths. (e) Finally, minor bodies of the solar system (asteroids, NEA objects and comets) have been imaged in several occasions. A large number of images mentioned here can be found at the Aula EspaZio Gela website [1].

IV. PLANETARY ATMOSPHERES SCIENCE CONTRIBUTION WITH SMALL TELESCOPES

There is ample possibility to make significant scientific contribution using small telescopes in planetary sciences [9]. The number of amateur astronomers with good equipment and instrumentation has increased notably in recent times thanks to the accessibility to telescopes, cameras and open software for image processing. Students at the Aula Espazio have developed master theses dedicated to the set-up of small telescopes and the observation of the planets with these telescopes, following techniques widely used in the amateur world.

A. Venus

Regular observations of Venus with filters in the ultraviolet and violet filters (350-420 nm) and in the near infrared (920-980 nm) can be used to sense its upper clouds at two altitude levels (60-70 km above surface). Temporal series of images can be used to retrieve the motions of these features, measure winds and wave motions and their temporal variability. Recently, such studies have been used in support to the Akatsuki Japanese space mission [11].

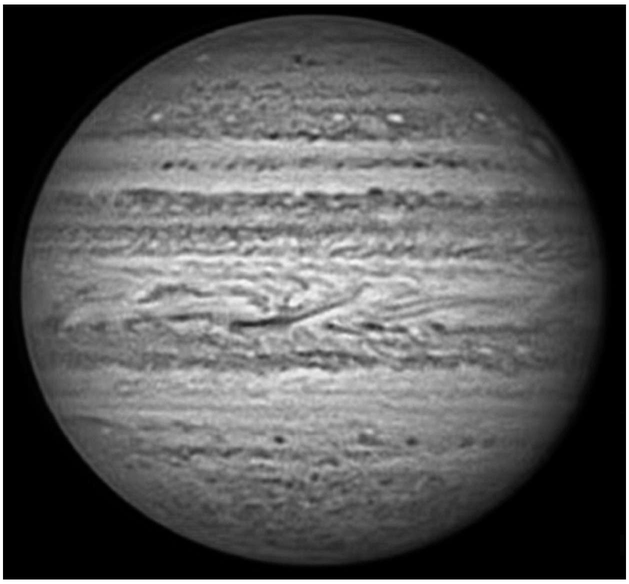

Fig. 4. The clouds of Jupiter observed at high resolution with a 28-cm telescope at red wavelengths (610-900 nm) on March 9, 2015. This is one of the images obtained with the telescopes of the Aula Espazio that has been used to retrieve Jupiter winds [14].

Fig. 5. Venus, Mars and Saturn in images obtained in visible wavelengths with the telescopes of the Aula Espazio. Some master students have developed observational works as part of their master thesis.

B. Mars

When near opposition, Mars offers good observing possibilities to study clouds, dust storms and the recession of the polar ice deposits [9]. However, the impact of small telescopes became evident with the stunning detection of a large "plume" at Martian limb captured by amateur images in 2012 [12]. This phenomenon, that still remains unexplained, was solely captured by a large team of amateurs, and measurements at limb indicated unexpected cloud top altitudes of about 200 km.

C. Jupiter

Because of its large size and the huge temporal and spatial variability of its cloud system, Jupiter's atmosphere is the preferred target for amateur observations with small telescopes. The scientific contribution of amateurs to the study of Jupiter's changing clouds in the history of observations is large. It has acquired particular weight with the Juno space mission, with its visible camera JunoCam dedicated to outreach and the promotion of citizen science [13]. Wind measurements, cloud evolution patterns, and studies of singular planetary-scale disturbances have been performed with our telescopes in support to JunoCam observations [14-15].

D. Saturn

Saturn's rings are a major attraction when observing this planet with small telescopes. The detection of atmospheric features is difficult because of their small brightness contrast, except when a major and rare convective event known as "Great White Spot" erupts in the atmosphere [16]. Nevertheless, isolated features ("spots") sometimes appear at particular regions and allow studying interesting atmospheric phenomena using small telescopes, even during the Cassini era. One such example is a long-lived equatorial spot rapidly moving within the Equatorial jet that has the record of longevity in the Saturnian atmosphere [17].

E. Uranus and Neptune

These two planets show a small diameter at the telescope and until recently, they have been very difficult to observe with enough quality to obtain scientific results. However, under good seeing conditions, telescopes with diameters above 30 cm are able to capture and track bright spots in Neptune at red wavelengths (650-900 nm), allowing to study the winds and the atmospheric activity [18].

F. Software Development

Several Master theses have been dedicated to software development. Among the different projects, we highlight: (i) Research on image analysis algorithms that can be used to detect impacts on Jupiter producing short and bright flashes. These algorithms later on materialized in open-source software now used by the community of amateur astronomers [19]. (ii) Improvements of software tools designed to analyze wind motions using image correlation velocimetry techniques [14].

V. CONCLUSIONS

In this paper we have presented some teaching and scientific activities performed using small telescopes with students of the Master in Space Science and Technology at the UPV/EHU. Details on them can be found in the cited bibliography.

These activities try to encourage and involve students toward a scientific career on astronomy and astrophysics, and a in a more ample sense toward space science in general. We have attained a direct participation of the students in specific projects and students have presented the results at scientific and educational meetings, and co-authored resulting educational and scientific papers, encouraging them to continue their scientific career towards a PhD.

ACKNOWLEDGMENT

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"Space & Satellite Technologies" intercollegiate master-degree courses of study in Tri-City (Poland)

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***Abstract*— Since summer semester of the academic year 2016/2017, two faculties of Gdansk University of Technology GUT (Faculty of Mechanical Engineering and Faculty of Electronics, Telecommunications and Informatics) together with the Gdynia Maritime University (Faculty of Electronics) and the Polish Naval Academy in Gdynia (Faculty of Command and Naval Operations) have opened intercollegiate master-degree studies called: Space and Satellite Technologies (TKiS). Each of these faculties offer for their candidates and conduct special education in case of certain speciality. This initiative is supported by Polish Space Agency and received additional funding from the National Centre for Research and Development. Under the project entitled: Adaptation of the second-degree studies Space and Satellite Technologies, to the needs of the labor market, people involved in the space industry were included in the didactics.**

Keywords*— *university, education, employers, space sector, curriculum

I. INTRODUCTION

Three big universities in Tricity (the agglomeration of 3 cities: Gdańsk, Gdynia and Sopot in Northern Poland), namely, Gdańśk Univeristy of Technology (GUT), Gdynia Maritime University (GMU) and Polish Naval Academy in Gdynia (PNA), started in 2017 the recruitment for interdisciplinary, MSc degree studies on Space and Satellite Technologies (SST). Each of these universities offer for their candidates and conduct special education in case of certain speciality.

Faculty of Electronics, Telecommunications and Informatics GUT, recruits students for specialty: *Information and telecommunications technologies in space and satellite engineering.*

Faculty of Mechanical Engineering GUT, recruits students for specialty: *Mechanical and mechatronic technologies in space engineering.*

Faculty of Electronics Gdynia Maritime University, recruits students for specialty: *Marine satellite and space systems*.

Faculty of Command and Naval Operations Polish Naval Academy in Gdynia, recruits students for specialty: *Space and satellite applications in security systems*.

This new initiative in the field of education in Polish Pomerania region is an answer to the development of such innovative industry sector as space exploration and utilisation technologies. It is expressed by the increase of a number of companies and other entities related to space sector in Poland, also in Pomerania region. The new space sector entities are both the Polish branches of well recognised international corporations operating for a long time in space industry, and smaller local firms offering services in the areas including satellite telecommunications, satellite navigation, Earth observation and Geographic Information Systems.

The curriculum of the SST studies combines the contents of basic courses, like mathematics, physics or astronomy, with advanced topics of satellite technology utilisation (namely, satellite telecommunications, remote sensing and navigation), space missions, space mechanisms and constructions, as well as space applications in security systems. The graduates of SST studies will also obtain skills on using as well as designing of specialised space equipment. The students will be also provided with basics of legal regulations with respect to space activities.

The wide spectrum of topics covered by the SST studies curriculum will result in obtaining by students the background in numerous fields related to space. It will constitute the strong basis for choosing the area of specialisation by them.

Within the scope of educational activities predicted for of SST students during their studies, the directly take part in scientific research projects, under the supervision and in cooperation with the academic and research staff. As a result, the student will be well prepared to independent formulating and solving scientific problems, performing the research, communicating with others and presenting the research results. He/she will be also able to solve several technical issues effectively, both in individual as well in team work. It will include the design and implementation of the solutions specific to the area of a given speciality of the studies, also on the system level and including non-technical aspects in conditioning. The SST graduate will be well prepared to the next degree of studying, i.e. the PhD degree.

II. CURRICULUM

The curriculum of the SST studies is presented in tables from I to VII. The optional subjects (Table VI) are realised during the second semester of the studies. Students choose the optional subjects from the list of them proposed by the university. The lists containing the subjects proposals are different for particular SST specialities, and the amount of them may also be changed each year. In the same table, subjects connected with the dissertation project implementation are also enclosed.

TABLE I. CURRICULUM – GROUP OF COMPULSORY SUBJECTS FOR ALL STUDENTS

SUBJECT NAME	TERM	Number of hours				ECTS
		Lecture	Exercises	Lab	Project	
Applied Mathematics	1	15	15			3
Astronomy with Elements of Astrophysics	1	15	15			3
Mechatronics in Space Applications	1	15			15	2
Space Security Technologies	1	15	15			2
Space Mechanisms and Constructions	1	30	15			3
Space Missions	1	30	15			3
Satellite Remote Sensing	1	30		30		4
Satellite Telecommunication	1	30		15		3
Global Navigation Satellite Systems	1	30		15		3

TABLE II. CURRICULUM – GROUP OF COMPULSORY SUBJECTS FOR SPECIALTY: INFORMATION AND TELECOMMUNICATIONS TECHNOLOGIES IN SPACE AND SATELLITE ENGINEERING

SUBJECT NAME	TERM	Number of hours				ECTS
		Lecture	Exercises	Lab	Project	
Geospatial Data Processing Technologies	1	30		30		4
Satellite Observation Sensors	2	15		30		3
Antenna Technique	2	15		30		3
Satellite Sensing of the Earth Environment	2	15			15	2
Space Applications of Advanced Information Technologies	2	15			30	3
GNSS Applications Programming	2	15		15	15	3

TABLE III. CURRICULUM – GROUP OF COMPULSORY SUBJECTS FOR SPECIALTY: MECHANICAL AND MECHATRONIC TECHNOLOGIES IN SPACE ENGINEERING

SUBJECT NAME	TERM	Number of hours				ECTS
		Lecture	Exercises	Lab	Project	
Unmanned vehicles	2	30			30	4
Flows under non-gravity conditions	2	15	15			2
Mechanical vibrations. Dynamics of space and satellite constructions	2	30	30			4
Analitycal mechanics	1	15	30			4
Robotics in space exploration	2	30		30		3

TABLE IV. CURRICULUM – COMPULSORY SUBJECTS FOR SPECIALTY: MARINE SATELLITE AND SPACE SYSTEMS

SUBJECT NAME	TERM	Number of hours				ECTS
		Lecture	Exercises	Lab	Project	
Fundamentals of celestial mechanics	1	15	15			3
Fundamentals of microwave and antenna technology	1	15		15		2
Production and processing of electricity in marine and space conditions	2	15		15		2
Global Navigation Satellite System	2	15		15		2
Measurement and control systems in space technology	2	15		30	15	3
Microwaves and antennas - satellite solutions	2	15		30		3
Marine applications of satellite and space systems	2	30				2
Space navigation	2	15	15			2
Physical education	2		15			0
English classes	2		30			2

TABLE V. CURRICULUM – COMPULSORY SUBJECTS FOR SPECIALTY: SPACE AND SATELLITE APPLICATIONS IN SECURITY SYSTEMS

SUBJECT NAME	TERM	Number of hours				ECTS
		Lecture	Exercises	Lab	Project	
Security strategy	1	30	15			3
Methodology of research on security	1	15	15			2
Remote sensing and environmental monitoring	2	15		30		3
Analysis of satellite data	2	30		30		4
Satellite recognition systems	2	15		30	15	4
Teleinformation security of satellite systems	1	15		15		2
Power systems for artificial satellites and space probes	2	30		15	15	4

TABLE VI. CURRICULUM – FACULTATIVE SUBJECTS FOR ALL STUDENTS

SUBJECT NAME	TERM	Number of hours				ECTS
		Lecture	Exercises	Lab	Project	
Facultative subject I	2	15		15	30	4
Facultative subject II	2	15			30	3
Facultative subject III	2	15			30	3
Facultative subject VI	2	15			30	3
Team project	2				30	4
Dissertation seminar	3				15	5
MSc dissertation project	3					20

TABLE VII. CURRICULUM –GROUP OF HUMANISTIC AND SOCIAL SCIENCE SUBJECTS FOR ALL STUDENTS

SUBJECT NAME	TERM	Number of hours				ECTS
		Lecture	Exercises	Lab	Project	
Facultative humanistic-social subject	3	30				2
Law basics activities in space	3	15	30			3

III. SUPPORT IN EDUCATION

The newly started studies of SST has obtained the financial support from the Polish National Centre for Research and Development in the form of the European Social Fund resources allocated for the implementation of the educational project "Adjusting the MSc studies Space and Satellite Technologies to the needs of the employment market". The activities undertaken to achieve the aims of the project rely on strict co-operation of the employers representing the space sector with the university. The representatives of firms operating in the space sector are taking part directly in preparing the programme and the contents of lessons for students, and also in delivering lectures and working with students during labs, seminars etc. Also, the Team project and student dissertation projects are realised in co-operation with firms. As a result, students are better prepared to the requirements of the space sector employers.

The space sector entities co-operating with 3 Tricity universities under the scheme of this project include: Blue Dot Solution Sp. z o.o., Space Forest Ltd, Space Research Centre of the Polish Academy of Science, Wasat Sp. z o.o., Astri Polska Sp. z o.o. and also Polish Space Agency.

IV. STUDENT ACTIVITIES

Degree course met with enthusiasm and interest from applicants, as 68 people have been recruited. After one year, current students have numerous achievements. HEDGEHOG [1] team has qualified to REXUS/BEXUS programme, organized by German Space Agency (DLR) and Swedish Space Agency (SNSB), coordinated by ESA. Apart from that, a number of students participated in space related conferences, workshops and other activities, including hands-on courses by ESA Academy that expand their knowledge in space engineering, such as Concurrent Engineering Workshop, or Cubesat Workshop.

These students have founded a student organization SpaceCube. Its goals have been set to foster cooperation with academia and space sector companies as well as broadening the gap between course curricullum and future carees skills required by employers. Their main project is a nanosatellite type 1U Cubesat, aiming to test new type of solar cells developed at Gdańsk University of Technology. SpaceCube's activities include also popularisation of STEM sciences among middle and high school pupils. Furthermore, their concept of "Space Navigation System", allowing for precise navigation on LEO and beyond was awarded 2nd prize at Poland's edition of Galileo Masters Competition 2017.

Engagement of three academia in space engineering resulted in some scientific results as well. A first PhD thesis in dynamics of spacecraft payload vibration is ongoing. Furthermore, a cooperation with Centre for Space Research of Polish Academy of Sciences has been developed to work on their space robot testing facility [2]. Additionally, members of faculty together with local space sector companies have proposed numerous research and developement projects [3], some already funded by National Centre for Science and Development or European Commission.

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Sheffield University Solar Balloon Lifted Telescope (SunbYte - BEXUS 25)

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***Abstract*— Solar observations from the ground is often difficult due to the turbulent atmosphere distorting incoming light. Learning about the Sun is critical in modern society as solar flares have the potential to cripple telecommunication and global navigation systems. Project SunbYte (Sheffield University Nova Balloon Lifted Telescope) aims to revolutionise the industry by using a high-altitude balloon to lift a solar telescope to an altitude of 25-35km, where it has the potential to capture images of much better quality. As existing ground and space telescopes are large, complex and expensive, SunbYte will provide a new technique for scientists to collect low cost, high quality data. The experiment was launched on BEXUS 25 from ESRANGE, Sweden in Oct 2017 as part of the German-Swedish student programme REXUS/BEXUS. This paper will discuss the educational impact of the project and the science and engineering developed by students. It will assess the lessons learnt from a management and technical perspective.**

Keywords*— *Solar astronomy; Sun tracking; University of Sheffield; telescope; Balloon;

I. Introduction

In the UK alone, €22 million was invested in the Space Situational Awareness program emphasising the need to better understand and predict solar events [1] [2]. Even though experimental studies using high altitude balloon telescopes have been previously conducted, these are, in terms of cost, inaccessible to many mainstream research institutions across the world.

SunbYte is a University of Sheffield student led project with academic and industry partners - Northumbria University, Queen's University of Belfast, University of Hull, Andor Ltd, Astrograph Ltd and Alternative Photonics. Combining the latest practices in manufacturing, astrophysics science and engineering, the team aims to deliver a low cost, high quality method of imaging the Sun.

The team includes members from first years undergraduate studies to PhDs, from aerospace, civil, electrical, mechanical, materials, chemical and Automatic Controls and Systems departments within the Faculty of Engineering, to Physics, Astronomy and School of Mathematics and Statistics within the Faculty of Science. All working together to develop an integrated, accurate and stabilised system.

The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through the collaboration with the European Space Agency (ESA). Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. EuroLaunch, the cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles.

II. Design

A. Mechanical

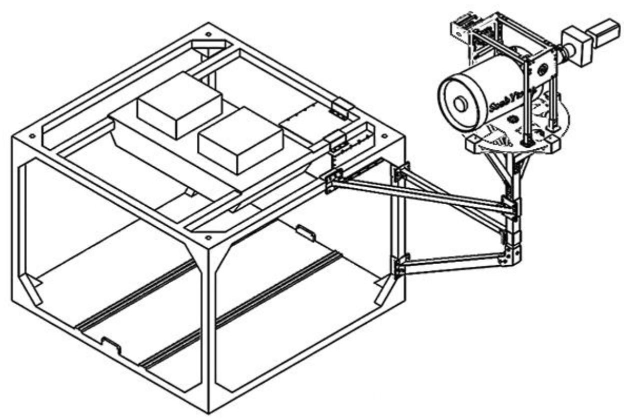

Fig. 1. Mechanical Overview

The experiment positioning on the gondola can be seen in Figure 1. This set-up provides height to the telescope to offer maximum field of view. It also moves the experiment away from the gondola's connections to the balloon. This support system has been designed to ensure the stability of the whole mechanical structure. By implementing a third horizontal metallic strut, transverse (side- to-side) low frequency vibrations caused by wind or gondola rotation can be minimised.

A mixture of aluminium square tubing and steel sheets was used to connect the supporting structure together. At areas of high stresses, additional bolts and steel plates were used to increase the local strength. Wire Electrical Discharge Machined (WEDM) parts were used where precise 90 degree bends were required (e.g. gondola clamps).

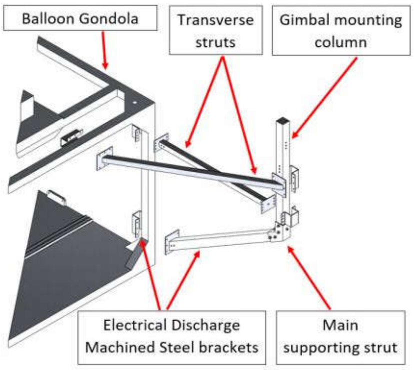

Fig. 2. Exploded view of supporting structure

Above the supporting structure is the two-axis gimbal which aims the telescope at the Sun. The gimbal is split into a fixed square platform and a rotating circular platform. The square platform also provides a mounting position for the yaw motor housing and C-clamps which secure the rotating platform. The rotating platform consists of a circular plate on which the telescope support sits.

Fig. 3. Exploded view of gimbal

Within each motor housing, is a stepper motor and the motor driver. The team was able to learn from real industrial Engineers to select a harmonic drive which would meet torque, speed and power requirements, suitable for use with the motor. Due to the complex geometry necessary to adapt the motor shaft to the harmonic drive input, the team worked with the university's materials research group to design and manufacture a custom 3D printed titanium part.

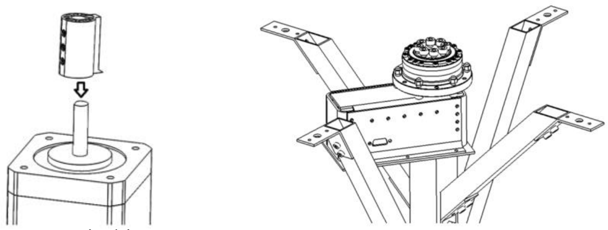

Fig. 4. Harmonic drive to motor interface

Students learned that the final design sometimes needs modifying even during final assembly. To ensure tight clamping, some clamps were initially designed to be 2mm shorter than the width of the strut. However, upon assembly, it was found that this caused the plates to significantly deform resulting in less contact area with the terminal surface of the strut. Here, the team utilised good judgement to deliver suitable modifications within the time constraint.

B. Optics

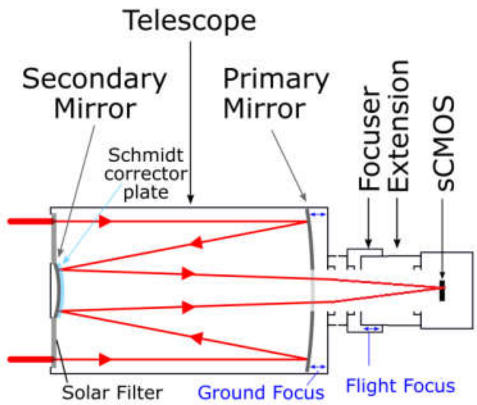

Fig. 5. Optics System

Fig 5 shows the optical design, a solar energy rejection filter reduces the energy entering the aperture of the telescope. This prevents overheating in a near vacuum environment. A Schmidt Cassegrains derivation of the Cassegrain telescope design was chosen because it is less susceptible to spherical aberration. It also has a long focal length with a compact length and volume. A focuser adjusts the distance between the camera and the telescope to account for thermal contraction during flight. The team learned the painful lesson that manufacturer deliveries can be late (often by months). The short project cycle was a surprise to manufacturers who were more accustomed to longer space missions. The H-alpha filter scheduled for arrival in summer 2017 did not arrive even by Oct 2017 so the experiment was finally launched without the intended h-alpha filter.

C. Electronics and its Modification

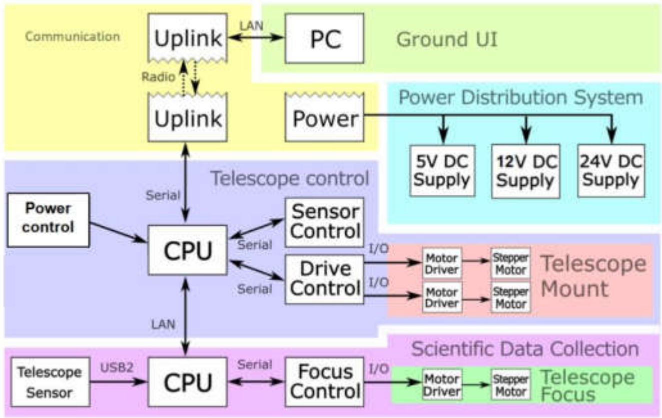

Fig. 6. Electronics system overview

The main goal of the electronic components is to provide a platform for the software that allows effective tracking and adjustment. Power distribution alters the voltage supplied (30V) and transfers this to the various devices (5V/12V/24V).

Telescope control gives commands for scientific data collection and controls the movement of gimbal. A Raspberry Pi (RPI) was used as main controller. Using sensor inputs, it calculates the motor movement required in order to position the Sun at the center of the telescope. In the scientific data collection system, a high resolution sCMOS camera capture pictures. The electronic layout, selection of programming language and components were conducted according to the design specification.

During final assembly, the team discovered that the power relay delivered a pulse to all connected devices on battery connection. The PC was supposed be in off mode by default to conserve power, however the relay accidentally turns this on with the pulse. The team identified this issue through a series of careful and logical tests to trace the error from the power supply to the user end.

During testing, the main RPI controller was accidentally destroyed. Current sensors between the battery to DC/DC converters and the RPI were supposed to monitor this. However, because the current sensors were connected together via data line, when the address pins were mistakenly connected to the 5V supply, the current sensor between the battery and the DC/DC converter was overpowered and 30V from the battery bypassed DC/DC converter via the data line of the sensors into the RPI.

D. Software Design

The aim of the tracking software was to center the sun in the sCMOS camera. This was done by capturing a feedback image from the RPI camera. Then, comparing the current position with the reference point. The required movement was calculated and output to the controller of stepper motor. There are three steps to the process: the high-speed tracking, fine adjustment tracking and the focusing system. There are many possible methods to accomplish tracking, the team conduced research and discussed the most appropriate approach. This was different from the typical classes where the teacher provides a system diagram and the students write code.

E. Summary

Despite the issues which arose during assembly, the team worked together and the experiment flew with basic functionality and a limited power management system without sensors or a focusing mechanism.

III. DATA EVALUATION

During the flight, the Raspbery Pi Camera was able to consistently take images of the sky for the tracking. The Sun clearly visible as a circle with a diameter of approximately 11 pixels against a black sky. Due to the strong solar filter used, the lack of glare and other visible light sources shows the solar filter film was operating as desired, but also far better than during ground-based tests. Pre-processing software filters mistook the Sun to be noise/dust particles and removed it prior to the tracking algorithm, see Figure 7. This led to the experiment being unable to acquire scientific data from the telescope camera.

Fig. 7. Image processing steps for the Pi *(Camera images with solar filter installed and modified filters.(a) original, (b) gaussian blurred (3x3), (c) threshold removal (240 to 255), (d) erode filter, (e) dilate filter.)*

Ground-based tests showed more glare/coma of the sun than in-flight tests and there was no way to have reasonably anticipated this. Changes to the image pre-processing parameters have been made and show proper functional tracking.

IV. OUTREACH

Public Engagement

Throughout the project, the team has worked with university societies such as “Women in Engineering” and the Sheffield Space Society to promote Engineering. They have participated in the UK Space Missions Forum, Sheffield Festival of Science and Engineering, Pint of Science, and the UK National Astronomy Meeting. The team has developed a website (http://sunbyte.group.shef.ac.uk/) with different social media channels (e.g. Facebook (facebook.com/Project-SunbYte) and Twitter (@Project_SunbYte). These allow interested parties to watch the team’s progress as they manufactured, tested and launched the payload. Viewers were able to see the team live at the launch campaign and learn more about the conditions near Space. Outreach into schools inspired younger students and gave them a broader idea of the Engineering involved to survive in these harsh conditions. Giving team members the opportunity to talk about their work also boosts morale and makes them proud of their achievements representing their university.

V. TEAM WORKING STYLES

As part of an investigation into the compatibility of team members, a Belbin working styles test was conducted on each team member at the beginning of the project. This was later repeated in the later stages of the project to see if team members adapted their style to work together. The Belbin test is used to identify behaviour preferences of an individual and has been developed over the last 9 years [3].

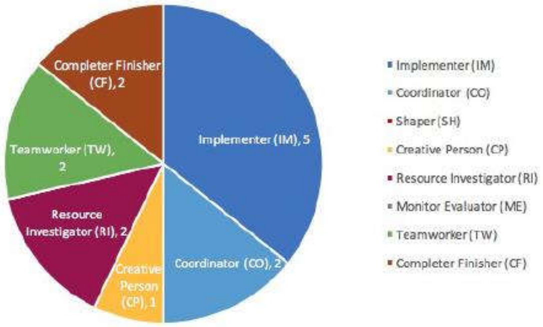

Fig. 8. Belbin test result

From fig 8, it can be seen that the highest occurring personality trait is "Implementer". Looking at the combined primary and secondary traits, “Implementer” appears in almost all the team members. This trait is prominent in people who like to turn ideas into reality and could be a reflection of the type of student Engineers who wish to join the project. However, those with this trait also tend to be slow to accept new ideas. This makes working within a dynamic design environment challenging, especially when combined with the lack of “Monitor Evaluators”. The lack of “Monitor Evaluators” means a decrease in ability to objectively assess different the options. A second Belbin test later in the project showed that team members changed working styles in order to fit the needs of the team. Previously lacking roles like the “Monitor Evaluator” mentioned above were more prominent and the team was much more balanced. It is therefore important that teams effectively analyse the way team members prefer to work and distribute tasks accordingly.

VI. IMPROVEMENT AND RECOMMENDATIONS

A. Time Management

Although it was envisioned that that each team member would only spend around 3-5 hours per week on the project, this was vastly underestimated. Successful members often need to spend closer to 10 hours per week. As conflicts of priorities arise, emotional management of the team is important to maintain morale and working efficiency.

This effect is exacerbated in the managers of the team. For example, a task requires 10 hours of work. If delegated to an unacquainted team member, it would take an additional 5 hours of the manager’s time to prepare a clear explanation of the task, how to approach the task and check up on the individual. Hence, there is often a trade off between the manager taking on task themselves or delegating the task. Until this effect was realised, the team often underestimated the time required to complete tasks and did not leave enough contingency time.

B. Leadership

As a consequence of the above, some sub-team leaders had a tendency to take on all the work instead of assigning tasks to team members. This led to students without sufficient training and experience. During critical periods or when the sub-team leaders were busy, the team struggled to meet the targets set. Therefore, it is recommended that no matter the circumstance, time is invested in training new members who are able to takeover more work during critical periods.

Contrary to expectation, the most senior student is not necessarily the most ideal to lead a sub-team. Team members have a variety of reasons for joining the project, for example, a high performing senior mechanical engineering student may join to learn new electrical knowledge. A proper recruitment process is needed to ensure that the individual actually wants to take on the role the team wishes them to do.

C. Project Management

Segregation of teams by disciplines is a terrible idea, projects are interdisciplinary so internal teams should be formed around functionality (e.g. gimbal mechanism, telescope system, etc.). This forces students from different disciplines (e.g. electrical and mechanical) to sit together and design mutually compatible systems. If this is not achieved, proper integration of systems is much more difficult and work often needs to be repeated.

D. Project scope

In the early stages, the team lacked student expertise in astrophysics. Instead, they relied on academics who had much a better understanding of the field. However, academics may not have a good understanding of what students can achieve within a year. The lack of understanding on both sides led to project creep with the team leader unaware of the impact of a high accuracy telescope pointing requirement until later in the project when it led to specification of very strong motors, very strong structure and excessive power consumption. Thus, emphasis on achieving secondary objective (proving the scientific value) affected the primary objective (demonstrating the tracking). Realistically, the team should have recognised their limitations and opted to deliver an achievable goal successfully rather than risk aiming for an amazing but unlikely result. However, as this was an educational program, the challenge was an opportunity for the students to gain massive technical experience and recognise their own limitations.

As the team of students matured, they learned the key areas to focus on and the areas to forget. The requirements document and risk assessment (created with guidance from the REXUS/BEXUS organisers) were a core aspect of the decision process. One critical area which was covered well was spare parts. During final assembly, anything which could possibly malfunction somehow broke. The team was only able to deliver the flight experiment (with limited functionality) because they had the foresight to bring enough parts and tools (including a 3D printer) which could be cannibalised for stepper motors and spare parts. In post flight evaluation, a smaller scale model could have been used to decrease structural requirements and reduce the need for high torque motors. The scientific camera used required a very high performance computer to receive all of the images. This was not provided due to the budget and as a result, some of the experiment's better components were underutilized. An internal post flight review by team members showed that a smaller telescope with increased emphasis on refining the software Sun tracking would be ideal. Once this is achieved, it is a matter of cost to put more expensive components on-board for higher quality images.

Now, the team successfully applied to NASA's High Altitude Student Platform to fly a smaller scale experiment. This time, using a 90mm aperture telescope with a smaller scientific computer and science camera. The experiment mass was greatly reduced. The motor specification was also relaxed leading to power savings. The experiment has now been preliminary accepted and the team is working hard to continue making the most of the opportunity that the REXUS/BEXUS program first provided. Old code which proved to work is being combined with new sensors to bring more data into the experiment and allows better diagnostics. In addition, new methods of Sun tracking are used as back-up systems to ensure that the Sun can be tracked. Finally, improved trial and error algorithms which adjust the on-board imaging filter parameters are being developed so that the experiment can automatically change key variables to prevent itself from accidentally erasing the Sun again.

VI. CONCLUSION

Nowadays research led teaching is extremely important in giving an opportunity for STEM students to work together, gain actual real life experience of the aerospace industry, apply their scientific and engineering knowledge and network with students and companies from all over Europe. During the course of the project SunbYte student team members attended a number of events organised by ESA in Netherlands, Germany and Sweden. Every three months 4-5 of students participated in review meetings organised by REXUS/BEXUS team to assess progress. All of this was very similar to preparation of real space missions and participating STEM students took their tasks very seriously. The success of the SunbYte mission inspired many of the students to continue in space engineering and science related projects. Also, STEM students who were not involved in SunbYte now wanted to be! Due to popular demand this led to the formation of the Sheffield Space Initiative (SSI) at the end of 2017. Working with the world's largest professional Engineering Institution (IET) and the University of Sheffield Space Society, SSI started to inspire the next generation of space engineers and scientists for a variety of exciting new projects. Our research led teaching project has now engaged more than 50 students from first year undergraduates to PhD students from the engineering and science faculties. The different engineering departments involved are Automatic Control & Systems, Aerospace, Civil, Electrical, Material, Chemical and Mechanical and the science departments are Physics & Astronomy and the School of Mathematics and Statistics. Through a lot of feedback from the students, it is clear that these projects definitely helped them become the best, open up their full potential and develop their knowledge. All of which will stand them in good stead to inspire life long learning and to achieve a fulfilled and rewarding professional life.

ACKNOWLEDGMENT

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Development of a Wildlife Tracking Satellite for International Space Station Deployment

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***Abstract*—WUSAT-3 aims to demonstrate a novel direction-finding space system which can be used to track the location of a low power signal originating from the Earth's surface. This system could be used to track global migration of animals using lightweight, low power tags as a complementary system to existing GPS technology. As part of a 6-year project, WUSAT-3 aims to design, optimise and test a 3-unit CubeSat which can be launched from the International Space Station into Low Earth Orbit for a 28-day mission providing a proof of concept for the tracking system. WUSAT-3 is in its 3rd year and each of the CubeSat subsystems are undergoing concept refinement and technological development. A Concurrent Systems Engineering approach has been implemented to aid rapid simultaneous development of subsystems. This paper will present the development of the subsystem designs through the use of concurrent engineering to meet the mission objectives.**

Keywords—CubeSat, Migration, Direction-Finding, University

I. Introduction

A. Application of CubeSat

The current location and data collection system used for studying and protecting the environment, ARGOS, has been operational since 1978 and utilises the Doppler effect to locate a source anywhere on Earth [1]. By mid-summer 2018, ICARUS (International Cooperation for Animal Research Using Space) aims to provide additional capability by providing a space system which tracks wildlife globally using a GPS tagging system; whereby a signal is picked up by the satellite, the data is processed and sent to the International Space Station (ISS) before being transmitted via a downlink to a ground station [2]. WUSAT-3 aims to demonstrate a novel direction-finding space system which can be used to track the global migration of very small animals using lightweight, low power tags that would not be required to record and transmit GPS data. Fig. 1 illustrates the CubeSat space system. A successful mission would demonstrate the technology, providing the potential for development of a future network of low cost satellites with increased ground coverage and reduced tag weight when compared to the other initiatives. This is of importance to scientists studying the migration of small birds as GPS tags can be too heavy for the migration of the organism.

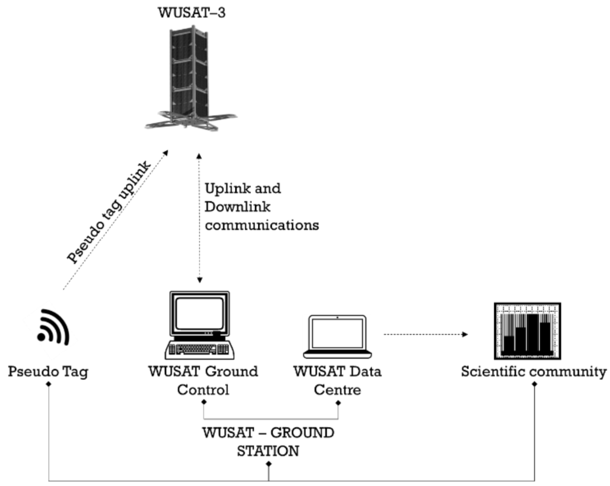

Fig. 1. WUSAT-3 CubeSat space system

As part of the University of Warwick's Masters of Engineering program, a multidisciplinary team of students have further developed the previous two years of work and are building on the designs of the subsystems. This includes enhanced development of project management, stakeholder engagement and technical designs of the University CubeSat project.

B. WUSAT-3 Aims and Objectives

WUSAT-3 aims to launch a CubeSat that can demonstrate the technology to track global migration of small animals using lightweight, low power tags.

To achieve the aims of the project the following objectives were set for 2017/2018 academic year:

- To communicate with stakeholders to verify and confirm mission requirements.
- To expand upon the previous year's subsystem designs, and ensure that updated mission requirements are met.
- To commence development of the thermal control, data handling and communications subsystems.
- To implement a Concurrent Engineering approach for simultaneous development of subsystems.

- To fulfil the academic learning objectives by working harmoniously as a multidisciplinary team.

C. WUSAT-3 2017-18 Project Team

The primary objective of this project is to serve as a final year group project for Warwick engineering master's students, worth 25% of their final year mark. The multidisciplinary team is formed of 7 students studying a range of specific streams, in this instance: two studying each of electronic, mechanical, and systems engineering, as well as one mechanical and manufacturing engineering student. The aim of this group project is to enable the team to experience what it is like to solve a substantial engineering problem in a manner similar to that of an industry project, gaining invaluable team working, communication, and project management skills.

To support the achievement of these aims, a number of deliverables are required throughout the year. Initially a project brief and poster (WUSAT submission to European Space Agency's (ESA) Educational Symposium) are due in the first term, detailing the project's internal objectives and giving an overview of the progress respectively. In the latter stages there are three portfolio submissions: one regarding the design work undertaken in solving the given problem, the second providing evidence of the project management techniques employed, and finally an analysis of the state of the project at completion. The last submissions are a detailed technical academic paper on one aspect of the project and a presentation in which the overall progress is exhibited for evaluation.

II. Project and Technical Management Methodology

A. Project Set Up

The WUSAT-3 project is run by project directors Dr Bill Crofts and Professor Julia Hunter-Anderson who remain constant through the succession of different MEng teams. The project directors are responsible for the students developing the necessary skills to fulfill the Master's degree accreditation requirements. Furthermore, they support the communication with sponsors and any external links to the ESA, ensuring the project is eligible for the "Fly Your Satellite!" program. In addition to the core members, there are three PhD students, who have previously been in the WUSAT team, supporting the technical development of the CubeSat. This year, a Bachelor's level student is carrying out research for her dissertation thesis to support certain design decisions. Fig. 2 shows the WUSAT-3 team's set up.

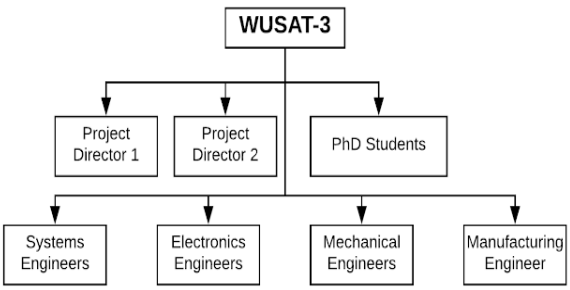

Fig. 2. WUSAT-3 team set up

Each member of the student team is assigned, by negotiation, to a subsystem which aligns to their academic field. Multiple members can be assigned to a subsystem depending on its development stage. In addition to advancing the subsystems' designs, the team also has a responsibility to manage the project and its sponsors, processes and equipment. Each member also chooses an additional administrative or organisational role, i.e. health and safety or marketing manager, to support the management of the project. The team has been allocated a lab by the School of Engineering department where meetings and working sessions are carried out. A progress meeting with the directors is held weekly, with the students creating agendas, recording minutes and chairing the meeting. University resources are used wherever possible, with professors, library resources and engineering facilities used to advance designs.

B. Systems Engineering

Systems engineering has been employed throughout the life of the WUSAT-3 project to manage the CubeSat design at a system level.

The generation of the WUSAT-3 requirements are an important detail of how the systems engineering approach has been implemented. The requirements are the drivers of the CubeSat design, which are generated to ensure the end-user requirements are fulfilled. WUSAT-3 requirements have been maintained and updated as the project progresses until a preliminary design is finalised. Further to the creation of requirements, another significant part of systems engineering is the verification of said requirements. Although, currently the CubeSat is not developed enough to verify the requirements, they have been written in such a manner that future teams will be able to create and conduct a verification plan.

Budget tables and margins are exploited to observe the systems compliance to constraining requirements. The mass budget defines the system's mass as a combination of the subsystems, whilst the power budget looks at the power consumption of each of the different subsystems in different operational modes. Margins are used to account for a certain amount of error at both subsystem and system levels.

C. Concurrent Engineering

Following some of the team members' involvement in the ESA's Concurrent Engineering challenge and CubeSat Concurrent Engineering workshop, the team recognised the importance of the approach to managing the project and is actively implementing ESA's best practices.

One of this year's objectives was to adopt a Concurrent Engineering approach to allow systematic development while ensuring end-user expectations are of paramount importance. Implementation embodies team values and cooperation to establish effective and efficient communication supported by harmonious multidisciplinary team decision-making.

Within the current team, the division into subsystems was performed to allow all of the subsystems to reach the same stage of design. Regular team meetings are used as working sessions to facilitate efficient communication and achieve design compatibility.

As design and development are iterative processes, Google Drive is currently being used as an active document management system, with a specific WUSAT network drive used as a vault for when documents are completed. Well managed documentation is of crucial importance to allow the transparency of designs and decisions for both current and future team members.

III. Subsystem Design and Development

A CubeSat is typically made up of the following subsystems: Structure and Configuration, Power, Communications, Thermal, Attitude Determination and Control System, Data Handling, and Payload. Mission Analysis is then used to support the requirements analysis, subsystems and operations design. This year, development was focussed in certain areas of the subsystems, as described below.

A. *Mission Analysis*

One of the biggest areas of uncertainties was mission analysis. As there is currently no definitive information about the deployment date or the ESA requirements to be suitable for the application to 'Fly Your Satellite!' program, a lot of decisions had to be based on extrapolation of the available information. When creating mission requirements, which are essential to shape the design of each subsystem, the general strategy was to follow the industry-imposed standards, created by ECSS, ESA and even NASA, as well as to relate to the requirements of the similar past ESA programs, i.e. 'Build Your Satellite!', implying the deployment of the CubeSat from the International Space Station via the NanoRacks launcher.

Furthermore, assumptions about the orbit around the Earth had to be made. The Systems Tool Kit (STK) software was used to run the simulations of the orbit to both visualise and extract data for calculations to derive a more refined design of the subsystems. For example, the illumination times of the CubeSat are essential to obtain the cold and hot case scenarios of the thermal subsystem, as well as for the calculation of power produced by the solar panels throughout the operational life of the satellite. Moreover, the use of STK helps to analyse the effect of the chosen orbit on mission requirements and selection of the imaging payload.

B. *Structure and Configuration*

The major advancement to be achieved this year regarding the structural subsystem is the development of a deployment system to allow the antenna arms to release from their stowed position, which is required for launch. This system is being designed such that there is minimal risk of activation while being stored aboard the NanoRacks system to be utilised in the CubeSat's deployment from the International Space Station, with the probability of the antenna arms releasing and damaging NanoRacks being minimal. To guarantee this, SOLIDWORKS finite element analysis is being employed to simulate the vibration to be experienced in the launch to the ISS and understand the modal shapes and fundamental frequencies of the antenna arm geometries. These results are then used to inform decisions in the progression of antenna arm design, as well as how the arms are to be secured before deployment. Further simulations are to be performed in Abaqus FEA to corroborate results and further inform future design decisions.

C. *Thermal*

Detailed thermal analysis is required to ensure the CubeSat can cope with the harsh environment encountered in Low Earth Orbit (LEO). The design must account for extreme thermal cycling, from -120 °C to +120 °C, with maximum temperatures caused by solar, infrared and albedo radiation plus any internal heat dissipation [3]. Furthermore, the CubeSat's design must be able to withstand the low temperatures experienced when in eclipse, and control the thermal energy transfer from internal electronic components. Initially, a preliminary analysis was completed whereby the worst case hot and cold temperatures the CubeSat might experience were calculated. These temperatures were initially verified through the use of a MatLab steady state model, as well as SolidWorks simulations, where the temperatures were within 10% of each other. The analysis included modelling the outer structure with simplified solar panels, chassis and antennas. An internal analysis was completed on the inner cage, payload, PCBs and ADCS. Currently, a detailed thermal analysis is being completed using ESATAN-TMS, the industry approved thermal modelling software. This will be used to verify our initial designs including an outer coating, and three internal patch heaters distributed within the CubeSat. Table 1 shows the operating temperatures of the internal components, a +/- 10°C margin will be applied to ensure WUSAT-3 meets the ECSS standards.

TABLE I. Component Operating Temperatures

Component	**Temperature Ranges (°C)**		
	Minimum Operating Temperature	***Maximum Operating Temperature***	***Operating Range per ECSS***
Battery	-10	+45	0<t<35
Payload	-40	+55	-30<t<45
PCBs	-40	+55	-30<t<45
ADCS	-35	+75	-25<t<65
Chassis	-40	+80	-30<t<70

D. *Attitude Determination and Control System (ADCS)*

Previous years have developed a MatLab control system which reduces angular velocity after launch (detumble) and controls pointing direction (slew). The system has been tested on a simple model of the CubeSat in one dimension (with the axis of rotation aligned with the earth's magnetic field). Work this year has focused on designing a system to enable experimental reaction wheel characteristics to be evaluated against the ideal operating conditions. Using low-cost additive manufacturing (3D printing), a test system has been designed to evaluate the torque produced by a range of reaction wheels. The system has been designed in such a way that future teams can adapt the geometry of a single component (by modification of a SolidWorks file) and print a custom part to enable any motor and reaction wheel to be evaluated within 4 hours. In doing this it is believed that future teams will be able to rapidly evaluate and compare ADCS designs (specifically Motor and Reaction Wheel combinations) at negligible costs. It is hoped that by providing detailed design documentation the same approach could be applied to testing many other aspects of the design using low cost methods.

E. Radio Communications

Previously, the payload frequency had been selected and an initial link budget was completed. This year, the system and analysis has been further developed and the optimal components have been selected. The focus is on the design of the ground-to-satellite communication system. A variety of system designs at various frequencies were evaluated and the best design for cost, power consumption, weight and size was selected. This system utilises the existing payload communications system to enable telecommand and the payload downlink to ground, without additional structural changes.

F. Electrical Power

The main developments in this subsystem are the power distribution and switching systems. As the battery used is 3.7 volts, DC-DC converters were picked to convert this voltage to 3.3 and 5 volts for various components. These converters were chosen based on their temperature ratings and efficiencies. For the switching circuit, solid state relays were selected. The specific models have not been decided as the components that the relays would control such as the motors have not been defined yet.

The power budget from 2016-17 has also has been defined further by adding component values and calculating powers when possible. The operating phases of the mission listed in the power budget have also been revised. The power available to the satellite has been recalculated to create a more accurate power budget.

IV. Future Work

A. Project Management

The concurrent engineering approach should be adopted by future teams to ensure consistent integrated development of all subsystems aligned to the end-user requirements. The requirements should be amended as the WUSAT-3 design iterates. A verification plan should be formulated, detailing how the CubeSat meets the specified requirements, either through detailed analysis or testing. Future teams should update budgets and margins as the design becomes finalised.

B. Technical Subsystem Development

WUSAT-3 2018-19 should aim to advance the CubeSat's subsystems by completing the following technical developments. The structure and configuration team should aim to manufacture and test the antenna deployment system to validate this year's findings and finalise the design, with an end goal of a fully operational deployment system on all four antenna arms.

Furthermore, the thermal subsystem team will need to build on the ESATAN-TMS thermal analysis model, and simulate the internal heat transfer effectively. Once a thermal design has been finalised, thermal vacuum cycling and thermal balancing tests must be undertaken to verify the thermal design meets the subsystems requirements.

Next year's ADCS team will need to evaluate the design requirements of the subsystem, make initial estimates for any missing information and design a rudimentary proof of concept for the ADCS. The team should also manufacture a rig to allow 3-dimensional testing of the control system using an air levitated bed. Through doing this, the detailed design of the subsystem can be developed such that by the end of the next stage the design is clear and specified. Future teams can then progress to specifying components or manufacturing elements of the design in-house.

For communications subsystem, the selected components will need to be tested and, after further work has been done on the data handling system and on the power budget, the system feasibility will need to be evaluated.

C. Project Realisation

For the aims and objectives of WUSAT-3 to be realised, a successful application to the European Space Agency's 'Fly your Satellite!' program must be achieved. Furthermore, the designs of each subsystem must be finalised, and the manufacture of the CubeSat carried out. Component and systems tests can then be completed, verifying the final designs. Providing University and sponsor support is maintained, WUSAT-3 should realistically achieve its aim to launch a direction-finding CubeSat within three years as a technology demonstrator.

V. Conclusions

Year 3 of the 6-year WUSAT-3 project to develop a Wildlife Monitoring CubeSat is making significant progress in the continued progression of the existing structure and configuration, mission analysis, power, and ADCS subsystems, while commencing work on the new communications, data handling, and thermal control subsystems.

This advancement can be accredited in part to the adoption of a Concurrent Systems Engineering approach to allow interacting subsystems to develop efficiently in parallel, aided by the invaluable experience gained by some team members' attendance at the ESA Concurrent Engineering challenge and CubeSat Concurrent Engineering Workshop.

Relevant stakeholders are in open communication with the team to clarify mission requirements defined through mission analysis, which are in the process of being met by the aforementioned work on various subsystems.

Finally, and most importantly for the primary goal of the project to act as part of the students' final year Masters accreditation; the university's formal learning objectives are being met as evidenced through first class feedback received for all assessed submissions to date.

ACKNOWLEDGMENTS

As a University project we are grateful for the assistance of; Roke Manor Research, SSTL, ESATAN-TMS, RS Components, Harwin, Andrew Little Fund, Proctor Group, and EuroCircuits for the support and assistance they provide during the CubeSat's design and development process.

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Space Education with The Living Textbook, A web-based tool using a Concept Browser

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***Abstract*—The ability to recognize the relationships between concepts is a crucial aspect of meaningful learning. Expert-generated concept maps have been shown to help students in forging connections by acting as scaffolds for cognitive processing. The Faculty of Geo-Information Science and Earth Observation (ITC) of the University of Twente is developing a Living Textbook which combines an online knowledge repository with an interactive map visualizing the relationships between concepts. Our teachers and students have started to use this in the core modules at the start of our MSc programme. Tests show that this is a promising approach that drives us to further develop its procedures and applications.**

***Keywords*— technology, education, earth observation, GIS, wiki, ontology, concept browser**

I. Introduction

Developments in media technology have triggered the re-thinking of educational materials beyond electronic text books [5]. Interactive websites let students explore and navigate course content more easily and at different abstraction levels. They also allow teachers and students to communicate more directly and to identify improvements of the teaching materials. The ability to recognise the relationships between concepts is a crucial aspect of meaningful learning. Concept map based navigation systems [2] also support individual learning paths.

We are developing The Living Textbook[1], a tool with which students can interactively explore the content of our Geo-Information Science and Earth Observation course and its key concepts. The basis for this tool is a collaborative website (a wiki) with course content, accompanied with an interactive diagram (a concept browser) showing the key concepts as circles and their relationships as arrows between them. The concepts in the diagram are connected to the course text via clickable links.

II. Related work

A. Concept maps

Concept mapping as a tool has been defined as the process of visually linking two or more concepts with propositions to form statements from which meaning can be induced [10]. Fig. 1 provides an example concept map of three concepts - orbit characteristic, orbit and satellite. The concepts are labeled and depicted as circles. Arrows represent relations between concepts expressed as propositions. Propositions should be read in the direction of arrows to understand the meaning of relations. For example, from the figure one can read that Orbit characteristic is a part of orbit and orbit, in turn, is used by a satellite.

Initially, concept mapping was developed primarily as a medium to help learners visualize what they did and did not know [10] but concept maps generated by experts have also been shown to have a positive effect on learning and retention [17].

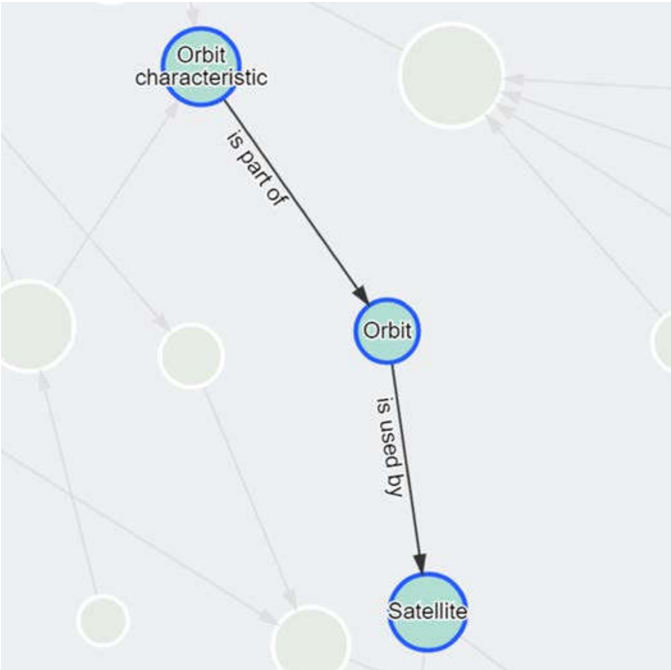

Fig. 1. Example of a concept map depicting concept and relations

These expert-generated learning aids have the capacity to act as advanced organizers for students, thus enabling them to more easily develop the cognitive schemas needed to develop conceptual understanding of complex curricula [9].

In addition, concept mapping has been found to benefit students across all education levels [13]. O'donnell [11] showed

[1] https://itc-giscience.utwente.nl/

that concept map tools can specifically benefit students with low verbal ability as they provide a more straightforward way to access complex knowledge.

B. *Ontologies*

Ontologies are created and maintained by experts as a result of conceptualization and formalization of domain knowledge [6,7]. Formal ontologies possess explicit hierarchical structures of concepts and can be seen as a layered pyramid with more general concepts situated on top. Ontologies are often used to provide structure for knowledge base systems allowing meaningful exploration of connected information.

The W3C Web Ontology Language (OWL)[2] is a semantic markup and knowledge representation language for publishing and sharing ontologies on the World Wide Web. OWL ontologies can be used as a source to generate concept maps [4].

C. *Existing systems*

Leveraging on modern computer mapping software and the internet, concept maps can enable navigation of large bodies of information and facilitate students to engage in self-regulated resource-based learning [3].

The Concept Mapped Project-Based Activity Scaffolding System (CoMPASS) [12] integrates the spatial navigational aids in the form of concept maps with the conceptual structure of the domain to support navigation and help learning at the same time.

The ontology-based concept map learning system (CLS) [1] also uses concept maps to facilitate visual navigation through learning content. However, in contrast with CoMPASS which uses a database to define courses for learning, the maps and the content of CLS are organized based on an ontology. This allows finer information grounding which leads to a more homogenous content delivery as well as enables interoperability with other knowledge domain representations expressed as OWL ontologies.

III. Creating Content

Coloborative ontology engeneering via concept mapping

To create the content of the Living Textbook we have taken our existing core book as a basis [15] and created a structure for it in DokuWiki[3]. In addition, we created an ontological structure to capture the concepts underlying the book content as a basis for the concept map displayed in a separate view but linked with the DokuWiki text. Here, we built upon Collaborative ontology engineering [8,14]. To create the ontology, we have setup short workshops with lecturers and asked them to portray their domain of expertise with a graph editor, basically entering key concepts as text boxes and connecting them by labeled arrows, representing directed relationships (see Fig. 1). We conditioned this process by the restricted use of 13 relationship types, such as ‘is a kind of’, ‘is used by’, etc. After the lecturers created their individual domain of concepts they were asked to provide cross-

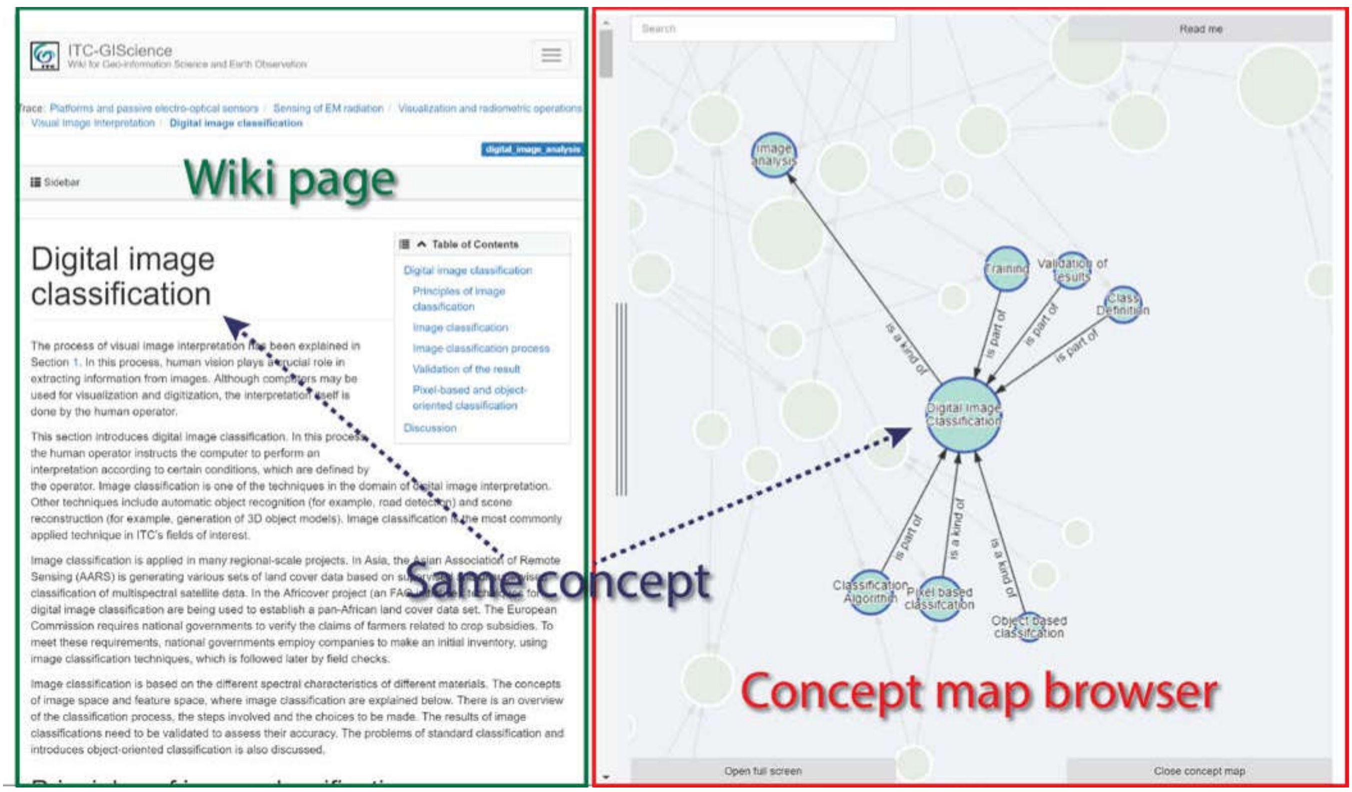

Fig. 2. User Interface of the Living Textbook consisting of the wiki page and the concept map browser

[2] https://www.w3.org/OWL/

[3] https://www.dokuwiki.org/

domain relationships. In this process we identified and fixed gaps and inconsistencies. After first gaining experience in building a concept corpus for the domain of GIS, we built an ontology for the domain of Earth Observation and provided links between the two domains, basically representing the overall book content.

IV. Application design

The user interface of the Living Textbook consists of two main areas (see Fig.2) – a concept map browser (on the left) and a wiki page. A user explores the content of the Living Textbook by browsing the concept map. By clicking on a circle in a concept browser, a user retrieves the related page of the wiki (i.e., explanation of what digital image classification is).

The concept browser is built using the forced layout of the D3[4] visualization library. In the early prototype, rendering of the map was based on the Scalable Vector Graphics (SVG)[5] technology. However, as number of concepts grow, the performance of the visualization dropped. Rendering using the HTML5 canvas element[6] significantly improved performance of the concept map browser. The concept map browser is integrated with DokuWiki via the iframe HTML element.

V. Testing

We created the application based on a number of evaluation sessions held with lecturers and technical staff. Having a first stable implementation, students and teachers of our faculty were interviewed about their experience with the concept map tool, and a think aloud walkthrough and usability test were conducted with students (see Fig. 3). They were given a few simple tasks to perform with the application as described in Section IV and were asked to think aloud about how they perceive the working of our application, both in positive and negative ways.

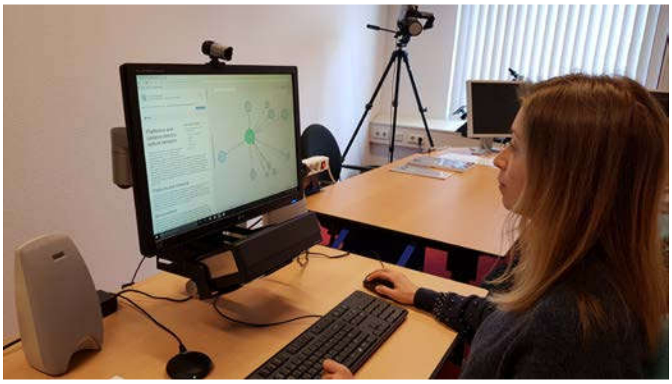

Fig. 3. Usability test using eye-tracking

VI. Conclusions

Based on first experiences, faculty staff emphasize the tool's value in helping to order and structure course content and stress the importance of introducing hierarchy to make its navigation more effective. Based on the usability tests, two sets of design guidelines for the tool were proposed, one related to the support needed by students (mitigate cognitive overload, prioritize certain content and increase content depth, introduce detail on demand, improve ease of access) and another related to what teachers need (increase ability to manipulate tool, track frequently visited concepts, enable student teacher interaction, reduce effort to update content) [16]. We have started to address these issues in a second development phase.

VII. Future work

Implementing the Living Textbook on a larger scale would amongst others entail the following actions:

1. Further development of the Living Textbook application in such a way that the content can be updated more easily, adding discussion forum functionalities, adding links to practical materials and software, the implementation of learning paths, etc.
2. The book is living, this means that the content will change. We plan to set up a procedure to update the text on a regular basis and ensure quality and describing roles of different persons involved.
3. Opening up opportunities for teachers and students to connect to relevant external resources and course content within the same user interface.

As this initiative evolves quickly, we expect to introduce it into a wider scope of our educational activities, with tailored new functionality.

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Development of a reliable and low cost miniaturized Reaction Wheel System for CubeSat aplications

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Abstract— **Generally the attitude control systems of CubeSats use magnetorquers as the main attitude control component and these have a full range of control at polar orbits, becoming less effective at lower inclination orbits. Stringent mission and payload designs in CubeSats, require faster and more accurate pointing systems. These requirements can only be achieved by using reaction wheels for attitude control purposes. The paper presents the design and development of a Reaction Wheel System (RWS) with a total mass of approximately 200 grams and a minimum service life of two years, which simultaneously satisfies the requirements for the control system. The proposed design features will enable new classes of missions currently difficult to achieve. This RWS is designed for the ECoSat-III, the Enhanced Communications Satellite, currently under development at the University of Victoria by a team of students from different backgrounds, which has won the 1st place in the Canadian Satellite Design Challenge (CSDC), whose main focus is to perform outreach to the community and with students to promote science, engineering and space. The optimal design, reliability analysis, and construction of a miniaturized reaction wheel prototype using a commercial off-the-shelf brushless DC (BLDC) motor is presented. The hardware design is described, with emphasis on the disk-rim flywheel design and on the RWS arrangement for minimum power consumption during the required orbital maneuvers. The flywheel's mass, maximum radial and tangential stress is minimized subject to constraints on the required moment of inertia, flywheel's thickness and type of material used. The required torque and the maximum external disturbance torque acting on the satellite were estimated. A full dynamic simulation of the RWS is also presented. The controller design for the BLDC motor and the determination of the mean time to failure of the system was also one of the objectives of this study. This COTS RWS satisfies all the constrains and requirements, to further be integrated on ECOSat-III mission.**

Keywords—Space Systems, Space Control Systems; CubeSats; Reaction Wheel System; Dynamics and Control.

I. INTRODUCTION

The use of satellites for military, scientific and commercial purposes has been rising year after year. One reason for miniaturing satellites is to reduce the cost, i.e, heavier satellites require larger rockets with greater thrust. The decreasing cost of this miniaturized satellites are making them accessible to academia and student-led projects [1]. Inside of this group of satellites there is a specific class type which has a volume of exactly one liter and a mass of no more than 1.33Kg - the Cubesats [2]. In September 2010, Geocentrix (a Canadian company) organized the first Canadian Satellite Design Challenge (CSDC) and invited twelve universities across Canada to develop a micro-satellite. This challenge has contributed to an increase in expertise and training of highly-qualified personnel at several universities. To answer to this competition the University of Victoria has created the ECOSat project, which is now on the third project competition. As of 2018, The University of Victoria has never had an aerospace/space focused curriculum, but a craving for such knowledge has not evaded students. Student-run projects such as ECoSat-III have fostered this curiosity by providing students with an opportunity to struggle with the real-world problems associated with space applications and engineering. Through these struggles, students build up a body of knowledge composed of designs, computer programs, calculations, and strategies that serve as a base of knowledge for future student-led satellite projects. A well designed, and well documented system such as ECoSat-III's ADCS will have a great impact on the speed at which students are able to climb up the steep learning curve associated with space-based systems.

Magnetorquers have a full range of control at polar orbits, and become less effective at lower inclination orbits. ECOSat-III will have an orbital inclination of $i = 51.6°$. Moreover, due to the primary mission requirements a precise pointing is required, which cannot be achieved if the satellite only uses magnetorquers as a control component [3]. Thus, the Attitude Determination and Control System (ADCS) must consist also in multiple reaction wheels that spin at a fast enough rates to allow the conservation of angular momentum to generate control torques on the rotation axis, so that the satellite can turn about this fixed axis and orient itself in the desired directions.

II. MISSION ANALYSIS

A. *Conceptual analysis*

According to the angular kinetic equations an object that is spinning has a quantity of rotation associated with it, known as its angular momentum. The time derivative of the angular momentum of the satellite neglecting all the external perturbation torques can de written as,

$$I_s \acute{\omega} + T = 0 \tag{1}$$

where I_s is the inertia tensor of the satellite; $\acute{\omega}_b$ is the angular acceleration vector in the satellite's fixed-body reference frame and t, which is the torque generated by the RWS [4].

B. Desired manouvre

ECOSat-III will have a circular orbit around 800 km above Earth's surface. According to ECOSat team simulations for the orbit of the satellite, using STK - AGI software, the torque needed to be provided to the satellite above Victoria around the axis of biggest inertia (Y-axis of the satellite in the fixed body reference frame), neglecting all the external perturbation torques is presented in Figure. 1.

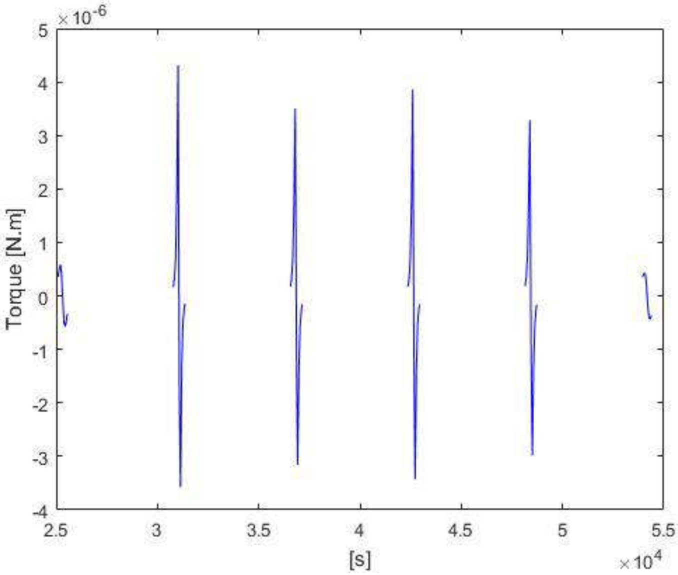

Fig. 1. Torque estimated to be applied to ECOSat-III during its manouvre above Victoria (maximum angular rate). No external perturbation torques condidered. Source: STK-AGI simulation

C. External perturbation torques

In space there are natural forces that in turn make bodies tumble. These forces are caused by solar radiation [5], gravity gradient [6], Earth magnetic field [7] and aerodynamics [8]. In the context of attitude and control these forces are called disturbance forces [9].

TABLE I. EXTERNAL PERTURBATION TORQUE MAGNITUDE

External Perturbation torque	Magnitude [Nm]
Gravity Gradient	4.31×10^{-8}
Aerodynamic	2.99×10^{-7}
Solar radiation	2.08×10^{-6}
Magnectic field	2.43×10^{-6}

III. RWS DESIGN

Based on the mission objectives and on the tradeoff between the several investigated motors, it was possible to conclude that FAULHABER 1202 004 BH was the best Commercial-off-the-shelf (COTS) motor to be used in ECoSat's satellite. This same motor was also used and studied by University of Delft and integrated on Delfi-n3Xt [10].

In some actual space programs, especially those involving imaging satellites, the interruption of an imaging mission due to wheel zero-crossing should be avoided. Thus, it shall be found an agreement between the reliability and the agility of the RWS. Since in this case the agility does not have priority, the wheels shall be forced to operate only within the half of the speed range without sign change. This scheme is also implemented by setting the operational speed equals to half of the maximum useful speed of this motor - 18400 rpm.

A. Flywheel Design

The value of the maximum speed ω_{max} is of primary importance in the design of the flywheel, since higher speeds results on higher centrifugal stresses which should not exceed the admissible values of the selected material to use. As modern designs require lightweight materials, the design parameters are chosen in order to ensure minimum mass and simultaneously the minimum stresses. After defining the simplified analytical model a shape optimization for the geometric parameters for the disk-rim flywheel was be considered. The major objective to optimize was the mass of the flywheel. Another factor considered was the radial and tangential stress at which the flywheel was subject.

The following feasible objective space graph shows several optimal solutions for the aforethought problem. Nevertheless, since the objective is to minimize the mass and simultaneously the radial stress at which the structure will be subject the optimum selected solution corresponds to the one given, see Figure. 2.

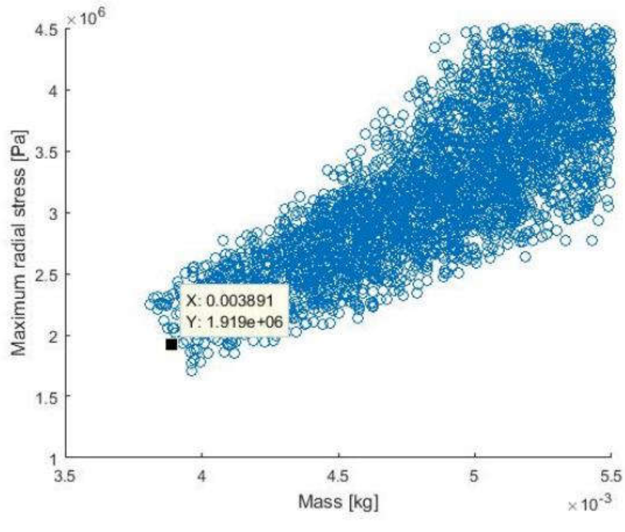

Fig. 2. Feasible objective space graph for aluminium

It was also concluded that aluminium has a better performance than the other materials for space application proposes not only because it is a lighter material, but also due to its mechanical properties.

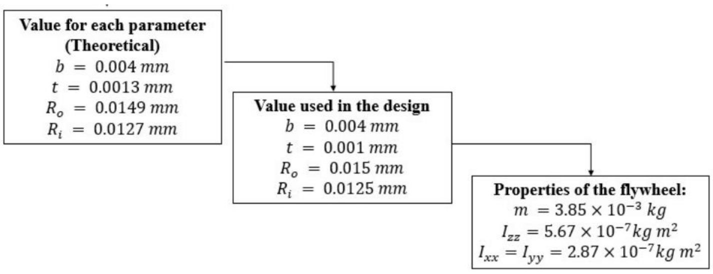

Fig. 3. Optmimum solution design for a aluminium flywheel

B. Pyramid Configuration

If 3-axis stabilization is required, three reaction wheels with mutually perpendicular axes should be used. For redundancy reasons a fourth wheel is normally added to maintain full 3-axis controllability when one wheel fails [11]. Pyramidal configuration is an approach that can be considered as a specific arrangement of actuators in satellites and attitude simulators [12 - 13]. Nevertheless, there are several factor in the RWS configuration that should be consider to optimize the all system. The major design criteria is to minimize the power consumption of the system during the attitude manoeuvre [14]. Obviously, choosing a proper skew angle will lead to achieve minimum power consumption. The scheme of a pyramid configuration is depicted in Figure 4.

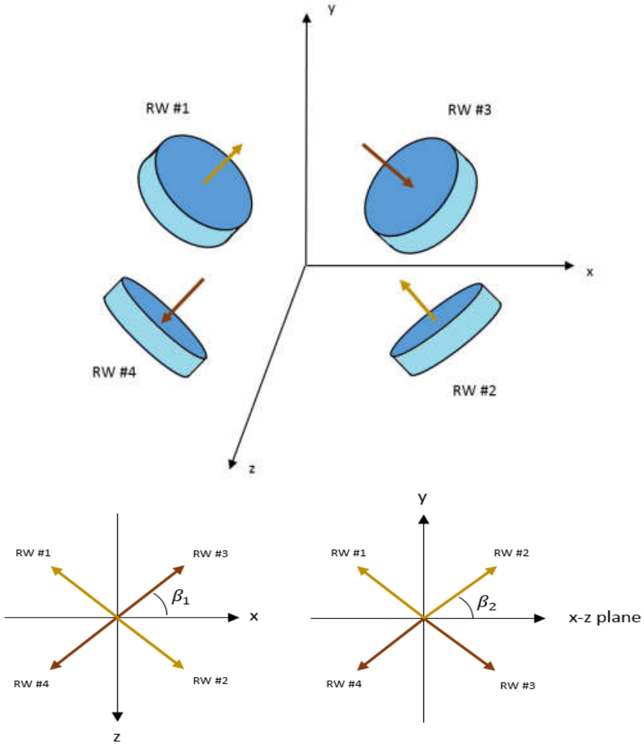

Fig. 4. Pyramid configuration scheme (adapted from [14]).

After defining the pyramid configuration as the one that is going to be used, the goal is now find the optimal angle β_1 and β_2 that minimizes the power consumption of the system. This configuration was optimized for the manoeuvre above the Vancouver Island. In this the y axis of the RWS should be aligned with the y axis of the satellite w.r.t. the body fixed reference frame, since this is the axis, over which, the system should shall have the biggest manoeuvrability. The determination of the power consumption was done by using the variation of the total angular momentum.

It was possible to conclude that the best configuration which minimizes the power consumption for the required manoeuvre implies that $\beta_1 = 45^\circ$ and $\beta_2 = 60^\circ$.

C. RWS Control

BLDC motors have been used in different applications such as industrial automation, automotive, aerospace, instrumentation and appliances since 1970's [15]. BLDC motor is a type of DC motor which commutation is done electronically instead of using brushes [16]. In this section the overall system model are going to be explored as well as its response to a desired input. Subsequently a close-loop PID controler will be designed. A BLDC motor can be modulated in a similar manner as a three-phase synchronous machine, but since there is a permanent magnet mounted on the rotor, some of their dynamic characteristics are different [16]. A modelling based on an abc phase variable is more convenient for this motors than using d-q axis [15].

Accordingly to the satellite requirements and the calculations already performed the minimum torque that shall be delivered around the y-axis of the satellite w.r.t. the body reference frame above Victoria shall be $T_y = 6.8 \times 10^{-6}$ Nm. It is difficult to estimate which torque is necessary to apply to the X and Y-axis, since only the upper bound of the perturbation torques caused by external factors were defined. Thus, it is going to be conjectured that the necessary torque needed will have a magnitude similar to the upper bound torques defined by the external perturbation forces. In sum, it will be assumed for the simulation a constant value of $T_x = T_z = 2.33 \times 10^{-6}$ Nm w.r.t. the satellite's fixed-body reference frame.

In this simulation to have more realistic results the update rate of the actuator variables have a step size of 0.1 s, which will be the update rate of the real system to be implemented in ECoSat-III. The RWS is projected based on the maximum torque that should be provided by the system. Each main manoeuvre above Victoria, B.C, takes approximately 400 s to complete. This means that the RWS should be operational and outside the saturation limits in order to guaranty the maximum pointing precision, for at least during this time. It is advisable to proceed to the desaturation of the wheel before this manoeuvre, as well as to start the manoeuvre above Victoria with the wheels rotating at its nominal speed, in order to increase the speed range available and prevent saturation. In nominal conditions, i.e. if all the wheels are operational, for the manoeuvre already specified, the RWS will entered into saturation only after 600 s, as it can be seen in Figure 5.

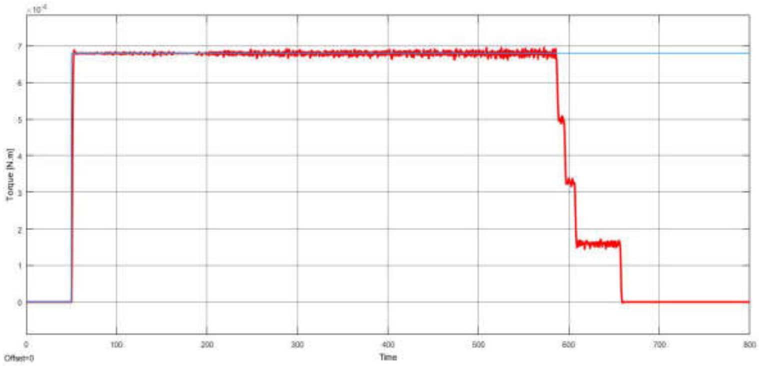

Fig. 5. Torque generated in the Y-axis direction by the overall RWS w.r.t. the satellite's body-fixed reference frame in normal conditions until saturation

Considering the failure of the wheel number #1, the following figure is obtained,

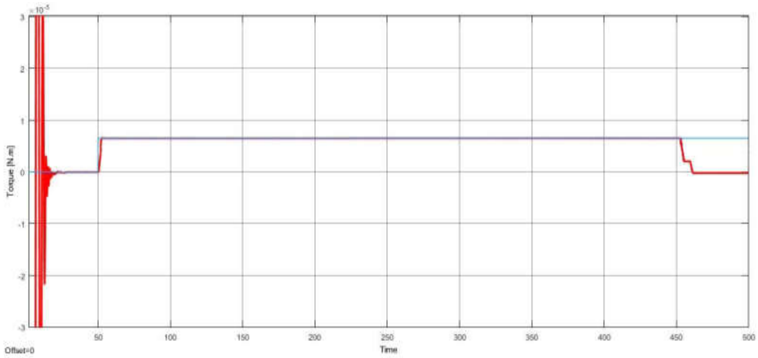

Fig. 6. Torque generated in the Y-axis direction by the overall RWS w.r.t the satellite's body-fixed reference frame assuming wheel #1 has failed until saturation

The initial oscillating torque presented in the beginning of the simulation is related to the fact that the wheel failure was considered exactly after the switch-on of the system. These torques cannot be cancelled, since it is impossible to generate a null space total torque vector.

Exactly as in the nominal conditions, one shall assume that a constant torque will be required during the orbital manoeuvre above Victoria. That step was defined at t = 50 s. As observed in Fig. 11, the system will take approximately 400 s to reach saturation, which is in the boundary of the defined limit. Nevertheless, this will not derail the RWS project, since this graphs were generated assuming worst case conditions. This means that the pointing precision shall not be affected, neither if one of the wheels fail.

D. Mean Time to Failure

Bearing life is an important factor to determine the survivability of the satellite under normal conditions. The modified L_{10} [17] formula gives the estimated mean time to failure of the bearings under normal conditions,

After some simple computations for a reliability of 99% it was concluded that for the current system L_{10} = 2.3years. The value for the basic rating life previously determined ensures that the satellite shall have success in its 2 years mission. Moreover, the use of four motors in a pyramidal configuration instead of three motors oriented according each axis in the body reference frame guaranties a redundant system, and consequently ensures qualitatively the increase of the life span of the RWS.

IV. CONCLUSIONS

First, an analysis of the requirements were made in order to determine the main characteristics of the RWS. Next, the calculation of the perturbation torques enabled to determine the maximum torque expected to be delivered by the RWS during its orbital movement.

Succeeding the motor selection, an optimization of the disk-rim flywheel design was performed based on the minimization of its mass and radial stress. The process here developed for the design of the flywheel can be applied to other industrial sectors. The optimal RWS configuration in order to minimize the power consumption was also obtained.

This analysis let to conclude that a pyramid configuration would be the best trade-off between the system's redundancy and its power consumption. The analysis based on the Simulink® model confirmed the viability of the system. It has been shown that a relatively precise and fast response for the desired input torques to be provided by each wheel is achievable. Moreover, the mean time until the system reaches the saturation is inside the design limits.

Finally, a MTTF analysis was performed in order to determine with a reliability of 99% if the future RWS would survive for at least during two years in space under nominal conditions.

In conclusion, it has been demonstrated that is possible to construct and developed a low-cost and reliable RWS to be implemented on a CubeSat (see Figure 7) and simultaneously enable precise pointing missions actually difficult to achieve with the current magnetorquer systems.

Fig. 7. ECoSat-III cutted section where is possible to obeserve the RWS and the batteries that will be integrated. Modulation made in SolidWorks™.

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Using ILWIS Software for teaching Core Operations in Earth Observation

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***Abstract*—Computational methods in GIS and Earth Observation are an important part of the curricula in Geo-informatics. Apart from the theoretical foundations students need to get acquainted with the practical application of these methods in software. However, many GI software packages are not designed for the purpose of educating principles of GIS and Earth Observation and therefor do not provide the right tools and interfaces for students and novice users to comprehend the core concepts. In this paper we describe our effort to build a GI software that does support students in learning through visual workflows and linked views of different representations of raster images such as maps, tables and graphs.**

***Keywords*— technology, education, earth observation, GIS, wiki, ontology, concept browser**

I. Introduction

The University of Twente develops the Integrated Land and Water Information System (ILWIS http://52north.org/communities/ilwis/). ILWIS is an open source, C++ based, Earth Observation and GIS software. ILWIS delivers a wide range of features including import/export, digitizing, editing, analysis and visualization of geodata. ILWIS software is renowned for its functionality and user-friendliness and has established a wide user community over the years of its development. ILWIS is currently being renewed and transformed into a more modular platform called ILWIS-Objects along with a redesigned plug-in platform and APIs. The modularity allows for the creation of tailored applications and the use of components in other software platforms. On top of ILWIS-objects we provide our own desktop interface (see Fig. 1) which is especially designed to help users understand better the data and operations which they are using. Researchers, trainers and students can now easily implement, store and share their methods via software, in addition to their written reports.

II. Working with workflows

In the education, projects and research at our faculty we see frequent use of methods consisting of chains of software operations. A workflow represents a combination of process steps to be handled by computers or humans. Geoprocessing

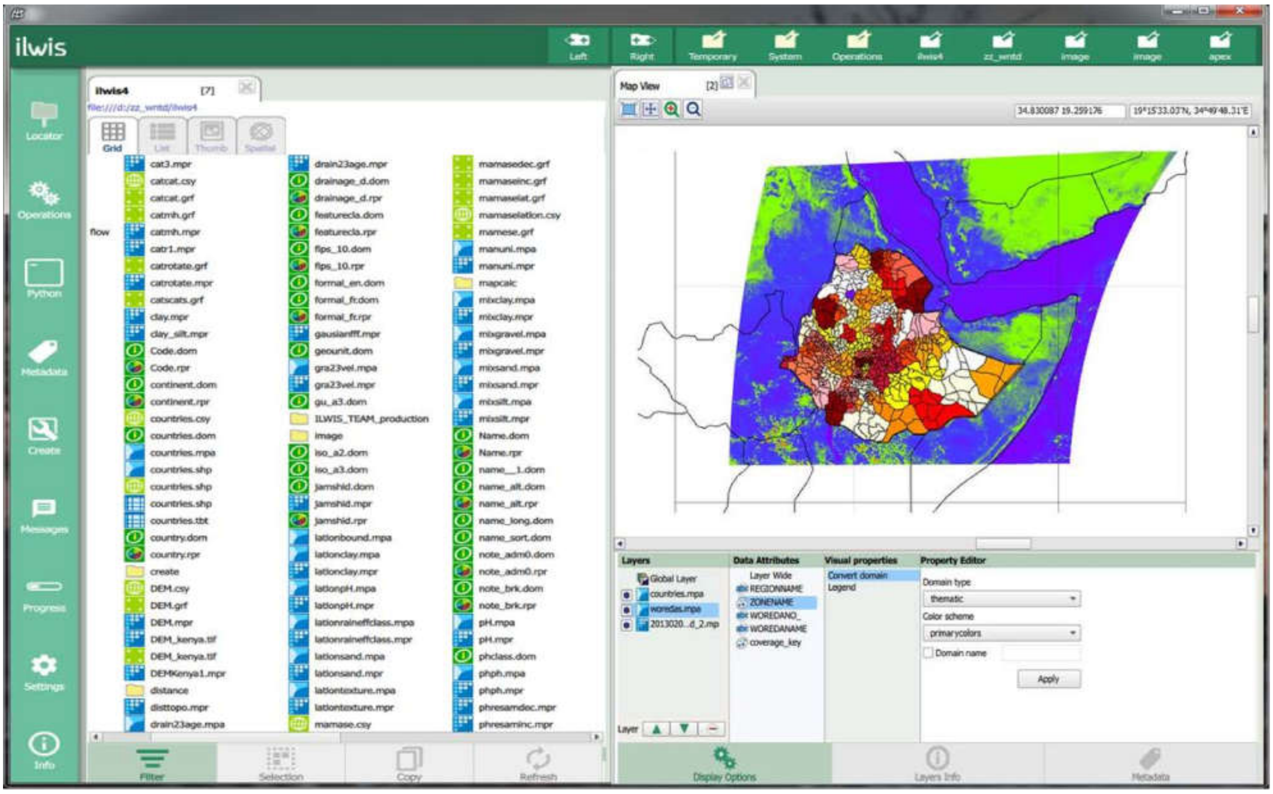

Fig. 1. User Interface of the ILWIS desktop.

workflows consist of geodata (satellite images, in-situ sensor data, human sensor data) and the operations needed for their storage, analysis and presentation.

In one of our projects (afrialliance.org) we develop methods for creating and sharing geo-workflows between humans and computers to support knowledge sharing and system interoperability. We distinguish between abstract workflows (software- and data-independent) and concrete workflows (software- and data-dependent).

A. *Abstract workflows*

An abstract workflow provides a general overview of process types and their input/output, without necessarily stating data sources and operation parameters. Fig. 2 shows an abstract workflow for calculating rainfall for administrative areas in one of our case studies in the MaMaSe project (mamase.org) in Kenya. This allows users to create and grasp the general essence of the process steps. An abstract workflow can turn into a concrete workflow and vice versa.

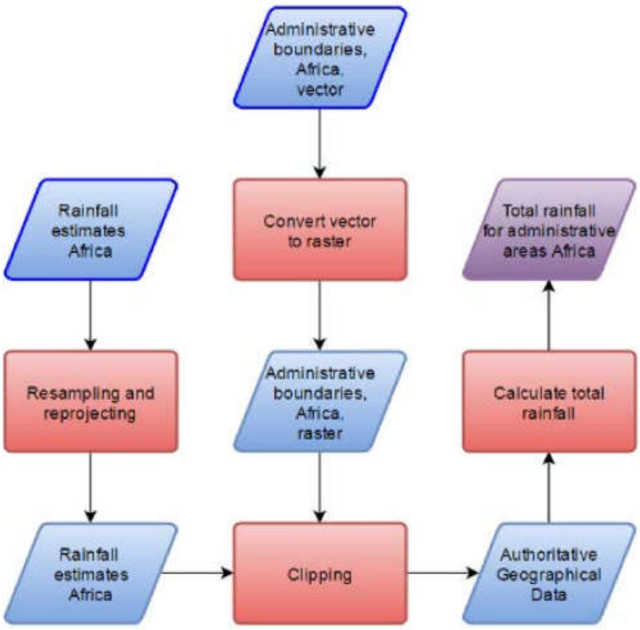

Fig.2 Abstract workflow.

B. *Concrete workflows*

A concrete workflow contains process steps which are executable by a specific software. Fig.3 shows the visualization of the system logic of the abstract workflow of Fig. 2. This workflow can be executed in ILWIS.

C. *Sharing workflows*

Several process languages such as BPMN allow standardized sharing of workflows. We have developed a collaborative web environment using a semantic web-based exchange format in JSON-LD which allows both sharing between machines and humans [2], see also Fig. 4.

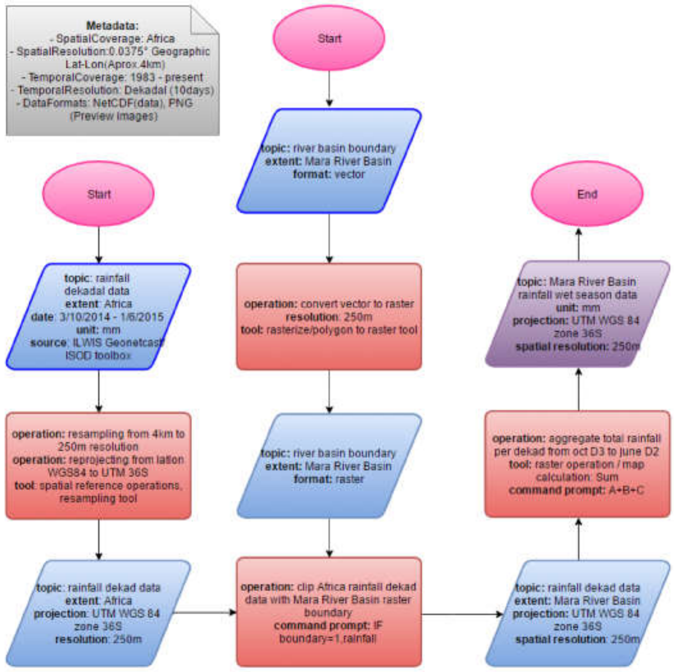

Fig.3 Concrete workflow.

Semantically enriched workflows can be visualized in a spatio-temporal explorer based on Linked Data [3].


```
"subworkflows": [
    {
        "id": 0,
        "metadata": {
            "longName": "PRODUCTION",
            "description": "The workflow for the MaMaSe project",
            "syntax": "MaMaSeWorkflow(raster,raster,raster,raster)",
            "resource": "Ilwis",
            "keywords": "workflow, MaMaSe, drainage",
            "inputParameterCount": 4,
            "outputParameterCount": 2
        },
        "operations": [
            {
                "id": 0,
                "metadata": {
                    "longName": "Anoperation",
                    "description": "AnOperationDescription ",
                    "syntax": "thefirstoperation(inputrastermap)",
                    "resource": "Ilwis",
                    "keywords": "operation, keyword,operation",
                    "inputParameterCount": 1,
                    "outputParameterCount": 1,
                    "final": false
                },
                "inputs": [
                    {
                        "id": 0,
                        "url": "veg.com",
                        "term": "",
                        "type": "map",
                        "value": "",
                        "units": "",
                        "min": "",
                        "max": "",
                        "name": "Vegetation structure",
                        "show": true,
                        "change": true,
                        "description": "",
                        "picture": ""
    }
```


Fig 4. Sharable workflow represented in JSON.

In ILWIS, workflows can be visually constructed, debugged and reused, see Fig. 5.

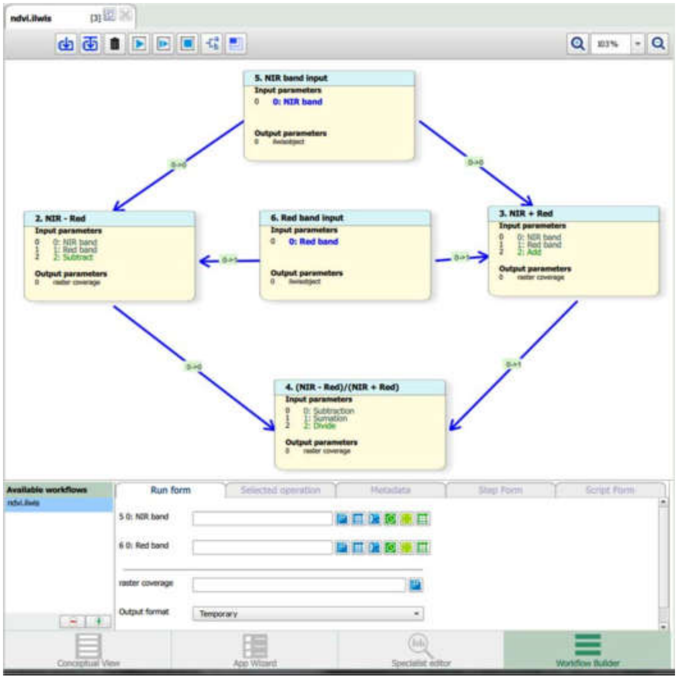

Fig. 5. Workflow builder in ILWIS. Depicted is the workflow for the calculation of a Normalized Difference Vegetation Index (NDVI).

III. Educational context

We are currently developing ILWIS to support our core education in Earth Observation. The theory is covered in our core text book [4]. The accompanying practicals entail the following topics:

- Introduction to Remote Sensing
- EM Radiation
- Visual Image Interpretation
- Sensors and Image Data Characteristics
- Visualisation and Radiometric Operations Digital Image Classification
- Geometric operations – Geocoding images
- SatSatellite-based Positioning – Planning a GNSS Survey

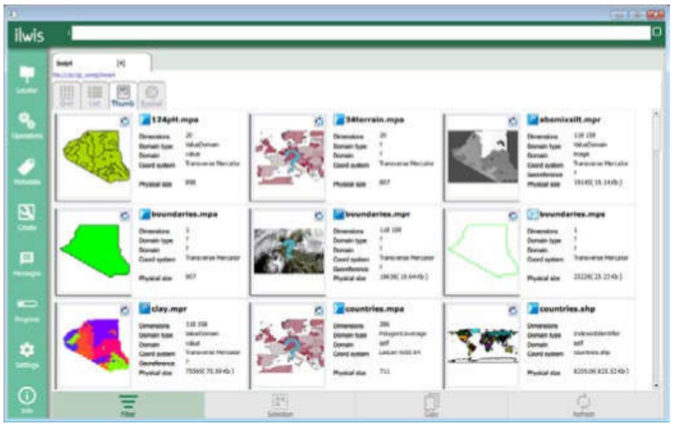

Fig. 6. Catalog view with thumbnails representing spatial data.

We believe that it is important for students to fully comprehend the data and functions they are using. For that sake we try to make such components as clearly visible as possible. Another example is the ILWIS catalog interface which depicts all data with their metadata and thumbnail preview (see Fig. 6).

IV. Conclusions

Our educational effort in GIS and Earth Observation is targeted towards the insightful creation and reuse of software. Typical education-focused software solutions include linked-views (e.g., a change in a histogram is instantly visible in a change in the corresponding raster image) and a comprehensible workflow environment for chaining software operations to support a good understanding of the combination of individual software functions. After implementing the functionality of our core module content, ILWIS will be further developed to be able to support further education, projects and research.

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Concurrent design approach in academic environment activities and lessons learned

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***Abstract*— Nowadays space systems are becoming more complex, dynamic, interconnected and automated. Because of these trends and the increasing involvement of stakeholders, decision makers are facing difficult decision-making processes. Even though most of the costs are expended in the latest phases of the space mission life cycle, the majority of them are driven by the choices taken during the earliest design phases, which is also characterized by the lowest level of knowledge about the system. For these reasons several design approaches have been developed and applied within the space industry. With respect to the classical sequential design, a promising alternative design approach is offered by Concurrent Engineering. This design approach provides better performances, taking full advantage of modern information technology. In this approach, the complete design team, composed of the various technical domain specialists, starts working concurrently on the different aspects of the project at the beginning of the design process. Systems and Technologies for Aerospace Research team of the Mechanical and Aerospace Engineering Department at Politecnico di Torino applies this approach both in teaching and designing of space missions. In this paper the benefits of the design approach are analyzed within an academic concurrent design facility. In fact, challenges such as short learning curve, intensive student turnover and synchronization of the design session with academic schedule, can be managed thanks to the concurrent approach. In September 2017, the developed approach and infrastructure have been tested and validated through the participation to the first ESA Academy Concurrent Engineering challenge. The goal of this paper is to describe development, hardware setup, software approaches, knowledge management and application of a modular concurrent design facility, addressing the topic of the integration of the concurrent design approach into educational activities. At last, principal outcomes obtained from design sessions are presented in terms of lessons learned from both management and technical aspects, highlighting student's learning opportunities and possible improvements of this approach when applied in an academic environment.**

Keywords: Concurrent Design, Academic Concurrent Design Facility, Lessons Learned

I. INTRODUCTION

The CubeSat Team is a student team which deals with the design and development of space missions carried out by small platforms, in collaboration with other universities and research centers, international agencies and industry. The group consists of undergraduate and PhD students led by Prof. Sabrina Corpino and works in the Systems and Technologies for Aerospace Research Laboratory (STARLab), located inside the Department of Mechanical and Aerospace Engineering of Politecnico di Torino (DIMEAS). The Team, in parallel to lectures of space mission analysis and design, is willing to promote space related research and development activities by providing high-standard education, leading CubeSats technology development activities and enhancing its mission and system design approach exploiting the concurrent engineering one. Concurrent Engineering (CE) is now becoming a reality in many organizations active in the space industry. Leaders of these activities are the CDF at European Space Agency's ESTEC centre [1] and NASA JPL TeamX [2]and the new born TeamXc [3], which is targeted to Small Satellite design. This experience was followed by other space agencies (German Space Agency (DLR), [4]) and commercial companies, such as Airbus Defence and Space [5]. Academic environment requirements are focused on student education and research projects, as opposed to continuous product development[5]. Basic principles of a Concurrent Design Facility (CDF), such as team work, design model's data exchange and design sessions schedules remain quite the same. At Politecnico di Torino (PoliTo) the CDF activities began 2 years ago, with the objective of, after an understanding and implementation of the state of the art, enhance the current approach. Thanks to the participation of 2017 ESA Academy Concurrent Design Challenge the developed models, database and infrastructure has been tested and validated. This paper will firstly describe the process, facility and team management, able to fit the concept of Concurrent Design within academia and it will conclude with a dissertation about the lessons learned and possible improvements.

II. POLITECNICO DI TORINO CONCURRENT DESIGN FACILITY

A. Background

Studies on Concurrent Design was carried out since 2000 within PhD researches in collaboration with ESA/ESTEC CDF and Thales Alenia Space. The Concurrent Design (CD) approach has been used is the Space missions and systems design class for five years with excellent results. The Concurrent Design approach has been/is used to carry out phase 0/A/B of the CubeSat projects at PoliTO. In the last 2 years, an upgrade of the CDF infrastructure has been carried out within a PhD thesis. The current goal is to improve quality of education, to provide complement to system engineering curriculum, and to provide introduction to Concurrent Design approach.

B. Facility

The Politecnico di Torino CDF has been designed with the goal of modularity and flexibility. This is aimed to students who wants to learn and experience the Concurrent Design Approach. Functionalities of the CDF are related to the data exchange via the Ethernet connection in the university but to fulfil the objective of modularity and flexibility, the data exchange is guaranteed also via WI-FI connection. This approach allows students to connect their laptop to the central workstation which constitute the central node for the data exchange. The central facility also contains one projector and one 47 inches monitor to guarantee continuous sharing of design data during the design iterations.

C. Software

The software infrastructure has been chosen to support the design and to be compliant with the requirements of the ESA OCDT and ECSS-E-TM-10-25A[6]. Furthermore, Excel have been chosen as primary user interface due to the spreading of the Microsoft tool around both academia and industry, which is often used. Table 1 summarize the software architecture, in which, wherever possible, open source software has been preferred.

TABLE 1 POLITO CDF: SOFTWARE INFRASTRUCTURE

Software support	Functionalities
ESA OCDT ®, RHEA CDP4®	Data exchange and traceability
Microsoft Office Excel® 2010	models, OCDT interface
AGI System Tool Kit®	Mission analysis
Mathworks MATLAB® R2015a	Interfaces and assist trade offs
Dassault Systèmes SolidWorks®	CAD
VERITAS - Blender®	Visualization and VR
Cloud directory	Repository
Trello®	Project Control
Slack®/apper.in®	Communications

D. Process and implementation approach

With the objective of applying a flexible and educational focused process, Table 2 summarize the approach adopted by the Polito CDF. Multi Attribute tradespace exploration (MATE) [7] and structured stakeholder analysis have been integrated in order to makes students able to understand how to catch and manage stakeholder needs and observe the effects of each decision making process in the final mission utility.

TABLE 2 POLITO CDF: DESIGN APPROACH

Task	Objectives	Phase
Stakeholder analysis	Understanding of stakeholder prioritization	Preparation and identification of involved actors
Stakeholder interview	Eliciting utility function, attributes, attributes weights	Preparation and needs elicitation
Problem set-up	Defining design variables mission constraints	Problem set-up
MATE	Defining of optimal conceptual design (s)	Preliminary alternative exploration
Post optimality analysis	Performing Epoch-Era analysis concerning variation of preferences, sensitivity analysis	End of preparation: Sensitivity analysis
Team building exercise	To understand and learn how work in a team	Preparation and team building
Introduction to Concurrent Engineering and Polito CDF	To understand concurrent engineering approach, software and model infrastructure	Preparation and introduction to CD
Design Assessment and CD session	To iterate the design alternative from MATE to proceed to the next phase	CDF session from identified point design
Post session and knowledge management, 3D printing	To formalize gained knowledge, checking knowledge, showing how a conclusion was reached and storage	Post CD session

E. Models, Data Bases and team composition

Design models were created based on Wertz's Space mission analysis and design[8], Larson's Cost-effective space mission operations [9]. The sizing models are applicable to all class of satellites, but particular attention shall be given to peculiar models, e.g. Cost [10], which are tailored for Small Sat applications. Component databases were populated for all Nano and micro satellite subsystems. Moreover, to guarantee a widespread knowledge about all the mission elements, the following database have been developed:

- Small Satellites Mission & Suppliers (1160 Missions & 152 Companies)
- Launchers & Launch Site (104 Active Launchers & 90 Launch Sites)
- Ground Control Stations (260 Elements)
- Payloads (329 Payloads)

CDF relies on students to carry out projects. Students are enrolled in Master of Science program, and preferably are members of PoliTo CubeSat Team. The number of students varies from a small team of 4 to 25.

In the latter case students are split into focused teams depending on their background and attitude. Study leaders are mainly, doctoral students.

III. RELEVANT ACTIVITIES

A. 3STAR

The approach described has been applied to study a CubeSat mission. The mission objective was "*to inspect the International Space Station using a low cost, fast delivery system*" avoiding high-risk Extra Vehicular Activity (EVA). It was important to consider operational constraints, e.g., operations must fulfil safety constraint imposed by ISS legislation. Starting optimal solution within tradespace pareto front (**Figure 1**), the team had developed all phases and scenarios of the mission, as shown in the Design Reference Mission in the **Figure 2**.

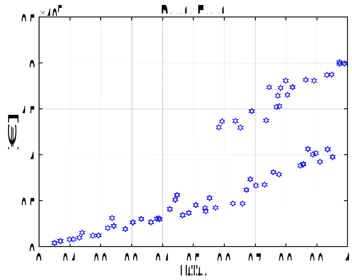

Figure 1 3STAR pareto front

After the deployment of the CubeSat by Cyclops[11], the operational phase starts with the insertion in an ultra-safe orbit beyond the Keep Out Sphere (KOS) and then the spacecraft returns with a manoeuvre to KIBO module in order to dock/berth safely. In case of a contingency, the escape trajectory consists in a rapid removal of the spacecraft, achieving 1.5 km in one orbit, with an impulse of about 10 cm/s along the in-track direction.

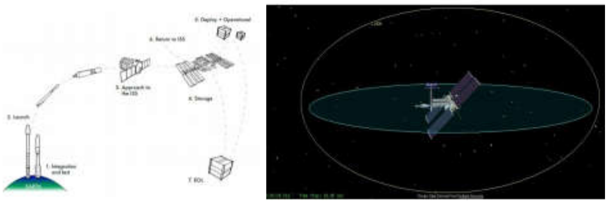

Figure 2 3-STAR ConOps and ISS RPO orbits

After few design session, a 4U CubeSat, with two cameras with different field of view to guarantee a macro and detailed inspection has been selected. The payload chosen is useful to best meet the objective of the mission, using the stereoscopic technique. The payload data could be saved in a SD Card inside the Spacecraft or sent in real time to ISS with a S-band channel, according to Space Station capabilities.

In order to have a good configuration evaluation of the satellite, the primary structure and the deployable solar array have been printed with 3D approach.

B. Concurrent Engineering challenge 2017I

The team had the opportunity to take part in the ESA Academy's first Concurrent Engineering Challenge. Three European universities, Politecnico di Torino, University of Strathclyde, and Technical University of Madrid, have been selected to participate in the challenge in parallel with the design activities in ESEC. Each group of students (**Figure 3**), was then divided into teams to design the subsystems of the mission.

Figure 3 Politecnico di Torino students with their certificates

The objectives proposed by ESA were divided in primary and secondary objective mainly focused on the exploration of the Moon. Mission constraints were identified in: 1) The total mass of the whole system shall be 300 kg; 2) The mission shall stay in Lunar orbit for 2 years. The duration of the activities was 5 days, to be at the same level of employed tools and methods, a traditional concurrent engineering approach was adopted. Due to the objective of the mission, PoliTo team named the mission "Water Ice South pole Explorer" (WISE). A direct orbit to the Moon has been proposed, to insert the probe into a lunar circular polar orbit. After several iterations, a quasi-300 kg small satellite has been designed. The system integrates 3 payloads: 1) visible camera for south pole visualization, 2) spectrometer for soil characterization and 3) passive radiation detector capable of reliable measurement up to 200 km of altitude, for radiation environment characterization. During two years of observation, the team decided to focus its attention to a south lunar crater (Shackleton) due to the planned human outpost.

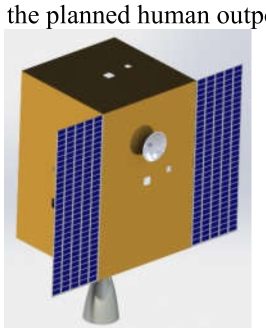

Figure 4 Wise system visualization

C. From scratch to implementation

Once that the preliminary design has been consolidated, the team is able to proceed to the next development phase in the STARlab. STARlab is equipped with state-of-the-art equipment for space systems design, assembly, integration, and verification:

- 3D printer for additive manufacturing, used in order to support CubeSat preliminary design. In addition to PLA and ABS, the team can print in metal material thanks to the supporting of an additive manufacturer from Turin.
- Hardware-in-the-Loop Simulator, fully compliant with space products requirements.

- Ground Control Station. It is used to support CubeSat projects, in particular for testing communication features during the platform development.
- Clean Room (CR1). The clean room ISO7 is used in the assembly, integration and functional verification of CubeSats and products which need to be developed in controlled environment.

IV. Lessons Learned and advancement

Nonetheless the benefits within the design of space mission given by the CDF, it is important to underline the additional challenges born in an academic environment that is important to overcome. Examples are given by short learning curve of the students, projects that should be synchronized with academic schedule, teams which change very quickly and internal knowledge that can be lost. In order to identify possible enhancement to the current CD approach, this section will present the lessons learned by the team during these 2 years of activities.

A. Knowledge management

Intensive student turnover is one of major difference between a CDF industries and academia. Indeed, in academia it is necessary to train and retain experts for studies. Moreover, due to the student turn over, the gained knowledge about subsystem design can be lost. To avoid this loss of knowledge, it is important to guide students in model development and documentation writing. The objective is to teach students how to handle documentation and preparing presentation with goal of clear and understandable knowledge transfer.

Considering the design team as/or within an actual student team would help in managing team working skills and share knowledge among team members. At last, online assistance of AI algorithm such as Knowledge Based Systems could improve the knowledge management and assist during the training of new students.

B. Models, Databases and facility

The active work with models and databases, assist students in the understanding the models and technological feasibility.

WI-FI functionality aids students in managing and update design models thanks to the capability of working in their own laptop without constraints given by laboratory schedule. The versatility given by the modularity of the develop CDF allows the team to organize the sessions without worrying about logistic related problems within the university. Integration of innovative design methodology such as MATE methods, allows students to understand the importance of stakeholder analysis, advanced subsystem modelling and the drawback given by each taken decision. Even in this topic, Artificial Intelligence algorithm, e.g. genetic algorithms are able to assist students in the design and learning process. At last, nonetheless the known performances and benefits given by sensitivity analysis in industries, it has been proven that even in academia it results useful to understand the sensibility of each decision This enhancing also the understanding related to the strong interconnection among different disciplines and stakeholders.

C. Team management

The CDF operates in student environment and is constrained to the schedule: flexibility of sessions is mandatory. It is important to prepare a work statement very clearly for each student on the team and monitor his or her progress weekly. This process encourages presentations, team discussions and document writing. Students are effective in updating equipment databases for various subsystems, especially if PhDs have developed models and helps them in the understating of technological constraints. The key point within the team lessons learned resides in encourage teamwork: Exercise, team building before sessions resulted very important in order to elicit team attitude. This also assist in guiding students throughout a soft integration into CDF mentality. Project management tools such as Trello and Toggl help in the formulation of work packages for each student. These tools help the students in the project control and allows them to learn how to mange their work. Shared calendar also helps in the definition of available dates for the CD sessions.

V. Challenging the challenges: Technology push-up and Smart CDF

From the lessons learned in these 2 years of activities, the roadmap of the CDF involves research and development four topics that are beyond the state of art for a CDF: 1) Integration of an on-line Virtual Reality (VR) to support the decision-making process, 2) the adoption of negotiated trade space exploration, 3) expert design supported by Artificial Intelligence (AI) and 4) autonomous knowledge management. Going into details, the main objective is to increase the benefits given by the state of art of CDF thanks to knowledge-based systems, which can assist the designer through the design session thanks to an autonomous explorations of design alternatives and the virtual reality, which can give a visual real time feedback through the evolution of the system design iterations.

A. Autonomous knowledge management and tradespace exploration

Autonomous knowledge management can be performed via knowledge-based systems (KBS) tailored for students application. Knowledge can be stored in the form of simple logical rules (if-than syntax). This will help students in the formalization of the gained knowledge and the following transfer of it.

B. Stakeholder interview

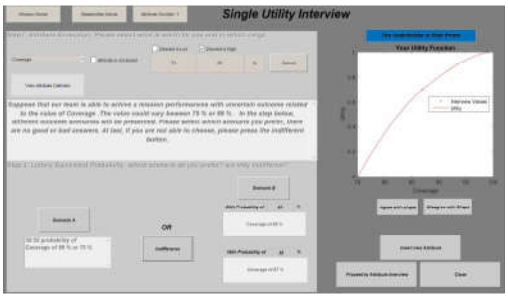

Figure 5 Stakeholder Interview Graphical user interface

KBSs incorporate the significant skills of an interviewer. They also have many additional features that improve the measurement of needs and train students in learning new skills. **Figure 5** illustrate the graphical user interface employed for stakeholder needs elicitation.

C. Designers assistance

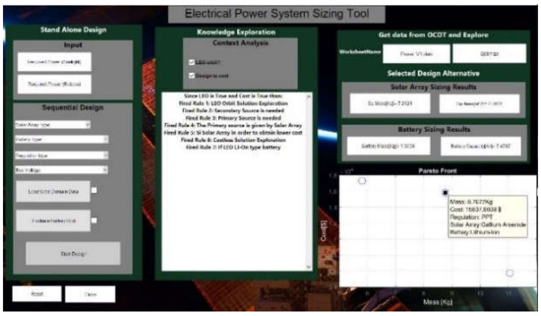

Figure 6 Expert Graphical User interface

Figure 6 shows the new student interface in which is possible to highlight the exploited knowledge (in the middle section) and autonomous domain tradespace exploration able to assist the expert throughout the exploration of domain design alternatives.

D. Autonomous virtual reality generation

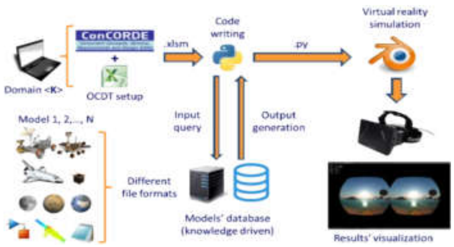

Figure 7 Autonomous virtual reality architecture

Incorporating the concepts of autonomous managed visualization (**Figure 7**) with the system design process can assist both learning and negotiation goals, by reducing complexity and directing attention to effective areas of the design alternatives.

VI. Conclusions

The Concurrent Design Facility at Politecnico di Torino has been operational for the last 2 years. The Concurrent Design approach can be applied for education in space systems engineering. Significant experience was gained on how to engage students and how to include CD studies into educational activities. A process was established to develop both models and databases to create ingredients for SoA Concurrent design facility. This system can be maintained, updated and synchronized with academic schedules. Students can learn how to overcome trials and working in a multi-disciplinary team. Facing actual issues such as negotiation and group decision making, which are an important and essential aspect of the design process.

Important objective is to fill the gap between academia and industry by teaching the ability to work together facing incredible time and cost constraints aiming to the satisfaction of the stakeholder needs. At last, integration of artificial intelligence and tradespace exploration methods, have proven the effectiveness in assisting students in their learning experience. It is foreseen in the current CDF development roadmap to increase the capability and the integration of these methods to fully exploit its beneftis. The CubeSat team of Politecnico di Torino believe that Concurrent Engineering is and will be one of the key parts of engineering education, giving to students a complete curricula not only about technical skill but also in team working ones.

Acknowledgements

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Microgravity Research on Earth - The Bremen Drop Tower

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***Abstract* - The Center of Applied Space Technology and Microgravity (ZARM) founded in 1985 is part of the Department of Production Engineering at the University of Bremen, Germany. ZARM is mainly concentrated on fundamental investigations of gravitational and space-related phenomena under conditions of weightlessness as well as questions and developments related to technologies for space. At ZARM about 100 scientists, engineers, and administrative staff as well as many students from different disciplines are employed. Today, ZARM is one of the largest and most important research center for space sciences and technologies in Europe.**

With a height of 146 m the Bremen Drop Tower is the predominant facility of ZARM and also the only drop tower of its kind in Europe. ZARM's ground-based laboratory offers the opportunity for daily short-term experiments under conditions of high-quality weightlessness at a level of 10-6 g - microgravity. Scientists may choose up to three times a day between a single drop experiment with 4.74 s in simple free fall and an experiment in ZARM's worldwide unique catapult system with 9.3 s in weightlessness. Since the start of operation of the drop tower facility in 1990, over 8000 drops or catapult launches of more than 250 different experiment types from various research fields like fundamental physics, combustion, fluid dynamics, planetary formation / astrophysics, biology and materials sciences have been accomplished so far. In addition, more and more technology tests have been conducted under microgravity conditions at the Bremen Drop Tower in order to prepare single space instruments or appropriate space missions in advance.

Keywords - drop tower, weightlessness, microgravity experiments, space technology, education

I. Introduction

In February 1987, the planning and construction period of the Bremen Drop Tower began and were completed within only three years. With a total height of 146 m and its characteristic glass roof the drop tower was manufactured of a steal vacuum tube with a height of 122 m which is enclosed by a concrete tower (Fig. 1). In September 1990, the ZARM Drop Tower Operation and Service Company (ZARM FAB mbH) owned by the State Government of Bremen was established as a public company operating and maintaining the drop tower facility simultaneously with the time of beginning microgravity experiment operations. Up to now, ZARM's drop tower is the only ground-based facility of this kind in Europe for short-term experiments under conditions of high-quality weightlessness. Furthermore, ZARM's drop tower has become one of the important and outstanding microgravity facility worldwide.

The high-quality weightlessness achieved for microgravity experiments at the drop tower in Bremen is of the order of 10(-6) g which is nearly comparable to drag-free satellites. Such an excellent microgravity quality exceeds that of manned sub- or orbital platforms (e.g. ISS) by orders of magnitude. The Bremen Drop Tower also represents an economic alternative with a permanent access to weightlessness on earth.

At the drop tower facility, the free-fall duration of a microgravity experiment is about 4.74 s given by a height of the inner cylindrical drop tower vacuum tube of 122 m (110 m drop distance). In December 2004, the world-wide unique capsule catapult system developed by ZARM has started its operation of microgravity catapult experiments. During a catapult operation the experiment capsule performs a vertical parabolic flight inside the vacuum tube of the drop tower. This way the condition of weightlessness can be extended to 9.3 s at which the same high quality of microgravity is achieved as for the simple drop mode.

Fig. 1: The Bremen Drop Tower with a total height of 146 m located on the campus of the University of Bremen (technology park).

II. CATAPULT SYSTEM

Located below the base of the drop tower, a chamber of 11 m depth contains the catapult system (Fig. 2). During the catapult operation the experiment capsule performs a vertical parabolic flight inside the drop tower vacuum tube. This meets scientist's deamands on extending the experiment time to slightly over 9 s at the same high quality of microgravity (10-6 g).

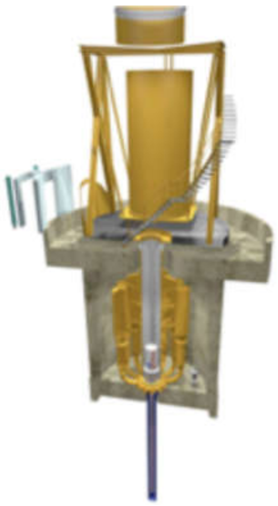


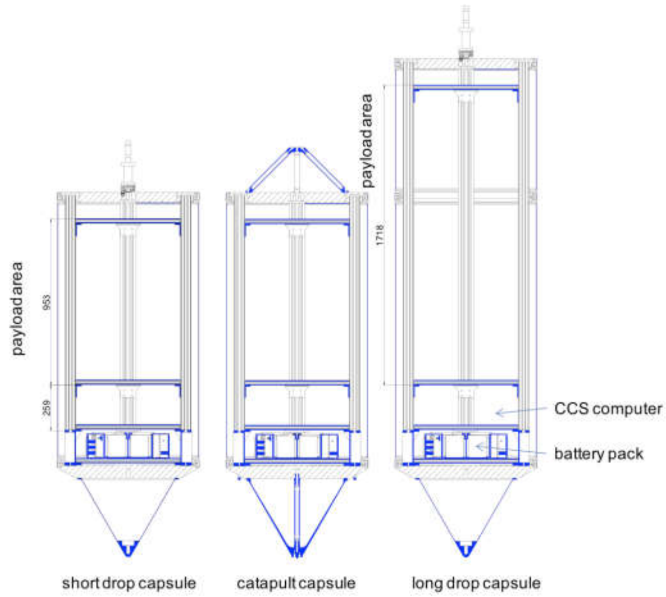
Fig. 2: Scheme of the catapult system of the Bremen Drop Tower including the catapult capsule on the pneumatic piston, the pressurized air tanks and the moveable deceleration container on the top.

The catapult capsule is accelerated by a pneumatic piston driven by the pressure difference between the vacuum of the evacuated drop tower tube and the pressure of the pressurized air tanks of the catapult system. The capsule acceleration level is adjusted by means of a servo hydraulic braking system controlling the catapult piston velocity. The deceleration container inside the vacuum chamber is moveable to fall back in the capsule capture position within 3 seconds after the lift-off and passing of the catapult capsule.

ZARM's catapult system is currently able to accelerate catapult capsules with gross weights up to the actual limit of 400 kg (an enhancement of up to 500 kg is available on special request) to a lift-off speed of 46.9 m/s within 0.28 seconds.

III. EXPERIMENT OPERATION

The microgravity laboratory system consists of a cylindrical capsule with an outer diameter of 814 mm and a total length of 2,094 mm for the short drop / catapult capsule and 2,860 mm for the long drop capsule (Fig. 3). Inserted platforms bordered by aluminum profiles form the modular capsule structure. The number of platforms depends on the space required for experimental studies. The standard equipment of each experiment capsule includes a computer platform as well as the accumulator platform necessary for the internal power supply (nominal 24 V / at charging 28 V DC, max. 40 A, 25 Ah). The Capsule Control System (CCS) of the drop or catapult capsule performs the experimental control and data storage, as well as interactive experimental regulation through telemetry during the test on ground and the following test phase in microgravity. After the integration of the experiment the capsule will be closed pressure-tight with an aluminum cover.



Version	short	long	catapult
stringer lenght [mm]	1341	2107	1341
max. payload height [mm]	953	1718	953
total area of experiment-platform [m²]	0.359		
base structure incl. batteries and CCS [kg]	122.8		
top lid plate incl. video transmission unit [kg]	32.9		30.2
pressurized cover incl. clamping rings and thermal isolation cover [kg]	38.5	61.1	38.5
4 stringer [kg]	36.8	57.4	36.8
nose cone incl. connection rod [kg]	4.6		10.2
1 experiment-platform incl. brackets [kg]	15.5		
capsule net weight [kg]	235.6	278.8	238.5
capsule gross weight [kg]	500		400*
max. payload mass [kg]	264.4	221.2	161.5

* actual limit, enhancement up to 500 kg in future depends on evolution progress

Fig. 3: Experiment capsule types of the drop tower.

The inner steel vacuum tube of the drop tower has no connection to the outer concrete tower. The pedestal of the vacuum tube is fixed to the lower positioned deceleration chamber with a height of 13 meters and it is eccentrically arranged to the vertical axis of the concrete shell. By this, one can avoid the transfer of wind-induced tower oscillations to the sensitive experimental operation to the greatest possible extent. Depending on the experiment campaign, for a drop with 4.74 s of microgravity the capsule must be brought up to a height of 120 meters by a winch, for the catapult operation with 9.3 s of microgravity the capsule must be placed on the catapult piston pulled down to 11 meters below the base of the drop tower (Fig. 4).

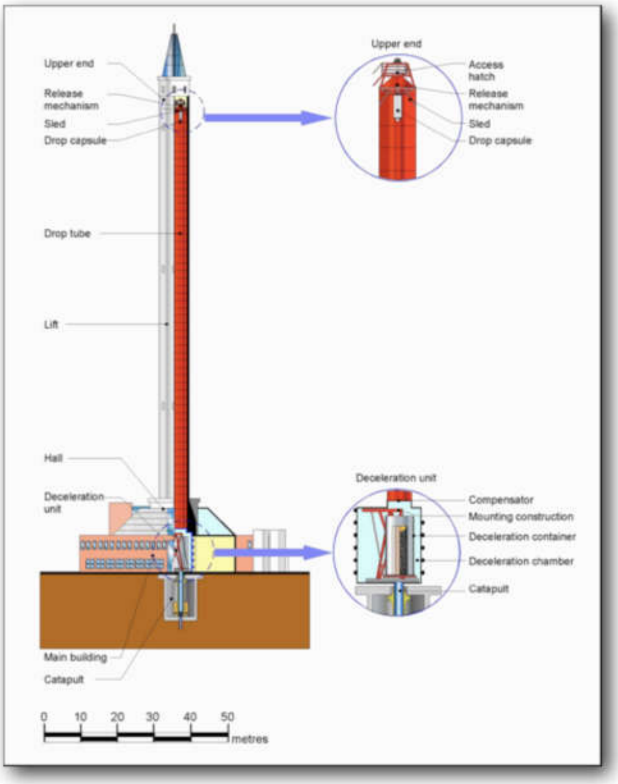


Fig. 4: Scheme of the Bremen Drop Tower including drop release, catapult and deceleration mechanism.

Then, the inner steel tube of the drop tower must be closed pressure-tight so that the evacuation of the 1,700 cubic meters capacity of the drop tower and the deceleration chamber can start - this is necessary to minimize the effect of the air drag on the freely falling capsule. 18 combined vacuum pumps requires about 1.5 hours for the evacuation of the steel tube. The capsule is then launched at a residual pressure of 10 Pa. For this, the final launch command will be given by the scientist from the ground control station of the drop tower (Fig. 5). As soon as the initial disturbances caused by the drop release or catapult launch have been damped down, residual accelerations of 10(-6) g can be detected during the free fall from 110 meters for a drop experiment or during the vertical parabolic flight of a catapult experiment.

Fig. 5: Ground Control Station of the drop tower.

The drop capsule arriving at the braking zone with a final speed of 167 km/h and the catapult capsule achieving a lift-off speed of 175 km/h are gently stopped in the deceleration container. The container is filled with fine polystyrene pellets. The nose cone of the capsule reduces the entry peak and stabilizes the vertical axis during braking. Here, a maximum deceleration of 50 g acts on the incoming capsule (Fig. 6). The duration of the impact of the capsule is about 200 ms. During a catapult launch with a total duration of about 300 ms the catapult experiment is accelerated up to 30 g (Fig. 7). The acting acceleration force on the catapult capsule is very smooth due to a sinus curve velocity profile of the catapult piston movement.

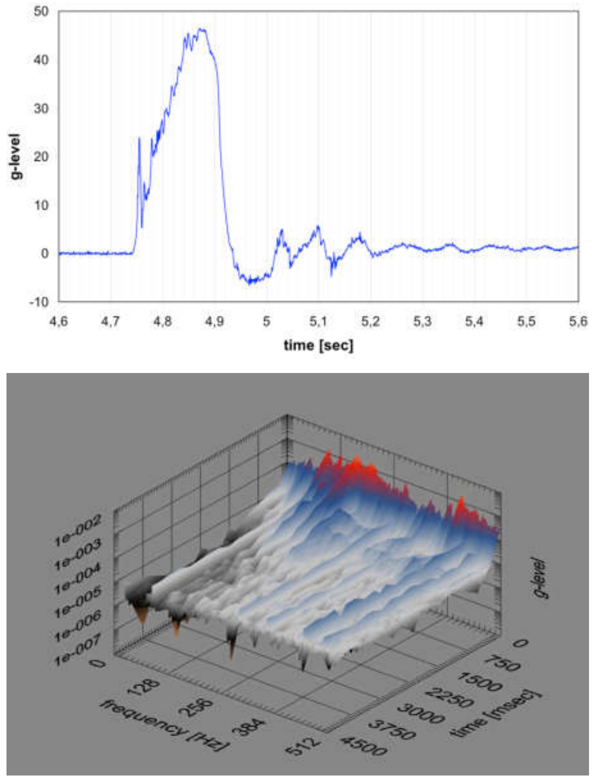
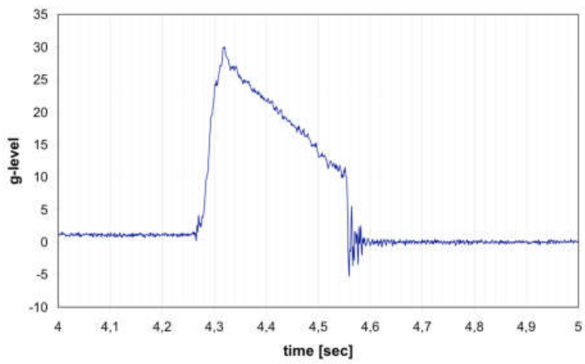


Fig. 6: (top) Typical capsule deceleration plot. Here, during drop operation. (bottom) Waterfall amplitude spectrum of drop axis.



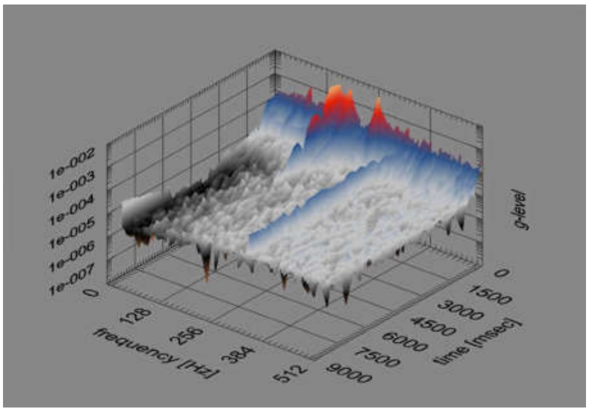


Fig. 7: (top) Typical catapult capsule acceleration plot. Note the delay time of about 4 s after initialization of launch (adjustable). (bottom) Waterfall amplitude spectrum of catapult axis.

To recover the capsule from the deceleration container (Fig. 8), the vacuum chamber must be first re-flooded with preconditioned air - this takes about 20 minutes. Afterwards, the scientists and researchers regain the capsule and the integrated experiment at the integration area at the machine hall immediately.

Fig. 8: Capsule deceleration container at the bottom of the vacuum tube of the drop tower.

IV. STANDARD CAPSULE EQUIPMENT

The Capsule Control System (CCS) located at the bottom of the capsules is part of our standard capsule equipment that operates the drop and catapult experiments via remote control. The CCS is based on a National Instruments™ PXI Chassis 1000B-DC with a Real Time Controller 8145 RT containing a PXI-6031E (Dev1), a PXI-6527E (Dev2), a PXI-6713 (Dev3) and a second PXI-6031E (Dev4) device. The connection of the experiment's analogue and digital I/O channels to the CCS is performed via an interface board (Fig. 9).

In order to control the experiment hardware during the drop tower operation, each part of the I/O channels can be displayed and managed on a LabView™ screen in the control station on the ground floor. All data acquired during the experiment will be continuously transmitted via WiFi to the ground control and saved to the password-secure user account.

As a further standard equipment of our drop tower capsules the Power Distribution Unit (PDU) provides six switchable current channels supplied with power by a rechargeable battery pack for the experiment operation during free fall (nominal 24 V / max. 40 A, 25 Ah - continuously buffered by an external power supply (28 V / 10 A) in laboratory and until approx. 1.5 min prior to the launch command). The standard on-board sensor pack (further capsule sensors are available on request) includes:

- acceleration - three axes (range: ±1 g)
- deceleration - capsule axis (range: ±50 g)
- capsule pressure (nominal pressure: 1.013 hPa)
- capsule temperature
  (in general: room temperature)

All sensor values are monitored during drop tower operation and stored on the password-secure user account.

Fig. 9: Capsule Control System (CCS).

V. SPECIAL CAPSULE EQUIPMENT

On request, the ZARM Drop Tower Operation and Service Company (ZARM FAB mbH) provides color CCD-cameras and problem-specific lenses for all drop and catapult campaigns. The available CCD-cameras meet the CCIR-standard and the corresponding recorders are of DVCam™-standard.

Furthermore, we can provide all experiments with a digital high performance video system (Photron Fastcam MC2™ - 2 GB). This high-speed video system is based on light sensitive monochrome or optionally color CMOS imaging sensors (Model 10K; 512 x 512 pixel resolution) and its live video output can be transmitted to the ground control prior to and during the experiment. The transmitted data has a bandwidth of standard video and the high-speed data is directly stored onboard at a chosen frame rate up to 10,000 fps.

If required, all experiments can be connected to a thermal liquid heating and cooling circuit. This liquid circuit (glycol/water-mixture) is linked to a thermostat outside of the drop tower vacuum tube. Through a closed loop regulation, the temperature can be adjusted between -20 °C and +60 °C. The liquid circuit will be disconnected approx. 1.5 min prior to the launch command. In addition, we offer the option of a non-standard power supply for both drop and catapult experiments. This external power supply provides an adjustable DC voltage with up to 100 A and will be also disconnected from the capsule lid plate approx. 1.5 min prior to the launch command.

The release of gases during the experiment (e.g. from cryogenic devices or combustion exhausts) is regulated/served by a vent line. Its connectors are located on top of the capsule's lid plate (alternative use of the connectors of the heating and cooling circuit up to approx. 1.5 min prior to the launch command). The gases can be either released outside of the drop tower vacuum tube or directly to the ambient vacuum. To avoid thruster effects during the free fall, the vent line must be closed prior to the launch of the capsule and the gases must be stored in on-board containers.

For experiments which request data from accelerations between 1 g and 0 g we recommend the application of a specially designed on-board microgravity centrifuge (Fig. 10). Basically, this centrifuge consists of a rotating platform equipped with a number of slip-ring transducers for the supply with electrical power and signal transmission between rotating platform and capsule. The on-board microgravity centrifuge is not applicable for catapult operation due to safety aspects.

Fig. 10: On-board microgravity centrifuge inclusive experiment integrated into drop capsule structure.

ACKNOWLEDGMENT

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Active Learning in Astrodynamics & Mission Design with NASA's GMAT

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Abstract— **Astrodynamics is the study of the motion of artificial satellites, subject to natural and artificially induced forces. Aside from its relevance to spaceflight, it provides opportunities to demonstrate fundamental concepts such as gravitation, Newton's law of motion, and Kepler's laws; it is as applicable to a description of the motion of natural bodies in the universe, as it is to the planning of space missions. At High School, a simple treatment of orbits based on the balancing of gravitational and centripetal forces leads to familiar results such as Kepler's laws, that can be appreciated in two dimensions. But in reality the subject involves time-varying parameters in three spatial dimensions, and extension to three or more bodies leads to rapidly increasing complexity which is much more challenging for students to visualize and explore. To enhance its education and training in this area, the University of Leicester has adopted NASA's General Mission Analysis Tool to support astrodynamics courses at Level 6 (BSc) and Level 7 (MSc). This paper summarises the use of GMAT in these programmes.**

Keywords— Astrodynamics, Simulations, GMAT, Orbital Mechanics, Pedagogy

I. Introduction

Astrodynamics is the study of the motion of artificial satellites, subject to both natural and artificially induced forces [1]. Aside from its relevance to space exploration and spaceflight systems engineering, it provides opportunities to demonstrate the application of fundamental concepts such as gravitation and Kepler's laws.

Learners and instructors face several challenges when exploring the subject. At High School, a simple treatment of orbits based on the balancing of gravitational and centripetal forces leads to familiar results such as Kepler's laws, that can be appreciated in two dimensions. But the subject is intrinsically four dimensional, involving time-varying parameters in three spatial dimensions; extension to three or more bodies leads to rapidly increasing complexity. While generations of successful flight dynamicists had their first encounters with the topic in the traditional 2D teaching environments of blackboard and paper, the availability of sophisticated and validated software tools developed for the research and industrial space community is changing the way astrodynamics can be taught, using approaches which are aligned with current pedagogies to improve the effectiveness of the experience for both learner and facilitator.

II. The General Mission Analysis Tool

The General Mission Analysis Tool (GMAT) is open-source software developed in a partnership between NASA, industry, and public/private contributors, and is available to download without charge. It is designed to support the simulation and analysis of spacecraft trajectories, permitting orbits to be modelled, analysed and visualised in detail, perturbations to be studied and manoeuvres planned, propulsion system requirements to be determined, and mission lifetimes estimated [2]. GMAT interfaces with external tools such as MATLAB and Python, providing opportunities for expansion of the core capabilities. It is not a dedicated educational tool: it has been validated against real missions, and has been used to support programmes including MAVEN [3], Lunar Reconnaissance Orbiter [4], and OSIRIS-REx [5]. Hughes [2] cites 13 commercial firms who describe their use of GMAT in the literature, as well as organisations such as ESA and NASA. This number is growing. Thus, while the focus of this paper is the exploitation of GMAT as a tool to facilitate learning, there is a significant additional benefit in equipping graduates with experience in the use of a system that is being adopted in the professional community.

III. Workshop Philosophy

GMAT's open source code makes it possible to treat the entire system as a "white box": in principle, students can examine the code to see how the physics has been implemented, although given the complexity of the supporting code, this approach is unlikely to be efficient or to bring clarity to the learning. Conversely, the presence of a sophisticated Graphical User Interface can shield the student from the detailed operation of the code, with their interaction reduced to a "black box" approach, entering randomly chosen initial state parameters, and allowing GMAT to propagate these through a gravitational model and displaying whatever trajectory results. However, the principle of "garbage in, garbage out" applies to astrodynamics simulations – without sensibly defined initial values for orbital parameters, useful orbits with specific properties are unlikely to be generated, and many simulations will fail. Hence, the "hands-on" elements of the workshop are embedded within a wider set of activities designed to consider, question and explore the fundamental principles of astrodynamics.

The workshop is associated with a third year undergraduate module comprising 12 lectures and supporting screencasts providing an introduction to astrodynamics. The lecture module is not a prerequisite for the workshop; student's attention is drawn to the complementarity of lecture course and workshop, and approximately 80% of students take both, but the workshop is designed to be accessible to those who have had no exposure to the theory of orbits beyond a first-year undergraduate treatment of gravity. While it is arguably easier to design an effective workshop assuming knowledge from the taught module, the applicability of the concepts beyond the immediate astrodynamics topic makes it desirable to offer a self-contained practical activity in this area. Thus, the workshop begins with a review of conic sections and the "restricted two body" equation of motion, which leads quickly to important results such as the trajectory and vis-viva equation. Appealing to the concept of the scaffolding of learning [6] these cornerstone topics are appropriate points from which to develop an exploration of basic orbital motion. It is therefore essential that these topics are considered by workshop participants at the start of the activity, and before work with simulations begins, to avoid a "black box" approach. Hence, some preparatory reading and viewing of screencasts is needed on the part of the student before the workshop begins.

GMAT is supported with an extensive set of help documentation and online resources including an active user forum and YouTube videos. In the December 2015 pilot workshop, students were instructed to follow an introductory tutorial leading to the production of a simple orbital model. However, feedback indicated that an academic-led approach was strongly preferred at this early stage, and so the first 90 minutes of the workshop (which takes the form of eight contact sessions, each three hours in duration), are used to cover cornerstone topics and engage in a discussion with students about the key concepts. Students and the session leader begin by creating a blank GMAT scenario. The academic shows his/her GMAT session on the projector screen, and talks the students through the definition, entry and demonstration of a closed, elliptical orbit around Earth, which they replicate on their own machines. This allows the facilitator to explain the architecture of the user interface using a practical example, while encouraging real-time exploration of the physical parameters which are being defined in the scenario.

IV. Introducing Simple Celestial Mechanics

Following the walk-through, the workshop presents a number of problems (referred to as "missions") which students model and analyse. In the first instance, students are tasked with implementing a simple scenario in which a spacecraft is in a polar Earth orbit with specific requirements on the size, shape and orientation of the orbit. The initial state conditions are then "propagated" (passed through an algorithm which includes a force model describing how factors such as gravity, atmospheric drag and radiation pressure affect the motion of the satellite) resulting in a simulation covering one day of mission elapsed time. The motion of the satellite can be visualised in 3 dimensions on an accelerated timescale to give students an appreciation of fundamental orbit behavior. The "cookbook" approach is avoided at all stages by posing questions as part of each mission. This begins with a set of well-structured questions, but as the learner progresses through increasingly sophisticated scenarios with less prescriptive summaries in the supporting text, the questions move to a more "ill-structured" form where problems and the expected pathways to solution are less prescriptive [7,8]. In the case of the simple polar orbit, students verify that the characteristics of the orbit shown in the simulation (including quantities such as apoapsis/periapsis velocity and orbit period) agree with theory.

V. Increasing Detail: Perturbations

The initial exercises adopt the Restricted Two Body Problem (R2BP), assuming that the spacecraft is subject only to a single, spherically symmetrical source of gravity, with no other forces acting. In this simplified treatment, the motion of the satellite is confined to a plane, which is easy to represent in 2 dimensions. In reality, spacecraft are subject to other forces such as atmospheric drag; there are typically several significant sources of gravity (for example, the Earth and the Moon), and because real planets are not perfectly spherical or uniformly dense, their gravitational fields are not perfectly radial. These factors lead to orbital behaviour which deviates from the predictions of the R2BP - perturbations, which lead to motion which more closely represents "real" spacecraft behaviour. GMAT allows students to explore these concepts and the relationships between the mathematical descriptions of the environment and the resultant motion.

The J_2 perturbation is one of the most significant for a spacecraft in Earth-orbit, and is caused by Earth's oblateness, which introduces non-radial forces on the satellite, leading to a torque being exerted on the orbit which in turn leads to precession. In GMAT, perturbations can be appreciated by studying how the behaviour of a satellite is modified as the fidelity of the gravitational model is changed, from a simple spherical case, to increasingly detailed representations obtained by including higher degrees and orders of the spherical harmonic description of the field defined in GMAT's orbit propagator. In the workshop, students first encounter perturbations by building on the polar orbit model defined in the introductory session. When simulated over a period of several weeks, this satellite is clearly seen to follow an orbit that is fixed in the inertial frame – consistent with the prediction of the R2BP that orbital motion is confined to a plane. The satellite can then be "copied" so that two identical spacecraft are represented in the simulation. The student adjusts the level of detail in the force model applied to the second satellite to include Earth oblateness. Re-running the simulation, the non-radial component of force results in a torque which causes precession in the second case.

Investigations begin with a qualitative examination of the 3D Orbit View. A more quantitative approach is enabled using custom-defined reports and plots that can be generated by GMAT to examine time-varying parameters. The rate of precession caused by the Earth's oblateness is expressed in terms of the rate of change of the Right Ascension of the

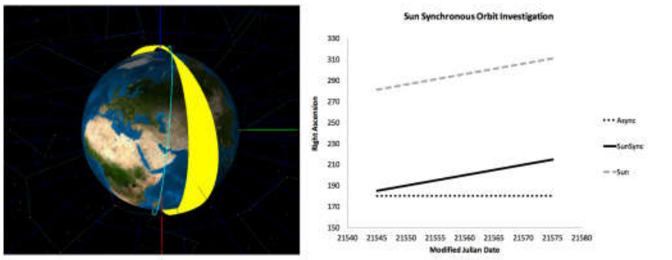

Fig. 1. A student's investigation of perturbations leading to Sun-synchronous orbits. The two satellites have identical initial states apart from a 5° difference in ascending node value to make them distinguishable on the plot. The motion of one satellite (cyan path) is based on a force model which assumes a spherical Earth. The motion of the other satellite (yellow) is calculated using a gravity model accounting for Earth's oblateness. The simulation covered 30 days of motion. The graph was generated using data exported from GMAT, showing that the Right Ascension of the Ascending Node remains constant for the first satellite, but varies with the second at a rate matching the Sun's apparent motion.

Ascending Node (Ω), and for a circular orbit can be shown to have the form

$$\dot{\Omega}_{J_2} = -\frac{3}{2}\sqrt{\frac{GM_\oplus}{r^3}}J_2\left(\frac{R_\oplus}{r}\right)^2\cos i \qquad (1)$$

where i is the orbit inclination, r is the orbit radius, G is the universal gravitational constant, J_2 is the perturbation coefficient (1.081874 x 10^{-3}) and $M_\oplus$ and $R_\oplus$ are the Earth's mass and radius respectively. J_2 would be zero for a perfectly spherical, uniformly dense Earth, resulting in no precession. Students explore this relationship in GMAT, extending the treatment to more general, elliptical orbits. Work from one student is shown in Fig. 1. The student chose an orbital radius r of 6778 km, and used (1) to determine that for this radius, an inclination of 97.03° results in an orbit whose rate of precession matches the rate at which the Earth orbits the Sun (360°/365.24 mean solar days, or 1.991 x 10^{-7} radians sec^{-1}) leading to a Sun-synchronous orbit, in which the orientation of the orbit plane remains fixed with respect to the Earth – Sun vector. The student plotted the value of Ω for the two satellites, and showed that the purely spherical potential resulted in a fixed value for Ω, while including the Earth's oblateness caused Ω to change at a rate equal to the rate of change of the Sun's Right Ascension over the course of the year (also plotted), confirming the expected behaviour.

VI. MANOEUVRES & TARGETTING

Propulsive manoeuvres are enabled in GMAT by adding "Hardware" (fuel tanks and thrusters) to the spacecraft, and then adding "burns" which use the hardware to change velocity. Thruster representation can be detailed, with chemical and electric propulsion options available, and thrust profiles, directions and reference frames definable. This level of detail means that the GMAT can be used to support courses in space propulsion and spacecraft systems engineering. But to maintain the workshop's focus on astrodynamics, chemical thrusters are generally used, and most propulsive manoeuvres are assumed to be "impulsive" rather than taking a finite period of time.

A simple manoeuvre commonly used as an introduction to the topic, is the Hohmann Transfer between two circular orbits.

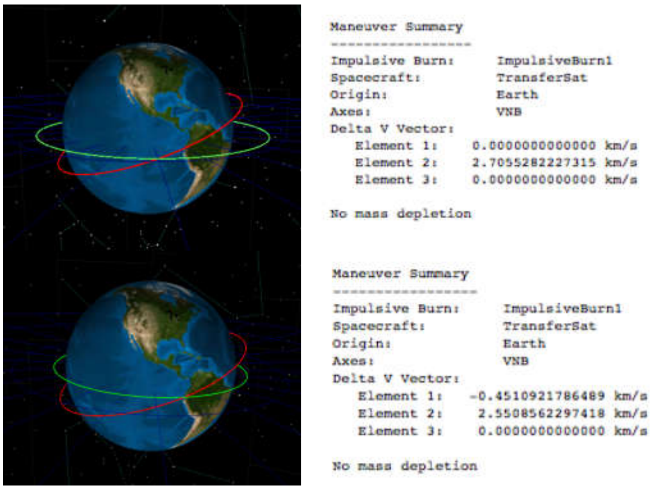

Fig. 2. A student's investigation of inclination changes. Top panel: student's first attempt showing initial orbit (red), and final orbit (green) with required inclination but increased semimajor axis. Bottom panel: second attempt with directed burn showing pure inclination change. Numerical outputs from GMAT summarise the parameters of the propulsive manoeuver (right panel), indicating the correct burn has velocity components in both the orbit velocity and orbit plane normal axes.

An elliptical orbit is used to transfer a spacecraft from one circular orbit to another in the same plane. The apoapsis of the transfer orbit is coincident with the higher circular orbit, while the periapsis matches the radius of the lower circular orbit. The transfer is achieved using two burns, one at apoapsis and one at periapsis, to increase or decrease velocity. The first manoeuvre causes the spacecraft to leave the initial orbit and join the transfer, the second one allows the spacecraft to join the destination orbit. Both burns are in a direction tangential to the circular orbits. Two approaches can be taken to investigate the Hohmann transfer: (1) definition of the initial orbit and manual calculation of ΔV magnitudes and directions which are then coded into GMAT, which simply implements the manoeuvres and simulates the result – students then analyse the results to confirm the expected behavior. Alternatively, a solver allows the user to define the initial and final orbits, and free parameters such as the ΔV and location of burns. GMAT then uses iterative processes within its Differential Corrector modules, to find the burn parameters which achieve the required transfer. Again, students analyse the results and compare with predictions.

Orbital inclination changes provide another useful example of a manoeuvre well suited to an introductory GMAT session. Simple vector geometry shows that the velocity change required to adjust the inclination of a circular orbit through an angle Δi while keeping other parameters fixed, is

$$\Delta V = 2V\sin\left(\frac{\Delta i}{2}\right) \qquad (2)$$

where V is the magnitude of the orbital velocity. Experience in previous years of the astrodynamics course shows that students understand this concept and can estimate ΔV magnitudes, but they often overlook the fact that that the propulsive manoeuvre has a direction which is not perpendicular to the orbit plane. Fig. 2 shows a student's investigation, in which in which a vehicle in a circular Earth orbit of radius 7200 km and inclination 20°, needed to perform a pure inclination change, resulting in an equatorial orbit (i = 20°). Two attempts were made, the initial attempt failing because the student assumed a burn perpendicular to the orbit plane. In the second attempt, the student used manual calculations to resolve the triangle of velocities and determine the burn angle correctly. This manoeuvre was explicitly coded in the GMAT mission sequence, achieving the desired result. Further investigations (not shown) used GMAT's targeting function to vary burn direction and magnitude to achieve other inclination changes.

VII. BEYOND EARTH ORBIT

The final workshop phases introduce topics relevant to interplanetary missions, introducing different coordinate frames for planetary fly-bys and orbit insertions. GMAT includes position and physical property data for the major planets along with Pluto and Earth's moon; other bodies can be added using data from SPICE [9]. A wide variety of concepts can be explored, including deep space missions that use gravitational assist (GA) manoeuvres to reach the outer planets. GMAT is not designed to calculate launch windows or to optimise GA trajectories; such computationally intensive studies are best solved using tools such as NASA's Trajectory Browser [10] or the European Space Agency's Pykep and Pygmo tools [11]. Pre-computed trajectories for specific targets can also be used [12]. Alternatively, course facilitators may consider introducing undergraduate projects on relevant concepts such as solutions to Lambert's problem, which leads to the identification of launch windows, directions and energy requirements (generating the so-called "pork chop plot"), which can then be used as initial state vectors for GMAT.

Nevertheless, exploring concepts relevant to GA trajectories is within the scope of the workshop. Spacecraft initial states can be given in terms of the arrival excess velocity V_∞ , and periapsis radius r_p in the frame of the destination planet. Students can thus investigate the geometry and energetics of a GA manoeuvre, without the need to calculate a trajectory from the Earth to their chosen planet. Missions at this stage in the workshop are less prescriptive than they are at the beginning, with students having developed in-depth familiarity with the system over the course of the activity. In the specific case of gravitational assist manoeuvres, students are asked to carry out an investigation of planetary encounters, using GMAT to demonstrate underpinning concepts and verifying the results quantitatively. Fig. 3 shows an example in which a student set up a series of encounters with Jupiter, varying arrival velocity and periapsis radius, to generate a series of encounters in which the eccentricity e and hence the turning angle φ of the trajectory (the angle between the incoming and outgoing asymptotes) changes, as shown in the graphical plot. Numerical outputs were then compared with the predictions of theory, to verify the expected behavior was obtained.

By exploring these fundamental relationships, completion of this investigation enabled the student to begin designing gravitational assist manoeuvres which achieved specific outcomes in terms of turning angle and spacecraft energy.

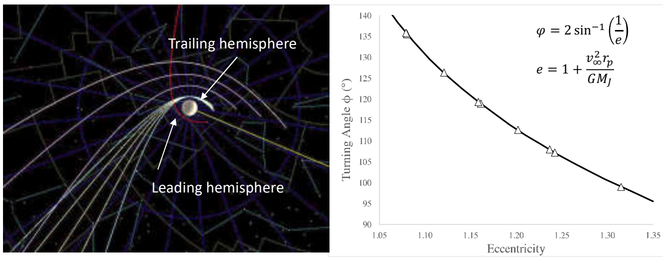

Fig. 3. A student's investigation of gravitational assist manoeuvres. Left: multiple spacecraft approaching Jupiter with different arrival velocities and periapsis radii (view direction onto the north pole). Right: testing the relationships (shown) between turning angle, arrival velocity, periapsis radius and eccentricity.

VIII. FINAL CHALLENGE & ASSESSMENT

The preceding discussion highlights selected exercises covering basic orbits, perturbations and manoeuvres. The current workshop contains sixteen exercises or "missions", each more challenging than the last. Each mission is worth a number of marks, depending on the level of complexity of the problem. Summative feedback is provided to students throughout the workshop in the form of group discussions and one-to-one conversations with the facilitators. Formative assessment is provided in two phases. First, a student's work on each of the missions is assessed in real time, in conversations between student and facilitator. The student discusses and demonstrates their solutions with the facilitator. These marks contribute 70% of the overall workshop mark.

The second element of assessment takes the form of a "final challenge" in which the cohort is divided into groups of 4-5 students, who are given the same extended problem which they have ~4 weeks to study, without instructor support. The topics to date have included:

- Phobos sample-return, with trajectories to/from Mars, and rendezvous with Phobos
- Analysis of Apollo missions to explore the difference between various trajectories used in the programme. A final stretch goal was to design an Apollo-like transfer for the present day.
- Study and reproduction of the Juno trajectory from Earth to Jupiter Orbit Insertion, with analysis of trajectory correction manoeuvres.

The Final Challenge is assessed during a Mission Presentation event, in which each group presents their solution to the rest of the class and a panel of 2 - 3 academic staff. A key feature of this event is the prohibition of PowerPoint presentations; students instead present their work directly in GMAT, showing supporting analysis in e.g. MATLAB or Excel as required. This is an important approach which the author was introduced to during a visit to the European Space Agency's Concurrent Design Facility [13]; practicing scientists and engineers who use this facility to design real missions, present solutions in this way because it is more efficient than copying work into a presentation slide; it facilitates a higher level of discussion by enabling "what if" questions to be explored, and subject experts to probe aspects of the models which the presenter may have overlooked. Effective use of this presentation style is a transferrable skill and a specific learning outcome of the workshop.

IX. Summary

NASA's General Mission Analysis Tool enables students to engage in active learning in astrodynamics, celestial mechanics, and elements of spacecraft systems engineering and mission design. Based on student feedback, it is evident that they gain much from the ability to visualise and test fundamental astrodynamics concepts in the GMAT environment. They also apply the skills developed in the workshop in other activities, particularly in project work.

A number of lessons have been learned during preparation and implementation of the GMAT workshop:

Synchronisation with taught modules: The timing of workshop activities must be planned so that prerequisite knowledge can be accessed by the student in advance. Alternatively a flipped structure can be used, using contact time for the simulation sessions, with lectures replaced by screencasts and directed reading.

Don't overestimate the pace. The use of simulation requires the student to gain familiarity with the software as well as the fundamental concepts to be explored. This overhead tends to be greatest early in the workshop, but is present throughout as the student uses the system in increasingly sophisticated ways. This overhead must be allowed for in the workshop schedule.

Test thoroughly before deployment. Course leaders will have excellent familiarity with the subject. But simulation can introduce unexpected complications; e.g. targeting algorithms can fail to converge on a solution which might easily be solved from first principles. Here, the instructor may wish to spend a little time discussing potential problems in numerical methods such as Newton-Raphson iteration, where oscillations around local minima and maxima can prevent a solution being reached - or adjusting initial parameters to avoid regions of such behavior. However, allowing students to experience these behaviours can lead to interesting discussions about the construction and limitations of numerical simulations.

Simulation cannot replace the effort needed to understand the scientific principles underpinning the system being modelled. Even the most simple tutorial or walk-through is little more than an exercise in entering numbers into a black box, without first of all providing the instructional scaffolding that gives meaning to those numbers and their origin. Only in this way can simulations fulfil their potential as environments which support learners to make meaning.

Adoption of GMAT at the University of Leicester has enabled students to explore and test the relationships developed in texts and lectures in a way that cannot be matched in more conventional teaching sessions, supporting students in their learning. From this perspective alone, introduction of GMAT as a core element of our teaching has been of substantial benefit. In addition, GMAT is not simply an educational platform; it is a professional tool produced by NASA and used by the agency for mission planning and development, and is gaining an increasing foothold in the research community. Gaining a working knowledge of GMAT therefore has the additional benefit of enabling students to develop skills which are directly transferable to employment in the academic and industrial space sector.

Finally, while this paper has focused on the use of GMAT in Higher Education, instructors in upper secondary education should find it an asset in science classes, whether to demonstrate fundamental principles by showing the outputs of simulations to students, or by leading groups of students through the construction and basic analysis of e.g. simple closed orbits for spacecraft, or exploiting the ability of GMAT to model the Earth's orbit, helping students to understand concepts such as seasons and moon phases.

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Development of an Ejectable Cubesat Onboard a Sounding Rocket

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Technische Universität Berlin is researching fluid dynamic actuation technology as a new means of attitude control for small satellites. Meanwhile, the Rocket and Balloon Experiments for University Students (REXUS/BEXUS) is an opportunity to realize a close simulation of a real space mission from start to finish. Student's from Technische Universität Berlin's Chair of Space Technology are currently developing the Technische Universität Berlin Pico-satellite Experiment-6 (TUPEX-6) within the framework of the REXUS/BEXUS program. TUPEX-6's goals are to experimentally demonstrate the utility of fluid dynamic actuators while simultaneously providing students a unique hands-on opportunity to design, build, test, and fly a small spacecraft. The mission is set to launch on-board the REXUS 25/26 mission in March of 2019, and will provide approximately 120 seconds in milligravity for the experiment to take place.

Keywords—CubeSat; technology demonstration; attitude control; sounding rocket

I. Introduction

Modern-day CubeSats rely on magnetorquers, a system of reaction wheels, or a combination of the two for active attitude control. Magnetorquers are cost-effective and robust; however, they are slow and coarse in their pointing ability. Conversely, reaction wheels allow for agile and accurate pointing. Additionally, reaction wheels tend to occupy volume within the spacecraft that could otherwise be allocated to larger payloads, which would expand the mission capabilities of CubeSats.

Pico-satellite fluid-dynamic actuators (pFDAs) are a novel means of attitude control for pico-satellites [1]. These actuators are being developed at Technische Universität Berlin (TU Berlin) with the goal to combine precise attitude control and low cost, while increasing the integration density. The student project Technische Universität Berlin Pico-satellite Experiment-6 (TUPEX-6) aims to demonstrate the pFDA technology in space. Through participation in the Rocket and Balloon Experiment for University Students (REXUS/BEXUS) program TUPEX-6 has the possibility to launch the experiment into milligravity. An attitude control system consisting of pFDAs is being incorporated into a free falling unit (FFU). A REXUS experiment module with a CubeSat ejector mounted inside is called the rocket-borne equipment (RBE). The FFU is deployed by the ejector to conduct the experiment in milligravity.

Since TUPEX-6 is a student project, it serves as an educational opportunity for the participating students. Except for the designated payload, the pFDA attitude control system, the system is being developed by the TUPEX-6 team. The FFU is closely resembling a single unit (1U) CubeSat, with most of the vital subsystems. Due to the fact that it ejects a pseudo-CubeSat, the RBE is designed complying with the CubeSat design specifications (CDS)[2]. A ground station is being developed by the team as well. Assistance in development is provided by the Chair of Space Technology at TU Berlin and Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation (ZARM).

II. REXUS Campaign

The REXUS/BEXUS program is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through the collaboration with the European Space Agency (ESA). Experts from DLR, Swedish Space Corporation, ZARM and ESA provide technical support to the student teams throughout the project. EuroLaunch, the cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Two rockets and two balloons are launched from Esrange per year with a total of about 20 students designed and built experiments.

TUPEX-6 has been selected for the REXUS 26 mission, with a launch target of March 2019. The REXUS rocket is an unguided, spin stabilized, single stage rocket capable of achieving 90 km altitude for 40 kg of experimental payloads. REXUS/BEXUS is the ideal program for TUPEX-6 versus alternate gravity reducing programs including parabolic flights or drop towers. While parabolic flights offer a lot of total time in microgravity, individually experiments are limited to 20 to 30 seconds. This problem is the same for drop tower experiments with the additional issue of a confined experimental compartment.

The REXUS/BEXUS program is a unique opportunity for students to gain comprehensive hands-on experience progressing a mission through all phases of a space project. Going beyond design phases, typical of master's level coursework, students get to order and build hardware. Additionally, they get to qualify their concepts for rocket flight, before integrating the experiment into REXUS's experiment module, and ultimately the rocket. Finally, student's experience a launch campaign and determine design and performance success after landing. Throughout the program, reviews are conducted with the REXUS/BEXUS program managers. The program is a great situation to educate masters level students in a practical manner which represents the ESA and ECSS frameworks as well as an avenue to trial a new system in attitude control technology. TUPEX-6 has recently progressed to mission phase C, having passed the preliminary design review at the Esrange Space Center, Sweden with agencies organizing REXUS/BEXUS in February 2018. The team is now working towards the critical design review, which will take place in June 2018.

III. Team

Project work is a collaborative effort by students from various areas of study at TU Berlin. However, the majority of students on the team are from the German Master of Aerospace Engineering and International Master of Space Engineering programs under the Chair of Space Technology within the Department of Aeronautics and Astronautics at TU Berlin. A team of at least two students is responsible for each subsystem of the FFU and RBE. The TUPEX-6 project has become part of the Space System Design Project course within the International program, and the German Raumfahrt-systementwurf lecture. The entire project is managed by a core team of nine students with a couple of senior members from the Department acting as advisors. Overall the team is composed of 40 students from 8 countries including Germany, India, Indonesia, Ireland, Mexico, South Africa, South Korea, and the United States. They have diverse backgrounds and experience in aerospace, electrical, and mechanical engineering as well as computer science and physics. This cooperation provides close inter-cultural exchange on technical and personal levels for students. In addition to the experience REXUS/BEXUS provides, TUPEX-6 has become an excellent vehicle for students to interact with researchers from the Department to draw on knowledge from prior and other current projects.

IV. Pico Satellite Fluid Dynamic Actuators

Fluid-dynamic actuators (FDAs) control the attitude of a spacecraft by conservation of angular momentum [3]. Developed for nano-satellites, a single, circular FDA is currently flying on the TU Berlin satellite TechnoSat[4]. Scaled down to a CubeSat form factor, pFDAs are the designated payload of TUPEX-6. A pFDA consists of liquid metal, flowing inside a 3D-printed closed loop channel. Figure 1 illustrates the basic configuration of a fluid-dynamic actuator. The motion of the fluid is controlled by an electromagnetic pump. The actuators do not include any mechanical moving parts and are therefore believed to be wear free. By changing the flow rate of the liquid, torque is induced about its vector of angular momentum. The attitude and magnitude of the vector of angular momentum is dependent on channel geometry. It

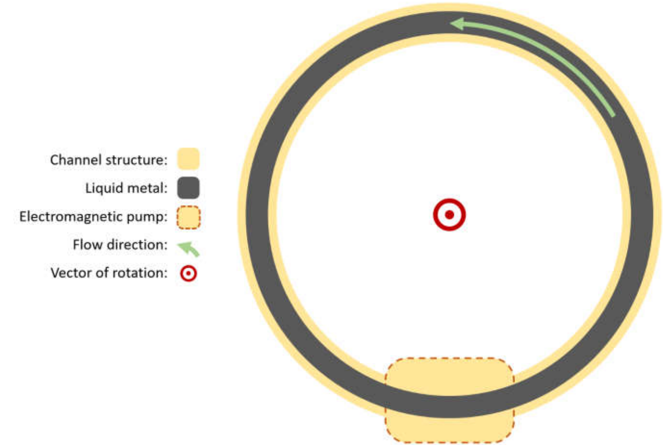

Figure 1: Fundamental configuration of a fluid-dynamic actuator

coincides with the vector of rotation and the main principal axis of the fluid in the channel [5].

Previously, a prototype has been developed and tested. Designed to be integrated in the side panel of a 1U CubeSat, pFDA-A2 has a square shape. Three pFDAs integrated in a 90° angle to each other are necessary for attitude control about all three axis. To achieve 3-axis redundancy, six actuators would be required.

Further research on pFDA technology, with the goal to develop a redundant attitude control system using four actuators, has already been conducted. This research resulted in an L-shaped pFDA. As previously described, the vector of rotation resides along the main principal axis of the moving fluid. For L-shaped pFDAs this principal axis lies in the remaining symmetry plane. Figure 2 shows a mechanical model of a L-shaped pFDA with its remaining symmetry plan and vector of rotation.

Using four L-shape actuators, a redundant 3-axis attitude control system can be constructed. The pFDAs are configured so that the four vectors of rotation are in a tetrahedral configuration. This configuration is often used in reaction wheel systems, since it allows for the highest angular momentum capacity [7]. A attitude control system consisting of four L-shape pFDAs in tetrahedral configuration is designated as the payload of TUPEX-6.

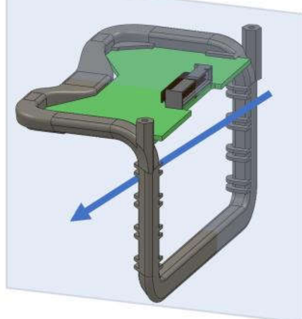

Figure 2. L-shape pFDA with remaining symmetry plane and vector of angular momentum [6]

Figure 3. Preliminary mechanical model of free falling unit [6]

V. FREE FALLING UNIT

A free falling unit is being developed within a mechanical structure very close to the 1U CubeSat form factor to house and support TUPEX-6's experimental payload, the four pFDAs. To increase the integration density, additional structure on the actuator channels was designed to hold printed circuit boards. The subsystems necessary to carry out the experiment, store, and transmit data will be built on these boards. The on-board subsystems are reflective of those necessary to a typical orbital Cubesat mission, however their complexity has been reduced to meet the time and budgetary restraints of the project. The pFDAs will serve as the attitude control system, but will work in parallel with an attitude determination system. The payload data handling unit and on-board computer will share a microprocessor while storing data on redundant SD cards. A communications unit will live stream data to the RBE throughout the experiment. The entire FFU will run on an electrical power system with batteries, but no solar cells. Figure 3 is a model of the FFU within a 1U CubeSat structure.

The recovery unit is colored red in the model, which will house and deploy a parachute for landing as well as provide GPS coordinates for search and recovery. This volume is made available by the pFDAs. The actuators' integrability creates space for potential payloads of the future that may otherwise be allocated to more traditional attitude control systems.

VI. ROCKET BORNE EQUIPMENT

The TUPEX-6 rocket-bore equipment is being hosted by an experiment module located in the upper half of the REXUS rocket. The RBE consists of an ejector for the FFU and the necessary electronics. The experiment module is provided by ZARM and modified to allow deployment of the pseudo-CubeSat. As the FFU complies with the CDS, the ejector does as well. The ejector features a container, in which the FFU is stored prior to ejection. The pseudo-CubeSat is held in place by an in-flight actuated hatch, which closes the container until it is released. A metal string is holding the

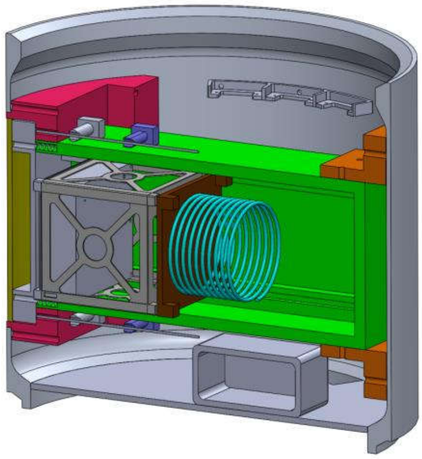

Figure 4. Cut away of mechanical model of RBE with experiment module, ejector and FFU [8]

hatch in place and is released using pyro cutters. Further the ejector hosts a spring with a push plate to perform the ejection. The push plate features an electrical interface between the REXUS rocket and the FFU. This interface allows for recharging of the FFUs' batteries, as well as booting prior to ejection. The ejection is designed to be a single mechanism, so by releasing the hatch, the pseudo-CubeSat is ejected by the spring.

Figure 4 shows a cut away of the preliminary model of the RBE. Visible are the hatch (yellow), the container (green), the spring (blue) with the push plate (brown). Furthermore, the REXUS experiment module, a FFU primary structure and a box containing any electronics (grey) are shown.

VII. EXPERIMENT

The experiment is a sequence of two phases performed autonomously by the free falling unit during its flight in milligravity, following ejection from REXUS and the RBE. It utilizes the 3-axis redundant pFDA attitude control system to demonstrate changes in its attitude. Using an array of sensors, the FFUs' attitude will be determined while in flight. The experiment will demonstrate the capabilities of pFDAs, as well as the redundant architecture of the system. After being launched to approximately 80km altitude, the FFU is being ejected, to conduct the experiment in milligravity, before reentering the denser atmosphere.

The first phase of the experiment utilizes only the actuator, by rotation about its main principal axis. This is done to demonstrate the capabilities of pFDAs. The second simulates the in-flight failure of one actuator. Therefore, during this phase, rotation about the same axis as in the preceding phase is demonstrated utilizing all pFDAs but the previously used one. This part of the experiment shows the 3-axis redundancy of the pFDA attitude control system. The system allows for attitude control about all three axis, even in case of failure of one actuator.

VIII. CONCLUSION

Attitude control technology currently available to small satellites, namely CubeSats, is becoming increasingly insufficient at a proper balance of volume consumption and cost versus operational payload support. TU Berlin is researching a new technology, fluid-dynamic actuation, and simultaneously attempting to scale it for pico and nano satellite form factors. TUPEX-6 is a mission to experimentally verify the utility of these pico actuators via the REXUS/BEXUS program. The nature of the mission necessitates students to develop every element of a typical space mission including, a free falling unit carrying the payload, RBE to support and eject the FFU, a ground station to receive data, and mechanical and electrical ground support equipment. As a result, the project is a superior educational experience for the students by very closely simulating a real space mission from start to finish.

ACKNOLEDGEMENTS

The entire TUPEX-6 team would like to thank the project adviser, Sebastian Grau, for his unending assistance with the project. Martin Buscher and Jens Großhans administered the lectures helping to drive the project. Cem Avsar and Professor Klaus Brieß allowed TUPEX-6 to be incorporated into the curriculum. All of the entities involved with REXUS/BEXUS: DLR, SNSB, ESA, ZARM, MORABA, and Eurolaunch. Finally, a big thank you to everyone at TU Berlin's Chair of Space Technology for giving time away from their own projects to share expertise with students.

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Rocket and Balloon Experiments for Students – Milestones to Success

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***Abstract*— Two sounding rockets and two stratospheric balloons are launched each year from Esrange Space Centre in the polar region of northern Sweden. The payload on board these vehicles consists of scientific experiments which are conceived, designed and built over several months by student teams participating in the REXUS/BEXUS (Rocket and Balloon Experiments for University Students) programme. The project life-cycle is based on that of professional space missions and incorporates a training week, several reviews, an integration and test phase and the launch campaigns, as well as the result analysis and dissemination. While passing these milestones, the students team always have a constant companion to complete and to update: their SED (Student Experiment Documentation). This document is a guideline based on the programme organisers' engineering and management experience and has been improved over the last decade during which the programme has been running.**

ZARM (Center of applied space technology and microgravity) has supported student teams for 5 years and gives an insight into the REXUS/BEXUS milestones which are not merely a design step, but rather they are composed of interesting events taking place at various space-related locations. As the SED is inseparable from the milestones and the most essential document for experiment preparation, this paper additionally outlines the SED content. The Milestones and the SED reflect the programme idea of how to document, design, build and test an experiment which performs successfully on board a REXUS or BEXUS near-space vehicle.

Keywords— REXUS/BEXUS, Milestones, Rocket, Balloon, ZARM

I. The REXUS/BEXUS Programme

The REXUS/BEXUS (Rocket and Balloon Experiments for University Students) programme is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA). On behalf of DLR Space Administration, the Center of Applied Space Technology and Microgravity (ZARM) carries out the German share of the programme. The experiment campaigns and the student support are conducted in close cooperation between DLR - Mobile Rocket Base (MORABA), SSC, ESA and ZARM.

The programme offers students the opportunity to fly a self-developed experiment on a sounding rocket or on a stratospheric balloon. While the student teams conceive, design and build their experiment for several months, they receive training and support from DLR, SSC, ZARM and ESA experts. Two sounding rockets and two stratospheric balloons are launched each year from Esrange Space Centre in the polar region of northern Sweden carrying up to 20 Students Experiments.

II. The Vehicles

The REXUS/BEXUS programme provides two types of near space vehicles, sounding rockets and stratospheric balloons, which are well suited for engineering and natural science experimentation.

The REXUS Rocket is a single stage, unguided, fin stabilized rocket system which uses surplus military rocket motors having a dual phase solid propellant. The launch mass is about 515 kg, the launch length is about 5,6 m and the rocket diameter is 356 mm. The fins are nominally canted to provide a four revolutions per second spin rate in order to neutralize any effects of nonsymmetrical thrust. To provide reduced gravity, a yoyo mechanism can be activated to reduce the spin rate of the rocket. In addition to the motor, the REXUS rocket standard includes a recovery-module, a service-module and systems to separate the motor and nosecone if required. The rocket carries up to 44 kg scientific payload up to an altitude of 85 km. The total flight time is about 10 minutes, within 120 seconds of reduced gravity with a quality of 10-2 g.

The BEXUS Balloon consists of a 12.000 m3 helium gas filled polyethylene envelope, communication, recovery and flight safety systems, as well as a gondola to carry the scientific payload. The gondola is a welded aluminium frame with the dimensions 1160mm x 1160mm x 850mm. The balloon carries up to 100 kg scientific payload up to 25 to 30 kilometers altitude. After the inflated balloon has been released it ascents with a rate of 5 m/s until equilibrium is reached where the balloon floats inside the stratosphere for the required time. For landing, the gondola is separated from the balloon and carried to ground by a parachute with a descent speed of 8 m/s.

III. Project Milestones

The life-cycle of the programme lasts 18 month at REXUS and 12 month at BEXUS. It starts with a selection workshop and ends with the submission of the final documentation, which also contains the experiment results and evaluation. In between, the teams are invited to various milestone-events where the progress of the teams is reviewed. While the participating teams conceive, design and build their own experiment, they must keep in pace with the following fixed programme milestones:

- Preliminary Design Review (PDR) and Training Week
- Critical Design Review (CDR)
- Integration Progress Review (IPR)
- Experiment Acceptance Review (EAR)
- Integration Week and Bench Test (only for REXUS)

The REXUS/BEXUS milestones are not merely a design step, but rather they are composed of several days events taking place at various space-related locations like Esrange/Kiruna, DLR/Oberpfaffenhofen, ESA-ESTEC/Nordwijk and ZARM/Bremen. The highlights of every milestone event are the reviews themselfes, which include a team presentation and a discussion between the team and several experts from DLR, ESA, SNSB, SSC and ZARM. Furthermore lectures, guided tours and environmental experiment tests are mostly in the schedule of these interesting events.

Two weeks before the review, each team has to upload a new version of their Student Experiment Documentation (SED) to ensure that experiment design can be checked in advance by experts [2]. The SED bundles a variety of aerospace documents into a single document containing the chapters: Scientific Introduction, Requirements and Constraints, Project Planning, Experiment Design, Verification and Test, Launch Campaign as well as Data Analysis and Results. To assist in the preparation of this document, detailed guidelines are provided to the teams. It is a living document that needs to be continually updated throughout the life cycle in 5 versions: A new version before each review and a final version at the end of the project, which contains all the results to receive the coveted REXUS/BEXUS certificate.The way to a successful Experiment

IV. Under pressure

Although the teams have often very ambitious objectives and little time for building a complex scientific experiment, most teams are successful! ZARM has supported student teams for 5 years applying the described life-cycle. It is a challenge for the teams to follow this preconceived way without falling behind. Some former teams came under time pressure and could not perform all their predefined tests before campaign which mostly ended up in not reaching all objectives. This a dilemma, because we believe that the key to successful experiment campaign is the successful completion of the functional and environmental tests. How can it be avoided that teams are so under pressure that they can not finish their test plan.

Evaluation of the supported DLR teams between 2014 and 2018 showed that teams were under pressure, because they underestimated the amount of work and the needed skills. For this reason DLR/ZARM starts to de-scope the scientific objectives and the experiment functionality appropriate team experience and abilities by PDR at the latest. It was also interesting for us to find out why 12 of 28 DLR teams with a similar level of complexity have not been short in time and reached remarkable full success. A good project management paired with a technical experienced team was the simple answer. But moreover it was noticeable that 10 of these 12 Teams started building critical experiment parts very early. In addition it was obvious that they were focused on fulfilling their test plan. As a result, we will deepen our support in the direction of early implementation and we will ask the DLR teams to build critical items very early, even before CDR, regardless of any wasted money. Furthermore it should be considered to expand the program by an Integration-Week for BEXUS containing functional, interference and Thermal-Vacuum-Tests to ensure that the experiments are tested like the REXUS experiments before campaign.

V. Adventure and Advantages for the Participants

Students with different experience and interests take part in the programme. Experienced PhD students may want to collect scientific data for their thesis by using an advanced experiment. On the other hand, first-semester students may just want to test a device in space. It varies in how the participants benefit from the programme and it depends on their own abilities and interests.

A. Upgrade your education:

It is a challenge for many students to work in one of the areas listed below because they may deal with this subject for the first time. But they get feedback, training and are supported in the editing and can thereby improve their knowledge and skills during their project. Participants gather a lot of new experiences and can deepen their education in the following areas:

- Writing a proposal and participate on a selection workshop
- Outline your project with an interesting abstract
- Declare your mission statement and explain the scientific background
- Find methods to analyse your data
- Get in touch with newspaper and journals to publish your results
- Present your experiment and results on conferences and design a scientific poster
- Experience a complete life-cycle of a space project

- Learn how to write a space-related project document
- Learn to define and classify your requirements and find methods to verify them
- Work with risk management methods
- Manage your team to conceive, design, build, test and fly a scientific experiment
- Present your design at reviews to experts out of the space business and defend it during discussion
- Specify and conduct functional and environmental Tests at professional Test-Facilities
- Prepare and operate your experiment on a launch campaign
- Design and program flight-software for experiment data handling, communication and control
- Make use of CAD based modelling for mechanical components
- Learn how to make thermal calculations and implement a complete thermal design
- Design electronic schematics and build PCBs and learn how to solder for space applications in a provided course
- And many more…

B. Experience a space project adventure

As you can see, students can learn a lot, but REXUS/BEXUS is also a space project adventure. The students travel to exciting places, meet other students from all over Europe and work hand in hand with professionals from the space sector.

- Get in touch with many other students from all over Europe
- Make new contacts with professionals from agencies, institutes and companies.
- Work hand in hand with established space engineers and scientist
- Travel to DLR-Oberpfaffenhofen and DLR-Bonn and work inside famous space facilities like the German Space Operations Center (GSOC) and inside the DLR-MORABA integration hall.
- Experience ESA-ESTEC
- Work next to scientist and engineers inside ZARMs drop tower integration hall
- Experience a real space campaign in an exceptional location
- Enjoy the supporting program at the milestone-events

C. Collect scientific data on a near space vehicle

As the vehicles are very well suited to gain scientific data, some institutions and university faculties are interested in using the vehicles for their research purposes. This is fine as long as the participation fees of the program are fulfilled. This means that the participants are enrolled in a university and their doctorate is not completed when they apply.

- Increase your scientific reputation
- Use your experiment for your Bachelor- Master or PhD Thesis
- Collect data or samples for your faculty or institute

D. What do former participants say about the benefits of the programme?

In order to evaluate the effectiveness of the programme three alumni surveys have been performed. The following is an extract on the career and skills from the survey conducted in 2016 (Becker, Kinnaird et al. 2017), with the exception of the topic Advantages for the study which is new.

[1] The 2016 survey was sent to 439 alumni with valid email addresses as well as promoted in alumni groups and shared between alumni. 107 responses were received, roughly corresponding to a statically relevant 10% of alumni at the time. The gender ratio (approx. 20% female) and nationality distribution (high numbers from DE, IT, ES and SE) also suggest an approximately representative sample. Answers were received from all vehicles apart from BEXUS 12/13 (2011), 16 (2013), 18 (2014) and REXUS 8 (2010). At least one answer was received from every cycle.

1) Carreer

- 92% have increased in their interest in a space- related career, with 79% saying they are ‘more’ or ‘much more’ likely to pursue a space-related career
- 88% say REXUS/BEXUS is relevant to their career and 78% say REXUS/BEXUS has been a ‘springboard’ for their career.
- Of those employed the largest areas of employment are ‘Aerospace’ (36%), ‘Academia’ (16%) and ‘Space’ (8%). 66% are engaged in self- identified ‘space-related’ employment.

An unintended result of the survey is the knowledge of current employment country vs. country of origin/study, with around 29% of alumni working abroad, with Germany, the UK and Sweden being the most popular countries for expat alumni.

2) Skills developed

- All learning aspects in the programme are valued, but participants placed particular emphasis on the usefulness of the practical aspect of knowledge in design (88% very useful or useful) and in building/testing (89%) as well as contact with experts (77%) and ‘self-learning’ (86%).
- In particular the practical application of knowledge in building and testing and ‘self-learning’ were both consistently ranked as ‘very useful’ when considering current and future careers.
- Participants consistently report that the participation has increased their understanding of the space project life cycle (91%), space project processes (91%).
- Participants consistently report participation has increased their design skills (92%), practical skills (93%) and team work skills (93%).

E. Advantages during the study

Many participants used their experiment or their results for their Bachelor, Master or PhD thesis. Of the 107 survey responses representing about one-tenth of the participants, 10 use their participation for their bachelor thesis, 17 used it is as part of their Masters Thesis, and 7 as part of a PhD thesis. If you extrapolate this number to the actual number of participants, then the remarkable number of around 100 Bachelors thesis, 170 master thesis, 70 PhD thesis works comes out, which are least partly based on REXUS/BEXUS projects until 2016.

In Germany, the structure of the study has changed due to the introduction of bachelor's and master's degrees. This gives students less time for external projects, such as REXUS / BEXUS. However, it can be observed that more and more universities are trying to support the students in participating in the REXUS / BEXUS program and even award credits for it.

Furthermore the survey received a lot of qualitative feedback, with a lot of praise for its effectiveness, but also a number of points which the programme could address within future cycles. The negative aspects which were often repeated focused on the large time commitment, problems with experiment funding, problems with support within universities, internal team conflicts and the documentation requirement.

The overall impression of the survey is one of very high satisfaction with the programme and a consistent message of appreciation of students for their participation.

VI. Conclusion

The REXUS/BEXUS programme provides two types of near space vehicles, sounding rockets and stratospheric balloons, which are well suited for engineering and natural science experimentation.

It is an ambitious way to follow the REXUS/BEXUS milestones in which challenging reviews take place and during which a sophisticated documentation must be made. But it's worth it, because the programme offers students many opportunities to benefit from. Students with different education levels can benefit in different ways. All facets are possible ranging from learning a simple practical activity over developing a CAD-model up to receiving a scientific award. And it is a space project adventure where participants travel to several space-related locations and work hand in hand together with space-engineers and scientists. The highlight is of course being part of a launch campaign in the polar region of Sweden at Esrange Space Center.

Most of the participating teams are very successful but some teams came under time pressure because they underestimated the workload and needed skills. To prevent teams from being under pressure the DLR experiments are de-scoped by the organisers appropriate team experience and team abilities.

Especially with the BEXUS branch of the program, insufficient testing also seems to be a cause that some teams do not achieve all of their goals. In order to improve this, the introduction of an integration week for BEXUS, similar to REXUS, should be considered.

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High-quality Experiment Dedicated to microGravity Exploration, Heat Flow and Oscillation Measurement from Gdańsk

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***Abstract*—In this paper we propose HEDGEHOG (High-quality Experiment Dedicated to microGravity Exploration, Heat flow and Oscillation measurement from Gdańsk) REXUS experiment to investigate vibrational and heat flow phenomena during the whole (ascent, microgravity phase, descent and recovery) flight of a sounding rocket.**

First, a proposed system of cantilever beams is discussed to study dynamic behaviour of dummy payload. Dimensioning has been chosen as a results of initial FEM analysis. Secondly, a novel approach to measuring heat flux has been proposed, according to team leader's pending patent. A inverse heat transfer problem (IHTP) has been solved for SMARD (REXUS-18 experiment) data to enable for dimensioning of the experiment. Finally, an initial design is briefly described.

Keywords—REXUS; vibrations; heat flux

I. Introduction

As access to space conditions becomes more available, both technically and economically, scientists' interest in launching finer and more sophisticated experiments grows. This applies now more than ever to fragile by nature biological and chemical experiments [1].

To be qualified for launch, such experiments need to be carefully tested prior to the event. The tests should represent actual launch conditions as closely and in as detailed manner as possible. For this reason, comprehensive measurements of launch conditions are required.

Most important acceptance tests required for module acceptance are vibration tests and thermal tests. This experiment focuses on measuring acceleration and vibrations (especially eigenfrequencies) conditions and heat transfer inside a sounding rocket as a reference for future ground acceptance tests.

II. Scientific and Technical Objectives

The experiment's scientific challenge is to obtain precise information on acceleration and vibration environment that payload is subject to during whole course of sounding rocket flight. Although an envelope of environmental conditions is known and publicly available, including spectral data [2], their application is usually limited to serving as general guideline due to their lack of details. In case of vibrations, this is usually low frequency range of measurements, as high frequency vibrations tend to be less important for sturdy REXUS experiments.

The second scientific objective is to measure temperature in various locations of the section of the sounding rocket. With such data, it would be possible to create the model of heat flux transfer [3] inside the launch vehicle. Obtained results will allow for precise verification of future payload. Previous REXUS experiments typically included single point temperature measurements, focusing on local effects rather than heat transfer phenomena.

As the experiment will be equipped with high precision MEMS accelerometer, the quality of microgravity could be measured as a secondary objective. This requires despin, so it highly depends on other teams' and Eurolaunch requirements.

One of the greatest technical challenges we detected is to design a dummy payload to study its vibrations. This is due to the fact that the dynamic behaviour of the object depends not only on the external environment, but also on object's own properties, such as system's resonant frequencies.

Another technical challenge is to properly and precisely measure heat flow inside the rocket. As the environment (i.e. convection coefficient) is not well known, the experiment must ensure simple, homogenous heat flow to allow for model identification, and in result, calculation of heat flux in rocket skin.

III. Solution Approach

A. Vibrational part

The first part of the experiment focuses on vibrational phenomena. We plan to construct an experiment consisting of several cantilever beams, each tuned to a specific eigenfrequency acting as acceleration amplifiers. In preparation to this application, our science team has found a paper by FH Aachen scientists and REXUS engineers on modal analysis of REXUS 11 rocket [4]. The main resonances were identified to be: 364 Hz, 600 Hz and 780 Hz. After consultation with our endorsing professors, we decided on 10 cantilever beams with frequencies ranging from 300 Hz to 800 Hz, focusing on resonant frequencies. Initial values were chosen to be: 300 Hz, 364 Hz, 400 Hz, 500 Hz, 590 Hz, 600 Hz, 610 Hz, 770 Hz, 780 Hz, 790 Hz.

In order to fit cantilever beams inside the rocket and distribute them equally, we have designed a round, thin plate with beams on the perimeter. This is considering the centre of mass coordinates and moment of inertia limits required for REXUS experiments. For manufacturability reasons, all beams and the ring that connects them will be water jet or laser cut from aluminium plate (see figure 1).

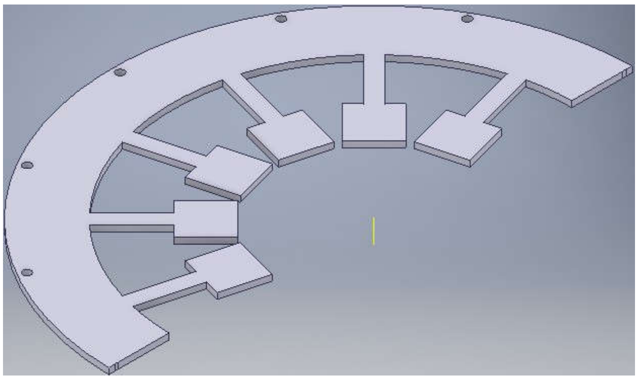


Fig. 1. Aluminium plate with cantilever beams.

Variation in beam resonant frequencies will be achieved by varying their dimensions (other than thickness, see table 1). These sizes were defined upon a Finite Element Method analysis performed in ANSYS (see figure 2). Chosen material is 6060 aluminium, based on its availability and similarity to rocket skin material.

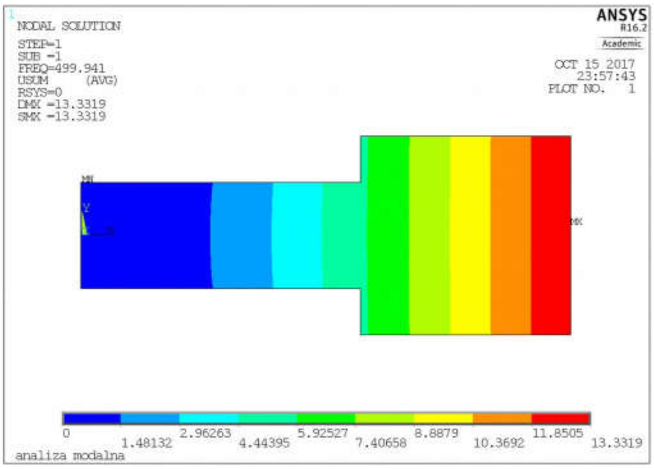
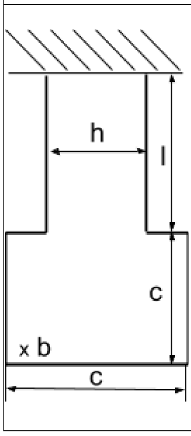


Fig. 2. Beam modal FEM analysis in ANSYS.

TABLE I. CANTILEVER BEAM DIMENSIONS

	dimensions: c=30 mm l x h x b [mm]	*first resonant frequency [Hz]*
	51.2 x 10.0 x 4	300
	43.3 x 10.0 x 4	364
	40.0 x 10.2 x 4	402
	40.0 x 16.2 x 4	500
	40.0 x 22.7 x 4	591
	40.0 x 23.5 x 4	601
	40.0 x 24.3 x 4	610
	35.0 x 29.2 x 4	771
	35.0 x 30.0 x 4	781
	35.0 x 30.0 x 4	790

Each experiment beam will be equipped with a MEMS accelerometer to measure its vibrations (see figure \ref{fig:location}). The bandwidth should allow to capture both first resonant frequency of the beam and full test frequency range required by ECSS for mechanical loads to allow comparison of norm tests with real conditions.

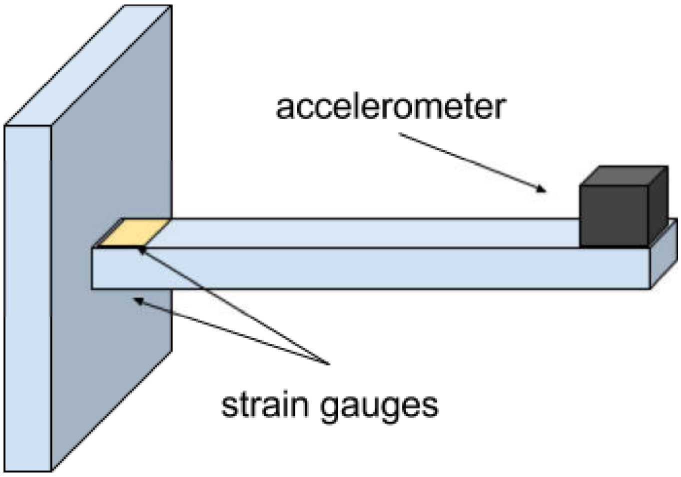


Fig. 3. Accelerometer and strain gauge location

Additionally, each experiment beam will be equipped with a set of two differential strain gauges that will allow to measure its stress and displacement. This could be also achieved by double integration of acceleration values, but this leads to integrating errors [5].

Also, a high precision, wide bandwidth (widest commercially available) MEMS accelerometer will be installed for general (not on "tuned" beams) acceleration and vibration measurement. This would allow for cross-correlation of vibrations of beams and in other parts of rocket. As a secondary objective, the quality of microgravity with 10^{-4} g precision and 15 kHz frequency will be measured and shared with other teams and Eurolaunch team if needed.

Finally, a camera will be mounted for constant visual inspection. A specific model will be required to have small size and autonomy (starts recording when powered). This is subject to further analysis of our team.

B. Heat transfer part

The second part of the experiment focuses on heat transfer phenomena. We plan to construct a cylinder of aluminium covered with thick layer of insulation (styrofoam, MLI, to be determined).

The design with necking (see figure 4) forces homogenous heat flow, creating a simple 1D flow situation, easy for model fitting. At each end of the "neck", a thermocouple will be placed in such a way as to interfere the heat flow as least as possible. The bigger inner part will act as a heat tank that will hold a specific amount of thermal energy.

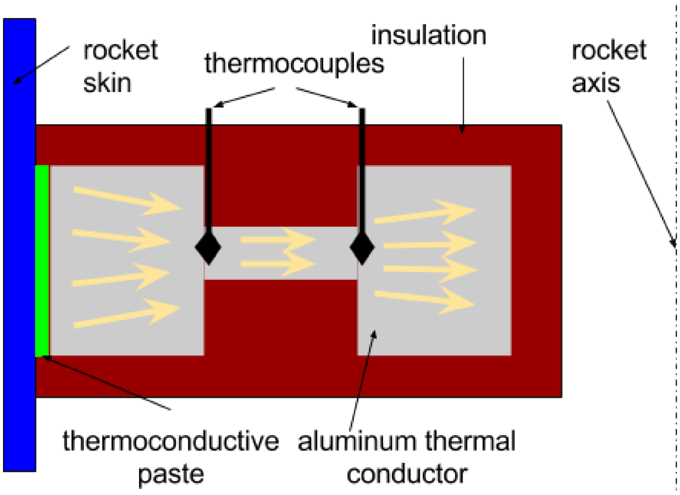


Fig. 4. Heat flux measurement device (patent pending).

The heat transferred Q [J] can be calculated using Fourier's Law [3]:

$$Q = k \cdot A \cdot \Delta T / L \quad (1)$$

where k is thermal conductivity of material [W/(m·K)], A is the cross section [m^2], ΔT is temperature difference [K] and L is length of the necking [m]. By measuring temperatures with thermocouples ΔT can be calculated, while other values are constants. This would allow for calculating external heat flux on rocket skin.

To allow for dimensioning, initial guess for heat flow on the rocket surface was required. This has proved to be difficult, as not only no other REXUS experiment has measured heat flux through rocket skin during flight. A heat flux on rocket skin was measured by DLR [6], but they focused on heat flux from the propulsion engine rather than on this from aerodynamic friction. Most of REXUS teams focused on local temperature changes.

We decided to use SMARD, REXUS-18 experiment [7] data (temperature vs. time, see figure 5) with precise location and geometry of their experiment to solve *inverse heat transfer problem (IHTP)*, i.e. find the heat flux given temperature. As their setup was not designed for it, the results can only be used as a first educated guess.

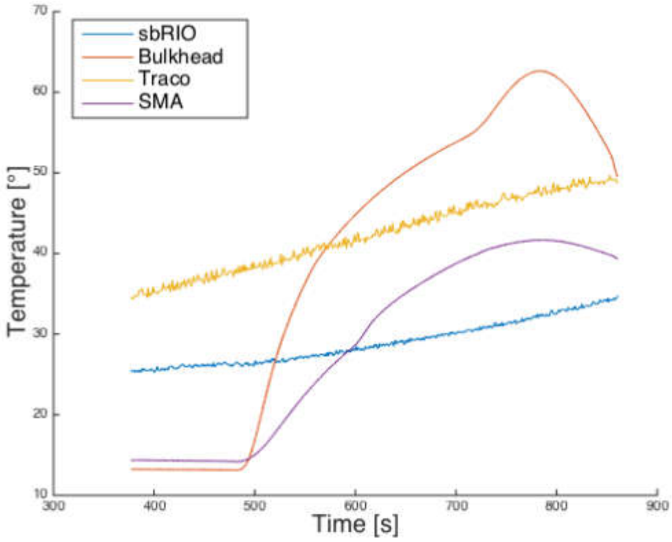


Fig. 5. Temperature curves of SMARD (REXUS-18) experiment [7].

The procedure was based on [8]:

1. Initial guess for heat flux density on walls [W/m^2].
2. Forward heat transfer problem in ANSYS using SMARD CAD model (figure 6).
3. Comparison of results with SMARD data.
4. If, the results are not satisfactory, change heat flux and go to 2.

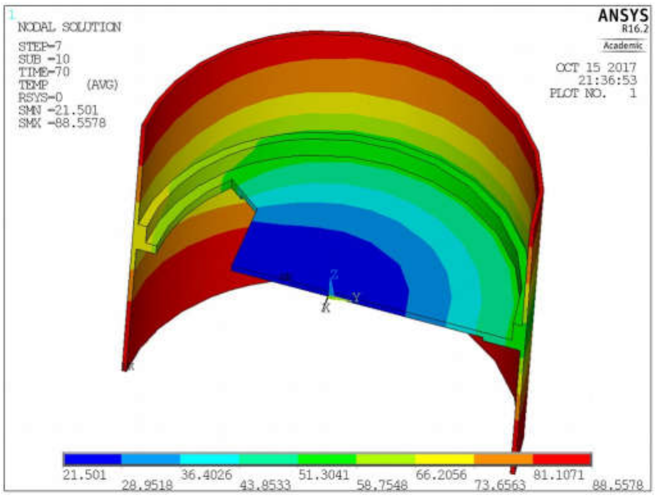


Fig. 6. Heat flux of SMARD (REXUS-18) experiment.

This allowed for dimensioning of our experiment. Initial heat transfer simulation with previously obtained heat flux was performed (see figure 8 and 9, thus suggesting that our experiment can precisely fulfill its goal. We would like to further verify this idea in REXUS programme.

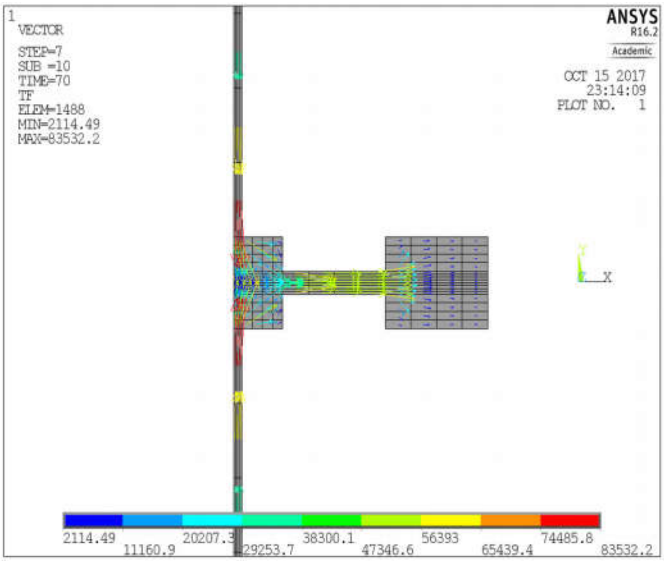


Fig. 7. ANSYS simulation of our heat transfer experiment. Vectors show heat flux. Note 1D flux in the necking.

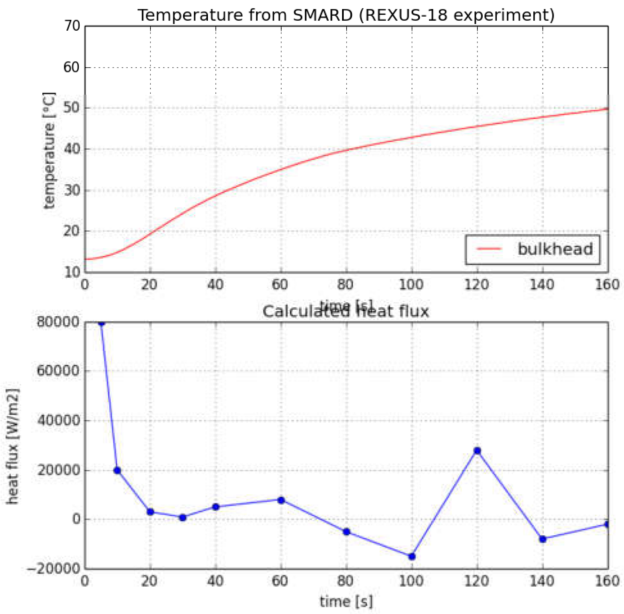


Fig. 9. Results of simulation of our heat transfer experiment: calculated heat flux.

IV. Experiment Setup

The mechanical system consists of two cylindrical parts. Upper one consists of a plate where electronics will be placed. It is connected to vibration experiment with a thick ring that allows for mounting it to rocket with radial bolts (to be discussed with Eurolaunch). Lower part is a thermal cylindrical structure that will be bolted radially to skin surface. It is covered by layer of insulation. The camera will be mounted between two cantilever beams, bolted to the beams mounting ring.

Electronics in the project include:

- MCU based on STM32 microcontroller,
- ADCs (Analogue to Digital Converters),
- external memory based on flash memory,
- main digital accelerometer (Analog Devices ADIS16223),
- 8 thermocouples, type T with multi channel amplifiers to thermal experiment,
- 20 foil strain gauges with Wheatstone bridge circuits to differential measurements,
- 10 analogue accelerometers,
- 3 RTDs (resistance thermometer, resistance temperature detector) temperature sensor,
- digital pressure sensor,
- step-down voltage converters for camera, MCU and sensors,
- current sensor, to detect if the camera is working
- external camera with own SD memory card.

Every analogue sensor will include a passive RC low pass filter. RC filters will be used to cut off the noise that are results of Foucault currents in the connections, conductors and paths on the PCB board.

For each pair of foil strain gauges (attached above and below the beams) a Wheatstone bridge will be added to compensate for the influence of temperature. This type of connection is a differential circuit. Differential circuit double the measurement signal and (with appropriate calibration, by selection of resistance) increase accuracy.

Our experiment setup is presented in figure 9.

Acknowledgments

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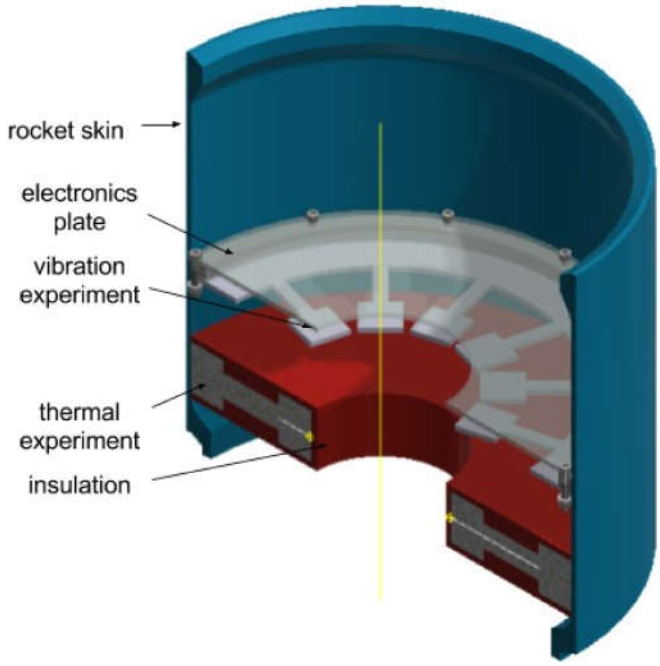

Fig. 9. Experiment cross-section.

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About *in situ* resource utilisation for oxygen production on Mars using non-thermal CO_2 plasmas

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1 Introduction

Developing a supply of oxygen on the Red Planet would go some distance towards sustaining a human colony on Mars. The solution proposed by NASA (MOXIE), mostly a CO_2 electrolysis device, barely exploits the specificities of the atmosphere there. Finding ways to benefit from the very low pressure and the temperature averaging around 210K can potentially improve our usage of the 96% of CO_2 in the atmosphere. Non thermal radio frequency plasma can, under a precise set of circumstances close to the surface conditions of Mars, dissociate quite easily the CO_2 into O_2. However, this set of settings has yet to be determined, and the influence of many parameters remains to be tested. Here we report the conception and optimisation of a low pressure non thermal CO_2 plasma with quantification of the influence of the different parameters.

We show that pulsing the discharge allows us to lower the temperature of the device and thus improve the dissociation rate and the energy efficiency. Then the study of different parameters (injected power, frequency and duration of the pulse, temperature/pressure/flux of the gas) gives us the optimal settings for the plasma in itself, and are as we believed really close to the natural conditions on Mars. We then study the influence of external parameters such as the adjonction of a set of catalysts (iron, titanium and silicium oxide or nitrogen among others) to maximise the dissociation rate and the energy efficiency. Another major issue we tackle is the gas separation since we want to extract the newly formed O_2 from the CO_2, O_2 and CO mixture that we get out of the plasma reactor. For all of these measurements we use an infrared spectroscopy device in the Plasma Physics Laboratory (LPP).

It is to be noted that the O_2 produced would not only allow astronauts to breathe but it could also fuel rockets enabling a potential trip back to Earth or further space exploration. NASA actually sees the second option as the most likely use given the yield of their system. When many engineering aspects are managed, such as gas injection or dust filtering, which will probably take a few years, we can hope to be able to propose a comprehensive alternative to the existing systems for air recycling and oxygen production on Mars.

We want to thank Olivier Guaitella (Plasma Physics Laboratory in Polytechnique-CNRS Paris Sud) for being the mentor of this student project and always leading us in the right direction in a benevolent way.

2 State of the art

With its plan to send the first manned mission to Mars by 2040, the NASA proves to be very interested in finding a reliable and cheap way to master in situ resources utilisation for oxygen production. The solution they made public for their 2020 Martian Rover, MOXIE, is an electrolysis device which collects the atmospheric gas through dust filters, heats it up to 1000K and compresses it up to $1atm$. After collecting the gas, it is fed to the Solid Oxide Electrolyser which electrochemically splits the CO_2 into O_2 along with a CO/CO_2 mixture. Michael Hecht[1], whom we got in contact with, told us that one of the reason they had adopted this strategy was because of its high TRL[2], which means it has been duly tested and proved to be extremely trustworthy.

MOXIE announces a yield of 10 grams of pure O_2 per hour, with an electrical consumption of 300W. As of today it is a test module : it is the size of a battery car and human missions on Mars will requirer 100 times larger device. If it works as planned, it will be able to provide 3/4 of the required amount of propellant to explore the Red Planet.

It is to be noted that Mars receives a flux of $\sim 600W/m^2$ from the sun and as of today, the best solar panels are able to collect 20% of this power.

3 About the non-thermal RF Plasmas

The most surprising aspect of Moxie is that it requires to heat up the gas and to compress it which seems to cause massive loss of energy, when the temperature averages around 200K and the pressure is about 600Pa ($\sim 4,5$ Torr). The idea that our tutor, Olivier Guaitella, submitted to us was that we could

[1]Head of the MOXIE project
[2]Technology Readiness Level

make better use of the local conditions to dissociate CO_2 by using non thermal plasma.

3.1 What is a non-thermal Plasma ?

The point of using non-thermal plasmas (also called non equilibrium plasmas) is that we have an increased control over the excitation of the CO_2 molecules. Indeed in a non thermal-plasma, the electric field tears some electrons away from the CO_2 molecules we put in the reactor, and the temperature (ie. the energy) of the electrons far exceed the temperature of the ions and remaining molecules[3]. That way, the molecules are a lot more stable and we can slowly excite them until the precise point where it dissociates into CO and $\frac{1}{2}O_2$.

When energy is given to the plasma some of it is used to increase vibrations inside the CO_2 molecules and the remaining power heats up the gas through translational excitation. The CO_2 molecules dissociate when their vibrational temperature exceed 5.5 eV. Translational excitation is an energy loss. Non thermal plasmas, because they enable better selectivity between translational and vibrational excitation, are relevant to achieve greater energy efficiency.

Furthermore, low pressure on Mars is an asset because the power required to ignite the plasma meets a minimum around 1 Torr which is in the same range than the pressure on Mars. Because vibrational to translational energy exchange is easier when the translational energy is high, low temperature on Mars fosters vibrational pumping against translational losses.

3.2 Our set up

For all of our work, we used the apparatus provided by our tutor in the facilities of the LPP in Ecole Polytechnique. Our set up consists in a Radio Frequency generator, connected to both the electrodes around a Pyrex cylindrical plasma reactor (13cm length, 2cm diameter), operating under flowing conditions about 1-5 Torr and 7,4sccm of CO_2. These conditions are achieved through a scroll pump that controls the overall pressure and some mass flow controlers. We measure the dissociation with a FTIR (Fourier Transform InfraRed) spectroscope that gives us the absorbtion rate of CO_2 and CO, of which we deduce the dissociation rate of our set of settings.

The intrinsic parameters we can test are the **injected power**, the **pressure** of the plasma, the **temperature** of the injected gas and finally **pulsing** the generator.

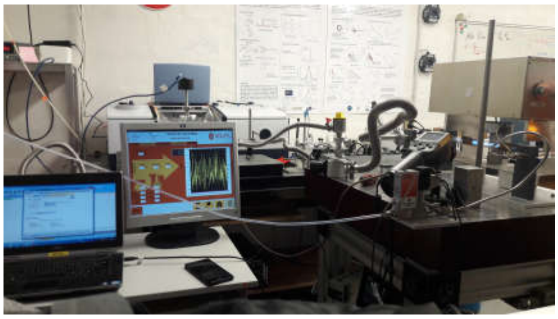


Figure 1: Our entire setup : from the FTIR to the reactor through the remote controled mass flow controler

Then we can evaluate the impact of the adjonction of various **catalysts**. Indeed, we hope that using catalysts will enable us to reach even higher energy efficiency rates. It could be performed in two ways: by rising the reaction's speed, and thus enabling us to put a more important gas flow; by making the selectivity of the reaction better in promoting the recombination of O atoms in dioxygen or preventing the reverse reaction that would see dioxygen molecules turning back into CO_2 molecules.

There are only a few articles that explain which catalyst works best for dissociating carbon dioxide. There are even fewer which could give us relevant insights, because of the specific conditions we must cope with. Not only the low temperature and pression can be a problem, but the nature of a non-thermal plasma is to be out of chemical equilibrium. We had to guess possible good catalysts, and we plan to test them individually to see which works best.

We also had to find a compromise between small chemical components (typically a micro-millimeter dust of oxides) which offer big surface of contact and big chemical components which are easier to use. We were lucky to be offered the support of Saint-Gobain™, who proposed us to have samples of Microspheres™ of various metal oxides. Those spheres offer a high contact surface ($90\text{m}^2/g$) in a convenient way: 2-3 millimeters beads we will place directly inside the reactor. Among others, we chose iron oxides (given the fact there's plenty on Mars), titanium and siliceous oxides (given their affinity with oxygen).

We are to obtain the catalyst by beginning of March. We will try them as soon as we get them.

Another major issue we are still handling is gas cooling. It has come to be suspected as one of the most important parameters to evaluate the impact of. In the very first stages of experimentation, we attempted to measure its influence on the dissociation rate, but it proved challenging. Our naïve setup, consisting of a gas tubing coil submerged in liquid nitrogen, not only solidified the CO_2 but the remaining

[3] On the other hand, in thermal plasmas both these temperatures are extremely high and have the same size, which makes the molecules as reactive as the electrons thus decreasing the stability of the plasma.

amount of gas was too hot by the time it reached the reactor. We are currently in the design process for a glass double envelope exchanger which, in conjunction with proper gas tubing isolation and preliminary apparatus cooling procedures, will enable us to probe much lower temperatures and to compensate for the heat produced by the plasma itself, which would certainly go a long way in cleaning up our experimental results.

A critical element not yet mentionned is the matchbox. As in all high frequency electrical circuit, the impedance of our set up implies some reflected power which has to be minimised in order not to degrade the generator. Without a high quality matchbox we are extremely limited in the range of measurements we can make (especially for the injected power but also for the pressure). Indeed, the generator could be damaged if the reflected power caused by the impedance of the plasma would rise too high. To be able to experiment at high input power, we had to reduce the reflected power and to do so, calibrate the matchbox for our set up. It is a simple electronic circuit that adds variable induction and capacitors in our circuit and thus varies the impedance of the system. A simple solution came at ease, by testing different possibilities of adding varying capacitors, we found that in a certain pattern, we could modulate the **amplitude** and **phase** of the reflected signal with full control. The matchbox is now completely calibrated and lets us reduce the reflected power to 0.01 W in any conditions. Its present dimensions (30x50x15 cm) could easily be diminished for a more practical use.

Figure 2: The matchbox we conceived

3.3 Our results

More specifically, our work consists in finding a sufficiently optimal setting. We decided in the beginning we would only study (to begin with) on the bases of a 7,4sccm[4] flux of CO_2 and a distance between the electrodes of 12cm because it was the most adapted values regarding the geometry of our reactor. Then we tried optimising the energy efficiency by varying pressure and injected power. To measure how good each setting was, we calculated the dissociation rate α (ie. the proportion of broken CO_2 molecule) and then evaluated the ratio $\frac{P_{injected}}{\alpha}$ which is proportional to the energy required for each broken molecule[5], that same amount we want to minimise. In the following graphs, we plotted our measurements and extrapolated in a linear way to all other values. We use here the injected current instead of the power since it is easier to measure and a lot more precise.

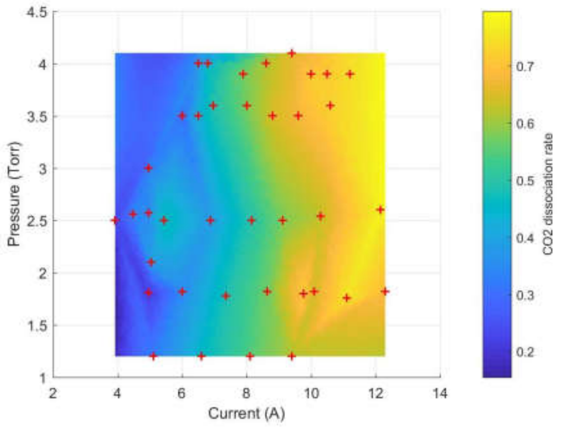


Figure 3: Visual representation of the dissociation rate regarding pressure and injected power

Here we can see, as suspected, that the dissociation rate rises as we send more and more power to the reactor. One very interesting feature of this graph is that it shows that the pressure is not such a relevant parameter than we believed. Yet if we look very closely it appears that it increases a little along with pressure. That assures us that we can get good dissociation rates at the atmospheric pressure of Mars. Yet, as mentionned before we have to evaluate the ratio $\frac{P_{injected}}{\alpha}$ to measure the energy spent per broken CO_2 molecule.

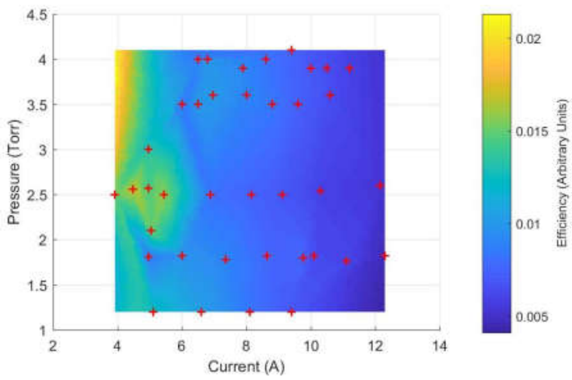


Figure 4: Visual representation of the energy spent per broken molecule regarding pressure and injected power

[4]Standard Cubic Centimeters per Minute.

[5]That particular quantity being the best indicator we can get to compare different settings.

Here we fathom that actually, as we send higher powers, there are more and more energy losses since it heats up the gas more than it excites the molecules in order to break them. Once again it appears that pressure is not a decisive parameter but efficiency is a slightly increasing function of pressure.

One important thing to understand is that the power sent there is not the exact power sent to the plasma, but it also includes the losses in our whole circuit (matchbox, cables, electrodes, pyrex tube, etc). We are in the process of measuring the power really injected inside the plasma in function of the intensity which does not change. It will allow us to know how little the energy per broken molecule can get with our system.

All in all our goal is to be able to provide a solution for oxygen synthesis on Mars, better suited to its atmospheric conditions than MOXIE. The use of plasma seems to offer consistantly better dissociation rates than MOXIE with comparable amounts of injected power, yet their device is a comprehensive tool that has a pure O_2 output at the anode. In order for us to have an overall evaluation of our energy consumption and to claim we do better than MOXIE, we have to get an idea of how expensive is the gas separation that we have to proceed.

4 Gaz separation

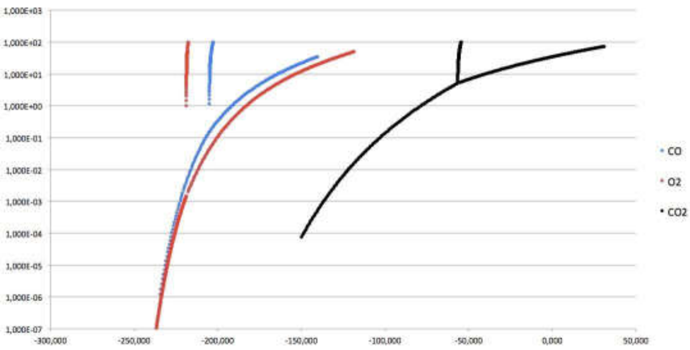
4.1 General problem and issues about the separation of gases

A factor that seemed at first anecdotic turned out to be of capital importance for the viability of the project : how to sort the produced O_2 from CO_2 and CO side-products, and at what cost ? Even though CO_2-O_2 separation is well-known on Earth, CO-O_2 separation is trickier, for these two gaz share very similar physical properties. Moreover, industrial processes on earth use other reactants missing on Mars (such as water) to get rid of CO, which is present in much smaller proportions than in our process (in which there is 2CO for one O_2). After consulting specialists in the industrial (AirLiquid) and academic field (ENSTA Paristech), we chose to adopt the cryogenic separation process.

4.2 Study with Aspen HYSYS

We do not have yet an estimate of the purity of our product, yet from our first simulations on Aspen HYSYS, we can roughly estimate the energy cost of the cryogenic process to a few watts, which is a fraction of the total consumption of the entire prototype. We decided to chose a process where no solid CO_2 is produced (which is not obvious since its triple point is at -56°C). From the starting point of a few mbars and -30°C (the alleged conditions at the output of the plasma), the gas is condensed up to 20 bars, where CO_2 can be distilled and extracted on its liquid state. Then the vapour phase at the top of the column containing the remaining O_2 and CO is cooled down to -145°C, where the distillation produces O_2 on its liquid form at the bottom, with some CO residuals.

Superposition of the (P,T) diagrams of CO_2, O_2 and CO used to determine the different steps of the cryogenic purification.



5 Our objectives

To sum up where we stand today, we almost concluded the proof of concept that a non thermal RF plasma could dissociate quite easily in Martian conditions. Yet our efficiency, which proves to be around the one MOXIE announces can and will be hugely improved. Our biggest challenges to come are :

1. **Pulsing** the discharge : regarding that matter we did little experiment since our priority was to prove the efficiency of the plasma in itself. Yet the few measurements provided us with a good insight of what we could achieve with an adjusted pulsing ratio. Pulsing the discharge means we switch on and off the generator with a precise frequency and a precise ratio of on/off time. As a matter of fact the energy given to the plasma is massively reduced and the temperature of the gas rises a lot less, and yet the dissociation rates we got were not bad at all. We want to take advantage of the momentum of the plasma which allows it to stay ignited even though there are phases without injected power. Recent research in the LPP confirmed that pulsed glow discharge plamas dissociate CO_2 with better results than classic discharge, our main objective in the following month will be to find the best settings for the pulser and to prove its usefulness.

2. **Cooling** the gas : as we mentionned before, gas temperature is a very relevent parameter to test for two reasons. The first one is that on Mars, temperature averages around -60°C and we only experimented at room temperature : to prove the efficiency of our system in real Martian con-

ditions, we need to be able to lower the temperature. Luckily for us, cooling down the gas to those temperatures can only make our efficiency rise. The second reason is that, as we mentionned, we want to minimise heat losses and those are increasing as the initial temperature rises. Finding a compromise between the energy required to bring the atmospheric gas on Mars to the perfect temperature and the benefits of it being cold will probably make our efficiency a lot better. As of today, we designed a gas cooling device that takes into account both our mistakes from the first try : not cooling down the gas to low, and maintaining it at the right temperature. It is expected to be conceived by the school glass blower in the following month.

3. Last big improvement we intend to make is testing **catalytic** materials.

To conclude we are now certain that a similar system could, provided that many engeneering aspects are resolved, be as efficient as MOXIE is, and we now want to prove that it can go far beyond that objective.

6 Educational Content

This project was very multidisciplinary. From fondamental plasma physics to gas separation engineering we had a chance to meet a broad range of subjects. This is certainly the educational benefit of these kind of student projects. When it comes to space, one has to think the whole system to come up with a relevant idea.

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PAPELL: Experiments, Prototyping and Mechanical Engineering

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Abstract — In this paper the experiments conducted, prototypes developed and mechanical engineering undertaken during the student project „Pump Application using pulsed electromagnets for liquid reLocation" (PAPELL) are depicted, with special consideration to the related education aspects.

PAPELL has been selected for conduction on the ISS within the "Überflieger" competition of the German Aerospace Center (DLR) [1]. PAPELL will be conducted for one month on-board and is supervised by ESA-astronaut Alexander Gerst in 2018. The experiment is set up in a NanoCube experiment container with the dimensions 10 x 10 x 15 cm³, posing severe limitations to the mechanical setup.

The goal of the experiment is to demonstrate a pumping mechanism without any mechanically moving components. This is achieved by using a ferrofluid as working medium and magnetic fields to drive the liquid. This is possible as magnetic nanoparticles, e.g. iron oxide, are suspended in a carrier liquid. The liquid is magnetically neutral, unless a sufficiently strong magnetic field source is present, which magnetizes and attracts the liquid.

This principle will be demonstrated in two distinct experimental areas. The first area will be used as a proof of concept for arbitrarily moving ferrofluid on a grid of electromagnets and, if successful, producing graphical shapes and symbols for outreach purposes. The next phase of the experiment will be executed in the second experimental area with the objective to move secondary bodies in a pipe system. Initially gas bubbles, in this case by the surrounding air, are transported in between individual ferrofluid droplets. Then injectors introduce solid spheres into the pipe system which are sorted in a three-way valve according to their respective color.

The challenge for a ferrofluid experiment with camera observation is the inherent property of the ferrofluid to stain most surfaces. In this paper several experimential runs to determine a suitable coating material are detailed, with special attention to the educational aspects of conducting proper scientific investigation within a student team.

The solution for the staining problem was found in close collaboration with the NeptunLab of the University of Karlsruhe [2], which developed Fluoropor, a coating with a powerful Lotus effect that repels the utilized ferrofluid. Tests with COTS coated materials proved to be unsuccessful.

As the project schedule is limited to a development time of approximately one year measures for rapid prototyping and short iteration cycles need to be implemented. Well-structured organization, frequent communication and clear responsibilities are critical to a project success. A steep learning curves maximizes the training the involved students gain by participating.

Keywords— International Space Station, student experiment, ferrofluid, pumping mechanism, education

I. INTRODUCTION

The Experiment PAPELL „Pump Application using pulsed electromagnets for liquid reLocation" – a reminiscent to Steve Papell from NASA who developed ferrofluid in the 1960, is a student experiment for fundamental research purposes of ferrofluidic mechanism. Conventional pumping mechanisms require high qualifciation effort and come with high costs, including maintenance and repair of moveable components which are subject to wear. Wear is always a limiting factor of lifetime and usability.

This is critical in space systems as maintenance of satellites is economically not feasible and time schedules for crewed space vehicles are always tight.

A pump mechanism without moveable components requires less maintenance. It is versatile applicable, durable and wear-resistant and furthermore mostly noiseless.

The PAPELL experiment is developed by 30 members of the Small Satellite Student Society of the University of Stuttgart (Ksat e.V.) [3] and supported by the Institute of Space Systems (IRS) of the University of Stuttgart [4].
The expected launch of the Antares rocket to the International Space Station is from Wallops Island in Virginia on the 9th of May 2018. The experiment begins with the “Horizons” mission of ESA-Astronaut Alexander Gerst, prospectively in June 2018. Previously Nanoracks, the company known for deploying CubeSats from the ISS, determines that the experiment is conform to the safety and technical requirements given by NASA.

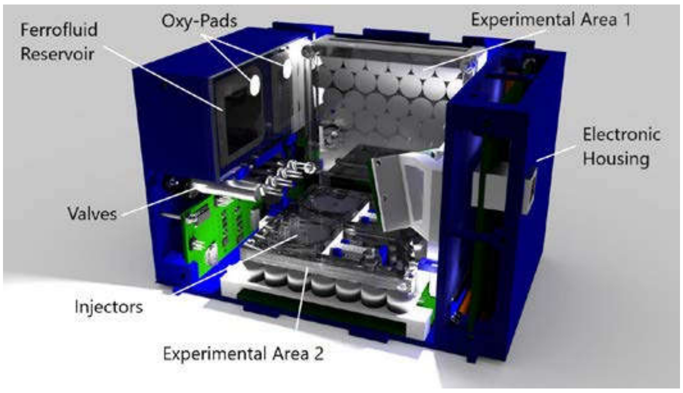

Fig. 1: CAD rendering of the PAPELL experiment Cube, with highlighting of mechanical setup of the experiment. © M. Schneider

II. MECHANICAL SETUP

An illustration of the mechanical setup of the PAPELL experiment is given in Fig. 1. An original picture of the complete setup is given in Fig. 5.
Initially the ferrofluid is located in two reservoirs. Inside the tank case is a bladder tank that slowly collapses once the ferrofluid flows into the experimental areas. The limited dimensions of the cube makes it a necessity that existing space is used optimally. To meet this challenge many components had to be custom produced. A non-technical aspect of this challenge is the fact that the communication with potential suppliers proves to be very difficult. For example, a potential supplier initially confirmed to produce a bladder tank in the required dimensions. After keeping this status for nearly half a year he revealed that he was not able to even produce the tanks.
The result of this is a potential delay in schedule and required significant effort to find a suitable replacement supplier in the shortage of time.

A lesson learned is that a stated commitment of a supplier, to be able to produce your product, does not necessarily represent a guarantee that the capability does exist. Especially for projects with such a tight schedule it is highly advised to have alternative suppliers at the ready to avoid single point of failures.
A single ferrofluid bladder tank holds about 20 ml ferrofluid. The utilized ferrofluid is APG 313 by ferrotec [5].
At the front of the ferrofluid reservoir casing is a panel made of polycarbonate with small venting holes at each side of the bladder tanks to allow pressure to equilibrate and the tanks to contract.
In the worst case assumption of a damaged ferrofluid tank it needs to be ensured that the ferrofluid does not leak from the reservoir. This is prevented by Oxy-Pads attached to the venting holes [6]. An Oxy-Pad is a semi-permeable membrane allowing air to enter but prevents leakage of liquid.
In the beginning of the experimenting phase, the ferrofluid is pumped by conventional means into the respective experimental area. Unintended leakage of ferrofluid into the experimental areas is prevented by using a system of four valves. They are working together to form a double-layer-barrier between the tank and the experimental areas. They are closed in a powerless status. Two different experimental areas are part of the PAPELL experiment design. Both have been successively tested on the ground.
Three cameras are mounted inside the experiment, two for perpendicular views on each experimental area and one to have a third view, which allows to monitor an injector, throughout the entire project and supplement public outreach activities as well as allowing some maintenance checks during flight. The view of one camera on the experimental area 1 is given in Fig. 2.
In addition, different sensors for measurements of sound, vibration temperature or magnetic field strengths are integrated into the experiment.

Fig. 2: Camera view of PAPELL experimental area 1, with original LED lighting. On the top right battery compartment is visible and, on the Bottom left, ferrofluid supply tubes. The marking grid indicates the positions of electromagnets for follow-up analysis.

III. FERROFLUID MONITORING

Ferrofluid is a liquid containing nanometer sized ferromagnetic particles suspended in a carrier liquid. This carrier liquid can be water- or hydrocarbon based. Initial tests with hydrocarbon based ferrofluid shows that ferrofluid does have a low surface tension and a constant layer of ferrofluid on surfaces remains. This means that after being used once there is no possibility to locate ferrofluid on the dark stained surfaces and further operation is irrelevant.

To avoid this effect the utilization of water based ferrofluid was envisaged. As a a fact water has a significantly different density and does not wet the magnetic particles well enough and is therefore useless as a carrier liquid for long term applications.

It decays after approximately 30 days under normal conditions which would be far from the targeted storage capabilities.

The liquid decomposes directly after production and no suppliers is able to give a guarantee on the duration of which water based ferrofluid is incapable to react on magnetizing effects.

It could have been possible that the ferrofluid would increasingly lost its effectiveness during the experiment or in worst case would not even perform when the experiment is started.

Hydrocarbon based carrier liquids are used to produce a very stable suspension, with ensures a long-term effectiveness.

Therefore, another solution needed to be found that enables the utilization of hydrocarbon based ferrofluid.

In order to find a suitable foil or coating that repels ferrofluid many materials in the areas of household, medical and technical products have been tested. Silicone, Polytetrafluoroethylene (Teflon), baking paper, aluminum foil, and more did not produce satisfactory results.

The NeptunLab of the University of Karlsruhe developed a new type of coating, Fluoropor. This coating causes a strong Lotus effect on hydrocarbon-based liquids. Thus, the ferrofluid is no longer capable to stain any surface and visual monitoring allows to locate the ferrofluid during the complete experiment. With this requirement met, the decision for the right foil could be based on other factors like heat-stability and safety.

IV. EXPERIMENTAL AREAS

Experimental area 1, shown in Fig. 3, consists of 37 magnets arranged in a honeycomb structure which are mounted on a baseplate. On the magnets a marking grid made from paper is placed, can be seen in Fig.2. On top of that a foil coated with Fluoropor is fixed in a frame made of polycarbonate that provides the sidewalls of the experimental area.

A polycarbonate plate with two holes, to be supplied with ferrofluid, forms the cover of this. Each ferrofluid tank is connected to this area by a flexible tube.

In the initial phases of the experiment, this area is used for ferrofluid movement experiments. At first a basic proof of concept is attempted. This means, that the ferrofluid is moved from one electromagnet to another. After this is successful the next step is demonstrating more complex experiments like complex paths, repeated movements, cycles and splitting and merging of droplets. After this first experiment phase ends the injected ferrofluid will remain in the area and can’t be retrieved but be reused in further experiments in this experimental area.

Fig. 3: PAPELL experimental area 1 with ferrofluid supply tubes but without marking grid.

Experimental area 2 consists of 28 magnets arranged to be able to manipulate a connected two-loop tube system. This experiments in this area are part of the second phase. Here, a Fluoropor coated foil is placed directly on the electromagnets, as it was tested that a marking grid paper layer does impede the performance due to the sheer thickness. On the foil a half-pipe system (U-Shape) is mounted. Primarily, a full pipe-system (O-Shape) was considered, but tests showed that the effectiveness of the ferrofluid is minimized if the distance between the ferrofluid and the electromagnets is too large. The half-pipe-system is milled in a polycarbonate plate and subsequently polished. This process was very cost-intensive but necessary because comparable cheaper models showed negative effects and worse results. The insides are coated by Fluoropor.

In this system solids in two different colors are to be transported. These are to be sorted in the Y-section of the double loop system. As ferrofluid is used to open and block paths for the solids to move. Before the experiments are conducted the solids are contained in slots of a disc of an injection mechanism. Three solid spheres are contained in each injector as seen in Fig. 4.

A steppermotor rotates the containing disc, which allows the solids to enter the pipe system by inertia. The inner diameter

of the pipe system is approximately 3 mm. Thus solid sphere required a smaller than this inner diamter, which are not usual. It proved extremely difficult to find suitable components in the desired dimension. The original usage of the now used solid spheres transported in the pipe system of this space experiment is the decoration of fingernails. The spheres were also coated with Fluoropor . This is required to minimize staining and identification will be possible.
For both areas it was permitted to attach the foils with NASA approved epoxy adhesive on the polycarbonate plate or pipes. Unfortunately, Flouropor cannot be bonded due to its highly repelling ability and so the foil did not adhere to the polycarbonate plate well enough, so under stress the coating sheared off. Therefore, the NeptunLab coated these foils fitting to the glued areas according to the drawings and CAD-based models.

Fig. 4: Experimental area 2 of PAPELL. Transparent structure is the pipe system, where individual ferrofluid droplets are transported. White objects are solid sphere injectors, each containing three solids.

V. CONCLUSION

Conventional pumps do not have optimal properties, especially in space systems this is much more complex and demand to a considerable extra effort.
PAPELL tries to find an alternative way to this. First, it is a proof of concept to show that it is possible. Even if there is primary ferrofluid and solids moved in this experiment, this is not limited by this. Also, other fluids and gases can be transported on this way.
Due to the lack of compareable techniques a huge development potential for this completely new concept was given and there was a steep learning curve for all members.

Fig. 5: Picture of the experiment before placement in the green aluminium Cube beside.

VI. EDUCATIONAL ASPECTS

As a student project with mainly young students, most participants were fairly inexperienced in the field of mechanical engineering in general and in space-related design in particular. A steep learning curve allowed team members to apply new skills and theory directly into developing the experiment. Practical skills, such as drawing with CAD software, had to be acquired, before an effective design that fits the given requirements was possible. Other abilities are not part of the curriculum of within aerospace engineering and other studies, i.e. soldering and the design of PCBs. This posed a challenge due to the time-constraints of the project and the limited time available to the students for both the project, their studies and other commitments.
Furthermore, participation in the project had the effect among the team that regular university subjects with direct relation were studied with much increased interest, the provided background knowledge was vital and the pressure to succeed was a strong motivation. The necessity to work harder to fit all tasks into the constrained schedule time increased the will to work even harder in the subjects related to the projects, while attention to non-related subjects partially required some attention.
In the following the attainments acquired in the different mechanical subsystems are reviewed and compared to the study contents.
First of all, in every subsystem team management and planning abilities had to be developed by respective team leaders, which posed a general challenge, as it is not part of the curriculum.
Direct and effective communication with suppliers as well as internally for conflict-solving skills had to be trained quickly.

For the mechanical system advanced literature research had to be performed to gain insights into the possibilities and concepts of efficient small-scale design.
The next step then was to learn advanced design methods using the CAD tool Siemens NX. Due to the necessity of producing clear and detailed CAD-files in a quick manner for further investigation and discussion quick learning far beyond the university level was required and achieved. These acquired skills were reapplied within official courses later in the year when a construction-exam had to be written.
Additionally, material constraints and capabilities had to be mastered by reviewing a large number of design examples and guidelines prior to developing an actual design.
Going beyond theoretical studies into practical manual work was a large set of skills. The team learned how to work with the used materials as well as the available tools used and gained experience in small-scale fabrication and new ways of effective manufacturing. This included the handling of space-qualified materials such as Epoxy resin and specialized COTS parts.
The actual acquired skills within the team are very heterogeneously distributed as responsibilities and respective requirements are equally heterogeneously distributed.
Although a though schedule like PAPELL is a severe challenge to the students involved it is overall an overwhelming success in terms of education for practical training as well as general motivation to apply acquired theoretical knowledge.

VII. ACKNOWLEGEMENT

PAPELL is funded by the Federal Ministry for Economic Affairs and Energy based on a resolution by the German Bundestag (grant number: 50JR1705) and supported by the Faulhaber group [7], Bergmaier Präzisiontechnik [8], Bartels [9] and Mannel-magnet company[10].

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PAPELL: Student team lead tenets and challenges in an international project

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Abstract— This Paper will detail educational aspects as well as communication, leadership and bureaucratic challenges encountered during the development of the ISS experiment PAPELL, which is an acronym for "Pump Application using Pulsed Electromagnets for Liquid reLocation".

The experiment is a student project conducted mainly by members of the Small Satellite Student Society of the University of Stuttgart (KSat e.V.) and the Institute of Space Systems of the University of Stuttgart.

PAPELL is a technology demonstration of a non-mechanical pumping system, which means that fluids are transported without direct mechanical interaction. This is achieved by switching individual electromagnets to produce local magnetic fields. The working medium is a ferrofluid, which responds to the generated fields. Ferrofluid itself is a magnetically neutral liquid, when no external magnetic field is applied. Suspended nano-scale iron oxide particles are aligned by an external magnetic field source, magnetizing the liquid, which is then attracted to this magnetic field source and will flow accordingly. Consequently, it is expected that a low wear, low maintenance, high-lifetime pumping mechanism can be achieved, as no solid surfaces are in direct contact, negating friction and abrasion effects.

The experiment was a winning proposal of the "Überflieger" competition of the German Aerospace Center (DLR), where three German student experiments were selected for transportation to and conduction on the International Space Station (ISS) in 2018.

PAPELL had to be developed in approximately one year and needs to fit the boundary conditions given by a NanoCube (10 x 10 x 15 cm^3) and limited power supply of 4.5W. Challenges were encountered with respect to a tight schedule, changing boundary conditions and a young student team. For this, a well-structured project plan had been established, frequent meetings were held and modern forms of communication allowed for short response times and fast design iterations. The student team with approximately 30 members is segmented in three distinct working groups: Mechanics, Electronics and Software – where clear responsibilities are vital for project success.

Good leadership and systems engineering is achieved, when conflicting interest (e.g. power consumption, volume demand etc.) are openly discussed and resolved by determining a suitable solution best for the experiment success. External challenges are given by export and safety regulations, which had to be met, when exporting the experiment to testing facilities of NanoRacks in Houston Texas, US. Here, direct and frequent communication with responsible safety personnel of the University, shipping companies and customs is important to allow for smooth and successful process.

Keywords—International Space Station; Student Experiment; Ferrofluid; Pumping Mechanism; Education

I. Introduction

PAPELL is made possible by members of the student society KSat, the "Überflieger" competition organized by the DLR, and the experiment opportunity provided by NanoRacks and DreamUp.

A. Organization KSat e.V.

The Small Satellite Student Society at the University of Stuttgart KSat e.V.[1] is an organization of students for students to gain technical knowledge by taking part in different educational space programs like REXUS/BEXUS with the experiments ROACH and MIRKA2-RX. It is a non- profit organization founded in 2014 which already has more than 60 members belonging to different semesters and is open to students of the University of Stuttgart of all disciplines.

B. PAPELL

The PAPELL experiment is an experiment designed and executed by students to demonstrate a non-mechanical pump in micro-gravity environment on the ISS. It is one of the three winners of the student competition „Überflieger" advertised by the DLR [2] in 2016. NASA engineer Steve Papell is the inventor of ferrofluid and the eponym of the experiments description.

1) Mission

"Überflieger" is a competition of the DLR. Technical support is provided by NanoRacks and DreamUp.
The winning experiments will be executed by the German astronaut Alexander Gerst during the Horizon Mission in summer 2018.

2) Team Structure

The PAPELL team has 30 students from aerospace-engineering, electrical engineering and computer science. Initial team sessions had the aim to come up with creative solutions to design a suitable experiment setup.
The team structure has a strong hierarchy. There is one team leader who represents the team externally, to have a single contact person. The leader is supported by a system engineer, who is also the co team leader and further support is given by a supervisor. Due to the team size it was necessary to organize into different groups with a distinct group leader. Therefore, a mechanics, electronics and software group have been established to focus on the different aspects of the experiment. An overarching group called Operations defines the exact experiment steps and management of experiment time on the ISS.

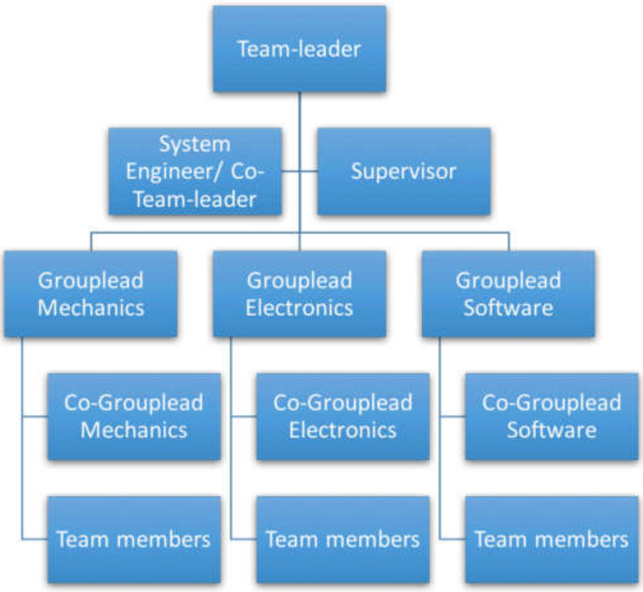

Fig. 1: Teamstructure

Supported by experts, like Priv.-Doz. Dr.-Ing. Herdrich from the Institute of Space Systems of the University of Stuttgart, electrical engineers from NanoRacks and experts from DreamUp and DLR assisted the team to develop the experiment and to work out the respective bureaucratic documentation.

3) Experimental Setup

Ferrofluid is stored in two 25ml tanks. Four valves, two pumps and flexible tubing are making up the feeding system (See Figure 2 and 3). Three cameras are observing the experiment. Two experiment cameras are focused perpendicular on the experiment areas and one PR-Camera is placed in a corner monitoring both areas and the tanks, pumps and valves. Additional to the USB-3 connection to the ISS - the only external power supply - five batteries for the power supply of the experiment are implemented.
Experiment area 1 consists of 37 electromagnets arranged in a honeycombed array. The magnets can be switched by the on-board-computer.

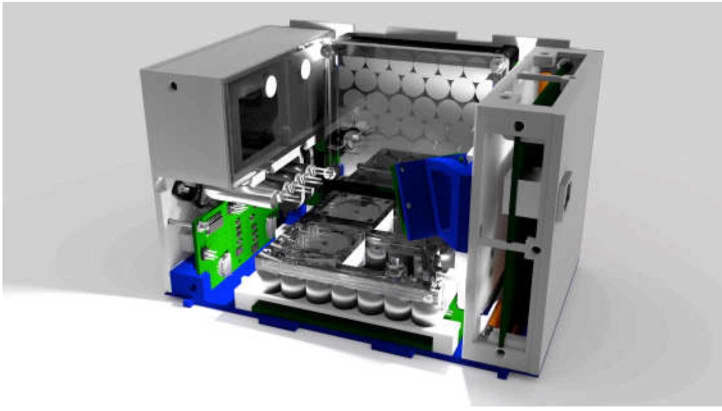

Fig. 2: Experiment Setup: PAPELL Experiment Setup CAD Rendering © M. Schneider. Outer aluminium as well as two-panels, batteries and cameras removed

Experiment area 2 consists of a transparent Y-pipe system. In this pipe ferrofluid can transport air and solid spheres. The latter is realized by a spinning disk. Data are generated by various sensors e.g. a microphone, magnetometers, thermometers and an accelerometer. This data can partially be downlinked and fully stored on on-board SD-cards.

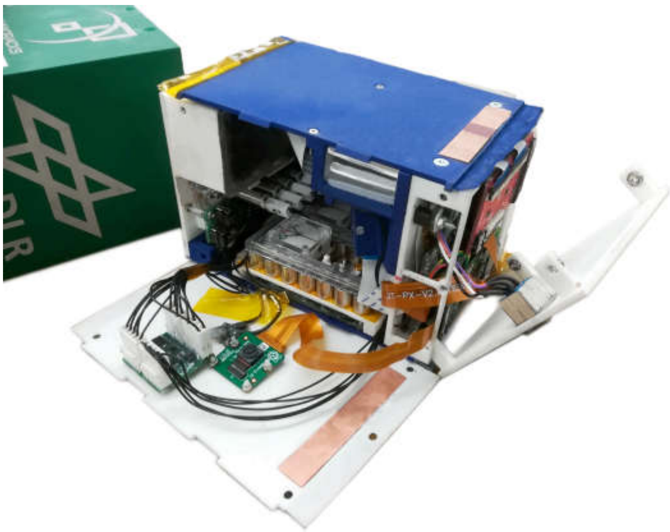

Fig. 3: Experiment Setup: A picture of the PAPELL Experiment Setup before the final integration next to the aluminium cube.

II. Tenets and Challenges

A. Time Management

Due to the competition the execution time was strongly limited through the deadline of the Gerst Mission in 2018. Therefore, a strict time plan was worked out. The results of the schedule and given deadlines are shown in Figure 4.

Fig. 4: Timeline

B. Team Communication

Having effective communication within the project is a challenge based on the motivation of each member. For a team leader and a member, it is vital to inform everyone else equally. Otherwise misunderstandings are likely, which drain motivation and time or information is lost. A so-called N-N communication was realized by switching from multiple group chats of the instant-messaging app WhatsApp Messenger to the cloud-based team collaboration tool Slack, where different channels and threads can be opened on relevant subjects. This change is more productive, as individual or group chats and interests could be met more precisely. At least daily e-mail is a necessity to keep up with external inputs, as well as having frequent contact to the two other teams ARISE [3] and EXCISS [4] who participate in the "Überflieger" project. This helps to reduce the questions to the American and German experts and makes the stream of information more polydirectional.

C. Resolving Conflicting Interests

Producing an experiment for the ISS is a complex challenge, from the beginning to the end. Each group is interested in having as much of available volume, mass and power budgets as possible assigned to them. These conflicts of interests are mainly solved by discussions and sometimes by decisions from the lead level.

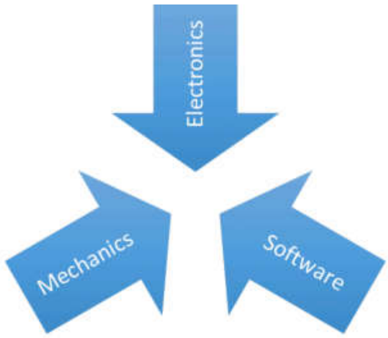

Fig. 5: Conflict Schematic

D. Acquire Skills

Most of the team members were in the third semester of their bachelor when the PAPELL team applied for the "Überflieger" competition. Thus, the practical and theoretical expertise was low compared to the current stauts. A steep learning curve was encountered by most members due to the novelty of such a practical space project.

1) Heritage Expertise

To mitigate to this issue, older members of KSat offered different workshops to extend the knowledge of the new members. In this way a soldering workshop, an Arduino workshop and python lessons were organized.
Another way of increasing the knowledge contained reading respective papers, studying books and websites or practically experimenting.

2) Team Leader

For effective team lead it is important to have an overall overview of e.g.: the available time, the motivation and workload team members, the overall state of the project. Bureaucratic challenges are given by safety regulations, shipping orders, a risk assignment, verification data sheets and documentation by a payload data template.

E. Motivation

Due to the compact project schedule and the permanent stress of studying parallel, free time is rare. The associated permanent stress can demotivate members equally as short deadlines caused by limited time. As a result, the task of the team leader is to keep the team motivated and be a reinforcement, were possible. Establishing a working friendly environment, where every single member can be productive is a duty that has to be fulfilled. This can be achieved by dedicated workshops and organized free time activities as well as project milestone celebrations.

F. Bureaucracy

Project spending has to adhere to the regulations of the University of Stuttgart approval process.
Export regulations are defined by the Federal Republic of Germany, customs and safety institutions, with individual process to adhere.
Space flight regulations are strictly regulated by NASA, which are especially hard due to the crewed nature of the space station.
All these processes require time to understand, learn and execute. The time consuming nature of bureaucracy should not be underestimated when leading a student team.

G. Outreach

Outreach is a way of advertising the project, but also keeping the team motivated as they become aware of the relevance. When presenting the project PAPELL on space conferences [5], public events like the YURI'S night or at open days of the University of Stuttgart, people who are interested in space and the ISS have the chance to take a closer look at the experiment.
Furthermore, the PAPELL experiment has been presented in local newspaper, university radio, a podcast and local tv channel.

H. Acknowledgement

The PAPELL project received support from different organizations in Germany. The critical component of the experiment, the electromagnets, were sponsored by the company MMT Mannel Magnettechnik GmbH [6].
The NeptunLab KIT supplied a specific PTFE coating, called Fluorpor, that is ferrofluid repelling [7], which is critical for ferrofluid stain avoidance.
Other companies like Beta Layout donated custom made Printed Circuit Boards.
PAPELL is funded by the Federal Ministry for Economic Affairs and Energy based on a resolution by the German Bundestag (grant number: 50JR1705).

I. Documentation

To execute a complex project of this magnitude, it is important to document every step, process, decision and component to be able to track and to reproduce the project.

III. Conclusion

To accomplish an international project, the team has to be clearly structured. The complexity must not be underestimated when looking at the time management and communication. Resolving conflicting interests, providing the opportunity of workshops and motivating the members are necessary duties of the team lead. On the other side the team lead has to deal with the technical supervisors from NanoRacks, DLR and DreamUp and is the externally counterpart of the project to the newspaper and supportive organizations.

IV. Outlook

After the ISS model is completed and delivered the production of the ground model will begin and the respective software will be implemented. Launch with Antares OA-9 is scheduled for 9th of May, which will transport the experiment to the ISS. Data analysis will begin with the receipt of first data. PAPELL will be returned to Earth in August 2018 and detailed post-flight will follow.

Fig. 6: Picture of Experiment Area 1 taken by Camera 1 inside the Cube after the final integration

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Results of the rate control system RaCoS on REXUS 22 and suggestions for further developments

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In order to reduce the residual angular rate in the roll axis after the yo-yo de-spin and motor separation of the spin stabilized REXUS sounding rocket, the student experiment RaCoS was built. The experiment RaCoS (Rate Control System) was successfully tested on REXUS 22 in March 2017 at Esrange Space Center. Even though a malfunction of the REXUS rocket during the motor separation occurred, the system worked flawlessly and was able to revise the unexpected higher angular rate in the roll axis.

The results - primarily the achieved angular rates and accelerations - measured by the experiment itself will be discussed and compared with the data measured by the REXUS Service Module. The experience gained during the construction can be used to improve the system and upgrade the RCS to a full attitude control system (ACS) using the same principle but with a more complicated pneumatic and mechanical setup. A different controller as well as more cold gas thrusters, each individually triggerable, would also be needed. Concrete suggestions for the realization of a three axes rate and attitude control system under the limiting size factor will be discussed.

Keywords: RCS, ACS, REXUS/BEXUS, cold gas system, rate control system

I. Introduction

The unguided, spin-stabilized sounding rockets of the REXUS/BEXUS programme can be equipped with a yo-yo de-spin mechanism which will reduce the spin rate from 1440 °/s to about 30 °/s in the roll axis. The residual angular rate influences the milli-g environment and can be problematic for other scientific experiments. The approach of reducing the residual rate after the yo-yo de-spin mechanism led to the decision in participating in the REXUS/BEXUS programme and developing, building and actually testing a cold gas rate control system under lifelike conditions. The experiment was built by using only commercial off-the-shelf components such as a paintball air tank. Since the programme is addressed to students, the complexity of the experiment has decreased by reducing and controlling only the angular rate of the roll axis of the REXUS payload. All other axes were not influenced by RaCoS.

II. Mechanical Setup

In the following the mechanical setup of RaCoS is being presented. The pressure vessel is a commercially available paintball tank with a volume of 0.7 litre and a maximal filling pressure of 300 bar. The operating pressure was 200 to 250 bars with nitrogen as propellant.

The remaining pressure inside the tank is monitored with a pressure transducer. The pressure transducer is directly attached to the first pressure regulator which is screwed on the air tank. A non-return valve is connected with the regulator, respectively with the tank, and is used for refilling. To conduct a refilling procedure prior to the launch of the rocket, a refill connector is placed behind a late access hatch.

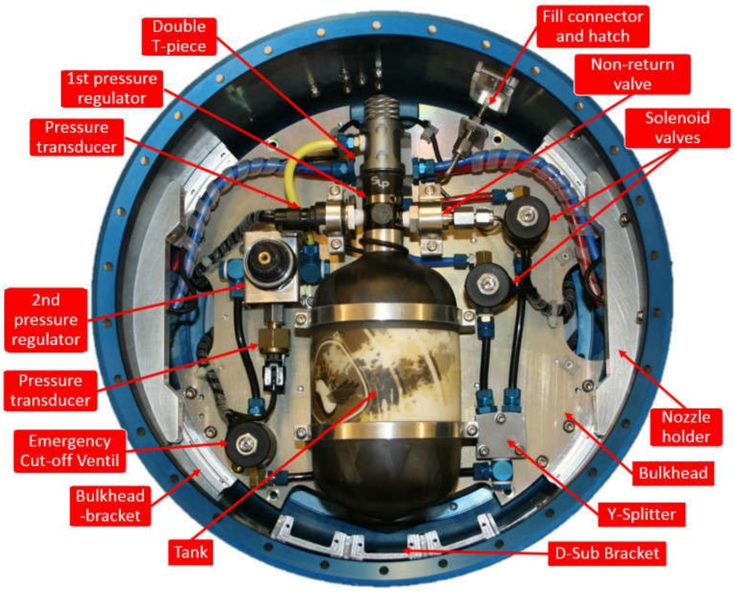

Fig. 1: RaCoS components

The first pressure regulator has the opportunity to mount high and low pressure burst discs which are only used during testing and will be removed prior to the flight. The outlet of first pressure regulator feed the second pressure reducer with 21 bar. The second pressure reducer delivers 5 bar to the rest of the system. The system pressure is measured directly at the regulator with an additional pressure transducer (Fig. 1).

Followed by the emergency cut-off valve, which can only be triggered with a corresponding signal from the RXSM can cut off the gas flow. After this solenoid valve, the pressure line is splitted to two additional solenoid valves, each one is responsible for Roll+ or Roll- operation (Fig. 2). After both solenoid valve, a T-piece is used to distribute the gas to both nozzle holders. The nozzle holders are mounted on the module itself and each nozzle holder is equipped with two nozzles.

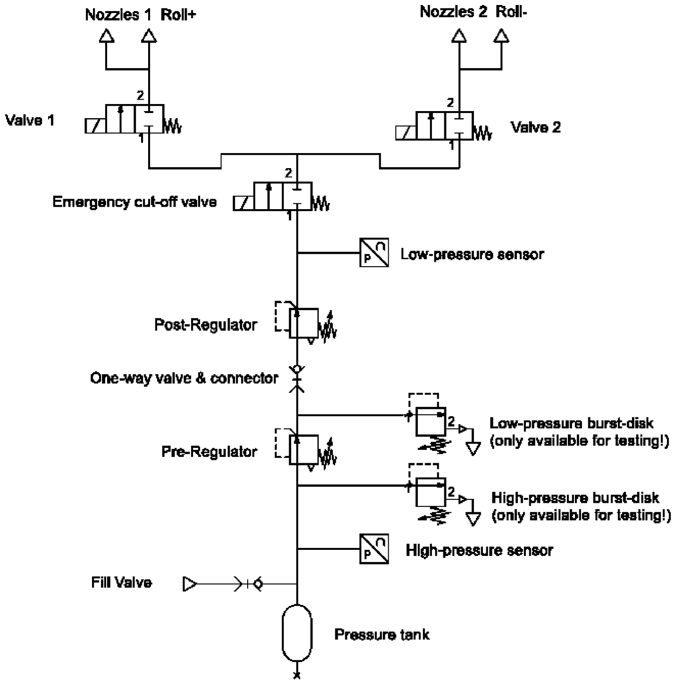

Fig. 2: Pneumatic layout of RaCoS

All pneumatic parts are mounted on top of the bulkhead. The electronics, as well as both IMU's, are fixated on the bottom of the bulkhead.

III. Flight Results

RaCoS successfully reduced the roll rate of the rocket during the flight REXUS 22 and kept it near to zero. Figure 3 shows the rates of the rocket during the main de-spin in all axes. The high roll rate of 144 °/s was caused by a malfunction of the rocket itself and should be nominal around 30°/s. While the roll rate has successfully been reduced from 144 °/s to below 1 °/s, a rate of up to 124 °/s in the pitch axis and up to 61 °/s in the yaw axis remained.

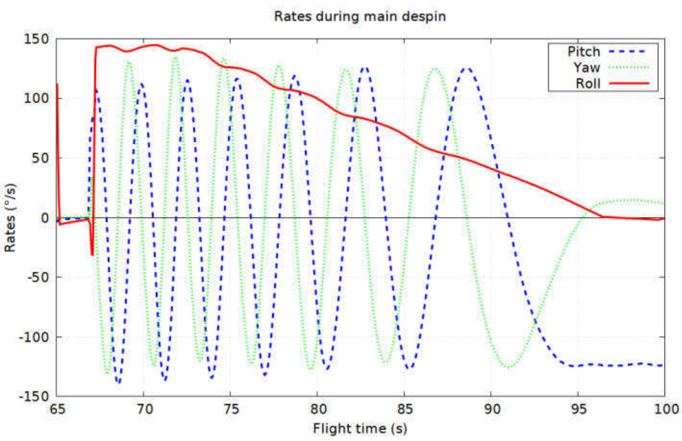

Fig. 3: Rates during main despin

The remaining accelerations showed that the milli-gravity on board of the REXUS rocket has been reduced by RaCoS. In figure 4 the accelerations measured by RaCoS' IMUs is displayed. In the pitch and yaw axes, the acceleration was below 0.02 g, while in the roll axis, an acceleration of 0.1 g remained. This is caused by the residual rates in pitch and roll axes, which could be reduced by a full ACS.

A trade-off between opening a solenoid valve and disturbing the weightlessness environment or keeping it closed to achieve a better milli-g environment must be made since the activation of a valve induces unwanted accelerations of up to 0.1 g in multiple axes (Fig. 4).

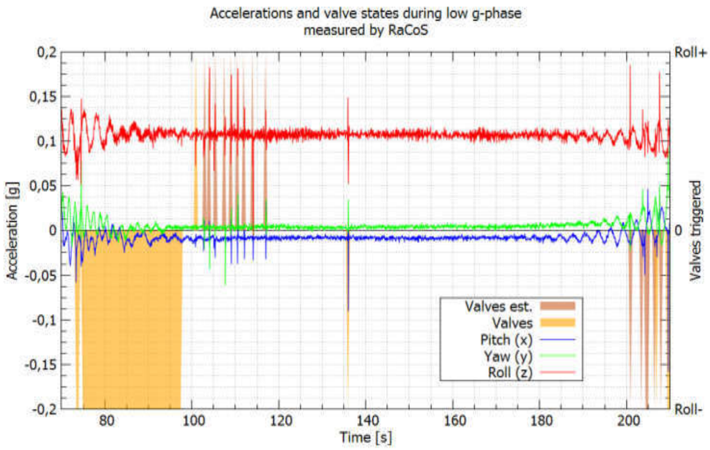

Fig. 4: Accelerations and valve states during low g-phase measured by RaCoS [2]

The accelerations measured by the REXUS service module differ from the ones measured by RaCoS (Fig. 5). Accelerations of up to 0.8 g for pitch and yaw and 0.2 g for the roll axis have been measured. This mismatch can be explained by the different locations of the accelerometers. The accelerometer of RaCoS was placed closer to the centre of gravity, approximately 70 mm below.

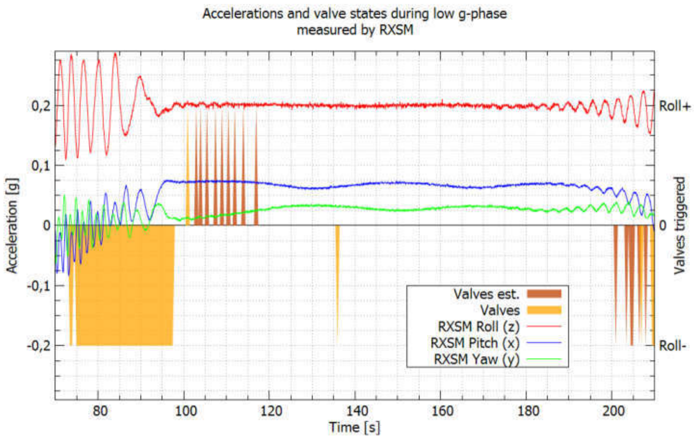

Fig. 5: Accelerations and valve states during low g-phase measured by RXSM [2]

RaCoS used two commercial IMUs (InvenSense MPU-9250), which are based on the MEMS technology. A comparison between the rates measured by RaCoS and the RXSM can be found in figure 6. The drift of the MEMS sensors used by RaCoS is clearly visible.

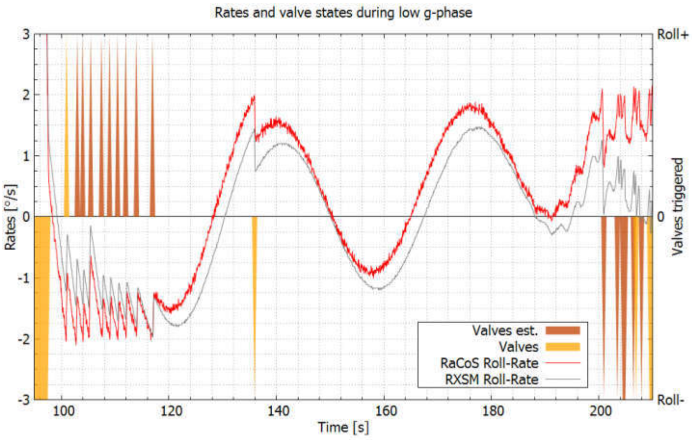

Fig. 6: Comparison of measured roll rates [2]

IV. 3-Axis Attitude Dynamics

In this section, the attitude dynamics of the REXUS rocket and its implications on the control strategy for a 3-axis ACS are being described.

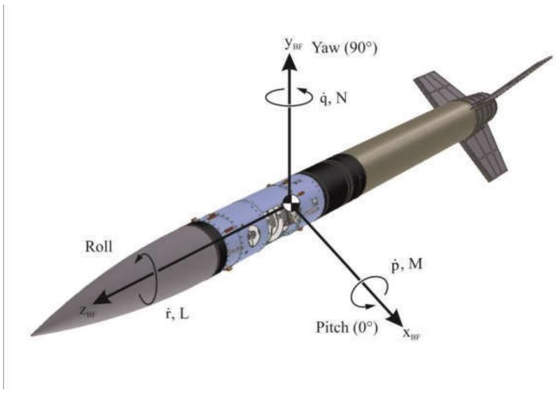

Fig. 7: REXUS coordinate system [1]

The attitude behaviour of a rocket can be described using the Euler equations (1-3).

$$I_x\dot{\omega}_x + (I_z - I_y)\omega_y\omega_z = T_x \quad (1)$$

$$I_y\dot{\omega}_y + (I_x - I_z)\omega_x\omega_z = T_y \quad (2)$$

$$I_z\dot{\omega}_z + (I_y - I_x)\omega_x\omega_y = T_z \quad (3)$$

Due to the geometry of the REXUS rocket (Fig. 7), the moments of inertia in the pitch axis (I_x and I_y) are nearly equal. Hence, the Euler equation for the roll axis can be simplified (4).

$$I_z\dot{\omega}_z = T_z \quad (4)$$

Thereby, the roll axis can be controlled independently from rates in other axes.

By assuming no external torques and defining $I = I_x = I_y$, the equations can be simplified (5-6).

$$I\dot{\omega}_x = (I - I_z)\omega_y\omega_z \quad (5)$$

$$I\dot{\omega}_y = -(I - I_z)\omega_x\omega_z \quad (6)$$

Since ω_z is constant if no external torques are present, a solution for this system of differential equations is (7-9).

$$\omega_x(t) = \omega_x(0)\cos(kt) + \frac{\dot{\omega_x}(0)}{k}\sin(kt) \quad (7)$$

$$\omega_y(t) = \omega_y(0)\cos(kt) + \frac{\dot{\omega_y}(0)}{k}\sin(kt) \quad (8)$$

$$k = \frac{I - I_z}{I}\omega_z \quad (9)$$

The equations show that the rates in the pitch and yaw axis change periodically with a frequency depending on the roll rate of the rocket. Therefore, a control algorithm should reduce the roll rate of the rocket to zero before reducing the rate in the other axes to avoid having to deal with periodically changing rates.

V. Controller Design

In this section the possible control algorithm for an ACS is being described.

As discussed in (IV.), the controller was able to reduce the roll-rate close to zero. In the original flight configuration, the controller was a 3-point-controller with an adaptive hysteresis which is calibrated at the beginning of the operational phase. As the flight results (Fig. 3) show, the calibration suffered from long-term effects which could have been prevented if the system calibrates for a longer period, maybe the whole operational phase.

For a full 3-axis-controller the system has to be extended to different operation phases:

1. Spindown of the roll-axis
2. Spindown of pitch- and yaw
3. Hold the rates

This is necessary because of the roll-rate's influence on the other remaining axis (V.) and also limitations in the gas flow to prevent a significant pressure drop. As the current attitude of the rocket is being influenced by the environment, the controller acts with priorities, where (1.) would always be the highest and (3.) be the lowest priority. Also, the controllers would differ depending on the precision level of the phase. For phases (1.) and (2.), the RaCoS-configuration controller would be sufficient, as the rates only have to be prepared for the Attitude-Hold in phase (3.). Changing to the (3.) phase, the calibration parameters of the 3-point-controllers provide a system behaviour estimation, which can be used to calculate a best fit of PID parameters for each axis by using the Ziegler-Nichols method. As the rates are being kept low, the controller has not necessarily to take influences between the axis into account and can control the rates with PWM triggered valves for fine adjustments.

VI. Sensor Fusion

In this section the sensor fusion is being described. For the flight configuration two MEMS IMUs were used to measure the angular rates and a sensor fusion filtered the noise. Therefore, the sensor fusion calculates the noise value of each IMU which is used afterwards to calculate the weight in a weighted average filter with the two IMUs and a linear extrapolation. This combination then works like a low-pass-filter to eliminate ADC-noise of the IMUs internal ADCs and little measurement differences. In the flight configuration the accuracy was sufficient but does not meet the requirements we have for an even more precise iteration of the system, especially if it comes to 3-axis. To get even better results, a mechanical or optical IMU replaces the MEMS typed. If multiple IMUs were used, a Kalman-filter would provide the sensor fusion.

VII. Further developments to an ACS

To gain control in all three axes, up to six nozzles have to be triggered individually. The accommodation of the experiment in the payload must not be in the center of gravity, otherwise the nozzles for pitch and yaw would have no effect. For the pneumatic setup, a single pressure regulator should be used to save space inside the experiment.

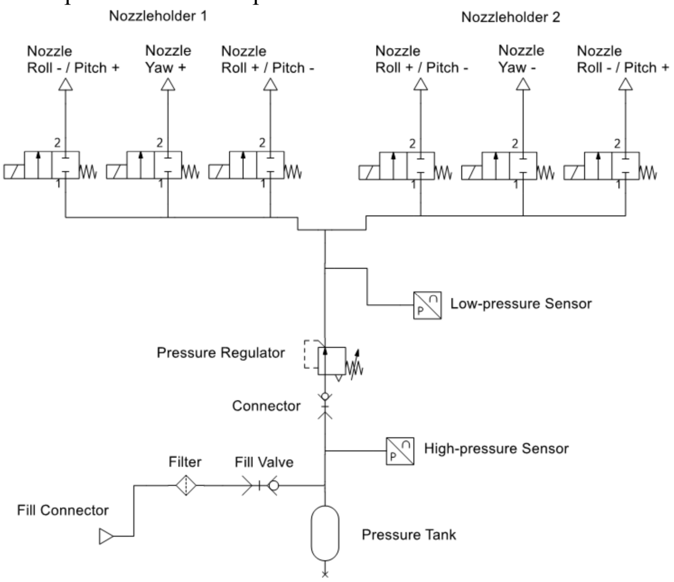

Fig. 9: Pneumatic layout of an ACS [2]

The pressure regulator will reduce the pressure of about 250 bar inside the air tank to the operating system pressure. To fill the tank, an additional late access hatch is integrated. The refill connector is followed by a filter and a non-return valve (Fig. 9). Followed by the non-return valve is the pressure regulator which is used as a bypass to the air tank. The pipes between the tank and the pressure regulator as well as to the non-return valve are continuously exposed to the tank pressure. This means, that this section is crucial and an adequate pipe system is needed to withstand the pressure without a major leak.

The fixation of the air tank is the same concept used by RaCoS. A high pressure transducer is directly attached to the tank connector to monitor the remaining pressure. The outlet of the pressure regulator is connected to splitter which branch off to both nozzle holders (Fig. 8).

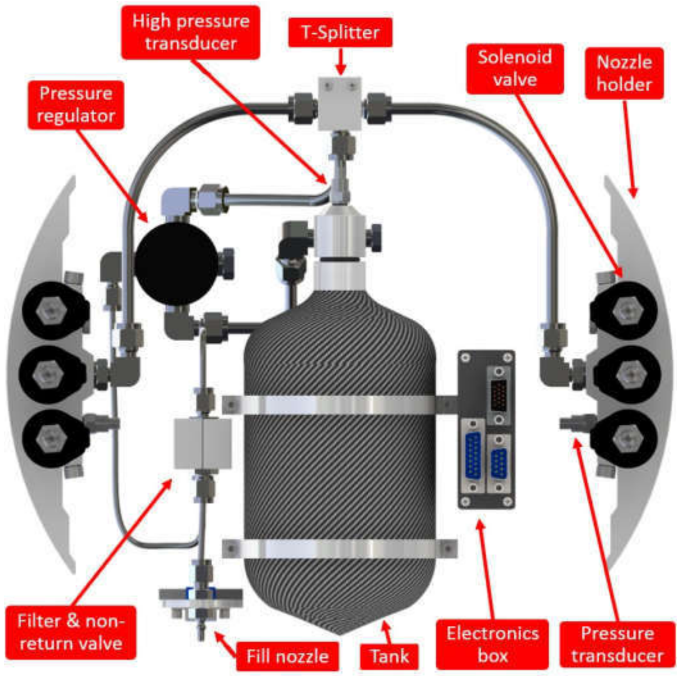

Fig. 8: Description of the components

The mass of the experiment should be as low as possible to create added value for the scientific experiments. Reducing the mass and gain more performance to control all three axes can only be achieved by choosing the smallest module size which has a height of 120 mm. RaCoS showed that the pressure drop induced by long hoses is not negligible. To reduce the pressure drop, the solenoid valves should be placed in the close proximity of the correspondent nozzle and the pressure lines should be kept short. By integrating the solenoid valves inside the nozzle holder using the manifold body mount configuration, additional pipes and fittings can be avoided.

The system consists of two nozzle holders, each equipped with a pressure transducer, three solenoid valves and three corresponding nozzles. The nozzle holders would be attached to the module. With this configuration, all other components such as the pressure regulator, air tank, filter, non-return valve and the electronics have to be attached to the bottom mounted bulkhead to fit in a 120mm module (Fig. 10).

The inlets of the three solenoid valves in each nozzle holder are interconnected by bores. The outlet of each solenoid valve enters the nozzle bore. The nozzle bore has a thread in which different nozzles can be screwed. Unlike RaCoS, normal convergent carburetor nozzles can be used for subsonic and laval nozzles for supersonic exit velocities.

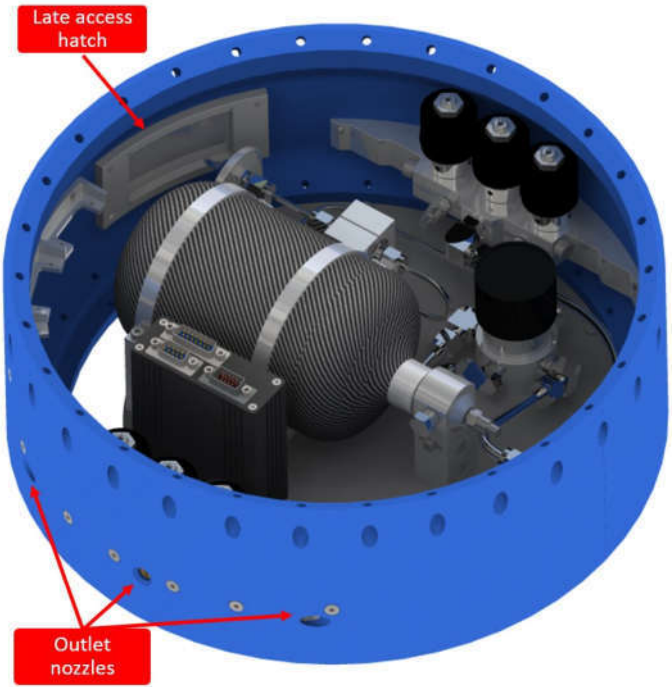

Fig. 10: ACS in rocket module

The suggested design of an ACS has a total mass of about 8.5 kg and is 0.3 kg lighter than RaCoS. The major part of the mass are the nozzle holders with mounted solenoid valves which result in a mass of 1.8 kg followed by the tank with 0.55 kg.

VIII. CONCLUSION

Based on the gained experience with RaCoS, a complete ACS for REXUS sounding rockets can be turned into reality. A follow up student team of the University of Würzburg could continue this idea and apply in the REXUS/BEXUS programme. The support of the Chair of Aerospace Computer Science VIII is certain and the team could benefit from the broad range in attitude control experience as well as pneumatic systems and real time operating systems running on microcontrollers such as RODOS which is developed at this department.

ACKNOWLEDGMENT

We want to thank to all organizers, supporters and people behind the REXUS/BEXUS programme. Without the help of the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB) an experiment like RaCoS couldn’t be built and tested under real-life conditions in space. Special thanks to Esrange Space Center of SSC, the Mobile Rocket Base (MORABA) as well as to the Center of Applied Space Technology and Microgravity (ZARM) and the European Space Agency (ESA) for their outstanding support!

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EduCube – The 1U Educational CubeSat

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***Abstract*—EduCube is a 1U Cubesat developed specifically for educational purposes. It is used in a hands-on training laboratory for masters students to allow them to gain familiarity with the satellite subsystems found in a Cubesat. The students work in groups, following a set of exercises and also devising their own experiments. EduCube was designed and built in-house and is largely compliant with the Cal Poly standard.**

***Keywords*—space education; CubeSat; satellite; space engineering; training**

I. Introduction

CubeSats are increasingly used for a wide range of space applications, as a cheaper and faster alternative to the traditional 'big space' approach. They offer an accessible way for diverse groups, including student teams, to launch a payload into space. CubeSats were developed in the 1990s and are defined as multiples of a base unit of dimensions 10 cm × 10 cm × 10 cm, called 1U. Typical systems range from 1–12U in size, with masses from 1–20 kg. Components may be bought 'off-the-shelf' from numerous providers and are highly standardised [1]. More than 800 CubeSats have already been launched. NASA and ESA hold competitions for students to develop CubeSat projects, providing mentoring, access to facilities and, ultimately, a launch opportunity. The strong growth of CubeSats as viable platforms across many space domains, including space science, navigation, communications and earth observations, has motivated our development of the 'EduCube' as a 1U classroom satellite, primarily (but not exclusively) for master's degree student training in space systems engineering. The development of EduCube was one of the factors that motivated the EIRSAT-1 mission concept [2].

II. Background

As a full member of the European Space Agency since 1975, Ireland plays an active role in the space sector, with more than 40 Irish companies actively engaged in space contracts. In 2013, University College Dublin (UCD) launched the country's first taught MSc degree in Space Science & Technology (SS&T). The programme is backed by industrial commitment in the form of internships and curriculum support. Student numbers have grown from an enrolment of 3 in 2013/14 to 18 in 2017/18, which is the maximum capacity with current resources. This programme seeks to satisfy the substantial appetite at postgraduate level for career development in the space sector, a development path that did not previously exist in Ireland.

The structure of the MSc SS&T programme is illustrated in Fig. 1. The main goal is to prepare graduates for careers in space research, the space industry, and/or with space agencies. The focus is on experiential learning, replicating the space project development life-cycle as closely as is feasible within a 1 year structure. Hands-on laboratories provide students with experience of detector calibration, performance simulation and extensive data analysis. The Space Detector Lab provides students with hands-on experience of detector calibration, performance simulation and extensive data analysis. This module also prepares students, through EduCube, for the Satellite Subsystems Laboratory, in which student teams design and build their own 'satellite' which is flown on a meteorological balloon and recovered. The third large practical module, Space Mission Design, involves concurrent design work that culminates in an intense one week activity in Tenerife with students and staff from two other academic institutions. The 30 ECTS placements are the capstone experience in which the students' new knowledge is given further context with more in-

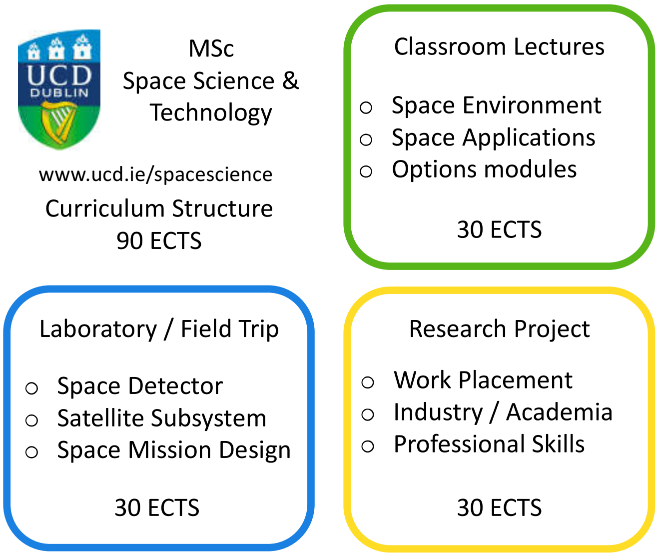

Fig. 1. Structure of the UCD MSc in Space Science & Technology.

depth study of a relevant topic within a company, agency or research group.

The EduCube (Fig. 2) has been used since 2015 as part of the 10 ECTS Space Detector Lab and accounts for 40% of the module mark. Students typically work in groups of four and, after a brief introduction, work independently through the manual testing of each subsystem. For each subsystem, there is a list of suggested exercises which must be completed, as well as some user-devised exercises. The load is approximately four to five weeks with 2× 3 hour sessions per week. The module is assessed based on one report from each team that provides clear statements on individual student contributions.

III. EDUCUBE

EduCube (Fig. 2) consists of several electronic subsystems, each connected through a primary bus at the rear. This bus contains all power channels coming from the Electrical Power System (EPS) and various data channels allowing the subsystems to communicate with each other. Certain channels in this bus may be tested using the bus breakout board.

A. Launch adapter

EduCube comes with a launch adapter (Fig. 3) which is a reasonable facsimile of an actual payload launch adapter that would be used to attach a CubeSat to its deployer. For convenience in the laboratory, the EduCube launch adapter can also be used as a ground station radio, by setting the toggle switch to the radio setting. The umbilical setting connects the USB port to the umbilical TTL serial connection that is present in the launch adapter. The umbilical features two data lines (RX and TX), ground, and a 12V power line which will power the EduCube if the 12V battery charger is connected to the launch adapter. The umbilical connectors are rotationally symmetric, i.e. the EduCube may be placed into the launch adapter in any orientation without affecting the correct functioning of the

Fig. 2. The EduCube classroom training satellite.

Fig. 3. The EduCube launch adapter.

umbilical connectors. They are spring-loaded so that the EduCube will rest on its legs while in the launch adapter and not put strain on the umbilical connectors.

The separation switch determines if the EduCube is still in the launch adapter or has been separated from the deployer. Before separation, all systems are powered down (except for EPS and C&DH which can only be powered off by the insertion of the RBF pin). When the C&DH detects that the EduCube has separated, it will power up all subsystems.

B. Structure

The structure is responsible for protecting the internal components of the CubeSat and providing a structure to which the other components can be attached. The structure comprises a black anodised aluminium frame and five clear plastic panels for the top and sides. The frame consists of four pieces: the Top Panel Assembly, the Bottom Panel Assembly, -X Frame Element, and +X Frame Element held together by stainless-steel M3×8mm counter-sunk hex socket screws. The plastic panels are held to the frame by stainless-steel M3×5mm counter-sunk hex socket screws. The transparent panels allow the operation of LEDs to be easily visible.

C. Electrical Power System (EPS)

The EPS is responsible for powering the EduCube. It regulates and monitors voltage supplies and switches power to various subsystems. The EPS consists of two 3.7 V lithium-ion batteries in series making 7.4 V available to the EduCube. This is dropped to 3.3 V and 5 V using voltage regulators and sent to each board on a dedicated channel. There is also a channel, which takes the output straight from the batteries, that is used to power the reaction wheel and thermal panels. The EPS is controlled by an ATmega328 microcontroller. This microcontroller monitors each battery temperature and voltage/current. The EPS provides ten different channels that other boards use for power which are also monitored by the ATmega328. Six of these channels may be switched on or off in pairs by the microcontroller. One switch controls the 5 V and 3.3 V channels to the AD&C, one switch controls the 5 V and 3.3 V channels to the thermal subsystem, and the other switch controls the 5 V and 3.3 V spare channels.

The batteries are charged via the 12 V adapter when available. The battery is charged with a 2-cell battery charger, which will simply charge the batteries while power is available if they are not fully charged.

The EPS also acts as a bus-structure interface. Electronic components of the structural subsystem (i.e. the umbilical connector and separation switch), which need to interface with the main bus, are routed through the EPS.

D. *Command and Data Handling subsystem (C&DH)*

The C&DH is EduCube's brain. It interfaces with all other subsystems to relay telemetry and commands to and from the ground, and monitors the system as a whole. The C&DH utilises a ATmega2560 microcontroller. It gathers data from all other chips and makes it available as telemetry, and it receives telecommands and sends commands to each subsystem accordingly. It also interfaces directly with the communications board, which does not have a microcontroller. Therefore, all commands sent to the EduCube over radio or umbilical are routed through the C&DH.

The C&DH communicates with the other subsystems via SPI, where it is the master (and the other subsystems are slaves). It communicates directly with the communications board components via TTL serial. The C&DH will detect the physical presence of the other boards even if they are not powered via a hot-plug detection pins on the system bus.

E. *Communications subsystem*

The Communications (comms) subsystem is responsible for transceiving all telemetry while the EduCube is operational, and for determining the EduCube's position using GPS. It consists of an XBee radio module and a u-blox GPS receiver.

The comms board does not have its own dedicated microcontroller; instead, both the radio and GPS modules communicate directly with the C&DH using TTL serial. The USB port of the comms board therefore serves a slightly different purpose. It can be used to debug either the radio or GPS module. When the comms board is connected to a computer via USB, one of the modules (selected using the switch next to the micro-USB port) will be disconnected from the C&DH and instead connected to the computer.

1) *Radio*

The XBee radio in the is specifically paired with another XBee radio which is built in to the launch adapter. This allows many EduCubes to operate wirelessly in close proximity (i.e. in the same classroom) on the same frequency.

2) *GPS*

A 'PPS' LED on the comms board will pulse once per second when the GPS module has a time fix indicating to students that the EduCube is receiving GPS signals. It will usually get a position fix very shortly after a time fix. The GPS module outputs data in the NMEA format over a TTL serial connection. During normal operation, the C&DH parses this data and transmits the coordinates in a much simpler format. When a computer is connected to the comms board and the switch is in the 'GPS' position, it is possible to view the NMEA output of the GPS module.

F. *Attitude Determination and Control subsystem*

The AD&C is responsible for measuring EduCube's attitude and maintaining it at a desired level. The attitude is determined using four sun sensors on either side of the EduCube, as well as a nine-axis Inertial Measurement Unit (IMU) sensor containing a magnetometer, accelerometer, and gyroscope with three axes each. The AD&C is controlled by an ATmega328 microcontroller. The attitude may be adjusted magnetically using the magnetorquers, or via angular momentum conservation using the reaction wheel. In practice, this attitude determination and control is done in an iterative scheme whereby the attitude is measured and an adjustment is made using the appropriate method and repeated in a PID algorithm.

1) *Reaction wheel*

The reaction wheel is a brass cylinder which, as it spins, causes the whole EduCube to spin in an effort to conserve angular momentum. The reaction wheel is spun using brushless DC motor.

2) *Magnetic torquers*

The magnetorquers are solenoids which orient the EduCube by aligning their magnetic fields with that of an external source, i.e. the Earth's magnetic field. They consist of a large number of turns of copper wire around an iron core. These solenoids generate a relatively large magnetic field and will turn the EduCube in the presence of an external magnetic field. Educube contains X and Y axis magnetorquers which may each be energised in either direction along their axis.

G. *Sun sensor*

Each side of the EduCube has a light sensor which contains a transimpedance amplifier. This converts a photodiode current to an output voltage, which is then converted to a 10-bit digital signal (0 to 1024). This digital value should be directly proportional to amount of light hitting the sensor. There is an on-board algorithm which works out the approximate angle of the sun using the values from the four light sensors.

H. *Thermal experiment*

EduCube is capable of hosting two on-board experiments. One experiment has been constructed, as an example for students. Each of two aluminium panels has been treated with a high-tech coating, called 'SolarBlack' and 'SolarWhite' manufactured by ENBIO Ltd. The panels are secured to the top face of EduCube (Fig. 2). These black and white surface treatments were developed by ENBIO for the European Space Agency's Solar Orbiter mission. Each panel has four resistors and three temperature sensors. The resistors are used to heat the panels and the temperature sensors are used to measure the resulting temperature of the panels.

I. *Protocols*

Several serial communication protocols for communication between subsystems and with sensors are used. TTL serial is primarily used to communicate between the EduCube and an external source e.g. the umbilical uses TTL serial, and all USB connections on the EduCube are simply USB to TTL Serial bridges. TTL serial is also used by the Command and Data Handling (C&DH) to communicate with the radio and GPS receivers. Serial Peripheral Interface (SPI) is used to send data between subsystems, specifically the C&DH and all other subsystems. In this case, the C&DH acts as the master and the other subsystems act as slaves. 1-Wire and i2c are other serial protocols that the EduCube uses to interface with various sensors e.g. temperature sensors.

J. Client

EduCube comes with a client that allows users to send and receive telemetry, either through the launch adapter or directly from a subsystem on a computer. This client runs in a Python script. It consists of a graphical web interface which allows users to send and receive telemetry through buttons and sliders, and a command line interface which allows users to send and receive telemetry programmatically. It thus allows telemetry to be exchanged in a Python script (or program). The EduCube client may be installed using Python's pip, i.e. *pip install educube*. Once installed, *educube --help* provides details on how to launch the web interface. The serial port may be set through the *-s* option, the location where it is mounted on Linux or macOS computers, e.g. /dev/tty.usbserial-CDH-2 on macOS, or /dev/ttyUSB0 on Linux; or with the appropriate COM port on Windows, e.g. COM4. As an example, if a user wishes to launch the web interface to interface with the C&DH board (which has been mounted to COM port 4), the user may do so via *educube -b 115200 -s COM3 start*. Alternatively, the user will be prompted for the serial port and baud rate (with suggestions) if not specified.

K. Student Experience and Future Development

From students' feedback on the EduCube, it is an effective tool for demonstrating how the different satellite subsystems work (both individually and together). Once students have understood what the subsystems do, they naturally want to understand more about how they work, and how they communicate. For many students, the EduCube is their first encounter with a serial port or a telemetry data packet. To make it easier for students to understand these concepts, they are first introduced to them with processed telemetry data through a user-friendly GUI. Ultimately, the students develop their own Python scripts for basic communication and telemetry handling, which provides them with the fundamental understanding of the system interface. Student feedback is that these are some of the most valuable and applicable skills they learn in the lab.

To make this learning process more effective, the user interface is being expanded to provide more direct access to telemetry. Further scripting exercises are being added in which the student will parse real-time telemetry and extract data themselves. The EduCube will therefore become a platform to lead students on a pedagogical path from understanding what satellite subsystems do (shown in the processed data accessed through the basic GUI), to how the satellite communicates (in the form of the transmitted telemetry data shown in an enhanced GUI), to how the user listens to the satellite (shown through students writing their own scripts).

The aim here is therefore to allow the EduCube to serve two purposes by providing an introduction to the functions of different satellite components and as a framework around which students can learn and understand some of the fundamental ideas and tools that they will need to master in order to create their own satellite systems later in the MSc course.

There is further potential to develop the EduCube into an undergraduate or high-school experiment.

Acknowledgments

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Educational Value and Lessons Learned from the Student High Altitude Balloon Programme IRBE

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Abstract — **This paper presents the educational value and lessons learned from the student High-Altitude Balloon (HAB) programme IRBE. IRBE is Ventspils University College electronics engineering student-made near-space HAB programme. During IRBE programme since 2015, three successful near-space missions have been launched. The paper will focus on main aspects of HAB mission results both technical (system engineering) as well as educational lessons learned, including the management, planning and motivation. Main goal of programme is to attract more students to space technologies and provide hands-on educational experience for young engineers through development of innovative short period projects to improve their know-how in space technology.**

Keywords — HAB; GSBC; IRBE; lessons learned; near-space

I. Introduction

Traditional teaching methods have been used in universities for decades. These methods were probably effective years ago, when rate of information flow was very low. In the time of globalization and information age, incredibly large amount of information is easily available for everyone. Traditional teacher-centered methods are losing effectiveness. It is important to introduce innovative teaching methods to maintain global competitiveness.

Hands-on project based teaching methods are becoming more and more popular over the recent years and results of use of these methods have proven themselves very well.

Although transformation of teaching methods is very important almost in all fields, especially crucial it is in STEM fields. It is widely recognized that education of STEM careers affects competitiveness in the global marketplace. And it is particularly difficult in the countries like Latvia, where the ratio of careers in STEM and high school graduates is very low. Latvia also doesn't have strong long-term traditions in space technology research and development, thus making promotion of space science even more difficult.

Based on above mentioned, it is very important to establish innovative teaching method and promote outreach of space and STEM sciences, in order to maintain sustainable global competitiveness.

In this paper the lessons learned during the programme are highlighted. In addition, we study how an educational space technology programme, the Student High Altitude Balloon (HAB) Programme IRBE, complements engineering curriculum and affects the space technology outreach. Learning outcomes of the Programme are discussed according to the list of Future Work Skills 2030 [1].

II. High Altitude Balloon Programme IRBE

A. Background

In 2015 the first HAB team IRBE, named IRBE-1, was founded by enthusiastic last year electronics master students from Ventspils University College as their own volition [2]. From 2015 to 2017 three missions came out in total. In 2018 IRBE evolved as HAB Programme IRBE and stable project based learning method for electronics engineering students, including it in VUCs electronics engineering curriculum.

The main goal of each team over last three years was to participate in worldwide HAB community organized competition Global Space Balloon Challenge (GSBC) taking a part in the HAB near space (20 - 100 km in Earth atmosphere) research missions. The major mission task is to carried out scientific experiment introducing community with innovation or used approach [3].

In 2015 the team IRBE-1[1] as scientific experiment decided to take a photos of the Earth surface in near-infrared frequency range giving a second life for old general purpose digital camera (Canon PowerShot A490) which was specially modified and adapted for this purpose - to assess quality of agricultural fields and to determine urbanized areas. During mission flight, more than 1000 images were taken of the Earth surface for later post processing. Mission duration time was 195 minutes, reaching approximately altitude of 23 km, with landing place at Striukai (Šiaulių Apskritis, Lithuania) in

[1] IRBE - InfraRed Balloon Experiment. IRBE not only stands for HAB Programme itself but also as name of the team, mission. IRBE is partridge in Latvian language and its local river name. Also, Irbe is last name of legendary Latvian hockey player Artūrs Irbe.

South-East direction from Ventspils. Total displacement was around 200 km.

Due to the success of IRBE-1, it was decided to take a part in next year competition. The name of the team in 2016 came out as IRBE-1: Legacy[2]. Instead of one probe, two probes were planned to build with very ambitious scientific (and technical) experiment. It was chosen to develop inter-balloon communication (using LoRa technology based radio modules) system to increase probe finding precision. Typically at very low altitudes (lower than 100 meters) and at far distances (more than 50 km), it is hard to receive low power radio signal with telemetry data transmitted from probe, because Earth relief, forests and radio frequency interference affects penetration of radio signal. Launching two balloons with time step, increases possibility to receive precise landing place GPS coordinates from first probe, while second is still in air, and it can transmit radio signal to ground station from first probe and itself. Ground tests were successfully passed, but technical flaws revealed during flight. Gained experience leaded to precise defined technical improvements for next year. Mission duration time was 197 and 180 minutes for HAB-11 and HAB-2 respectively, reaching approximately altitude of 26 and 25 km, with landing place at surroundings of village Vārme (Latvia) in South-East direction from Ventspils. Total displacement was around 70 km.

In 2017 daylight saw the IRBE-3 mission. Primary mission task was to accomplish scientific experiment measuring four different atmospheric gases: NH3, CO, CO2, and O3 to determine gas composition in low atmospheric layers. In this year a lot of improvements were done, starting from fully redesigned payload framework, providing better thermo isolation, continuing with precisely designed subsystems. Communication (COM) and sensor subsystems (SS) were introduced as IRBE's next generation subsystems. Mission duration time was 120 minutes, reaching approximately altitude of 14 km, with landing place at surroundings of city Talsi (Latvia) in East direction from Ventspils. Total displacement was around 60 km [4].

Launching place for each HAB mission was Airport of Ventspils. Radio station of VUC (callsign YL1VA) was used as a head for IRBE telemetry radio signal tracking[3]. In total 7 other radio stations took a part in HAB tracking during IRBE-3 flight, including colleague from Tartu (callsign: ES5T0). This shows amateurs radio operator's interest from Latvia in events like HAB nears space missions, increasing its popularity and familiarizing national society with it.

Two milestones over last 3 years can be determined. The first one: runner-up for the *Best Science Experiment* prize from GSBC organizers in 2015. This led to continue ongoing project started by near-space pioneers of the VUC. The second milestone was 1st place for the Best design prize in 2017. Success contributed to form HAB Programme IRBE, integrated un study process as project based learning for electronics engineering students

B. *Technical part*

All HABs developed by IRBE teams are classified as light unmanned free balloons (UFB) under restrictions of COMMISSION IMPLEMENTING REGULATION (EU) No 923/2012 of 26 September 2012[4]. This is done due to easier rules of administration for near space mission from Civil Aviation Agency. Light class UFB can carry payload of one or more packages with a combined mass less than 4 kg, unless qualifying as a heavy balloon[5]. The total mass of IRBE system typically is around 2 kg. Full mechanical and electronic HAB system is made up from two major compositions: payload and harness system. Each part is further subdivided in smaller blocks.

Harness system consists of latex balloon, which in flight day typically is filled with helium (rarely hydrogen is used, because of more danger), parachute - providing adequate descent rate, and payload framework. Balloon and parachute, as well as parachute and framework is conjunct with paracord rope. Specially bounded knots are used for high stiffness. For robustness and flexibility in some paracord connection points carbines also are applied.

Payload has three main subsystems: communications, sensors, and power supply. Each of it plays a critical role during mission. All electronic subsystems and mechanical parts, including parachute, are made by students themselves.

Power subsystem delivers an appropriate voltage and current for all electronic parts, including two sport type cameras SJCAM M10 and SJCAM 4000 (one located facing down to Earth surface, other for horizon view). System refusal means mission failure, because communications stops working. Thereby probe can be lost.

Sensor subsystem typically measures inside and outside temperature, humidity, pressure and acceleration, recording them in SD card. All data recorded during flight are very valuable for analysis. A temperature measurement greatly shows goodness of framework thermo isolation, humidity - cloud cover in lower altitudes, acceleration - wind power at the appropriate altitudes. System failure can lead to failed scientific experiment.

Communication subsystem provides radio link between probe and ground station at amateur 434 MHz (usually) band. It consists of GPS antenna, GPS receiver module connected with microcontroller, which sends data to radio module.

C. *Engineering lessons learned*

Development of robust and flexible design of electronics subsystems is a challenging task. For young electronics students it takes not only gained knowledge in studies what can be used for innovative engineering project, but also mechanical skills to construct and combine parts together for real life application.

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[2] Because of suspense that there will be even third mission with so great headway

[3] containing information about GPS coordinates, including horizontal and vertical velocity, internal and outer temperature, as well battery voltage

[4] OJ L 281, 13.10.2012, p. 1

[5] OJ L 281, 13.10.2012, p. 1

TABLE 1. HAB IRBE MAIN GUIDLINES

	IRBE-1	IRBE-1:Legacy	IRBE-3
Year	2015	2016	2017
Launching place	Airport of Ventspils		
Launching date	April 10th	May 22th	August 17th
Landing place	Striukai (Šiaulių Apskritis, Lithuania)	Surroundings of village Vārme, Latvia	Surroundings of city Talsi, Latvia
Duration time (min)	195	HAB-1: 197 HAB-2: 180	120
Reached altitude (approx., km)	23	HAB-1: 26 HAB-2: 25	14
Displacement, km	190	HAB-1: 70 HAB-2: 67	60
Scientific experiment	Photographing Earth surface in near-infrared range	Inner balloon communication system	Gas composition measurements in low atmospheric layers
GSBC nomination	Category: Best science experiment Place: 2nd	-	Category: Best Design Place: 1st

Evolution of the all system is iterative process, learning from mistakes and learning from successive ideas which passed during ground checks and mission flight itself. If the team failed at some point, if the team showed powerful result, they are learning from themselves and previous team members.

Therefore every check (test) is very important and need to be obligatory documented in common team document repository, including description of each subsystem's functionality, block diagrams, electronic schematics, software block diagrams, firmware code with appropriate comments, etc. Respectively, it is necessary to fully describe electronic device with all its mechanical parts, creating datasheets for individual system parts. Because as experience shows, it leads to misunderstanding and consumes more time, which can be used for direct development, not trying to remember how exactly constructive work was done.

D. Management lessons learned

Team management and positive mood maintenance are ones of the most challenging tasks in the project. The precise scheduling and content planning, of team meetings including to-do lists, takes the most important roles of overall project build-up. For this reason weekly meetings are obligatory where achieved results are discussed. Management itself oversees direct exercises for each team member what need to be done in given deadline, knowing his field of expertise and interests.

Because students mostly are inexperienced they can presume ambitious decisions. This can lead to inner disputes and inability to make decisions in critical situations. Therefore mentor is compulsory. Mentor or team leader must be a person with great technical knowledge and experience from previous years to monitor total work and in the same time with appropriate communication skills to be a good motivator, because using right words, encouragement need to be served. Motivation and inner assistance within the team is rated as key for successful technical development and realization of the project. If some arisen problems cannot be solved by skills of younger involved participants, advice can be ask from older members with gained experience and knowledge from previous years. Because of this, veterans are very important to be strictly necessary involved. For example youngest participants for the first time must be positioned as trainees to learn engineering skills and get familiar with project main guidelines. For trainee in the next year, management and planning skills must be expand. Two year learning cycle is efficient time, because practically fit into every Bachelor's curriculum. This is very relevant point, where all involved people are making project tribal tree to create and improve succession.

To maintain updated developed electronics and mechanical solutions, documentation is mandatory. This is hard task for young engineering students, because such skills are not formed yet. Students need to be teached by veterans and mentor itself.

Team leader is not only friend for each of the teammates, but also a pattern to encourage some of them to later let him take his place and form succession. Therefore know-how for more students can be given. And that is one of the goals of project based learning method. Providing a feeling that each person is needed and important, gives big strength and connection in their minds, and team leader is backbone for that. And in this manner, major management tasks need to be monitored. To promote it in practice, team building activities must be organized. There are two main possibilities. Team leader comes up with his own ideas letting others to choose, or team members themselves offer proposals. One of the opportunities is to prepare video trailer with corresponding actions what greatly shows progress of the project. This is very simple way how to familiarize society with technical and scientific activities. Multimedia material needs to be published in social networks as Facebook. Press releases for university and local national community need to written in style of popular science to let read about newest progress. Doing this, increases student ability to write in stylistically correct language, describing what is done.

Management not only includes annually planning for mission successful realization, but also improvements, therefore it is strongly recommended every year review organizational performance to analyze obligations what need to be done better the next year.

For example, we are planning to create Constructor Office of IRBE Programme. This will give more benefits, and the major will be special allocation of posts. If member is very successful and has proven his skills, promotion is earned. In case, if development of subsystem's hardware or firmware leads to a good overall improvements and usage, in the next year member can take a role as system engineer and start teaching youngest ones, which are involved. History of tribal tree is one more benefit for youngest participants to see the roots, where design ideas and improvements was coming from. This helps manage development over the years. In our understanding this is the way, how not only this particular project, but other similar projects too, can be managed in STEM field.

Guidance is not just an inner teamwork, but also a job with other institutions and companies - money management from university, coordination with Civil Aviation Agency about flight day, time, and trajectory of air space in the national territory. Also a good start place of the mission needs to be chosen. For this reason local aerodrome is very suitable and therefore coordination is vital necessary.

III. Comparison with the Future Work Skills 2030°

To show how needed skills, during realization of annual electronics engineering student project within IRBE Programme (since 2015), corresponds to expected skills according to Future Work Skills 2030, characterization, based on gained knowledge of IRBE Programme and HAB missions itself, was done.

A. Judgment and decision making

Judgment and decision making is defined as skill of considering the relative costs and benefits of potential actions to choose the most appropriate one [1]. Project and challenge based learning activities are considered as efficient approach to develop skills of decision making for students in different educational levels [5] [6].

Projects within IRBE programme are carried out without external expertise or mentoring. Usually most of team members have low experience in project based engineering activities that can lead to overambitious objectives, which cannot be achieved in limited time frame.

Since HAB projects are limited by financial, human resource and time constraints, team members have to be very careful in decision making. Because of limited time frame consequences of faulty decisions are very fast, thus highlighting the effects of decision making.

B. Fluency of ideas

Fluency of ideas is defined as ability to come up with a number of ideas about a topic (the number of ideas is important, not their quality, correctness, or creativity) [1].

HAB missions within IRBE programme is based on scientific experiment integrated in payload. Objective of scientific experience is proposed via brainstorming by team members. Thus ability to of fluent idea generating is developed. Besides, efficient judgment and decision making is improved, in order to choose most appropriate idea within existing constraints.

C. Active learning

Active learning is defined as skill of understanding the implications of new information for both current and future problem-solving and decision-making [1]. HAB projects within IRBE programme are launched without theoretical introduction or preparation course. Students are actively engaged with new information during the project, thus they are forced to perceive information and use it immediately to solve problems and make decisions.

D. Learning strategies

Learning strategies is defined as skill of selecting and using training/instructional methods and procedures appropriate for the situation when learning or teaching new things [1]. Participation in HAB project can provide insight in engaging learning experience and create basis of understanding of use of different learning strategies, in order to efficiency promote self-mastery.

E. Originality

Originality is defined as ability to come up with unusual or clever ideas about a given topic or situation, or to develop creative ways to solve a problem [1].

HAB missions within IRBE programme are not restricted by any regulations or specific development standards, excepting regulations of European Aviation Safety Agency and corresponding National Aviation Authorities.

In addition, technological process of payload development can be done in makerplace that can be found in most of high schools, vocational schools and technical universities. There is no need of specific laboratories or expensive equipment.

Taking in account abovementioned, there are good conditions for expression of originality. Besides team members are forced to come up with original approaches because of time, financial and human resource restrictions. RESULTS

Three missions have been launched in a row during the student High-Altitude Balloon (HAB) programme IRBE: IRBE-1, IRBE-1:Legacy and IRBE-3. All of these missions took a part in a HAB competition organized by Global Space Balloon Challenge (GSBC). IRBE-1 mission took a second place in the nomination of "Best Science Experiment". IRBE-

3 mission took first place in nomination of "Best Design Award".

More than 25 students of Ventspils University College have been involved in IRBE programme. Most of these students are from STEM related curriculum, but there were involved students of humanities and social sciences as well.

Curriculum of electronics engineering at VUC is supplemented with group electronics engineering project that is based on gained experience and learned lessons during IRBE programme. Thus ensuring inspiring low cost project based learning methods within this curriculum.

Mission activities of IRBE programme appeared in all conventional media channels including evening news and leading newspapers in Latvia. The most attention was paid on activities of launch dates. HAB launch is entertaining and it attracts lot of attention of society, because activities during the launch are easily perceptible without specific technical knowledge and give a fast and enjoyable feedback in the form of high altitude photos and video.

CONCLUSION

Student High-Altitude Balloon (HAB) programme IRBE is a successful example of introduction of low cost hands-on teaching methods in STEM curriculum. Besides, IRBE programme makes a significant contribution in outreach of STEM and space sciences.

IRBE type HAB projects are very effective in terms of material and service costs and time scheduling. Since required financial resources are below 1000 EUR, small scale colleges or high schools can afford to carry out such a project, taking into account that the appropriate laboratories and expertise is available. Taking in account experience of IRBE programme, such projects can be realized in 6 months period. Such period can be easily harmonized within length of semester in university or high school. Thus potential risks of team member succession are avoided. Such risks are common in CubeSat development projects, where projects lengths up to four years and team members are leaving, because of graduation or career development.

HAB based projects is effective entry projects for further engagement in CubeSat projects. Involvement in HAB development gives a base understanding of system engineering, mission planning, team management, space-to-earth communication systems, space environmental effects etc.

IRBE project proved itself as very effective outreach tool for space technologies and science. It is because launch of balloon is easily perceptible for society. HAB project gives a well understandable feedback via high altitude photos and videos.

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Modelling EIRSAT-1 dynamics and actuation to validate and test a novel attitude control system

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***Abstract*—This works describes a simulation environment which was set up in MATLAB and Simulink to test different attitude control algorithms for the 2U CubeSat EIRSAT-1. The dynamic equations of motion are derived from a quaternion kinematic parametrization, the geomagnetic field is calculated by a spherical harmonics approximation, and disturbance torques are computed from empirical models.**

***Keywords*— Cubesat, Orbital dynamics, 2-D magnetorquers, Attitude determination and control, Geomagnetics**

I. Introduction

EIRSAT-1 is a 2U cubesat being developed under ESA's Fly Your Satellite programme by students at University College Dublin. With ESA's support, and subject to meeting ESA's stringent requirements at each stage, the project is to design, build, test, launch and operate a satellite with three payload experiments. It is hoped to be launched late in 2019. Two of the payloads are physics experiments, while the third, added later, is to test Wave-Based Control (WBC) as an attitude control algorithm for space flight. WBC is a relatively new control system originally developed in University College Dublin. After launch from the International Space Station, EIRSAT-1 will use a standard, commercial, flight-approved, attitude control system for the first part of the mission. Later it will be instructed from Earth to switch over to WBC, and the subsequent attitude control performance evaluated. The satellite will be actuated by two-axis magnetorquers, comprising on-board current coils, whose magnetic field interacts with the Earth's geomagnetic field to produce torques for attitude control.

There are several challenges. First there is the common spacecraft challenge of 3-D dynamics with six degrees of freedom, whose equations of motion are coupled and non-linear. The next difficulty is that the available control torque is confined to a plane normal to the geomagnetic field, which, due to the inclination of the ISS orbit, continually changes in direction and magnitude. Furthermore, the direction of the magnetic dipole generated on board is restricted to two dimensions rather than three, which further restricts the dimension of the space of available control torques at any given time. Finally, the magnitude of the resulting torque is miniscule relative to the moments of inertia of the 2U cubesat.

A simulation environment has been set up using MATLAB and Simulink modelling software. The 3-D dynamics of the spacecraft are calculated with quaternion attitude representation; the geomagnetic field is modelled with spherical harmonics approximations; and empirical models are used to simulate disturbance torques due to atmospheric drag, solar radiation pressure, gravity gradient, and magnetic dipoles generated by other electronic components of the satellite.

This environment is used to simulate and assess attitude control under different control laws, including PD (proportional-derivative) and Wave-Based Control, for different satellite orbits. Also the effects of different actuator configurations and actuator limits can be investigated.

In the past, passive attitude control methods such as those relying on torques exerted by gravity gradients have successfully stabilized spacecraft [1], [2]. Nonetheless, such passive methods do not meet the pointing accuracy requirements of the EIRSAT-1 payloads, which will require a 3-axis active, attitude-control algorithm.

EIRSAT-1 will be equipped with a set of two magnetorquers, which will generate a magnetic dipole moment whose interaction with the Earth's magnetic field will produce the desired control torque. The decision to use magnetic actuation is motivated by the strong limits imposed by the mission's power, mass and volume budgets.

The dynamics of the satellite are underactuated for two reasons: on the one hand, the number of actuators is lower than the number of degrees of freedom; on the other hand, the control torque is restricted to a plane normal to the local magnetic field. However, despite the underactuated nature of a magnetically actuated spacecraft, controllability results still indicate the effectiveness and reliability of such attitude control systems [3].

The paper is structured as follows: section II presents a derivation of the equations of motion which are built upon Euler's dynamic equations and a kinematic quaternion parametrization. Section III presents the models used to simulate the environmental disturbance torques. In section IV the approximation of the Earth's geomagnetic field is discussed. Section V presents results from two different simulations. Finally, conclusions are drawn in section VI.

II. DYNAMIC EQUATIONS OF MOTION

A derivation of the equations of motion is presented in this section. The kinematic equations are written in terms of an attitude quaternion kinematic parametrization, while Euler's dynamic equations of motion are used to model the spacecraft dynamics. These equations govern the evolution of the position of a reference frame fixed to the spacecraft relative to an inertial reference frame.

A. Reference Frames

In keeping with the tradition throughout the literature (see, for instance [4], [5]) we shall first define a set of four different reference frames.

1) Earth Centered Inertial (ECI) reference frame:

The origin of this reference frame is placed at the center of the Earth. Its Z axis is normal to the equatorial plane and parallel to the Earth's rotational axis, pointing towards the Earth's North Pole. The X axis points towards the vernal equinox. Finally, the Y axis completes the right-handed orthonormal frame.

2) Earth-Centered/Earth-Fixed (ECEF) reference frame:

Its origin is also placed at the center of mass of the Earth, with Z axis pointing towards North Pole. Its X axis is constantly pointing in the direction of the intersection between the Greenwich meridian and the Earth's equator. Thus, it rotates with the Earth, sharing its angular rate. The Y axis completes the right-handed orthonormal frame.

3) Local-Vertical/Local-Horizontal (LVLH) reference frame - Orbital Frame:

Its origin is now located at the center of mass of the spacecraft. The Z axis points towards the center of mass of the Earth, aligned with the nadir direction, the Y axis is parallel to the orbit angular velocity (normal to the equatorial plane). The X axis completes the right handed orthonormal triad.

4) Body-Fixed Frame

Similarly, this frame is placed at the center of mass of the satellite. However, it is chosen to be aligned with the principal axes of inertia of the spacecraft. The orientation of this frame with respect to the inertial (ECI) frame is described by the quaternion parametrization discussed below.

B. Satellite Dynamics

The dynamics of the spacecraft are modeled as those of a rigid body rotating in space, and thus are given by the Euler's equations of motion ([5]–[8]).

$$\boldsymbol{J}\frac{d\boldsymbol{\omega}(t)}{dt} = -\boldsymbol{\omega}(t) \times J\boldsymbol{\omega}(t) + \boldsymbol{\tau^c}(t) + \boldsymbol{\tau^d}(t)$$

where $\boldsymbol{J}$ is a constant matrix, denoting the inertia tensor, $\boldsymbol{\omega}(t)$ is the angular velocity in the body-fixed frame, and $\boldsymbol{\tau^c}(t)$, $\boldsymbol{\tau^d}(t)$ are, respectively, control and disturbance torques acting on the satellite.

Without loss of generality, one can align the body fixed frame to the principal axes of inertia, resulting in a diagonal inertia tensor $\boldsymbol{J} = diag(J_1, J_2, J_3)$. The Euler equations of motion then become

$$\begin{cases} J_1 \dfrac{d\omega_1(t)}{dt} = (J_2 - J_3)\omega_2(t)\omega_3(t) + \tau_1^c(t) + \tau_1^d(t) \\ J_2 \dfrac{d\omega_2(t)}{dt} = (J_3 - J_1)\omega_1(t)\omega_3(t) + \tau_2^c(t) + \tau_2^d(t) \\ J_3 \dfrac{d\omega_3(t)}{dt} = (J_1 - J_2)\omega_1(t)\omega_2(t) + \tau_3^c(t) + \tau_3^d(t) \end{cases}$$

An important remark is that, by nature of the interaction of the magnetic dipole produced by the magnetorquers with the Earth's magnetic field, the control torque takes the following form

$$\boldsymbol{\tau}^c = \boldsymbol{m} \times \boldsymbol{B}$$

where $\boldsymbol{B}$ is the local magnetic vector and $\boldsymbol{m}$ is the magnetic dipole produced by the magnetorquers. From a control engineering perspective, $\boldsymbol{m}$ is the control input of the dynamic system.

This last equation implies that the control torque can only be applied in a plane normal to the local magnetic field, which further restricts the dimension of the space in which the control torque can be applied.

C. Quaternion Kinematics

Unit quaternions, or Euler parameters are used for the kinematic representation due to their computational advantages. A unit quaternion $\boldsymbol{q}$ is comprised of a scalar part η and a vector part $\boldsymbol{\epsilon}$

$$\boldsymbol{q} = \begin{pmatrix} \boldsymbol{\epsilon} \\ \eta \end{pmatrix} = \begin{pmatrix} \mathbf{e}\sin(\theta/2) \\ \cos(\theta/2) \end{pmatrix}$$

where θ denotes the Euler angle of rotation about the unit eigenaxis $\boldsymbol{e}$.

The kinematic equations can be written in terms of the quaternion as in [5], [6]

$$\dot{\boldsymbol{q}}(t) = \frac{1}{2}\boldsymbol{\Omega}(\boldsymbol{\omega}(t))\boldsymbol{q}(t)$$

where

$$\boldsymbol{\Omega}(\mathbf{u}) = \begin{pmatrix} 0 & u_3 & -u_2 & u_1 \\ -u_3 & 0 & u_1 & u_2 \\ u_2 & -u_1 & 0 & u_3 \\ -u_1 & -u_2 & -u_3 & 0 \end{pmatrix}$$

Quaternions are used for attitude representation only for simulation purposes, given their many advantages in computationover other methods such as DCM (Direction Cosine Matrix) or Euler Angle-Principal Axis. They avoid singularities and expensive trigonometric calculations. Nevertheless, results are converted and presented as the evolution of three Euler angles (roll, pitch and yaw) over time.

III. Disturbances

Along its trajectory, the satellite may be acted by some disturbing forces or torques due to unknown or uncertain phenomena. The controller should be able to overcome these, detecting their effects and taking the appropriate action to correct the perturbed maneuver. These are modeled as a disturbance torque $\boldsymbol{\tau}^d$, provoked by 4 distinct physical phenomena: gravity gradient, aerodynamic drag, solar radiation pressure, and internal magnetic dipoles from other components of the spacecraft.

$$\boldsymbol{\tau}^{\boldsymbol{d}} = \boldsymbol{\tau}^{\boldsymbol{g}} + \boldsymbol{\tau}^{\boldsymbol{a}} + \boldsymbol{\tau}^{\boldsymbol{s}} + \boldsymbol{\tau}^{\boldsymbol{m}}$$

1) Gravity gradient

This torque is related to gradients in the gravitational force exerted on different points of the spacecraft.

P.C.Hughes proposed an expression in [9] based on the assumption that the gravitational field is entirely produced by the Earth, which is considered a perfect sphere

$$\boldsymbol{\tau}^{\boldsymbol{g}}(t) = \frac{3\mu}{R^3}\, \boldsymbol{r}(t) \times \boldsymbol{J}\boldsymbol{r}(t)$$

where $\boldsymbol{r}(t)$ is the unit vector pointing towards the center of the Earth from the center of mass of the satellite, μ is the Earth's gravitational constant, and R is the distance to the center of the Earth.

2) Aerodynamic Drag

EIRSAT-1 is to be launched from the International Space Station, and targeted to move in Low Earth Orbit (LEO), at an altitude of approximately $400\ km$, where the presence of atmosphere is not negligible.

An aerodynamic torque is exercised on the satellite, which is modeled based on the drag coefficient C_d [4], [9]–[11]

$$\boldsymbol{\tau}^{\boldsymbol{a}} = -\frac{1}{2}\sum_i \left(\rho v^2 C_d A_i\,(\boldsymbol{v}\cdot\boldsymbol{n}_i)\right)\boldsymbol{r}_{cp,i} \times \boldsymbol{v}$$

where $\boldsymbol{v}$ is the velocity of the satellite relative to the atmosphere, $\boldsymbol{n}_i$ is a unit vector normal to each surface of the spacecraft, ρ is the atmospheric density at the orbit's altitude. $\boldsymbol{\tau}_{cp}$ is the position of the center of pressure of the i-th surface relative to the center of mass. A_i is the area of the i-th surface. The drag coefficient Cd is to be determined experimentally or by simulation once the CAD model is complete.

3) Solar Radiation Pressure

There also exists a momentum exchange between the sun and the surfaces of the satellite due to radiation pressure, which may be negligible for a small size CubeSats. Nonetheless, it is modelled in the present work as proposed by [4]

$$\boldsymbol{\tau}^{s} = -P\sum_i A_i\,\boldsymbol{r}_{cp,i} \times \left(2\left(\frac{\sigma_d}{3} + \sigma_s(\boldsymbol{n}\cdot\boldsymbol{s})\right)\boldsymbol{n} + (1-\sigma_s)\boldsymbol{s}\right)$$

where P is the momentum flux, σ_s and σ_r are, respectively, the specular and diffuse reflection coefficients, which are constant and characteristic of the material of the surface. The remaining terms are defined as in the previous section.

4) Internal Magnetic Dipole

In the same manner as magnetorquers do, other electronic components which are part of the satellite generate residual magnetic dipoles which interact with the local magnetic field and produce a disturbance torque.

$$\boldsymbol{\tau}^{\boldsymbol{m}} = \boldsymbol{m}_{res} \times \boldsymbol{B}$$

This equation is identical to the equation for the torque from the magnetic dipole generated by the controller, except that the magnetic dipole is now produced by unintended sources from other satellite components.

IV. Geomagnetic Field

The Earth's geomagnetic field needs to be modelled well, as it directly determines the effectiveness of the attitude control method.

In the present work, the field is simulated using the International Geomagnetic Reference Field (IGRF), which is a model proposed by the International Association of Geomagnetism and Aeronomy (IAGA). This model has been extensively used in other simulations aimed to test ADCS systems (See, for instance [5], [7]). The model is discussed in detail in [12] and [13], and we refer the interested reader to these works.

The magnetic field $\boldsymbol{B}(r,\phi,\theta)$ is expressed as the negative gradient of a scalar potential

$$\boldsymbol{B}(r,\phi,\theta) = -\boldsymbol{\nabla} V(r,\phi,\theta)$$

which is given by the spherical harmonic approximation

$$V(r,\phi,\theta) = \mathrm{R}\sum_{n=1}^{L}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n}\left(g_n^m\cos(m\phi) + h_n^m\sin(m\phi)\right)P_n^m(\cos(\theta))$$

where g_n^m and h_n^m are the set of IGRF gaussian coefficients, published and revised every five years by the participating members of IAGA (International Association of Geomagnetism and Aeronomy). The twelfth generation is used here, as the latest revision available for this work. These coefficients also include the secular variation (SV), which gives the model the proper time dependence, keeping track of the annual variation in nT per year. The coefficients for a specific year are referred to as IGRF. When real data about the geomagnetic field becomes available so that adjustments can be made, the model becomes definitive and changes its name to DGRF (Definitive Geomagnetic Reference Field).

The radius of the Earth is given by R, and r, ϕ, θ are the spherical coordinates in the ECEF frame, with ϕ the longitude and θ the co-latitude.

$P_n^m(\nu)$ are the Schmidt-normalized Legendre polynomials of degree n and order m.

In spherical coordinates, the three components of the magnetic field strength in the Earth-Centered/Earth-Fixed reference frame then take the form

$$B_r = \sum_{n=1}^{L} (\mathrm{n}+1) \left(\frac{R}{r}\right)^{n+2} \sum_{m=0}^{n} (g_n^m \cos(m\phi) + \\ + h_n^m \sin(m\phi)) P_n^m(\cos(\theta))$$

$$B_\theta = \sin(\theta) \sum_{n=1}^{L} \left(\frac{R}{r}\right)^{n+2} \sum_{m=0}^{n} (g_n^m \cos(m\phi) + \\ + h_n^m \sin(m\phi)) \frac{dP_n^m}{\mathrm{d}\nu} (\cos(\theta))$$

$$B_\phi = \frac{1}{\sin(\theta)} \sum_{n=1}^{L} \left(\frac{R}{r}\right)^{n+2} \sum_{m=0}^{n} \mathrm{m} \, (g_n^m \sin(m\phi) \\ - h_n^m \sin(m\phi)) P_n^m(\cos(\theta))$$

V. SIMULATIONS

At the start of the mission, the attitude control algorithms will be those of a commercial off-the-shelf ADCS board (supplied by Clyde Space), which will first detumble the satellite and then point in the desired direction. At a later stage, in response to an instruction from Earth, the satellite will switch to Wave-Based Control (WBC), which will be used for each of the three modes of operation, namely detumbling, sun pointing and zenith pointing.

Wave-Based Control is a control method which was originally developed for the motion control of flexible mechanical systems ([14]–[19]). It has also been recently adapted for different aerospace applications, such as the control of elastic tethers [20], and attitude control of spacecraft with fluid sloshing dynamics ([21], [22]). The third payload of EIRSAT-1 is to test and validate WBC as a feasible and reliable algorithm for attitude control.

In this section, two simulations are presented. In the first, from a given initial attitude, the satellite is commanded to adopt different attitudes, using WBC with two magnetorquers as actuators. For instance, Fig. 1 shows the evolution of the three Euler angles when, starting from rest and aligned with the inertial reference frame. The satellite is commanded to rotate 90 degrees about one of the principal axes of inertia and come to rest again. Fig. 2 shows the evolution of the angular velocity for the same maneuver. A different maneuver in which the satellite's body-fixed reference frame is to be constantly aligned with the LVLH reference frame, with the axis of minimal inertia pointing towards the zenith direction, is recreated in figures 3 and 4, which show, respectively, the evolution of the Euler angles and angular velocity components.

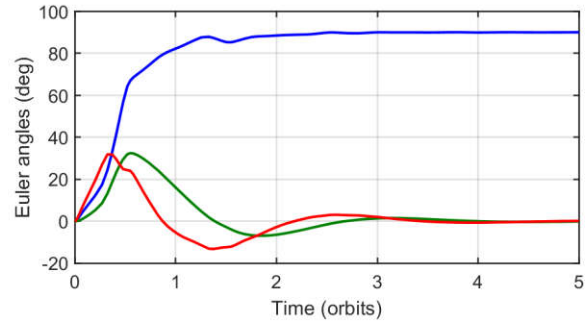

Fig. 1. Euler angles-From rest, the satellite is commanded to rotate 90 degrees around one of the principal axes

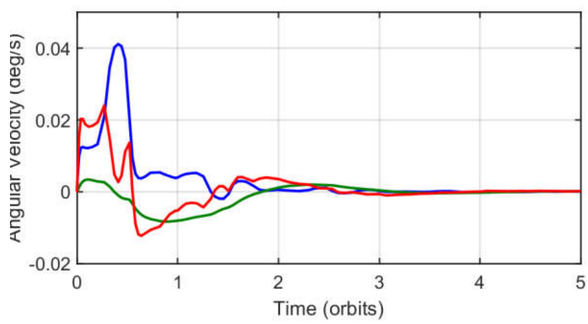

Fig. 2. Angular velocity-From rest, the satellite is commanded to rotate 90 degrees around one of the principal axes

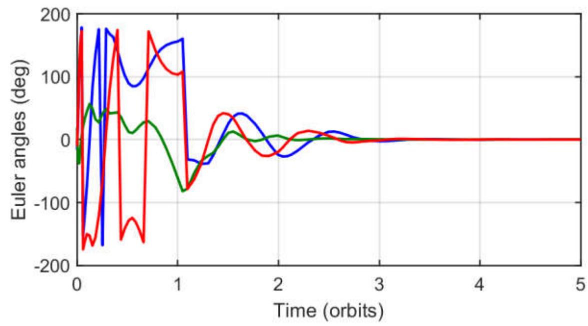

Fig. 3. Euler angles error-The satellite is to maintain its allignment with the LVLH (Orbital) reference frame

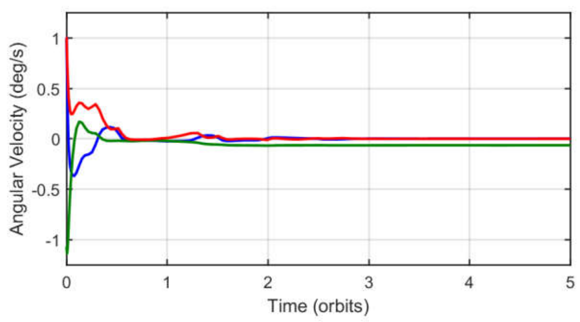

Fig. 4. Angular Velocity-The satellite is to maintain its allignment with the LVLH (Orbital) reference frame

VI. CONCLUSIONS

A simulation environment has been set up using MATLAB and Simulink to test and validate different control algorithms to be included in the EIRSAT-1 ADCS system. The model successfully simulates the dynamics of the spacecraft and replicates the evolution of disturbance torques and the magnetic field along the trajectory of the LEO orbit. Simulations are presented as the evolution of the Euler angles over time when one of the control algorithms (Wave-Based Control) is used. The model proved useful to the engineering design process of EIRSAT-1.

ACKNOWLEDGMENT

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Testing for High Altitude Balloon Missions

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***Abstract*—This paper describes how the main principals of standard spacecraft development and testing process introduced to university students through the development of a universal high altitude balloon platform.**

Keywords—high altitude balloon; development; testing;

I. Introduction

Our team of university students from Simonyi Károly College for Advanced Studies is developing a universal balloon platform for small payloads. The platform called Reusable High Altitude Balloon (ReHAB) which is a modular system that can be configured easily for different kind of missions. The goal of the project is to provide a reliable, affordable balloon platform and launch service for experiments of university research groups and also to help university students to gain hands on experience in space engineering.

II. Flight Computer

The ReHAB modular flight computer (Fig. 1) has three core modules for basic operation. These modules are the On-board Computer (OBC), the Communication Module (COM) and the Electric Power System (EPS). The system can be expanded with additional sub-modules connected to the internal system bus according to the actual mission. The additional modules could be data acquisition units, camera modules or a mission specific payload interface.

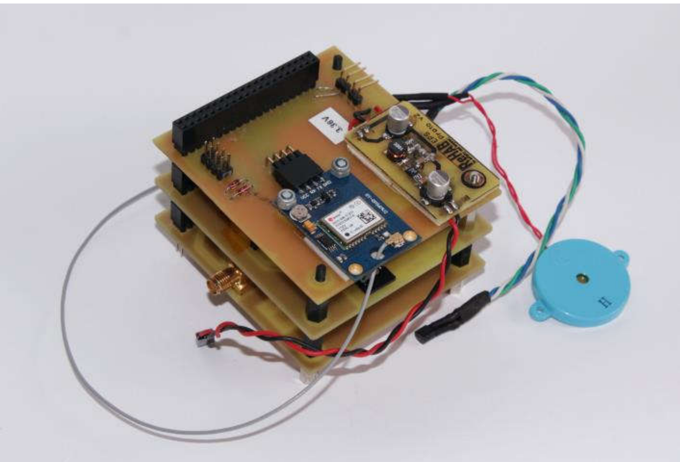

Fig. 1. ReHAB Flight Comuter Engineering Model in stacked configuration

The tasks of the On-Board Computer are to synchronize the sub-modules and overview the execution of the flight plan. During the mission it processes and logs the telemetry and house-keeping data, manages the Global Positioning System (GPS) receiver module, communicates with the sub-modules via the System Bus and is able to operate the science payload.

The Communication Module provides a two-way communication channel between the balloon and the ground station. The telemetry and house-keeping parameters are available during the flight thanks to the live radio link. Also it makes available to download science data and send commands to the flight computer or the science payload.

The Electric Power System provides the proper bus voltage for each module and monitors the power consumption, battery level and battery temperature.

The flight computer is built up in a stack configuration and the modules connected through an internal system bus. Right now the modules connected via a Universal Asynchronous Receiver-Transmitter (UART) based bus and using National Marine Electronics Association (NMEA) protocol [1] for communication. On this bus the OBC acts as the master and the sub-modules are the slaves. The communication is driven by the OBC, but the slaves are able to trigger an interrupt if needed. In the future we will introduce a Controller Area Network (CAN) based communication line for more reliable and faster communication.

The electronics are designed to be able to fit in a one unit CubeSat frame as a proof of concept for small satellite missions and to introduce students to the design of pico-satellite missions.

III. Development Process

Through the development our team tried to follow the space industry development process. During the initial planning phase we used the concurrent engineering principals when all sub-systems designed side-by-side through several iterations. This phase was closed with a System Design Review (SDR) in which we clarified and finalized the specifications, selected possible hardware components and set up a preliminary schedule for the development.

The initial planning phase followed by building the breadboard models. For each sub-system we used development boards to connect the individual hardware (HW) components and develop the corresponding software (SW) modules. In this version of the flight computer both the OBC and COM modules are based on Atmel/Microchip Atmega328p microcontroller (MCU) which led us to use Arduino UNO boards for the breadboard models (Fig. 2). The Arduino environment provides an easy and fast way for prototyping. In this phase unit tests were run on every component.

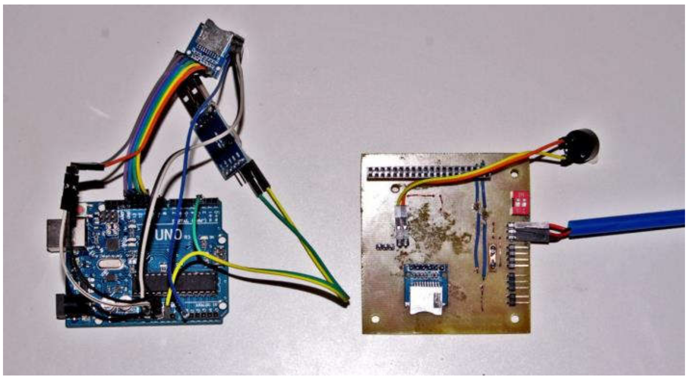

Fig. 2. OBC breadboard (left) and Engineering Model (right) side-by-side

After successful unit tests each breadboard was run through integrity tests when all HW-components were connected and all SW-components were implemented. Integrity tests were used to ensure all individual components can work together and does not interfere with each other.

This design phase was closed with a Preliminary Design Review (PDR) when we reviewed the schematics and preliminary printed circuit board (PCB) designs, checked if every component meets the specifications both in size and power consumption. During the PDR phase several trade-offs were made featuring the selection of the GPS module and the radio transceiver (RF TCVR) module.

After the hardware design based on the breadboards finalized, an Engineering Model (EM) for all sub-system was built. The PCBs of the modules were manufactured in-house by our team but flight rated HW components were used. The EM versions of the modules were integrated to finalize the flight software and conduct further tests. In this phase an elegant breadboard configuration was used where the EM boards were connected via ribbon cable in flat layout, test points and bus analyzer were also added to the system (Fig. 3).

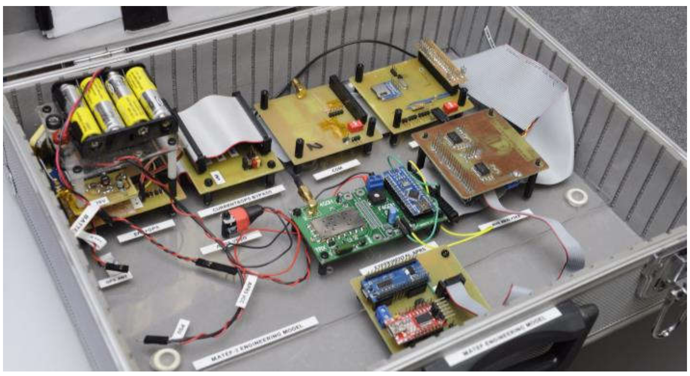

Fig. 3. Engineering Model in flat layout with test equipment

Tests conducted with the EM system were driven by different flight situations and complete flight simulations. At this point the observation was concentrated on the complete system behavior not the individual modules. We conducted bench tests, long-term operation tests and environmental testing in thermal chamber. During this period we have tried to minimize the changes on the hardware and after every change all tests were run from the beginning.

This design phase was closed with a Critical Design Review (CDR) when we reviewed the finalized schematics, PCB designs and the flight software. During the CDR phase we selected a third-party PCB manufacturer who meets the requirements of our specifications.

At the moment of writing this paper the development is in its last phase when the flight model (FM) (Fig. 4) is assembled and integrated to flight configuration. The PCBs of the FM are manufactured by professional third-party company and populated by our team members who have experience in soldering. Smoke tests will be conducted on all assembled modules individually before integration to ensure the FM modules are working as expected. Minor configurations should be made before the launch campaign, including the internal temperature sensors and the radio TCVR. We are planning a test on the completely integrated flight computer prior flight. This will include a simulation of a complete flight in cooperation with the launch/recovery team and ground station operators.

Fig. 4. Populated OBC Flight Model

The pre-flight tests of the flight model will be followed by the launch campaign during which the launch date will be selected based on weather forecast and flight simulations and the flight itself will take place.

IV. TEST PROCESS

Our team pays serious attention to testing because the flight computer must operate in an autonomous fashion and the operators can only interact with the balloon through radio messages. During test planning we examined previous balloon flights conducted by our team and others to cover as much flight situations as we can. For the best result the test environment was also developed by our team including several test and simulation software and special hardware components to interact with the flight computer.

Every development stage was closed with a test campaign, each on different functional level of the system. Each module was tested on component level first when both the individual hardware and software components went through unit tests:

Component tests were followed by sub-module level integrity tests. These were hardware in the loop (HIL) tests when we examined the operation of a designated module while the rest of the system was simulated by a software running on a personal computer (PC). These tests were focused on component integrity and module level interactions according to the specifications.

The next step in testing was system level integrity tests when all sub-modules were connected and operated as a whole. During these tests we measured different parameters (power consumption, RF interference, bus communication) in several flight situations and complete flight simulations. These were bench tests and the system level breadboard (Fig. 3) was used with the EM versions of the sub-modules.

The system level integrity tests were used to validate the system for environmental testing. The biggest challenge in high altitude balloon flights is the low temperature in the tropopause and in the stratosphere. We use commercial off-the-self (COTS) components which are usually rated to operate -40°C - 85°C (-40°F - 185°F) compared to the -56°C (-69°F) temperature in the tropopause. We used previous flight data and a thermal chamber to validate the COTS components and the integrated flight system at low temperatures.

We also specified testplans for module and system level smoke tests. These testplans are the backbones of the pre-flight tests conducted on the flight model. At the moment of writing this paper these smoke tests are in progress on the FM versions of the sub-systems.

After every modification and bug-fix the complete test process was executed from the beginning to ensure none of the changes caused further issues in the system.

V. Test Tools

Most of the test tools we used were developed by our team to create a test environment suitable to test our flight computer with an option to be expanded for testing other third-party high altitude and near-space devices.

A. TestLink

TestLink is an open-source web based test management software we used to create and manage testplans. The software gives support for test execution by leading the test engineers in a step-by-step fashion through the test cases. TestLink stores the results in a database and gives the option to generate test reports which were used by our team in the review process at the end of every development step to validate the design.

B. GPS Module Simulator

COTS GPS modules provide information via NMEA protocol. The physical layer and the message format are described in NMEA 0183 Standard [1], however some GPS modules operates higher baud rate than specified in the standard. Our team developed a PC software that emulates a GPS module through serial port (Fig. 5). The emulator is able to playback NMEA logs collected during previous flights or generated by trajectory simulators. The software has an option to generate NMEA messages from coordinate list supplemented with the current (actual) time. Since some modules operates different baud rate than the standard we added the option to select the specific baud rate matching the GPS module emulated. Functions to simulate GPS malfunction were also added to the emulator.

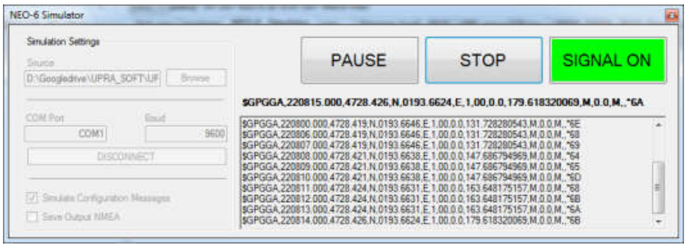

Fig. 5. GPS Simulator software in operation

This software was used to validate the GPS parser and test altitude triggered functions of the OBC.

C. GPS Signal Simulator

We used a National Instruments (NI) USRP-2920 software defined radio (SDR) to generate GPS satellite signals (Fig. 6). The software was written in LabVIEW based on an example application provided by NI. The simulation software runs on a PC and configures the radio channel of the USRP according to the GPS standards [2]. Currently the simulator provides signal stream for only a static 3D position (latitude, longitude, altitude). The application makes it possible to select a satellite almanac (saved on the computer) and to set the GPS date and time. The signal stream is generated and buffered by the PC and transmitted by the USRP SDR hardware.

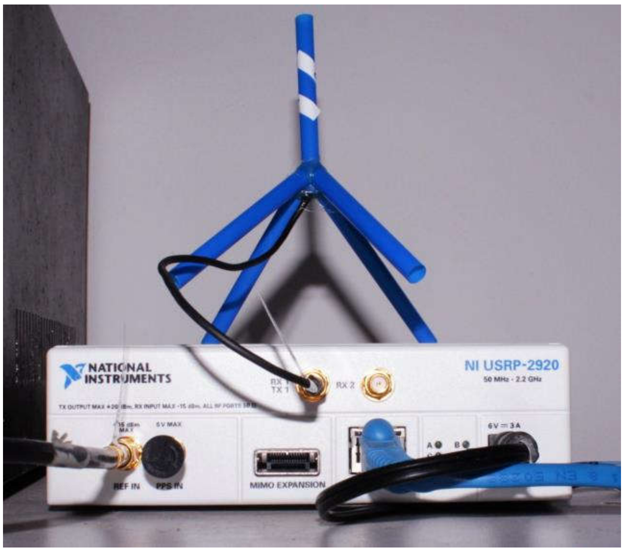

Fig. 6. NI USRP-2920 as GPS Signal Simulator

We used the GPS Signal Simulator to validate the GPS module for high altitude operation and to provide valid GPS signal for system level integration and thermal chamber tests.

D. UPRA Simulator

Our team developed a simulator software for module level HIL tests. The application generates system bus messages and connected to the selected module via serial port. The Universal Platform for Robotics and Aerospace (UPRA) Simulator is able to emulate individual sub-systems according to the specifications while the tested module is physically connected to the simulator. The operational parameters of the simulated modules can be set manually or by playback of simulation files. The software gives the option to generate malfunctions of the simulated modules and also to trigger a reset in the tested module. The simulator generates a detailed log of the test and gives the option to export only the transmitted and received raw bus messages.

This tool was used for module level HIL tests and smoke tests.

E. Bus Analyzer

A bus analyzer toolkit was developed by our team to read the internal communication between sub-systems (Fig. 7). The current version of the tool was designed for the UART based communication line and reads both master out (TX) and master input (RX) lines. A separate UART channel was also added to monitor the main GPS module NMEA messages. Both Transistor-Transistor Logic (TTL) voltage level UART channels are converted to Recommended Standard 232 (RS-232) serial voltage level to increase the distance the signals can be transmitted. This conversion is needed for the reliable connection when the flight computer is in the thermal chamber. A microcontroller is used to read, pre-process and transmit the bus messages to the PC software via USB-serial port. The analyzer software displays the bus messages separated by sub-systems, creates a detailed log of the serial communication and individual logs of the messages transmitted by the sub-modules.

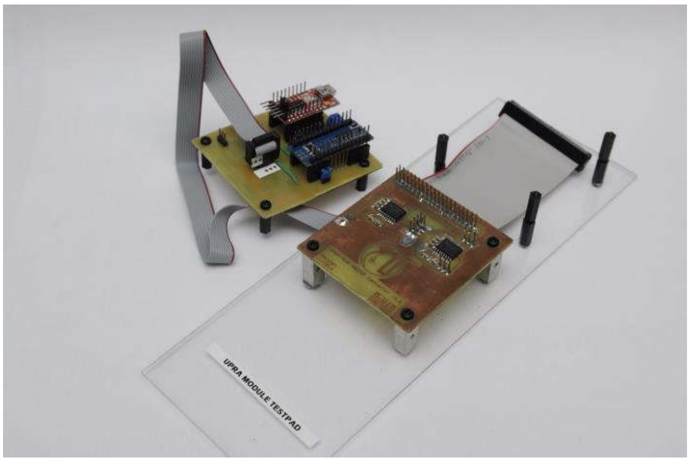

Fig. 7. Bus Analyzer hardware components

The GPS NMEA messages are forwarded to the PC by a simple Universal Serial Bus (USB)-UART converter and displayed in a general serial-terminal application.

The Bus Analyzer was used during system level integrity and thermal chamber tests to monitor the communication between sub-systems.

F. Radio Communication Test Tools

During tests we used our ground station hardware and software to decode radio messages sent by the flight computer and to transmit control commands towards the flight system. The ground station has the same hardware as the COM module but runs with a different firmware and connected directly to the PC via serial port. The current version of the ground station software (EZ-GND) is also developed by our team and displays the house-keeping and telemetry data on screen. It generates different data and trajectory logs and also calculates azimuth and elevation data for antenna rotation.

To validate and fine-tune the radio transceiver a spectrum analyzer was used (Fig. 8). The fine tuning was needed because the system is using a third-party RF circuit (sold as a module) and the production scattering is compensated by software.

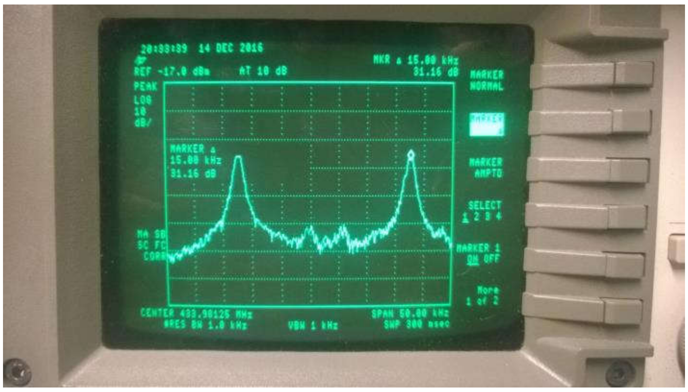

Fig. 8. Spectral measurements of the radio downlink

During tests and flights an SDR based solution is used as a control radio. The reception is provided by a USB 'Digital Video Broadcasting — Terrestrial' (DVB-T) receiver and processed by the SDR-Sharp radio software. SDR-Sharp displays spectrum information and waterfall-diagram providing monitoring option over the radio communication.

G. Thermal Chamber

Our thermal chamber is a modified refrigerator with freezer function (Fig. 9). We modified the internal chamber configuration, added extra insulation and replaced the temperature control circuit to achieve -20°C (-4°F) temperature. Although during a high altitude balloon flight the temperature can reach -56°C (-69°F), according to previous flight data inside the insulation capsule the temperature drops only to about -16°C (3°F). According to this information the flight computer was tested without insulation at -16°C (3°F).

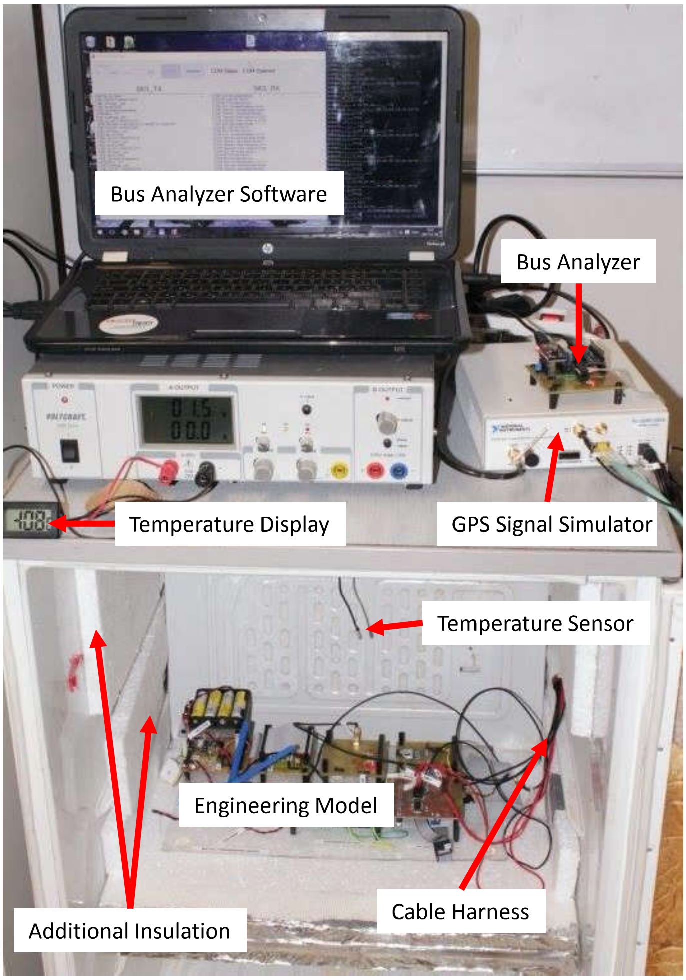

Fig. 9. Thermal chamber in test configuration

The thermal chamber has an opening for a cable harness which contains twisted wire pairs for bus analyzer output and coax cables for RF TCVR antenna out and GPS Signal Simulator antenna input.

We used the thermal chamber to validate that COTS components and batteries are able to work properly in a cold environment.

VI. Future Plans

At the moment of writing this paper we are testing and preparing the flight model to final integration. Our plan is to conduct a mid-altitude test flight with this system with a target altitude of 20km (65000ft) without any science payload. After a successful test flight several earth observation missions are planned where our team will provide the balloon platform and help in the development and testing of the payload. The latter flights will have a target altitude of 30km (98000ft) and possibility of a longer floating period during flight.

We would also like to upgrade the test environment to support the testing of third-party devices and build a test facility for high altitude experiments and provide launch service to university research teams.

VII. Summary

By organizing the development and test process described in this paper our goal was not just to build a reliable balloon platform but also introduce university students to spacecraft design through hands on experience. It is proven that participating projects like this is a great addition to the general university studies and helps students to master their field of interests. By providing launch opportunities and a test facility we hope we could help students in STEM fields to gain knowledge and experience and later successfully apply to other space related projects.

Acknowledgment

The development was supported by Simonyi Károly College for Advanced Studies by providing a laboratory/workshop and equipment.

In the early phase of development we received great technical support from the 'MASAT-1' CubeSat development team and BME-GND University Satellite Tracking Station.

We would also like to show our gratitude to the Department of Fluid Mechanics and the Department of Physics of Budapest University of Technology and Economics for balloon launch assistance and the Faculty of Electrical Engineering and Informatics for accepting student theses connected to our project.

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GPS-based navigation solution for the ESA ESEO educational mission

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Abstract— ***Since 2013 the Microsatellites Laboratory of the University of Bologna is involved in the ESA ESEO Educational Mission, as a provider of the GPS Navigation Payload. This sub-system, specifically designed for microsatellite platforms, aims at providing real time on-board high accuracy position fixes with reduced manufacturing time and cost. Following the design philosophy that usually drives the development of small satellite sub-systems, this payload includes a combination of commercial components, such as the single frequency GPS L1 C/A Novatel front-end, and custom-designed boards, like the main Navigation Computer, that hosts positioning filters and handles power and communication.***

The navigation component of the application software includes two algorithms with different levels of accuracy. The Kinematic Mode, based on a least squares algorithm, allows to achieve a navigation accuracy in the order of 10-15 m 3D rms, which satisfies the typical requirements of most small LEO missions. The second and more precise algorithm, included in the Reduced Dynamic Mode, implements an Extended Kalman Filter that fuses the a-priori information to the likelihood of observations. In this case, the expected accuracy is around 1 m 3D rms, which fits the needs of more demanding missions.

The GPS Payload underwent a thorough verification phase through several environmental and functional tests, aimed at validating both the hardware and software design. In particular, validation and tuning of the reduced dynamic filter were addressed with the aid of GPS signal simulators.

This paper describes the GPS Payload development process and test campaign performed on the two elegant breadboard (EBB) models. The protoflight model (PFM) is in the final development and validation phase and will soon be ready for integration within the ESEO platform. The next steps of the project include PFM completion and delivery, Test Readiness Review, integration and launch, currently foreseen in Q3/Q4 2018.

Keywords— ESEO; GNSS; Kalman filter; small satellites; insert (key words)

I. INTRODUCTION

The issue of autonomous navigation of spacecrafts has always been of great interest in the astronautic field, as the classical ground-based techniques represents an expensive solution for orbit determination. While high costs are not usually a problem for high budget missions, they can represent a limitation for missions involving small satellites. Furthermore, the opportunity to have the spacecraft position, velocity and time (PVT) information on-board and in real-time provides benefits for the automatic handling of the payloads and a considerable support to other platform sub-systems.

While a class of spaceborne GNSS receivers, tested on board of major space missions and capable to provide high quality position fixes, is already available on the market, there's a lack, instead, of similar solutions for small satellite platforms. Although small satellites are nowadays considered a valuable resource for the future of space research and industry, their diffusion is subordinated to the advancements on the miniaturization and scaling process of technologies already available for bigger spacecrafts. Within the framework of the ESEO microsatellite mission, funded by ESA education office and managed by the Italian company SITAEL, the University of Bologna team worked on the development of a GPS-based navigation sub-system that was selected to fly as secondary payload for the spacecraft mission, whose launch is expected for late 2018. The development of the ESEO GPS-payload described herein followed a different path with respect to previous spaceborne navigation technology, aiming at fitting the reliability and quality requirements with the limited resources of the small satellite missions. Based on the results available in literature, considering the selected hardware and software configuration, an accuracy between 1m and 10m should be achievable, with different techniques, with the higher accuracy obtained when including also the spacecraft dynamics within the processing filter.

II. DESIGN PHILOSOPHY

The ESEO GPS payload design process followed the guidelines and technical requirements typical of small satellite missions. As small satellites usually undergo several constraints in terms of budget, power, volume and weight, this navigation subsystem was designed to fit all the mentioned needs, implementing a simple hardware architecture [Figure 1]. The sub-system includes:

- COTS components, used where an in-house development would have been too expansive in terms of time and costs, and so incompatible with small satellite platforms philosophy;
- custom designed parts, for components whose operations are critical for the management of the entire sub-system and whose failure can represent a problem for the payload mission.

In this regard, a simple commercial baseband processor from Novatel, model OEM615, GPS L1 frequency only, was selected to perform the critical signal acquisition, tracking and demodulation process. Having a small amount of observations to manage every epoch, allows for a more relaxed hardware resources selection, maintaining reduced costs and time of development. However, it is demonstrated in literature that single frequency accurate spacecraft navigation is possible, if coupled with sophisticated navigation algorithms [8]. In this regard, the goal of the GPS payload mission is twofold: testing of a COTS-based receiver in space and the assessment of the achievable real-time positioning accuracy with this configuration. The decision to include a commercial baseband processor allowed the University of Bologna team to focus on the design of the application software and of the navigation computer, the PCB in charge of managing power and data internally and externally with the OBDH and the S-band transceiver. In order to take into account possible failures or malfunctions of the commercial baseband processors that may occur due to the effect of space radiations, two copies of the same front-end are included, in cold redundancy. Other hardware solutions were adopted to maintain a high reliability level of the overall payload and to guarantee robustness to radiation events, avoiding also that a failure propagates to the rest of the spacecraft:

- An isolated voltage regulator stage was implemented with dedicated voltage protection circuit, meant to shut down the payload in case an anomalous voltage levels is detected in the main circuit.
- A current limiter circuit, coupled with each front end, which monitors the power absorbing behavior of the active device. It is enabled as soon as the current drain exceeds nominal levels.

Another custom PCB is used as amplification stage of the signal coming from a GPS antenna with fly heritage, Sensor Systems series S67-1575, and the signal is split and driven to the two RF front ends.

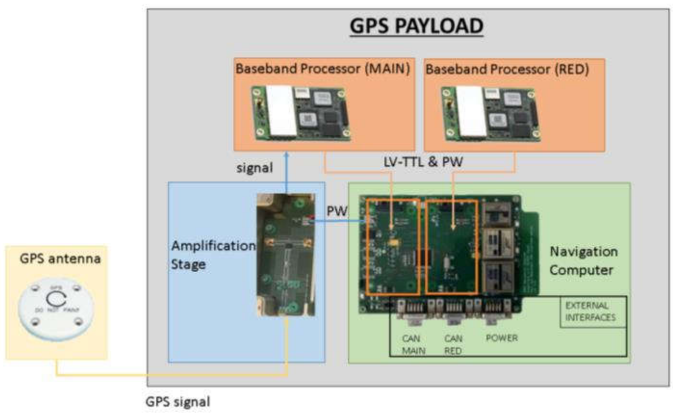

Figure 1: GPS Payload hardware architecture

Figure 2 : Payload first EBB model

All electronic parts are inserted inside an aluminum enclosure covered with an alodine coating, to protect adequately against launch loads and to provide the necessary mechanical interfaces with the rest of the platform. According to the ESEO model philosophy, three models of the payload were produced for this mission: two elegant breadboards (EBB), meant to be used for electrical hardware verification, enviromental testing and embedded software development [Figure 2]; the proto-flight model, which was subjected to qualification tests and now is ready for the integration and launch. Following the test plan agreed with SITAEL and ESA, several tests were performed on the EBB models, in order to be compliant with technical requirements:

- Thermal balance test, to assess hardware compatibility with thermal levels typical of LEO satellite missions. Payload functionality was monitored during the test at -25° and +75° and no degradation on selected components was detected [Figure 3].
- Baseband processor test: to verify correct functionality of selected COTS front end in presence of GPS signal as received by an antenna on a LEO spacecraft. This test was performed at ESA ESTEC facilities and highlighted the need for a dedicated setting routine of the tracking channels.
- Electrical tests: to check consistency of the hardware design with technical requirements.
- Communication test: to verify correct implementation of the communication interfaces between navigation computer and front end.
- Vibration test: to validate the mechanical design and to verify that no structural failure or modification occurs during the launch.

Figure 3: Payload second EBB model under test inside the thermal chamber

III. NAVIGATION TECHNIQUES

To achieve an acceptable level of positioning accuracy, compliant with modern missions requirements, the relatively simple hardware architecture is compensated with two processing techniques for the raw GPS data. In both cases, the GPS Payload is designed to generate position fixes every 30s, to provide a conservative processing time to the microprocessor, adequate to the computational resources. The Kinematic Mode, is based on a least-square algorithm and relies only on the GPS pseudorange observable information to compute the position [5]. It is the simplest and default navigation mode, and the expected accuracy of the position fixes is around 10/15 m 3D rms, based on previous studies. The velocity fixes are computed using the Doppler shift for every tracking channel of the baseband processor, providing an accuracy in the order of cm/s.

The second and more sophisticated navigation mode is called Reduced Dynamic Mode and processes the position using the information coming from the GPS measurements and an accurate mathematical model of the spacecraft dynamics [1]. It makes use of two different GPS observables: pseudorange and carrier phase, which is still a GPS satellite-to-user range measurement but obtained by counting the number of cycles of the RF carrier signal and featuring a noise level down to 1mm. However, these measurements require the introduction in the filter of a new unknown: a bias value for every tracking channel, which is estimated as part of the receiver state within the filter.

This navigation mode is based on an Extended Kalman Filter, which is initialized with the outputs of the Kinematic processing and can be enabled only with a dedicated telecommand. Since major contribution to the GPS measurements error for a receiver in low Earth orbit is represented by the ionospheric effect, a combination of pseudorange and carrier phase is used within the filter, based on the fact that this delay is present in both observables, with the same absolute value, but with the opposite sign [6]. This new observable is called Group And Phase Ionospheric Combination (GRAPHIC) and is expressed as follows (1):

$$\rho_{C1L1} = (\rho_{CA} + \rho_{L1})/2 \tag{1}$$

where ρ_{C1L1} is the GRAPHIC combination, ρ_{CA} the pseudorange measurement and ρ_{L1} the carrier phase measurement.

For the definition of the dynamic model, the approach presented by O. Montebruck and E. Gill [4] was followed, in order to fit the computational constraints of a cost-effective embedded application with the need to generate high quality position fixes. The final model includes:

- Earth gravity field of 40x40 order
- Atmospheric drag
- Solar radiation pressure
- Moon and Sun gravity fields
- Earth solid tides

The state vector includes also the atmospheric drag coefficient and the solar pressure coefficient, in order to take into account the worst case scenario in which, for any reason, they are different from the design values. In order to account for the un-modelled effects and approximations, a set of empirical accelerations is included and their value is estimated as part of the filter state [7]. The state vector of the Kalman filter is then designed to include 12 elements plus 1 extra entry per tracking channel [Table 1]. Besides the raw GPS observables, (pseudorange, carrier phase and Doppler), the navigation computer software requests also several other data to the COTS front end, in order to perform its tasks:

- Channels tracking status, particularly useful during the acquisition routine, to monitor the number of channels that already built a stable link and to decide whether changing the setting of other channels or proceeding to the navigation mode.
- Receiver time status, that provides information about UTC time and receiver clock error, provided to the active navigation algorithm to process the spacecraft position.
- GPS constellation ephemeris: the orbital parameters of the tracked satellites are received as part of the broadcasted message and are used by the active navigation algorithm to process the ESEO position.
- Hardware and software status, including codified error words and temperature information. These data are provided to the OBDH upon request and composes the telemetry data pack of the GPS Payload.

In order to propagate the receiver state between two consecutive epochs, the equation of motions of the ESEO spacecraft are numerically integrated using a 5th order Runge-Kutta method. While for offline processing the working load of the model equations integration is not an issue, this method was selected in order to fit the limited computational resources requirements of the embedded application.

The results of the position processing, along with time and velocity information, are saved in the scientific data set and prepared to be broadcasted to ground through the S-Band transceiver. Also the raw observations are sent, in order to perform a second off-line processing on ground, using more expansive computational techniques, with IGS precise ephemeris products, to generate a reference orbit to assess the performances during the mission.

Table 1: State vector components

State parameter	Number of elements
User position [m]	3 elements, in ECEF coordinates
User velocity [m/s]	3 elements, in ECEF coordinates
Receiver clock offset [s]	1 element
Drag coefficient	1 element
Solar pressure coefficient	1 element
Empirical accelerations [nm/s^2]	3 elements, radial, tangential and normal coordinates
Bias parameters	N elements, where N is the number of tracking channels for the processed epoch

IV. FILTER TESTING AND TUNING

The issue of ground validation of a GPS receiver for space applications is not trivial to address. Using a GPS antenna on ground, the testing of several sections of the application code would be problematic, e.g. the signal acquisition routine, which expects high Doppler values, and the Reduced Dynamic navigation mode, that processes the raw observables considering the receiver moving on a LEO spacecraft. In this regard, in order to assess the actual performances of the navigation algorithms and to verify the real-time behavior of the complete payload, several tests were performed with the aid of GNSS signal simulators. The first sessions of testing took place at the Istituto Superiore Mario Boella (ISMB), in Turin (Italy), using a NAVX–NCS GNSS simulator [Figure 4]. As a reference to assess the actual performances of the navigation modes, the real position as provided by the simulator was used.

The first investigation involved the general behavior of the application software, hosted by the ESEO GPS Payload navigation computer, while receiving mission-like observables. The main focus was on the channels setting routine, that can be tested and validated only in presence of a GPS signal affected by an extended range of frequency shift. Since the baseband processor test, previously performed at the ESA ESTEC facilities, highlighted the need for a guided setting of the receiver channels after every power-on, a dedicated software routine was developed and verified. Its task is to check the tracking status of each channel and then shifting the frequency offset of the channel, around which the signal is searched. This is necessary because the typical frequency shifts experienced by a LEO spacecraft receiver can reach values in the order of 45 kHz, up to one order of magnitude higher than the terrestrial ones. Considering that the maximum frequency error considered by the COTS front end during the signal tracking is 10k Hz, the acquisition routine performs cyclic forced setting of the channels, with intervals of 10kHz, in the range between -45kHz and 45kHz. This test demonstrated the capability of the application software to autonomously lock and track the signal with a sufficient number of GPS satellite in a reasonable time, with an rms under 8 minutes, calculated over the results of 30 test sessions.

The second series of verifications was focused on the Kinematic Mode testing.

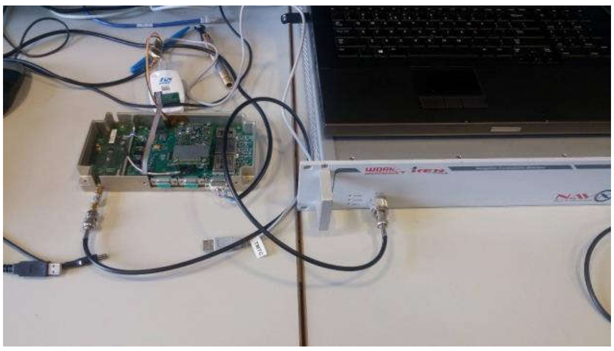

Figure 4 : Functional test with GPS signal simulator at ISMB, Turin

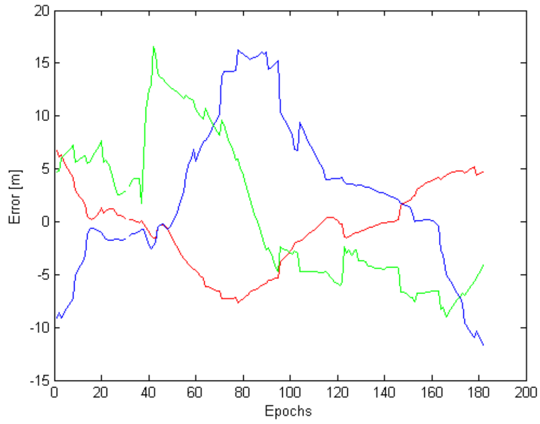

Figure 5: Tests Session 1 Error Plot in ECEF coordinates: x component (red), y component (blue) and the z component (green)

Data were acquired for an entire orbit, about 90 mins or 180 epochs (considering a position fix every 30 seconds), and the positioning error in ECEF coordinates was calculated, obtaining an accuracy of 10.959 m 3D rms, that meets the expectations (<15m) [Figure 5]. To verify also the reduced dynamic filter, another functional test campaign was performed at the Nottingham Geospatial Institute (NGI), Nottingham (UK). Thanks to the high quality of the orbit model provided by the Spirent Simulator available at the NGI facilities, it was possible to achieve a level of accuracy in the setting of the scenario that is suitable for providing useful indication about the performance of the Reduced Dynamic filter. For this test, the solution proposed by Avanzi A., Garcia A., and Tortora P. [3] was used as initial tuning and the orbital scenario model was set to include: Earth gravity model (order up to 70), Sun and Moon gravitational effects, solar radiation pressure, aerodynamic drag. The first real improvement in the performance was obtained by introducing a wider receiver clock error covariance, to compensate for the poor clock accuracy of the COTS front-end. Finally, also the covariance of the empirical accelerations coordinates was extended to consider possible discrepancies between the filter model and the one included in the simulator and the error between the simulated model and the real world

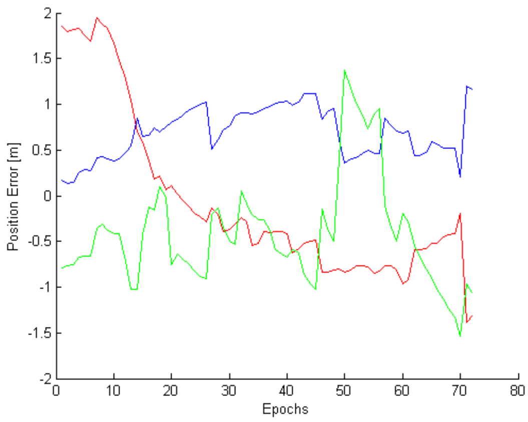

Figure 6: Reduced dynamic Error Plot in ECEF coordinates: x component (red), y component (blue) and the z component (green)

Table 2: Reduced dynamic positioning error

x position error mean (m)	-0.063
x position error STD (m)	0.909
y position error mean (m)	0.685
y position error STD (m)	0.277
z position error mean (m)	-0.417
z position error STD (m)	0.590
3D RMS (m)	1.378

. Once completed this tuning procedure, a more acceptable behavior was obtained from the reduced dynamic solution, with a final error of 1.378 m, after a transient of ~50 epochs, as shown in Figure 6 and Table 2. Although the final error rms is close to, but not lower than, the target threshold of 1m [2], the outcomes of the last tuning procedure can be considered a good result and show a clear improvement with respect to the Kinematic solution. Considering that the GPS observations are simulated and the reference trajectory of the ESEO spacecraft is based on a simplified version of the real set of forces, the assessment of the actual navigation performances is not an easy task. Unfortunately, due to the tight schedule of the ESEO mission no further testing of the reduced dynamic filter was possible, e.g. for longer testing session. In fact, the EBB and PFM models of the GPS Payload were required by SITAEL to perform the Test Readiness Review and qualification test. However, during the real mission, the raw and refined data generated on board will be downloaded and processed to perform a second tuning of the Reduced Dynamic filter, using real observables. With the dedicated telecommands, a reconfiguration of the process and measurements error matrices will then be possible, using data obtained from ground processing.

V. Educational content

As the work presented in this paper was carried out in the framework of an ESA educational mission, the entire project and the technical design activities were entirely managed by students. ESEO represented the perfect opportunity to understand and apply the principles of space systems design, gained during the University courses, through direct hands-on activities, covering the entire design, development and validation process of the GPS Payload. Thanks to the technical support offered by the SITAEL engineers and by ESA officers, the students involved in this project gained a valuable experience for their future careers in the space field.

VI. Conclusions

This paper deals with the contribution provided by the Microsatellite Laboratory of the University of Bologna to the development of the space segment of ESEO satellite, namely a GPS navigation payload. The work described herein investigated the main difficulties and obstacles encountered during the development of a GPS-based navigation sub-system for small spacecrafts. Reliability issues were addressed with dedicated hardware solutions, without exceeding the limitations about power absorption and costs, typical of small satellite missions. The hardware design was validated through an extensive test campaign, which demonstrated the correct implementation of the radiation protection solutions and the compatibility of the sub-system with the harsh space environment. The application software was designed to feature two alternative navigation techniques with different level of accuracy, theoretically capable to provide position fixes with an accuracy below 10m. From the outcomes of the validation phase performed on the navigation software it emerged that achieving a meter level accuracy in space using a COTS-based receiver is possible. However, the validation phase of the sub-system will be considered completed only after the in-flight performance assessment. In fact, as stressed in the paper, an accurate validation and tuning of the filter on ground is not possible, due to the limits of commercial GNSS signal simulators in terms of modelling of a spacecraft user scenario. However, the results reported herein are promising and can be considered an adequate starting point to perform the successive finer tuning during the mission.

Acknowledgment

ESA Education office is greatly acknowledged for the opportunity offered to the University of Bologna students to be part of this interesting and challenging project.

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EIRSAT-1: The Educational Irish Research Satellite

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***Abstract*—The Educational Irish Research Satellite, 'EIRSAT-1', is a collaborative space project that aims to build, launch and operate the first ever Irish satellite. The EIRSAT-1 spacecraft is a 2U CubeSat incorporating three novel experiment payloads: GMOD, a gamma-ray detector; EMOD, a thermal management coating demonstration; and WBC, an attitude control algorithm. The spacecraft is currently under construction at University College Dublin and will delivered to ESA in late 2019.**

Keywords—CubeSat; gamma-ray; astronomy; materials; control

I. Introduction

EIRSAT-1 is a 2U CubeSat which is being developed by students at University College Dublin (UCD). It will be Ireland's first satellite.

The project is primarily educational in nature and aims to:

- develop the know-how of the Irish higher education sector in space science and engineering, by supporting student teams to build, test and operate the satellite;
- address skills shortages in the space sector by fostering collaboration between student teams and industry through the launch of three payloads that use innovative Irish technology;
- inspire the next generation of students towards the study of science, technology, engineering and mathematics (STEM) by launching the very first Irish satellite.

To achieve these educational aims, the EIRSAT-1 team have developed the following scientific and technical objectives for the spacecraft:

- study gamma-ray bursts (GRBs) using a bespoke gamma-ray detector to assess the capability of this technology for use on next-generation gamma-ray astrophysics missions;
- perform the first measurements on the performance of SolarWhite and SolarBlack novel surface treatments in a low Earth orbit environment;
- implement and test a wave-based control algorithm to determine its potential as a viable alternative to standard attitude determination and control methods.

The project was initiated by the Space Science and Materials Research group within the UCD School of Physics. The group has a long track record of space science and astrophysics research, especially GRBs and the development of instruments and technologies related to the detection of gamma-rays. EIRSAT-1 was proposed as a mission concept to the European Space Agency (ESA) in response to their Fly Your Satellite! (FYS) announcement of opportunity.

EIRSAT-1 brings together several strands of the Space Science group's research and educational activities. An R&D programme into the development of a gamma-ray detector using novel sensors demonstrated that the footprint of such a compact detector would be compatible with a CubeSat platform. In parallel, an educational CubeSat called 'EduCube' had been developed to train students of UCD's MSc in Space Science & Technology in systems engineering [1].

Collaboration with the UCD School of Mechanical and Materials Engineering led to the inclusion of two additional payloads. The materials experiment (EMOD) is based on UCD patented technology, while the Wave-Based Control (WBC) payload implements a novel approach to motion control which has been developed by the UCD Dynamics and Control group.

After proposal submission, the EIRSAT-1 student team was invited by ESA Education to participate in a selection workshop at ESTEC in early May 2017 to pitch their idea to a selection panel of spacecraft experts from ESA. Shortly after the workshop, EIRSAT-1 was announced as one of six CubeSats selected for the FYS programme.

II. Team Organisation

EIRSAT-1 is primarily a student-driven mission. Students are supported to take responsibility, make decisions and own the relevant parts of the programme. Students are given prominence in outreach and publicity. There is a management structure in place which is composed of a Management Board, a Mission Team, and an Academic Oversight Board. The Management Board is composed of academics from the Schools of Physics and Mechanical and Materials Engineering, student leaders, and a space-industry mentor. The Mission Team comprises graduate students working on the project and is responsible for the implementation of EIRSAT-1. Undergraduates, visiting students, and interns join the Mission Team as associate members. The Academic Oversight Board comprises the supervisors of the students who are full members of the Mission Team. The EIRSAT-1 team has adopted a policy which governs this management structure and which includes a code of practice regarding "Equality, Diversity & Inclusion" that outlines the team's ethos towards team interactions, diversity of opinion and gender balance.

The EIRSAT-1 Mission Team is currently composed of 10 students. A further 15 students that were involved in the design of EIRSAT-1 up to Critical Design Review stage. The students come from Physics, Mathematics, and Engineering backgrounds and 40% of the current Mission Team is female.

III. The Spacecraft

The EIRSAT-1 spacecraft is based on Commercial Off-The-Shelf (COTS) CubeSat hardware components supplied by Clyde Space, augmented with payloads, electronic subsystems, and mechanical components, which have been designed and will be manufactured at UCD with input from industry partners. The spacecraft consists of typical electronic CubeSat subsystems which will be supplied by Clyde Space: Attitude Determination and Control System (ADCS), Electrical Power System (EPS), On-Board Data Handling (OBDH), Communications (Comms). EIRSAT-1 has two hardware payloads, the Gamma-ray Module (GMOD), the ENBIO Module (EMOD); and a software payload, Wave Based Control (WBC).

The EMOD payload includes an assembly which requires special accommodation on the exterior of the spacecraft, rendering most COTS CubeSat structures unsuitable. A Clyde Space 2U structure has been heavily modified to meet these requirements.

The design of the spacecraft was initially driven by the requirements of the GMOD payload. In order to accommodate the payload size along with the required supporting subsystems, it was determined that a 2U CubeSat would be required. Analysis of the GMOD performance (Fig. 5) indicated that a zenith pointing attitude would be optimal but that the mission would be feasible in any attitude configuration. Reaction wheels were considered and while there was sufficient mass budget and space to accommodate them, there would be insufficient power generated with body-mounted solar arrays. To use reaction wheels, the spacecraft would require deployable solar arrays. De-orbit simulations were performed for 2U configurations both with and without deployable arrays. As EIRSAT-1 will be launched from the International Space Station (ISS), atmospheric drag at this altitude, means that the lifetime of a mission with deployable arrays would be significantly reduced. These analyses demonstrated that reaction wheels are infeasible for a spacecraft of this size in a 400 km altitude Low Earth Orbit. An exploded view of the final EIRSAT-1 configuration is shown in Fig. 1, while a labelled view of the internal components is shown in Fig. 2.

A. ADCS

Although EIRSAT-1's primary objectives do not require attitude control and are achievable even when the spacecraft is tumbling, zenith pointing gives the best possible performance for the GMOD payload and has been determined to be the best compromise between the needs of both the EMOD payload and the solar arrays to be exposed to sunlight.

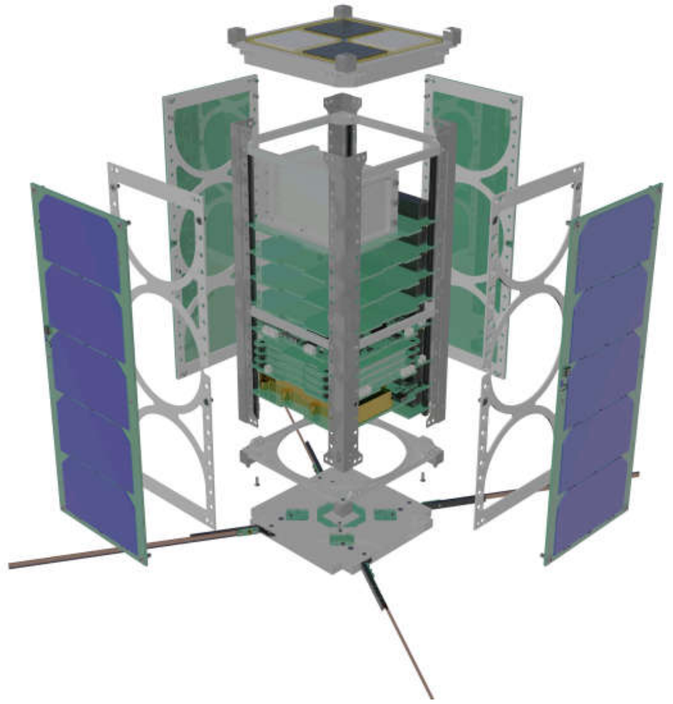

Fig. 1. Exploded view of the EIRSAT-1 spacecraft hardware.

The Attitude Determination and Control System (ADCS) consists of a magnetorquer based control system. It uses a Clyde Space ADCS Motherboard, which interfaces with magnetic coils that are integrated into the solar array PCBs, hence providing 2 × X-direction magetorquers and 2 × Y-direction magnetorquers. The baseline control algorithm for the ADCS is custom algorithm from Clyde Space designed specifically for EIRSAT-1 as this will be the first mission in which Clyde Space have performed magnetic-only control for a 2U spacecraft or for zenith/nadir pointing. The ADCS motherboard includes magnetometers and gyroscopes, utilises several external sensors such as coarse sun sensors built in to the solar arrays, and can incorporate information from the GPS module in the OBC. This hardware will also be used for the WBC experiment payload.

B. EPS

The Electrical Power System (EPS) consists of a Clyde Space 3rd generation 3U EPS motherboard, a Clyde Space 30Whr Standalone Battery, and 4 × 2U body-mounted solar cell arrays. The motherboard is designed for CubeSats larger than 1U but without deployable solar panels. The motherboard can provide power at battery voltage, 12V, 5V, and 3.3V, with latching current limiting over-current protection. Power may be supplied either directly or via switch-able power distribution modules, which are used to control power to the hardware payloads. The 30Whr battery has existing flight heritage with CubeSat deployers, such as NanoRacks, and is compatible with ISS manned flight requirements having been certified to NASA EP-Wi-032 standards. The battery has a 2s3p configuration and features additional built-in over-current and under-voltage protection independent of that functionality in the EPS module. The flight activation inhibits are implemented as MOSFETs in the battery. The solar arrays are placed on the X and Y faces of EIRSAT-1. Each array features 5 × Spectrolab UTJ cells in a

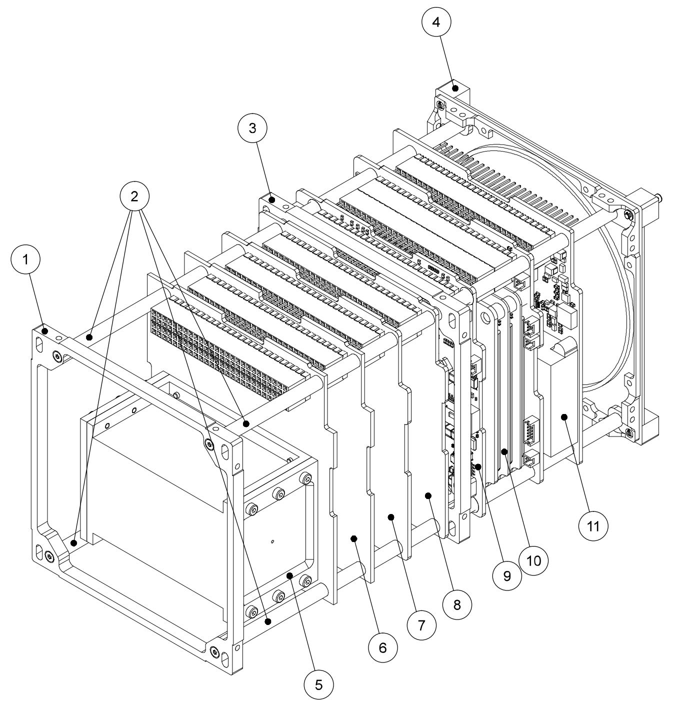

Fig. 3. Internal components. 1: Top support bracket, 2: PCB support rods, 3: Mid support bracket, 4: -Z end-cap, 5: GMOD, 6: EMOD motherboard, 7:ADCS, 8: OBDH, 9: EPS, 10: Battery, 11: Comms.

5s1p configuration for an optimal power generation of 5W per array.

C. OBDH

The On-Board Data Handling (OBDH) system is a Clyde Space Nanosatellite On-Board Computer (OBC). The OBC is based on a MicroSemi Smart Fusion 2 System on Chip. As the Smart Fusion 2 is flash-based, it is inherently SEU tolerant. The OBC includes other protections for radiation effects such as magnetoresistive RAM and a hardware watchdog. The OBC features a 150MHz ARM Cortex M3 processor, 8MB of EDAC protected MRAM, 4GB of NAND flash, a Micro SD card slot, and a GPS receiver. The FPGA fabric of the Smart Fusion 2 is used to create the various interfaces between the OBC and the other subsystems. EIRSAT-1 uses i2c for all inter-subsystem communication with 3 separate i2c buses used for system, comms, and payloads.

IV. GMOD - The Gamma-ray Module

GMOD is an experiment payload designed to detect cosmic gamma-ray phenomena such as GRBs which are short-lived intense flashes of gamma-rays associated with the collapse of very massive stars in the distant universe and with the merger of neutron stars [2]. It is based on the design of UCD Gamma-Ray Detector (GRD) which was developed by the Space Science and Materials Research group under contract to ESA. The GRD design utilises a 28 mm × 28 mm × 20 mm LaBr3 scintillator coupled to a 4 × 4 array of 36 mm2 SensL B-series silicon photomultipliers (SiPMs). A detailed description of the GRD can be found in [3].

GMOD is therefore the latest detector design in a series which have been developed at UCD in order to address the technical challenges of building sufficiently advanced next-generation high-energy astrophysics missions to meet the scientific requirements while being of manageable mass and complexity. These detectors benefit from several novel enabling technologies which have recently been made available to the scientific community, e.g. modern high-efficiency scintillators, SiPMs which replace bulky, high-voltage PMTs and for GMOD a dedicated SiPM readout ASIC. The SiPM Readout ASIC (SIPHRA) has been developed by Norwegian company Integrated Detector Electronics AS (IDEAS) based on the requirements of operating the UCD GRD in space [4]. SIPHRA has been incorporated into the GMOD design.

A. Detector Hardware

The detector assembly consists primarily the scintillator, SiPMs, the SIPHRA ASIC used to process and digitise the analog signals from the SiPMs, and a light-tight detector enclosure. An exploded view of the detector assembly is shown in Fig. 3. The scintillator is a 25 mm × 25 mm × 40 mm Cerium Bromide (CeBr3) crystal supplied by Scionix. The CeBr3 crystal is supplied by the manufacturer enclosed within a hermetically sealed unit. The housing includes a quartz window, exposing a 25 mm × 25 mm face of the crystal, allowing the scintillation light to exit.

The scintillation light is measured using 16 J-series 60035 SiPMs from SensL. The SiPMs are arranged in a 4 × 4 array which gives a very good match to the scintillator size. The array is a custom design implementing a common-anode configuration with all SiPM anodes being connected to a common negative bias supply via independent low-pass filters. The cathode of each SiPM is connected directly to the ASIC inputs via board-to-board connectors.

The analog signals from the SiPMs are digitised using the SIPHRA ASIC. SIPHRA is a 16 channel SiPM read-out IC which is used as a pulse height spectrometer in GMOD. Each of the 16 SiPM inputs have a current integrator, pulse shaper, and track & hold circuit. Additionally, a 17th channel provides the sum of the 16 inputs. Readout can be triggered by thresholds on any of the 17 channels. When triggered, the heights of all 17

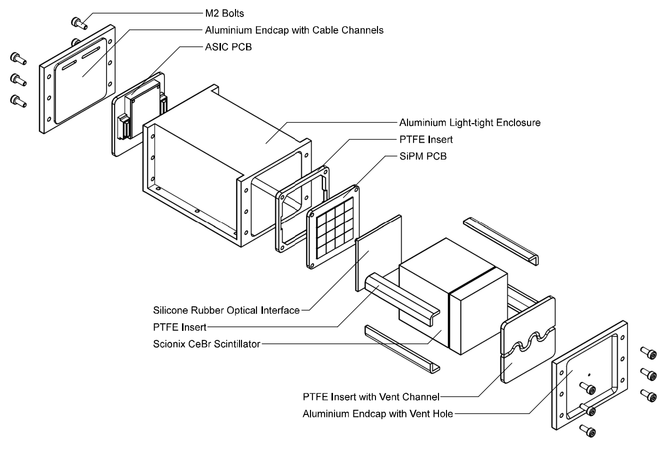

Fig. 2. Exploded view of the GMOD detector assembly.

channels are digitised by a 12-bit ADC. The 17 pulse values and trigger information are output via a high-speed serial output. SIPHRA is configured by programming its configuration registers via SPI. Configuration options include enabling of individual channels, enabling triggering and thresholds on individual channels, input offsets, pulse shaping parameters, and readout options. SIPHRA has specifically been designed for use in space applications with latch-up immunity, single event upset mitigation, and error correction, and low-power considerations. It is not expected that SEU will occur even in high radiation encountered in the South Atlantic Anomaly.

B. *Expected Performance*

GMOD's sensitivity has been simulated using the MEGAlib toolkit [5]. A simplified mass model of the EIRSAT-1 spacecraft was created and the response of the GMOD detector to a GRB spectrum with a slope of -1.1 was simulated. Fig. 4 shows the effective area of the GMOD detector as a function off-axis angle and azimuth of the source GRB. The effective area is calculated at the number of detected counts in the 50 - 300 keV range divided by the GRB flux. For each GRB in the BATSE 4B catalogue, the detection significance has been calculated. The cumulative detection significance distribution is shown in Fig. 5 at a range of spacecraft attitudes from zenith (0 degrees) to nadir (180 degrees).

Assuming the optimal zenith pointing attitude strategy and that for a single detector we would use a signal threshold of 10 sigma in order to avoid false positives, it is expected that GMOD will detect approximately 20 GRBs per year. Coincident GRB detections with other high-energy missions would allow for a lower detection threshold and therefore significantly increase the number of observed GRBs.

V. EMOD - The ENBIO Module

EMOD is an experimental payload which is designed to demonstrate and test the performance of SolarBlack and SolarWhite spacecraft surface treatments developed by ENBIO. SolarBlack and SolarWhite have been developed by ENBIO for use on ESA's Solar Orbiter mission. EMOD will measure the performance of these coatings using four 'thermal coupons'

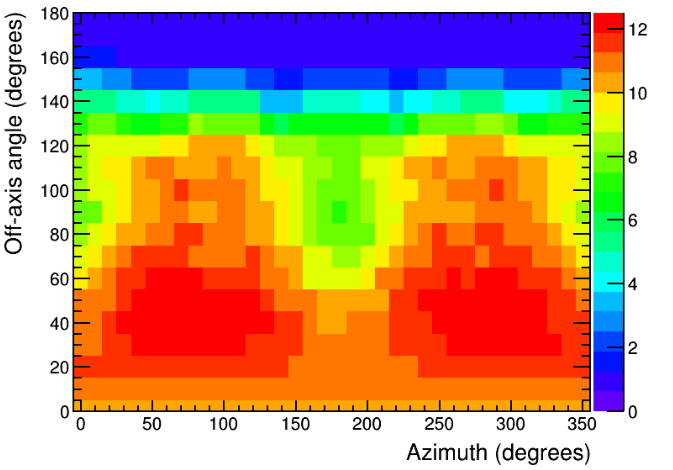

Fig. 5. Simulated effective area of the GMOD detector as a function of off-axis angle and azimuth of the source GRB.

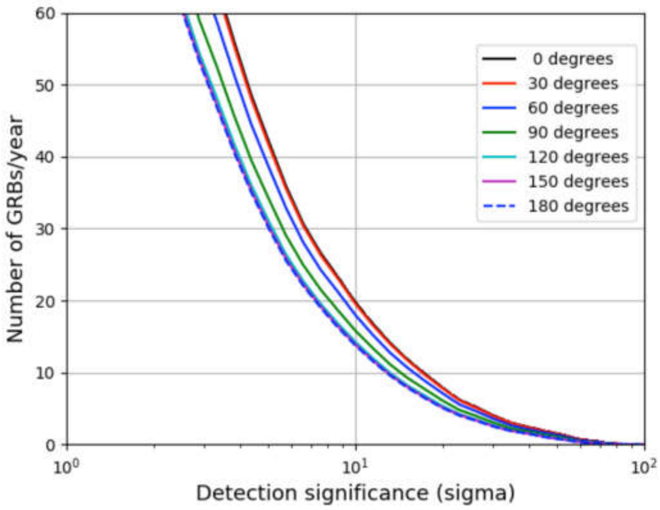

Fig. 4. Cumulative detection significance distribution of the GMOD detector for a range of spacecraft attitudes from zenith (0 degrees) to nadir (180 degrees).

which are attached to the +Z face of the spacecraft. As EIRSAT-1 orbits the Earth, the thermal coupons will be exposed to periods of solar illumination followed by eclipse which will thermally cycle the coupons. Though continuous monitoring of the temperature of the coupons as they are thermally cycled, it will be possible to characterise the coating performance and degradation.

A. *Thermal Coupon Assembly*

The coupons are made of aluminium 2024 and measure 35 mm × 35 mm × 1 mm with two coated in SolarBlack and two coated in SolarWhite. Each coupon has a RTD adhesively attached to its underside to monitor the temperature. It is important that the coupons are as thermally isolated as possible to prevent thermal energy from the spacecraft itself from influencing the temperature of the coupons. The coupons are therefore supported in a 'Thermal Coupon Assembly' (TCA) which is designed to support the coupons while insulating them from the spacecraft. The TCA is shown in Fig. 6. The coupons are suspended above a Multi-Layer Insulation (MLI) blanket using PEEK support struts. The MLI blanket and the support

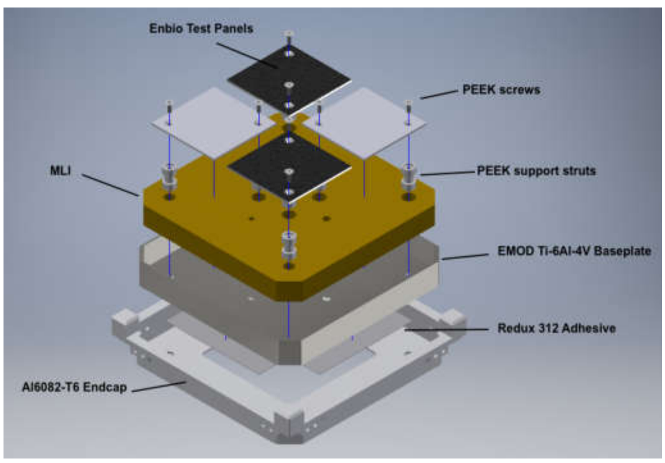

Fig. 6. Exploded view of the EMOD Thermal Coupon Assembly.

struts themselves are in turn supported on a titanium baseplate. The baseplate is adhesively bonded to a special Aluminium 6082 structural end-cap, demonstrating another ENBIO product, an adhesive primer which is based on the same process used to apply the SolarBlack and SolarWhite coatings.

VI. WBC - Wave Based Control

WBC is a novel motion control scheme that has been developed by the Dynamics and Control group at the School of Mechanical and Materials Engineering at UCD [6,7]. The WBC approach is particularly effective in controlling flexible or under-actuated systems with poorly modelled dynamics. WBC has been applied to simulations of the International X-ray Observatory and the DELIAN robotic arm as part of an ESA study and has been tested experimentally in parabolic flight. EIRSAT-1 will be the first time that WBC has been used in space.

During a series of tests, WBC will take control of EIRSAT-1's attitude to perform a number of manoeuvres designed to evaluate the performance of the control scheme. The WBC payload takes the form of a software component which runs on the OBC. The ADCS motherboard will be placed into a test mode which disables the COTS control algorithm and allows direct control of the magnetorquer actuators via i2c commands sent from the OBC.

While WBC is a motion control algorithm, as part of the WBC experiment on EIRSAT-1, students will also produce an attitude determination algorithm. This algorithm will also run as a software component on the OBC, interfacing with the ADCS motherboard to monitor sensor values. Before the WBC attitude control test manoeuvres are performed, this attitude determination part of the WBC experiment will be operated in parallel to the COTS ADC algorithm to evaluate its performance. The control test manoeuvres may then be performed using attitude solutions determined by the student-written algorithm or using solutions determined by the COTS algorithm.

Throughout the WBC control test manoeuvres, a Control Authority Watchdog will monitor the spin rate and several other parameters such as elapsed testing time. Control will revert to the COTS ADCS algorithm if any of these parameters exceeds predetermined bounds. The Control Authority Watchdog is also responsible for preventing the spacecraft from starting a WBC experiment in certain situations, e.g. if the spacecraft is in safe mode, or if the battery depth of discharge is too high.

WBC will be evaluated based on pointing accuracy, slew rate, settling time, and power consumption.

VII. The Future

Following close-out of the CDR process, the team will be focusing on production of the spacecraft engineering model and preparing for the ambient test campaign. It is anticipated that following successful spacecraft production, ambient and environmental testing, EIRSAT-1 will be delivered to ESA in late 2019. Once it has passed its Flight Readiness Review, the satellite will be launched to the ISS for deployment into Low Earth Orbit. Simulations indicate that EIRSAT-1 will de-orbit after a period of between 9 months and 2 years.

The educational aspects and opportunities of the EIRSAT-1 project will not end when the completed spacecraft is delivered for launch or even when the spacecraft de-orbits. Throughout the mission lifetime, spacecraft and science operations will be performed by students. As the mission is based around science and in-orbit engineering demonstration objectives, future generations of students will benefit from operating the spacecraft and its experiments, and from the data it produces for many years. This will allow students to learn about high-energy astrophysics, space science, and space engineering in an engaging manner which has not previously been possible in Ireland.

Acknowledgments

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Design of an Attitude Control Testbed for a CubeSat with Flexible Appendages

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Abstract— **This paper presents the design process of an experimental setup suited to testing attitude control systems of nanosatellites based on the CubeSat standard, in the context of educational projects. The final design is thoroughly described, and results from preliminary tests are presented.**

Keywords— CubeSat, Attitude determination and control, Testbed, Fly Your Satellite, EIRSAT-1

I. Introduction

Over the years, modern spacecraft have become increasingly flexible, due to the development of technologies such as deployable solar panels, large antennas or modular structures. This evolution poses new challenges in terms of attitude control, since the dynamics of flexible spacecraft are much more complex than those of their rigid counterparts. As a result, an active research field has developed over the last decades, with numerous approaches proposed to tackle this issue.

Besides large space structures and commercial satellites, the problem can also be found in nanosatellite applications. Due to stringent mass and size constraints, nanosat payloads often rely on lightweight deployable components for energy management, communications or scientific measurements. The resulting spacecraft can therefore exhibit highly flexible behaviours.

This situation leads to the current question: how can attitude control systems for flexible, and non-flexible, nanosatellites be developed, tested and improved, considering the limited resources available in an educational context?

The EIRSAT-1 project provides the motivation to answer part of this question by designing a low cost but robust experimental platform to study the performance of various attitude control systems before flight. This piece of equipment includes: a versatile testbed allowing 1-D rotational testing of CubeSats with standard dimensions [1], such as EIRSAT-1, as well as a stripped-down CubeSat model with more powerful actuators and flexible appendages.

II. Background

Spacecraft attitude control in general, and specifically of flexible spacecraft, has been identified as a key area of applied research in the future [2]. Faster, more accurate, more efficient and more robust attitude control is indeed essential to increase the performance and capabilities of future spaceflight missions. Beyond the fact that new technologies have enabled the production of lighter and generally therefore more flexible spacecraft, even small order flexible behaviours of almost rigid spacecraft need to be addressed when high performance pointing requirements need to be met.

Considerable research effort has thus gone into this topic in recent years. Various control strategies have been developed, optimized and applied to flexible spacecraft. The investigated approaches include classical control (PI, PD, PID), robust control (SMC, H∞) or adaptive control (L1), with a lot of different variations and combinations. New control schemes are also under development, for example Wave Based Control (WBC) which has shown promising results in simulations [3].

In this context, nanosatellites such as CubeSats occupy a key role for various reasons. First of all, due to their relative low cost compared to larger payloads, they provide an excellent platform for technology demonstration and academic projects in general. Moreover, the development of more sophisticated systems for CubeSats requires the use of lightweight and foldable structures to comply with the stringent mass and size constraints. As a result, future missions are more than likely to be subject to flexibility issues, increasing the need for high performance dedicated attitude control systems.

The EIRSAT-1 project lead by University College Dublin (UCD) as part of the European Space Agency's (ESA) "Fly your own satellite!" program, is an example of control system technology demonstrator. In addition to two scientific payloads, the CubeSat will carry a secondary attitude control system based on WBC and will provide a first test of this approach in real flight conditions.

For this project, as for all other spaceflight projects, it is essential to be able to test all onboard systems thoroughly before the launch. This of course includes the Attitude Determination and Control System (ADCS), which must be characterized and validated. In this regard, numerical simulations are used to great extent, but experimental results are eventually needed to ensure nominal functioning. The main challenge of building testbeds for ADCS is to replicate the full 3-D frictionless rotational freedom the spacecraft will experience in the space environment. High-end approaches such as parabolic flight, neutral buoyancy or active suspension experiments allow a good approximation of this state but demand a lot of resources which often makes them unsuited for educational projects. Therefore, most project of this kind rely on mechanical rigs with 1 up to 6 degrees of freedom (DOF), using technologies such as low friction rotational bearings.

III. Design outline & Principles

The need for an ADCS testbed for EIRSAT-1 and further experimental testing of WBC applied to flexible satellites, has motivated the design of the test setup described in this paper. It aims to provide both a low cost but robust experimental setup to test the ADCS functionality of EIRSAT-1, and an experimental testbed to assess and compare the performance of various attitude control schemes when applied to a rigid or flexible satellite.

The first principle used to design the experimental setup was to insure it was both simple and affordable. This allows the design to be used by teams working on educational nanosatellite projects with limited budgets. Therefore, it makes use of generic Commercially Off The Shelf (COTS) components along with parts produced using conventional machining (milling, turning, drilling) and 3D printing.

The second design principle employed was modularity. By using replaceable components, simple geometries and open software, this allows the experimental setup to be used as a base for future research projects with more specific needs. Furthermore, care was taken to make the design upgradeable to some extent, to satisfy projects needing higher performance.

Using these principles as guidelines, the following concept for the experimental setup was established. It is composed of two separate parts: A testbed and a nanosatellite model. The testbed is a simple 1-D rotary platform, with a clamp designed to hold a standard CubeSat nanosatellite along any of its axes. The nanosatellite model is a stripped-down version of a fully functioning CubeSat, with a reaction wheel for actuation, inertial measurement sensors and a wireless transmitter. It can be easily fitted with long structural appendages which allow the testing of attitude control performance for flexible spacecraft.

IV. Resulting design

The experimental test setup design outline can be seen in schematic form in Fig. 1. Images of the assembled hardware can be seen in Fig.2. This section provides an in-depth description of this design and highlights the underlying design choices.

The dimensions of the main structural components and the characteristics of the COTS components are listed in Table I. Detailed drawings and CAD files can also be provided by the authors upon request.

A. Testbed

The testbed is the 1-D rotary platform which accommodates a nanosatellite model allowing free rotation about a single axis during attitude control tests. It is built around a COTS single row deep groove ball bearing (16 – Fig.1). This technology was chosen because it is robust, cheap and easy to integrate. However, it induces a significant frictional torque, and may produce some parasitic vibrations. For test cases when these limitations become too restrictive the system has been designed to allow an easy upgrade to a more expensive, but higher performing bearing, such as a low friction air bearing [4].

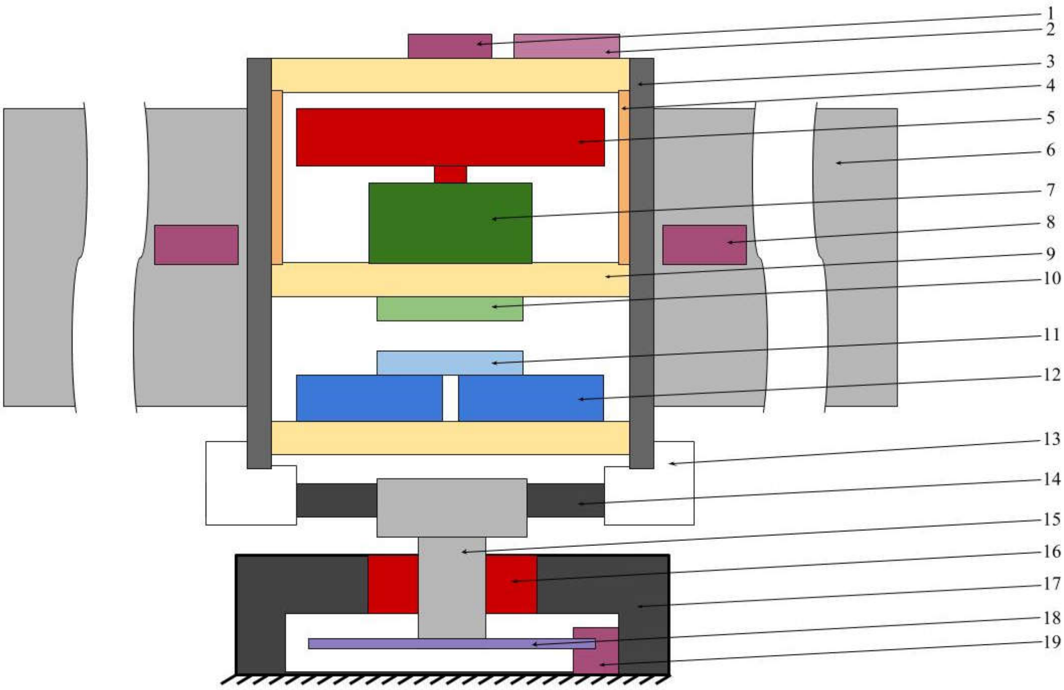

Fig. 1. Schematic of the experimental setup design

The bearing constrains an aluminum shaft (15 – Fig.1) to a single rotational DOF. A clamping mechanism, composed of a pair of aluminum rails (14 – Fig.1) and nylon clamp pads (13 – Fig.1), sits on top of the shaft. The clamp pads are designed to accommodate nanosatellites based on the CubeSat standard [1]. Two different clamp sets were produced to allow mounting of the nanosatellite vertically and horizontally.

Finally, an optical encoder (18 – Fig.1) is attached to the shaft [5]. Together with an adequate photo-sensor (19 – Fig.1), this allows the displacement and the rotational speed of the shaft to be monitored through a dedicated microcontroller data acquisition board (Arduino Uno). This independent attitude measurement channel will allow the data from the nanosatellite's attitude determination system to be verified and calibrated if needed.

All the elements of the testbed are mounted to an aluminum housing (17 – Fig.1), which is firmly connected to a stable ground plate.

B. Nanosatellite model

The nanosatellite model is based on a 1-U CubeSat geometry [1]. Its cubic frame is composed of vertical aluminum beams (3 – Fig.1) on the faces of the cube, accommodating three PVC component racks (9 – Fig.1). Thin removable aluminum panels (6 – Fig.1) are mounted on both sides of the frame, to replicate the behavior of flexible appendages such as antennas or solar panels.

The central level of the frame contains the nanosatellite's actuator: a 1-DOF reaction wheel system. It is built using an off-the-shelf DC drone motor (7 – Fig.1) and a weighted 3D printed flywheel (5 – Fig.1). A 3D printed fairing (4 – Fig.1) isolates the spinning device for aerodynamic and safety reasons. Using COTS drone components allows this system to have powerful actuation at a reasonable cost, with dedicated controllers and battery power supplies widely available. The use of 3D printing for producing the flywheel allowed fast prototyping and testing to ensure good balancing of the final system.

The lower level of the nanosatellite holds all the power management devices necessary for tether free operation. Four Li-Po cells (12 – Fig.1) provide power to the reaction wheel system, through a dedicated Electronic Speed Controller (ESC) (10 – Fig.1). A separate single Li-Po cell (11 – Fig.1) powers the instrumentation. This separation allows the voltage supply for the onboard measurement devices to stay undisturbed by the fluctuating power demand of the actuator.

The upper level of the nanosatellite is dedicated to instrumentation. It contains an Inertial Measurement Unit (IMU) board (1 – Fig.1).) for angular displacement and angular velocity measurements as well as the onboard computing unit (2 – Fig.1). The IMU's measurements are based on a combination of three different sensors: a gyroscope, an accelerometer and a magnetometer [6]. The computing unit was chosen to be a Wi-Fi enabled MKR1000 Arduino board, to allow fast wireless communication with a remote computer. This choice was driven by its relatively low cost and wide available. For the same reasons, the IMU is easily connected to the MKR1000 Arduino through an I2C bus.

The final instrumentation component is a set of piezo-electric sensors (8 – Fig.1) attached to the flexible panels [7], which are also easily connected to the MKR1000 Arduino board. This allows for measurement of vibrations in the flexible appendages, which can be used as a feedback signal in vibration absorbing control schemes such as WBC.

C. Software

The software for this project is distributed over three different devices: the Wi-Fi enabled Arduino MKR1000 on the nanosatellite model, the Arduino Uno board on the testbed, and a remote computer.

The remote computer is running a Matlab routine, which is the main part of the software system. Its role is to interact with the user through a Graphical User Interface (GUI), to handle the interactions with the computers file system (data storage and loading), and to command and synchronize the execution of local code on both Arduino boards.

The testbed's Arduino Uno board's only role is to acquire data from the encoder system. It therefore continuously runs a data acquisition loop, locally computing and holding the current position of the testbed. This loop only gets interrupted on request from the remote computer, to transmit the current position value.

TABLE I. MANUFACTURED AND OFF-THE-SHELF COMPONENT SPECIFICATIONS

Manufactured components			**Off-the-shelf components**		
Component	***Nature***	***Dimensions (mm)***	***Component***	***Model***	***Characteristics***
Housing	Aluminium, machined	80x80x30	Motor	Turnigy Multistar 3508-700KV	700KV, 27A max.
Shaft	Aluminium, machined	Ø20x45	Motor ESC	Turnigy MultiStar BLHeli-S	30A max.
Clamp rail (2x)	Aluminium, machined	Ø6x155, spaced 25	Motor battery (2x)	Turnigy Li-Po Pack	1000mAh, 7.4V, 30C
Clamp pad (2x)	Nylon, machined	35x22x20	Instruments battery	RS Pro Li-Po battery	2000mAh, 3.7V
Beam (4x)	Aluminium, machined	110x10x4	Encoder codewheel	Broadcom HEDM-6140#T12	2000 counts per rev.
Rack (3x)	U-PVC, machined	100x100x5	Encoder sensor	Broadcom HEDS-9040#T00	3 channels digital output
Flexible panel (2x)	Aluminium, cut	350x60x1	Piezo-electric sensor	DFRobot Gravity Piezo Sensor	Fully arduino compatible
Flywheel	PLA, 3D printed	80x20x10	IMU board	Adafruit BNO055	-
Fairing panel (4x)	PLA, 3D printed	92x47x1	Nanosatellite CPU	Arduino MKR1000	Wi-Fi enabled
			Testbed CPU	Arduino Uno SMD Rev 3	-

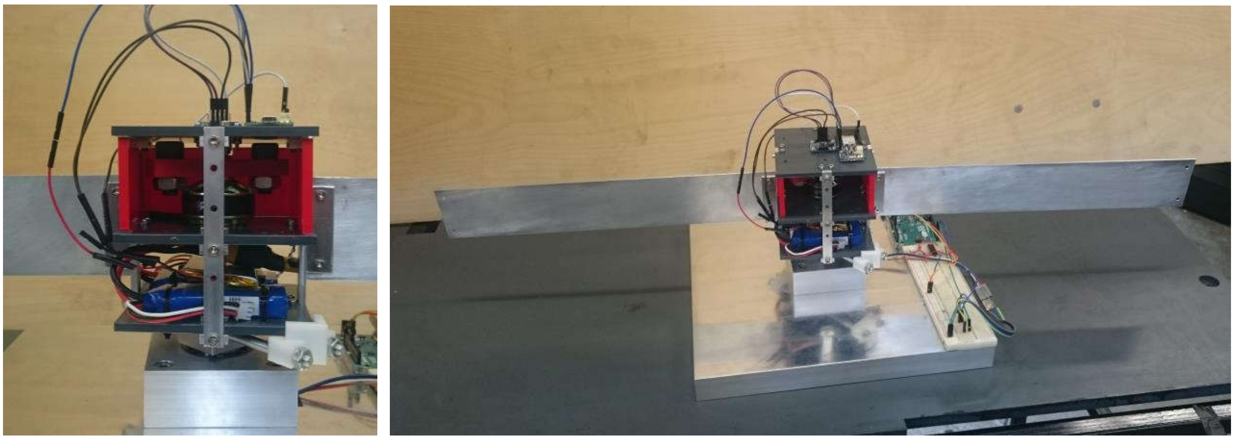

Fig. 2. Pictures of the assembled nanosatellite model, mounted on the dedicated testbed

On the other hand, the Arduino MKR1000 board onboard the nanosatellite model runs a more complex code, since it has more varied functions. First, it acquires and transmits data from the different instruments (MTU, piezo-sensors) on request from the remote computer, via a wireless network. Furthermore, it sets the reaction wheel system's speed through the ESC, either on direct request from the remote computer or by executing a locally stored command sequence.

V. Design Analysis & Assessment

Having finished the design and assembly process of the experimental setup, a first assessment of the system was conducted. This section presents qualitative observations and quantitative measurements that have been made during the preliminary testing phase, whose role is to assess the performances of the obtained system

This first analysis is useful to set objectives for this and future projects built around this experimental setup. Furthermore, the acquired experience can be beneficial for other teams designing similar systems. The presented findings will be completed by future, more in-depth quantitative studies.

A. Qualititative observations

On a functional level, the proposed design fulfills the set objectives. The nanosatellite model is able to move freely around a single axis of rotation, with the actuation system allowing aggressive rotational maneuvers around this axis. The mechanical structure withstands all possible maneuvers without significant deformations.

In terms of costs, the presented design has been produced for approximately 3000 Euros, with an estimated 2600 Euros dedicated to manufacturing tasks. This fulfills the objective of making the design affordable, especially for educational institutions who have readily available manufacturing facilities. Furthermore, although the use of 3D printing in this project was limited, this technology could be used to greater extent (e.g. for the component racks) to reduce the overall cost.

The actuation system was the most challenging part of the nanosatellite to setup. First of all, it requires the flywheel to be finely balanced, to avoid high amplitude vibrations that could damage the nanosatellite as well as the DC motor. Therefore, a trial error approach using weighted 3D printed parts had to be used, until satisfactory balance was achieved. Furthermore, the DC motor itself generates low amplitude vibrations, especially at high rotational speed. The influence of these vibrations on the system's behavior will have to be assessed through further testing.

The main drawback of the proposed geometry on the testbed side is the use of a single ball bearing. In addition to the frictional losses, it allows a small gimbal motion of the CubeSat outside of the single axis of rotation. This phenomenon can give rise to parasitic vibrations and will thus have to be taken into account during test experiments. It is therefore recommended, if funding allows, to upgrade the system with an air bearing device [4], as allowed by the testbed's design.

B. Encoder characterization

The encoder system is the most accurate instrument of the experimental setup, and its data is used as a reference for other measurements. The performances and limitations of the whole data acquisition chain (code wheel, sensor, Arduino board, software) therefore must be determined.

The code wheel and the sensor are both COTS components, with thorough documentation available [5]. This subsystem is rated up to 30,000 RPM and has a displacement resolution of 2000 counts per revolution. Regarding the Arduino board, its data acquisition performances depend on the code used. A test performed using a frequency generator showed that the maximal achievable sampling frequency is 2500 Hz.

Combining both characteristics, the overall encoder system is thus limited to rotational speeds below 7.8 rad.s^{-1}. This is low, but not incompatible with common rotational speeds of nanosatellites. If future tests require the faster rotational speeds, the Arduino Uno board could be replaced by a dedicated data acquisition system (e.g. NI-DAQ device) to increase the overall performances.

C. Overall dynamic behaviour

In order to assess the dynamic behavior of the overall system, it was subjected to a series of step torque inputs of various amplitudes throughout the operating range of the actuator. An example of the rotational speed response of the entire system to such a maneuver is given in Fig. 3, where the input torque is stepped to 25% of the maximum total value.

The obtained behavior shows an exponentially decaying rotational speed, which corresponds to a viscous friction model (the friction force varies proportionally to the rotational speed). Fitting an exponential curve to the gathered data allowed to identify the decay time constant as being about 0.24 s^{-1} across the whole speed range. At low speeds, the experimental data diverts from the viscous friction model, due to the apparition of nonlinearities (e.g. stick-slip motion).

The obtained speed decay model is due to different energy loss phenomena, the main components being the friction in the testbed's bearing but also due to the drag force on the nanosatellite (especially on the panels).

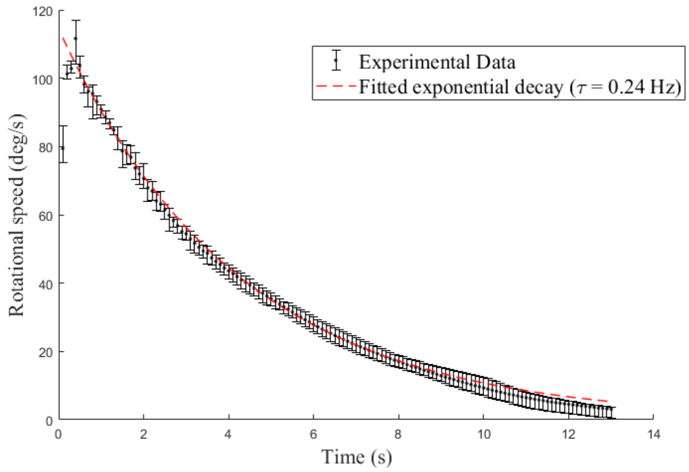

Fig. 3. Angular speed response of the testbed to a 25% torque step input (Averaged over 10 samples)

VI. Recommendations & Developpments

The presented work is part of an ongoing research in the area of attitude control of spacecraft. The experience gathered during the design and build of this testbed will be used to inform and define future more complex test setups.

First of all, the initiated experimental assessment process of the presented system has to be completed by more tests. This includes completing the characterization of the actuation system, characterizing the piezo-sensors, assessing the system's vibrational behavior, and finally establishing an accurate mathematical model of the system's behavior.

Following the characterization of the system, the next step will then be to proceed to the implementation and the experimental assessment of various control schemes, including WBC, applied to the flexible nanosatellite model. The aim will be to compare the performance of different control schemes when applied to the same flexible nanosatellite system.

In parallel, further work can also be done on improving the performance of the experimental setup. Possible approaches include: upgrade to air bearing technologies, design more intricate flexible appendages, reduce parasitic vibrations, upgrade the sensors and the data acquisition hardware. All those tasks are enabled by the modularity of the presented design.

VII. Conclusion

This paper has presented the design of an experimental tool that can be used to assess the performance of various control schemes designed for attitude control of rigid or flexible nanosatellites. Although the study is still in progress, useful experience has been gathered throughout the design and assembly process and reported here.

These preliminary results show the feasibility of simple yet robust experimental setups for characterizing the behavior of nanosatellites. Other research teams can use this experience to build their own affordable yet adequate testbeds for educational nanosatellite projects.

This project will also enable future educational projects on various topics, from the full characterization of the provided system to the analysis of different control schemes.

Acknowledgment

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COLLECTING MICROMETEOROIDS AND OTHER COSMIC-DUST-PARTICLES

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Abstract—**After many years of research, the composition of the upper atmospheres is still relatively unknown. This applies especially to the remains to meteors hitting the earth's atmosphere. As BEXUS provides an easy access to those atmospheric layers, an inexpensive experiment shall be designed to collect those remains. Due to the fact that not much research has been done, the origin of those meteoroids and their age as well as their chemical structure is still widely unknown. While some particles may come from our closest neighbours, some may even be interstellar. Through asteroid research and analysing the meteorites reaching earth's ground, we can suspect that some meteoroids are also made out of iron-nickel-compound. Collecting those meteoroids can easily be done by using magnets to attract them. Covering the magnets with a sticky material can help to hold onto the meteoroids as well as giving a chance to collect even non-magnetic particles. Compared to the bigger meteoroids, the micrometeoroids we want to collect will probably never reach the earth's ground. This is due to the fact that those particles are in the order of 50 µm. Therefore, they are sensitive to the winds at high altitude and insensitive to the earth's gravitation. In consequence, those micrometeorites are mostly unknown, as they are hard to reach and even harder to collect.**

Keywords—BEXUS; micrometeoroids; cosmic dust; basic research; student research

I. INTRODUCTION

A. *Scientific/Technical Background*

Each day, tons of cosmic particles fall on the Earth. (Love and Brownlee 1993; Peucker-Ehrenbrink and Ravizza 2000). This experiment (part of the REXUS/BEXUS-Programme) is designed to collect micrometeoroids. Compared to the bigger meteoroids, the micrometeoroids that shall be collected will probably otherwise never reach the earth's ground. This is because those particles are in the order of 50 µm. Therefore, they are sensitive to the winds at high altitude and insensitive to the earth's gravitation. For this reason, the origin as well as the chemical composition of the micrometeorites is mostly unknown, thus, an interesting field of research. While some micrometeoroids reach the lower atmospheric layers after quite some time, those layers are full of other particles, making the separation disproportionate hard.

An uncomplicated way to collect the micrometeoroids would be to attach a sticky surface to the BEXUS-balloon, this will only work passively. The design, using magnets to attract the iron-nickel-containing micrometeoroids, will actively collect those particles and therefore be way more effective. Moreover, different magnets for the different height of the flight will be deployed to extend the gained knowledge and help create an altitude profile for further missions.

B. *Mission Statement*

The BEXUS mission 'High Altitude Meteoroids-dust-catching Balloon constrUcted by a Revolutionary Generation' (HAMBURG) is designed to collect micrometeoroids in a height of up to 25 km. With the collected particles, as well as the temperature and pressure data also collected, a precise altitude profile of the micrometeoroid accumulation can be derived. The knowledge gained from the analysis of the particles may lead to the distinction of their origin, which is possibly the Asteroids or Kuiper belt. Moreover, there is a chance, however small it may be, that the collected data helps proving the Oort Cloud at the outer edge of our solar system.

C. *Experiment Objectives*

As stated in the previous chapter the three main goals of our experiment are to collect particles in the upper atmospheres as well as measuring temperature and pressure. Combining those three sets of data will lead to an even better understanding of the origin of the micrometeoroids. Afterwards the particles can be analysed to gather additional scientific data. This data includes but is not limited to the outer appearance, basic mechanical properties like weight and size as well as the chemical composition and structure. Moreover, the chemical data could lead to the determination of the origin and age of those particles.

D. *Experiment Concept*

While our main goal is to catch micrometeoroids in general, the experiment is mostly focused on catching ferromagnetic micrometeoroids. This choice is made as it leads to the usage of magnets as an uncomplicated way to collect them. For each side of the BEXUS gondola, a module with these magnets in it and a very thin layer of acrylic glass on the magnets gets built. These modules serve as particle collectors. The surface of the acrylic glass layer is coated with silicone oil, so the caught particles can't fall down and other non-ferromagnetic particles can be caught. To differentiate between different altitudes in which the particles were caught, the total magnetic surface is divided into multiple segments. Using a rotating lid only one segment is uncovered for a certain altitude while the other four are shielded (Fig. 1, Fig. 2). The four modules are defined with the letters A, B, C and D. Therefore the segment 1 of the module A is declared with A1.

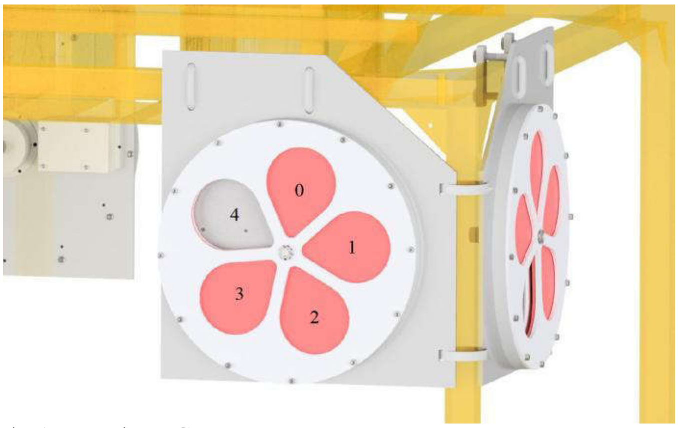

Fig. 1. Experiment Concept

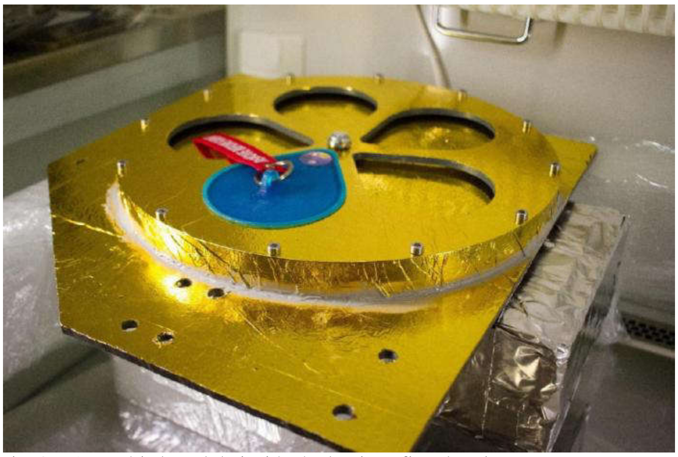
Fig. 2. Assembled module inside the laminar-flow-hood

E. Educational aspects

During this project, the team, that consists of matriculated students, learned how to manage, design, build and analyse the experiment and the gathered samples. As a hands-on project the students were able to transfer their theoretical knowledge into practical work. Additionally the team members learned how to work in different labs, clean rooms and work with other scientific instruments, respectively.

F. Protection against contamination

The team took samples from each material, that was built in the module (particle collector) and from every room, lab, workshop, ambient air (inside and outside), launch and landing site, clean room etc., where the modules stood, to analyse it. After the analysis those samples served as comparison to detect contamination. Additionally the team assembled and dissembled the modules in a clean room, the gaps of the modules were sealed with silicone paste, a protection lid against contamination was opened short before launch and closed after landing. The first segment '0' serves as comparison, too, because it's the opened segment in the troposphere with possible pollution and also at the launch and landing site. Furthermore the silicone oil , the acrylic glass and other instruments during the analysis were sterile.

II. RESULTS

A. Technical results

Concerning the technical part, the experiment performed very successful. Due to the constant downstream of data, mainly from the on-board measurements, a successful operation of at least two of the four Modules was already indicated in-flight. Upon receiving the Modules and the documentation and photos provided by the recovery crew (Fig. 3), as well as inspecting the recorded video during flight, a successful operation was approved.

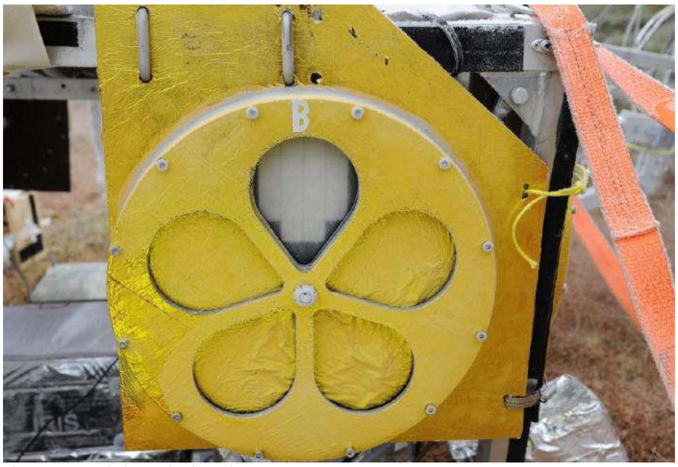

Fig. 3. Module B during the recovery

B. Scientific results

Immediately after the Modules arrived in Hamburg, those were brought into a clean room to avoid contamination while opening the sealing. Furthermore, as the rules of the clean room dictate, the responsible team members were equipped with a clean safety clothing. To clean the silicon oil with the contained samples, cyclohexane was used to wash the mixture from the acrylic glass. This was done with every segment of every Module, except for A2 and A3. The suspension from each segment was filled inside a separate 50 ml centrifuge tube. As the experiment provided up to 20 (4 Modules, 5 segments each) samples with each presumably containing multiple particles the analysis of all samples is quite an extensive task. Moreover, because of time limitations and high microscopy operating costs, so far only a fraction of those segments was selected for the first steps of analysis. Segments A0, B3, B4, C3, C4, D3, D4 were analysed partially. The outcome of this analysis is described in this chapter. After the selected samples were centrifuged, single droplets were trickled onto the object carrier of the Scanning Electron Microscope (SEM) Zeiss Supra 55 VP, each with a volume of 0.01 ml to 0.02 ml.

Due to a high surface tension, some particles might get adhered to the centrifuge tube's wall or the pipette. These particles cannot be analysed without further ado; therefore, those shall be judged as lost. Another possible loss of particles might have occurred while washing them from the foil into the tubes or during the dilution of the cyclohexane-silicone-oil-suspension. The first analyses using the SEM results in an overall particle count of approximately 70 within the first samples. Thus, the experiments task of catching particles can be assessed as fulfilled. Possible contaminating particles were identified by the visible shearing of the specific particle's surface (Fig. 4) and using the integrated energy dispersive X-ray spectroscopy (EDX) of the SEM. For example, a chunk of stainless steel, possibly from a bold or tool was identified easily (Fig. 5).

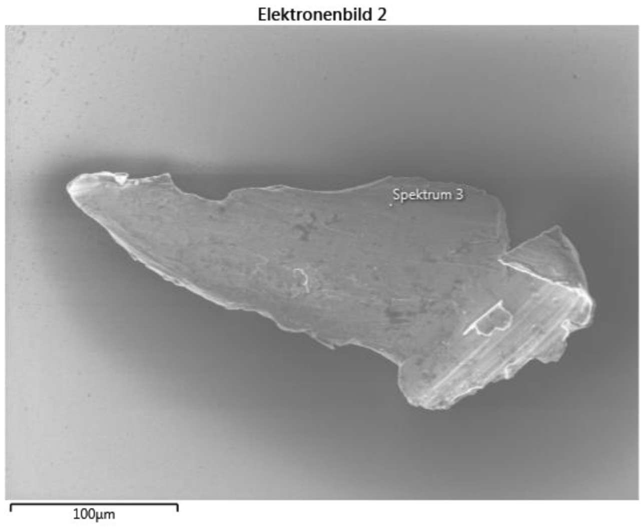

Fig. 4. SEM-Image of contamination with stainless steel

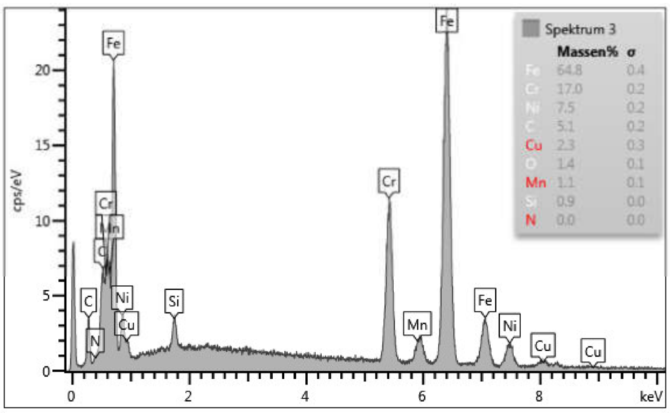

Fig. 5. EDX-Chart of contamination with stainless steel

Moreover, other particles, like natural-organic ones can be differentiated by their carbon proportion, as it was done with the remnants of a cleaning tissues.

One of the particles from the segment D4 was, with a very high probability, identified as a cosmic dust particle (Fig. 6). Its EDX (Fig. 7) shows that it contains the elements, which are common in chondrites. Of all meteorites 86 percent are chondrites. This mixture contains silicates, carbon, inclusions of aluminium and calcium. Furthermore, the proportion of carbon can be higher (Genge et al., 2008; Dartois et al., 2013), after the water in this rock steams away at higher temperatures. However, the material might not be homogeneous. In some areas the concentration of different minerals or elements can be higher than in other.

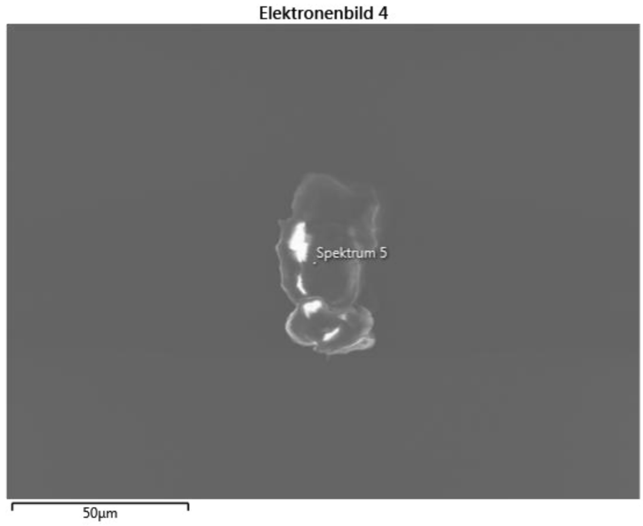

Fig. 6. SEM-Image of particle 'Space-Face'

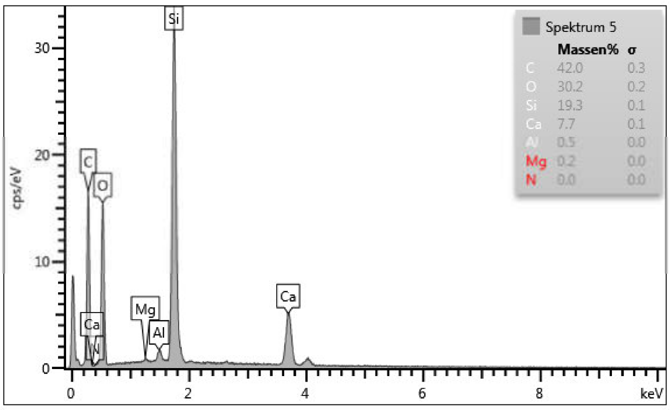

Fig. 7. EDX-Chart of particle 'Space-Face'

Another particle, having a higher probability of being of cosmic origin, consists of rocky silicate (Fig. 8, Fig. 9).

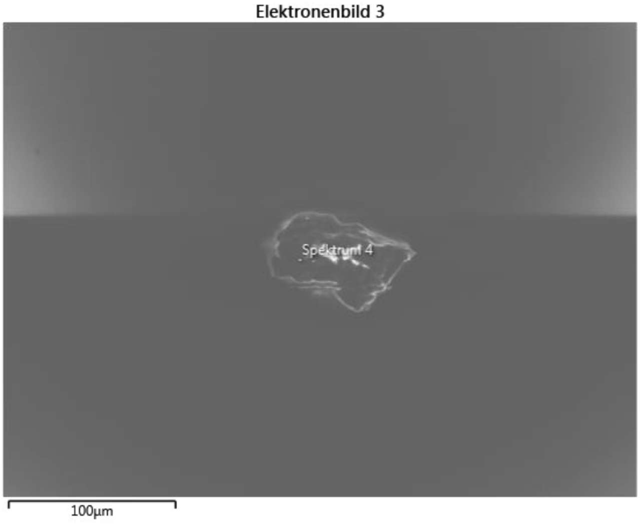

Fig. 8. SEM-Image of rocky particle

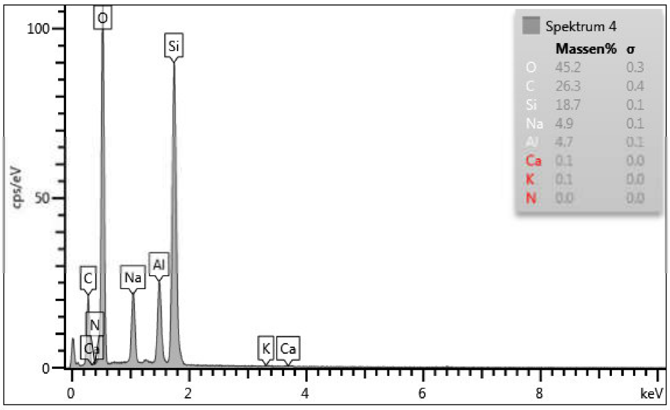

Fig. 9. EDX-Chart of rocky particle

Otherwise, the silicone oil might still influence the EDX. After the evaporating of the cyclohexane, the silicone oil forms bigger clustered aggregates with other solid particles. High peaks of silicon and organic elements are a result of the described phenomena (Fig. 10, Fig. 11).

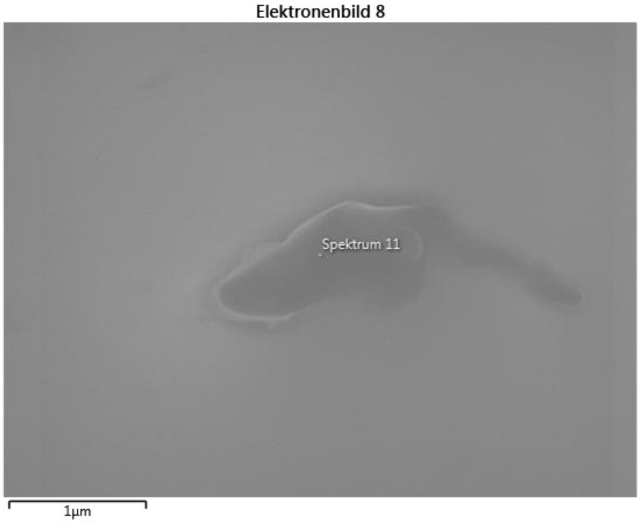

Fig. 10. SEM-Image of silicone contamination 'Space-Mouse'
Figure

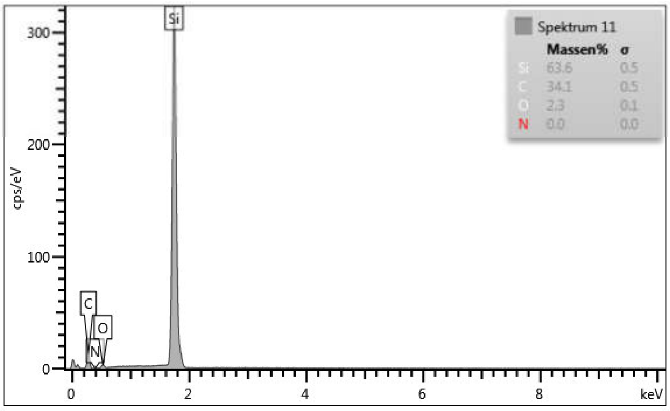

Fig. 11. EDX-Chart of silicone contamination 'Space-Mouse'

Another suspicious particle (Fig. 12) could have cosmic origin with a high possibility. It can't be a contamination from the magnets or a magnetic screwdriver, as it contains neodymium and other rare-earth elements like gadolinium and praseodymium (Fig. 13, Fig. 14, Fig. 15). The magnets used on the Modules are alloys with a high rate of boron. Yet, the EDX-Charts show, that this particle does not contain any boron at all. The particle is very porous; thus, it is unlikely part of a screwdriver. The detected rare-earth elements are very expensive; hence they are usually not used in ordinary applications.

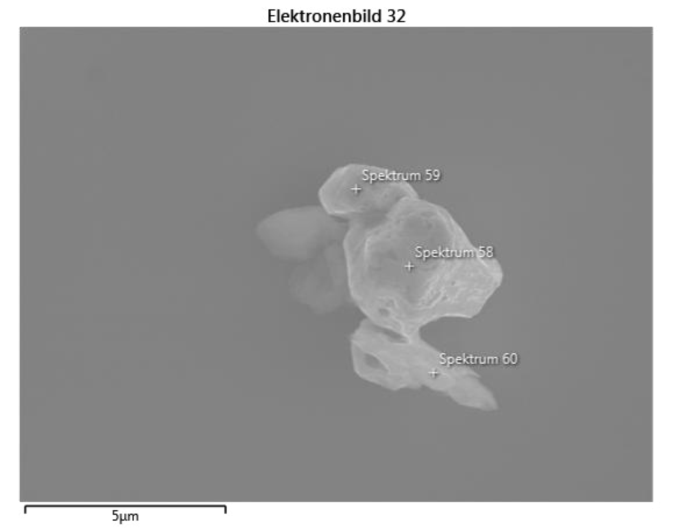

Fig. 12. SEM-Image of particle with neodymium

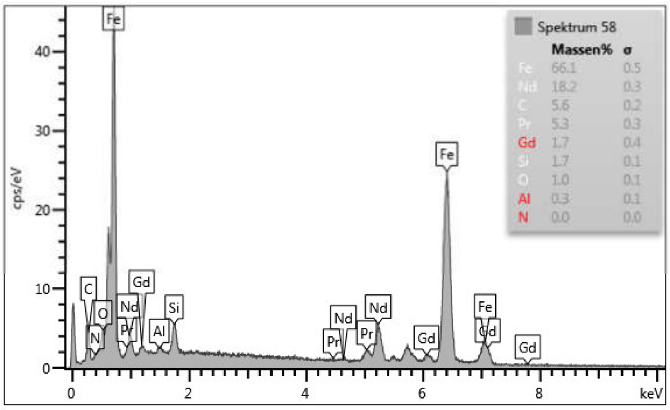

Fig. 13. EDX-Chart of particle with neodymium 'Spektrum 58'

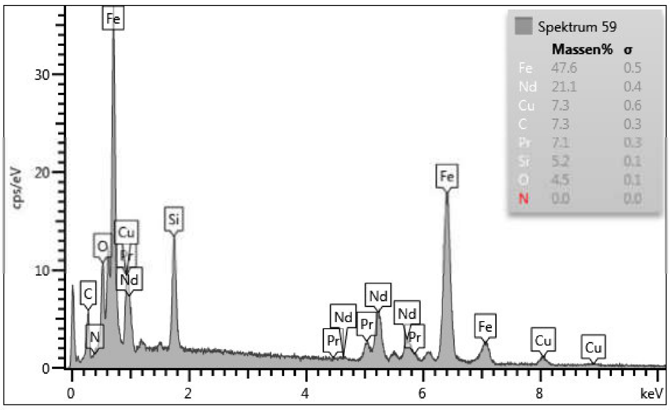

Fig. 14. EDX-Chart of particle with neodymium 'Spektrum 59'

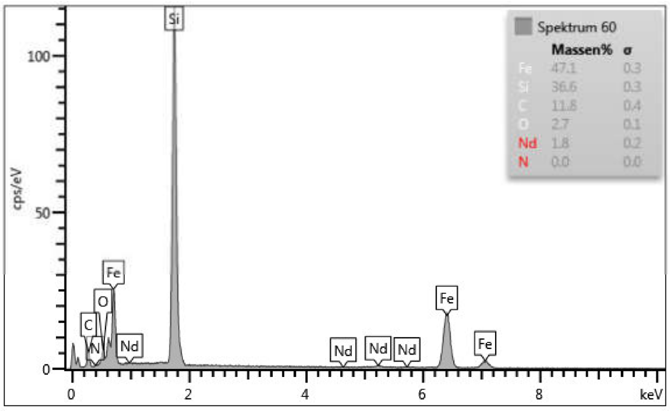

Fig. 15. EDX-Chart of particle with neodymium 'Spektrum 60'

Even though, there are many more particles to be analysed, the mission shall already be stated as successful. All methods, adhesives and the precautions against contamination worked properly. Thus, contamination has been decreased to a minimum. The still existing contamination can mostly be easily identified. Some suspicious particles have been found, with many of them having a high probability of cosmic origin. The big number of particles found within the first phases of the analysis is astonishing. More particles are to be expected in the remaining centrifuge tubes.

III. Outlook

The particles will be analysed with other methods like nanoscale secondary ion mass spectrometry (nanoSIMS) to determine the age by evaluating the isotopes , focused ion beam (FIB) and transmission electron microscope (TEM) to examine the inner structure. Afterwards we can judge, if these particles have cosmic origin or not for 100 percent.

Acknowledgment

We want to thank all supporters and sponsors for helping us and make this project happen. Moreover we want express our thanks to all team members, who worked besides the university at this project.

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Proof-of-concept of the "GNSS Direct & Reflected Combination Tester" (G-DIRECT) payload from a stratospheric sounding balloon experiment over land surfaces

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Abstract—**This work summarizes the first evaluation of a stratospheric sounding balloon experiment performed towards the proof-of-concept of the new cost-effective Earth remote sensing GNSS-DIRECT payload, suitable for small satellites such as CubeSats. This payload is expected to provide accurate GNSS Radio-Occultation (GNSS-RO) observations of the atmosphere, and GNSS Reflectometry (GNSS-R) measurements of the Earth surface for very low grazing angles, when coherent scattering effects provide strong forward scattered GPS signals. Unfortunately, due to an unexpected failure in the balloon, the system only could collect data during the ascent phase, characterized by significant fluctuations of the gondola' attitude (yaw, pith, roll).**

Keywords— Sounding balloon, education, remote sensing

I. Introduction

This work has been developed at ESEIAAT - UPC BarcelonaTech, in the frame of the INSPIRE3 initiative. More details can be found in a companion paper [1]. In particular, this project corresponds to some of the activities performed within the UPC Space Program [2], allowing vocational/motivated students to participate in hands-on activities, related with aerospace and systems engineering.

The fundamental objective is two-fold: a) to foster systems engineering activities in the frame of a Final Degree Project (TFG) of an aeronautics engineering school, and b) the proof-of-concept from a stratospheric sound balloon, of a new instrument aimed at GNSS-RO (GNSS Radio-Occultation) and GNSS-R (GNSS Reflectometry) [3,4]. The experimental set-up has been developed using COTS (Commercial Off-The-Shelf) components. Among these components stand out an ARM A-53 CPU with a 1.2 GHz clock rate (Raspberry Pi 3 Model B), two GPS receivers (one for the direct signal and the other one for the refracted signal), two single-patch RHCP (Right Hand Circular Polarization) antennas, a passive thermal control, and a Kalman filter-based Inertial Measurement Unit (IMU) that provides positioning information (very important for applications such as GNSS-RO).

In agreement with the aim of INSPIRE3 project, all the design, construction and testing were carried out by the first author, as part of his end-of-degree project in aerospace engineering.

The launch campaign of the balloon took place on December 23rd, 2017. Despite the float phase was expected to be ~ 28 km, the apogee of the trajectory was ~ 12 km (ascent phase) due to an unexpected failure in the "balloon". After the flight, the experimental set-up was examined on-ground using housekeeping data, and it was determined that both hardware and software operated correctly.

This work describes the main aspects of the set-up. At present, scientific data are being calibrated using information of the trajectory, the IMU, and the antenna radiation pattern. This first launch demonstrates a correct design and construction of the set-up, and future launch campaigns are scheduled to perform a comprehensive test of the G-DIRECT payload from the float phase ~ 28 Km, with a much higher platform's stability. Section II describes the experimental set-up, Section III provides an overview of the software, Section IV shows the testing activities performed on-ground to validate the design. Finally, the launch procedure is included in Section V, and very-first preliminary results in Section VI.

II. Experimental set up

In this section, the different subsystems that form the final solution are detailed to understand their connections and operation.

A. Electronic equipment

A PCB with all the electronic equipment was designed, manufactured and tested. The main components are the following:

- A "Raspberry Pi 3 Model B" microcontroller that was selected because of its high processing data speed, great capability of storage, and the four available USB ports.

- A "BOSCH BNO055" IMU with Kalman filter, connected to the microcontroller with a UART port and FTDI converter to USB.
- A "Copernicus II" GPS receiver, operated using NMEA protocol, to collect GNSS direct signals. The device was connected with UART, using a FTDI converter to USB.
- A second "Copernicus II", operated with TSIP protocol for scientific purposes (GNSS-RO). The device was connected to a Raspberry Pi with the native UART port (/dev/ttyS0).
- Two "Dallas DS18B20" thermometers used to record inner and outer temperatures. They were connected to the same Raspberry Pi GPIO pin, using the one-wire protocol.
- Other components: Two buttons (one for emergency reboot and shutdown the micro in a safe manner) and four LEDs to display the IMU calibration status.

B. Power

For this project, a lithium battery-based power bank has been used as it is rechargeable, does not need an additional component to control its output voltage (it provides a 5 V DC and 2 A), it is low cost and durable. The selected system was a Xiaomi, providing up to 10,000 mAh. Lithium batteries might release small gas quantities that in sea level conditions can be contained in its encapsulation material. However, under the low pressures at the expected altitudes (up to ~ 30 km), this can be a problem. Thus, the battery was tested in a vacuum chamber as described below.

C. High Altitude Balloon Module (HAB)

The module (Fig. 1) contains the electronic and communications systems. The structure must follow these requirements:

- Isolate the electronics from the extreme low stratospheric temperatures.
- Reduce the spin movement.
- The final weight of the capsule must be kept low to fulfill the legal maximum weight requirement (4 kg).

The material used to build the module is a rigid foam panel made of polyisocyanurate (PIR). It is coated on both sides with lacquered embossed aluminum. This material presents a high thermal resistance and on the other hand it is easy to manipulate. Additionally, it is covered with a thermal blanket to improve the material thermal resistance. The capsule should be sized to allocate inside all the electronics. Also, antennas have to be placed outside of the module in order to collect GPS signals, and to transimit data.

Fig 1. System inside the HAB module.

D. Communication Systems:

While the bulk of the data is saved in a micro SD card, the experimental setup has two communication systems used to transfer telemetry data. They are:

- Xbee, operating at 868 MHz of frequency with a dipole antenna and connected to connected to an Arduino Uno microcontroller via UART.
- A Iridium-based satellite communications system. Iridium is a satellite constellation form by 66 cross-linked Low Earth Orbit (780 km) satellites that can provide voice and data connections around the world. In order to communicate with these satellites and obtain the desire data an Iridium modem, a microcontroller and antenna are needed as well as contract a data line and credits. All this data from the communications systems is received in order to be able to follow the capsule. The data sent through Iridium is kept low to reduce the cost.

III. SOFTWARE

The data incoming from the four instruments (IMU, NMEA GPS, TSIP GPS) and thermometers is recorded using different processes that run concurrently. The software was implemented as follows:

- Thermometers: A Python script is used to read the thermometers digital data output, from low-level functions running in kernel space.
- IMU: A Python script, based on Adafruit Python library for the BNO055 [5,6] is used. The code records the orientation angles, accelerations and calibration status.
- GPS receiver with NMEA protocol: A C code was developed to detect the USB port where the NMEA GPS is connected and then to save the data. The detection of the USB port is needed as they are assigned randomly after each system reboot.
- GPS receiver with TSIP protocol: A C code is used. Note that the TSIP protocol is more involved than

NMEA. The code was validated comparing the results obtained with a proprietary TRIMBLE application [7].

Additionally, a watchdog code programmed in C is used to monitor each of the previous applications. In case of failure, the application is restarted. Each data line includes a Unix epoch time stamp so that the data streams from the different applications can be synchronized. A bash script executed after the restart of the Raspberry Pi (using crontab) starts all the aforementioned codes.

Fig 2. System inside the vacuum chamber ready for the low-pressure test.

Fig 3. System inside the temperature test box for the temperature test.

IV. Ground testing

Before launch the system it is imperative to ensure the system will operate as expected and all their components will not suffer any damage during the flight. Keeping this in mind, different tests were performed:

- Vacuum testing. With the purpose to ensure its operation, the system was tested inside a vacuum chamber to a pressure of about 800 Pa. The system is introduced in a metallic mesh to prevent accidental damages to the chamber (Fig. 2).
- Temperature testing: The actual heat transfer from the payload to the environment includes thermal radiation, solar radiation and convection and is difficult to model and reproduce in a experimental chamber, but as a worst case scenario, the payload is introduced in a box in partial contact with dry ice at -78.5ºC (Fig. 3). The insulation system plus the heat dissipated by the electronics allow the inner temperature to be above 0º during 3 hours.

Fig 4. Image of balloon during the launch campaign.

V. Launching procedure

Before the launch, different tasks and documents should be developed and asked in order to get the suitable permissions and make a good organization and schedule for the mission. The document that is imperative to fill is a NOTAM form prepared by ENAIRE [8], the air navigation manager in Spain, certified for the provision of route, approach and aerodrome control services. Date, location, the person in charge of the mission (project manager), the different specifications of the balloon (objective, mass, helium volume…) have to be defined in this document. After that, ENAIRE gives the permission and accepts the conditions or not.

The balloon trajectory is simulated with the Cambridge University Spaceflight Landing Predictor tool [9] in order to select a launch site from which the predicted falling point is far from populated areas. The launch site is typically at about 200 km of ESEIAAT. Once the experiment is launched (Fig. 4), the Iridium telemetry system reports the balloon position periodically. This, together with a good selection of the launching site, has allowed INSPIRE3 students to recover most of the experiments. A typical image from this mission is shown in Fig. 5, while an image recorded before ground contact is shown in Fig. 6.

Fig 5. Image taken by the on-board camera at ~ 12 km altitude.

Fig 6. Image taken by the on-board camera just before landing in a low population area.

VI. VERY FIRST PRELIMINARY RESULTS

This section is focused to show the results extracted from the thermometers results, IMU, GPS module with NMEA protocol, and GPS module with TSIP protocol.

- Trajectory. The recorded trajectory is shown in Figs. 7 and 8. As aforementioned, due to a balloon failure, the maximum altitude reached was ~ 12 km.
- Temperatures. The payload and the external temperatures are shown in Fig. 9. While the system performed correctly, an additional heating system might be needed. The next mission will include electrical heaters.
- IMU. The “BNO055” data was recorded correctly (Fig. 10) but the system lost its calibration, so we cannot be confident on the heading measurements. Future missions will include either a redundant IMU or a sun tracker system.
- A first evaluation of the Signal-to-Noise Ratio (SNR) as collected by the limb-looking antenna (Fig. 11) shows significant fluctuations, that could be attributed to the random movement of the gondola (Fig. 10) during the ascent phase flight. On-going activities include the correction of the antenna pattern using available information from the IMU.

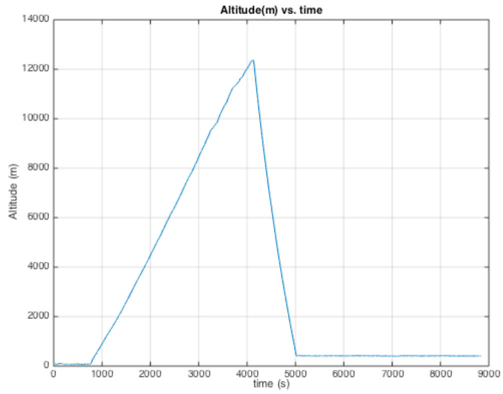

Fig 7. Altitude of the balloon as a function of the time during the experiment.

Fig 8. Trajectory followed by the balloon during the flight.

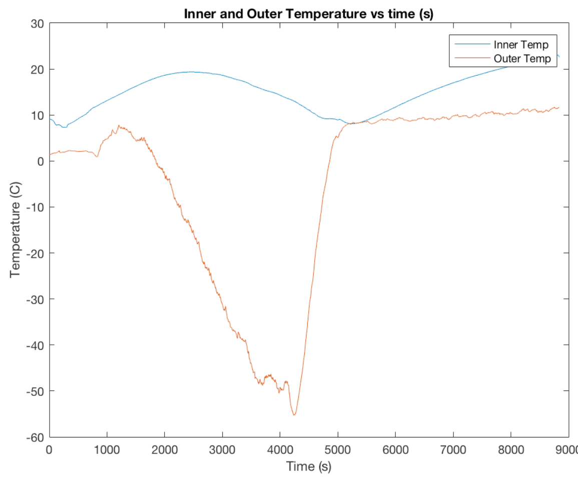

Fig 9. Evolution of the inner and outer temperatures of the payload box.

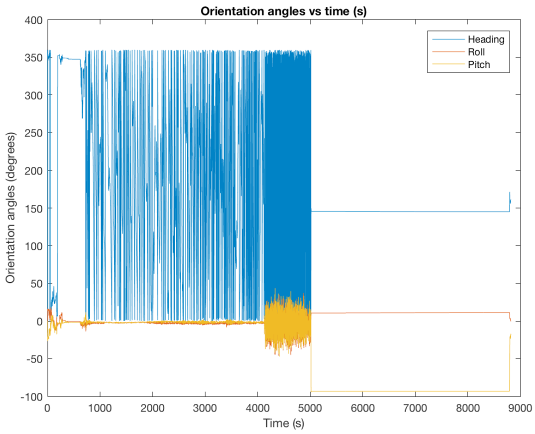

Fig 10. Evolution of orientation angles as a function of time.

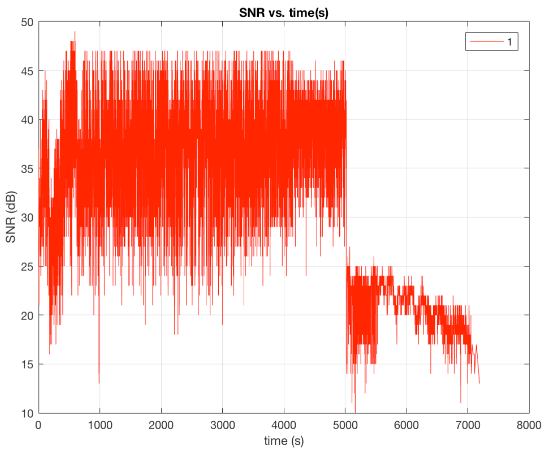

Fig 11. SNR evolution vs time for a given satellite in view (PRN 1).

VII. Conclusions and Future Actions

The design, assembly, testing, launch and successfully recover of the "GNSS Direct & Reflected Combination Tester" in a short period of time (one semester) was a challenge. The proposed system operates reliably and the data from all the documents has been recorded without problems, despite the unexpected failure of the balloon. The current emphasis is in the post-processing of the results, as well as the preparation of the next launch.

Acknowledgment

Authors acknowledge the support to this experiment provided by the ESEIAAT UPC by means of INSPIRE3 initiative, professors (especially J. Hutchinson), laboratory technicians (especially J.Sala) and students participating in former HAB experiments (especially J. Montserrat, E. Gómez, and D. Huete).

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Double-dipole antenna deployment system for EIRSAT-1, 2U CubeSat

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Abstract— **This paper describes the design, building and testing of the Antenna Deployment Module (ADM) for EIRSAT-1, a 2U CubeSat being developed under ESA's Fly Your Satellite programme by a team of students from University College Dublin. The ADM is the only mechanical device on board EIRSAT-1 and its proper functioning is critical to the mission. Although the main ideas are similar to those of commercially available systems, a number of special design features have been incorporated resulting from dissatisfaction with aspects of earlier designs. The paper describes the design, buidling and proposed testing of the module, and the educational experience in following this path.**

Keywords— CubeSat Communications; Dipole Antenna; Deployables; Mechanisms; Melt Line

I. Introduction

EIRSAT-1 is a 2U CubeSat which has been developed by students at University College Dublin (UCD) [1]. The EIRSAT-1 project was selected to be part of ESA's Fly Your Satellite (FYS) programme. The project is primarily educational in nature with the following aims:

- To grow the knowledge of space science and engineering in the Irish higher education sector, by supporting students in building, testing and operating the satellite.
- To address skills shortages in the Irish space sector by encouraging collaboration between student teams and industry through the launch of three science payloads that use innovative Irish technology.
- To inspire the next generation of Irish students towards the study of Science and Engineering by launching the very first Irish satellite.

The communications subsystem of EIRSAT-1 utilises two dipole antennae, one for VHF uplink and the other for UHF downlink. The complete system consists of a custom built Antenna Deployment Module (ADM) and an off-the-shelf transceiver board. A custom built ADM was chosen because it provides a richer educational experience for the students involved. Both dipoles are composed of tape spring antenna elements as seen in many previous designs [2]. The elements are coiled inside the ADM before deployment, within the (227mm x 100mm x 100mm) allowed volume of the 2U CubeSat. When EIRSAT-1 is clear of the CubeSat deployer the ADM will activate a release mechanism based on melt-lines allowing the elements to uncoil into their operational positions and remain in that configuration for the remainder of the mission.

This paper outlines the educational journey from initial design and prototyping through to an updated design, the justification for this design, including sizing of the mechanism and FEA of critical components, and the proposed test plan for the module. The main requirements of the ADM are outlined in section II. Section III describes the preliminary design of the module and the production of the first prototype. An updated design is then presented in section IV which addresses a number of issues identified during testing of the first prototype. Section V justifies a number of elements of the design and discusses the analysis tools used for justification. Section VI presents the proposed tests to be carried out on the module and section VII concludes and discusses the educational value of the project.

II. Requirements

The main requirements of the ADM are:

- The module will be attached to the –Z face (one end) of EIRSAT-1 and must fit within an envelope of 100mm x 100mm x 6.5mm.
- Upon a deployment signal from the on-board computer the antenna must deploy into a straight dipole allowing communications to be established.
- The module must have redundancies built in for critical parts, including melting resistors and melt lines.
- The deployment mechanism must operate in a vacuum and over the full range of temperatures experienced by the satellite.
- The deployment mechanism must operate after storage for 9 months before launch.
- The module must withstand the loads during launch and the space environment.

III. Preliminary Design and Prototyping

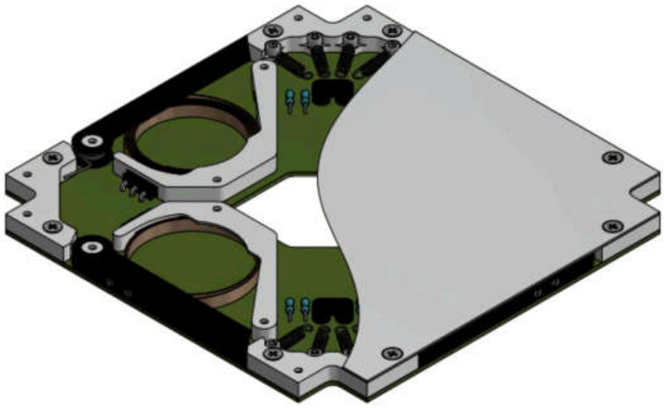

Fig. 1 - Preliminary Design for ADM

The preliminary design of the ADM for EIRSAT-1 is shown in Fig. 1. The base of the module is a 1mm thick PCB onto which the rest of the components and aluminium structure are attached. This PCB contains circuits for both the deployment mechanisms and interfacing the antennae with the radio transceiver. On top is a 0.5mm aluminium cover. The four tape spring elements are stored in circular coils at the four sides of the module before deployment and held in place by spring loaded doors. Each door is held in the closed position by a tensioned dyneema melt line. One end of the line is connected to a small extension spring to keep the line in tension and the other to the door. The line runs over two melt resistors. During deployment the melt line will be cut by passing current through the melt resistors, releasing the door and allowing the antenna element to uncoil into its operational position. Each door is opened and held in the open position by a torsion spring. For redundancy, a pair of melt lines running in parallel will be used for each door. Similarly, for each door two resistors are used to cut the melt lines. To ensure good contact between the resistors and melt lines, the lines are threaded over one resistor and under the other. A lever-type limit switch is used to detect the successful deployment of the antenna. Each switch is positioned such that the coiled antenna element depresses the lever in the undeployed position and releases the lever upon successful deployment.

Both pairs of dipole elements are connected via small coaxial cables to a balun transformers and a single MMCX coaxial connector is used to interface each dipole with the transceiver board. A transistor is used to switch on power to each primary melt resistor using a signal from the On-board Computer (OBC). The secondary redundant resistors are connected in parallel and powered by a separate switchable power supply on the Electrical Power Supply (EPS) board. In this way two completely different control chains are used for normal deployment and deployment using the secondary resistors and the redundancy is maximised.

A prototype of this design was built and is shown in Fig. 2. Deployment mechanisms for two of the antenna elements were included. In the prototype, standard measuring tape steel material was used for the elements which were 3mm wide and

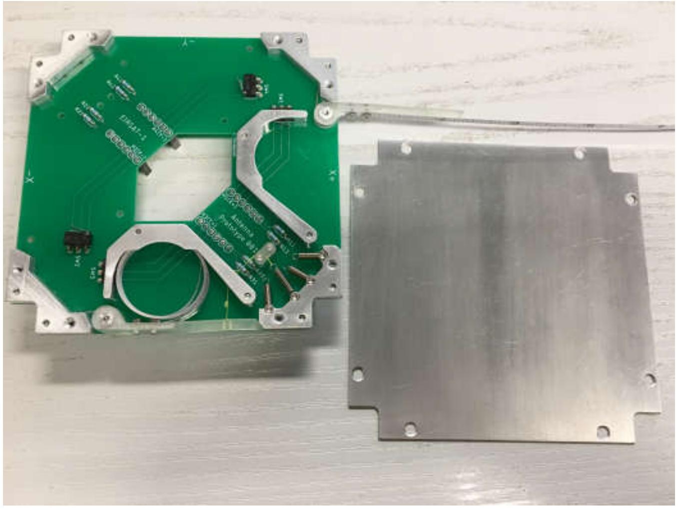

Fig. 2 - First Prototype of the ADM

the doors were 3D printed. The first design as described in the previous paragraphs is similar to many commercially available designs. A drawback of the design is the allowable width of the antenna elements and consequently their limited rigidity. This became apparent after some basic deployment tests on the prototype. A major requirement of the module is that after deployment the elements are as straight as possible to make the best dipole antenna. While this will be easier in a micro gravity environment, there will still be some residual bend in the element after storage in a coil before launch. Because the PCB is used as the base which supports the rest of the module, and this PCB must allow room for solder fillets and fasteners on the underside, the available width for the elements is limited. To have the maximum width available the thickness of the lid on the top of the module was set at 0.5mm but it was found that this lid was quite flimsy, difficult to attach using countersunk fasteners and not suitable if any additional sensors or parts were to be mounted on the top of the module. In the first design the doors open to be at right angles to the module which results in a misalignment of the two halves of the dipole. While this effect is small, it nonetheless reduces the efficiency of the antenna. A number of revisions were made to the module design after production and basic testing on the first prototype, to overcome these issues. The updated design is described in the next section.

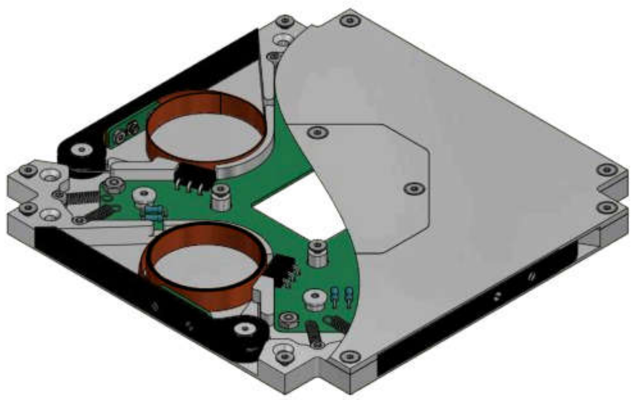

Fig. 3 - Updated design of the ADM

IV. UPDATED DESIGN

The updated design for the ADM is shown in Fig. 3. The main structure of the module was changed to aluminium and consists of three parts, a base, a central cover, and an outer cover. This made the module more rigid and also allows the main PCB to be reduced in size and mounted inside the base of the module. The new shape of the PCB means that it does not interfere with the stowed elements allowing them to be considerably wider. The width of the elements was increased from 3mm to 5mm. Each element also has a curve along its long axis to increase rigidity and straightness in the deployed configuration. To accommodate this curve the inside of the doors have a matching profile as shown in Fig. 4. The doors open to the wider angle of 120 degrees allowing the elements to align perfectly. A small PCB was included on each door which includes a small coaxial connector for connecting each antenna element to the main board. The two part lid of the module has two advantages. The first advantage is that either of the lids may be removed, and the other holds the stowed elements in place inside the module. For resetting melt lines the outer lid may be removed and for connecting/disconnecting the OBC or Communications board connectors the centre lid may be removed. The second advantage is the increased thickness of 1.5mm of the aluminium lids making it much easier to mount additional sensors on the top of the module.

Fig. 4 - Updated door design to accommodate curved elements

V. DESIGN JUSTIFICATION

A. Materials selection

The main materials used in the module are aluminium for the structure, stainless steel for the springs and fasteners, PolyEtherEtherKetone (PEEK) for the doors, Copper Beryllium for the antenna elements and dyneema (Ultra High Molecular Weight Polyethylene) for the melt lines. Aluminium is widely used for spacecraft structures and is the obvious choice for the main structure. The frame will be hard anodised for two reasons. It provides electrical insulation between elements in the stowed position and also provides a hard bearing surface for the doors to slide on. PEEK was chosen for the doors for its strength, stiffness, UV resistance and self-lubricating properties. For surfaces which slide against each other the ECSS standards for mechanisms and materials [3,4] recommend a hard material sliding against a softer material. The softer, self-lubricating PEEK against the hard anodised aluminium is a suitable choice. Stainless steel is suitable for springs and fasteners because of its strength and corrosion resistance. Copper Beryllium was chosen for the elements because while being a good spring material it also has a high electrical conductivity. Braided dyneema fishing line was chosen for the melt lines because it has high strength, resistance to abrasion and a lower melting point than nylon.

B. Mechanism sizing

The following methodology was used in sizing the parts of the deployment mechanism with reference to [3]:

1. A torsion spring was chosen that can deliver sufficient actuation torque to overcome friction in the mechanism and open the antenna doors. This choice was verified by testing on the first prototype.
2. A sufficient holding force must be supplied to the door at the melt line holding point. This force should be sufficient to hold the door closed against the torque of the torsion spring but also during the highest anticipated acceleration during launch. A maximum acceleration of 18g was applied in the opening direction of the door. An uncertainty factor of 1.2 was applied to the torsion spring force and the final required holding force was then multiplied by a safety factor of 2.
3. An extension spring was chosen to tension the melt lines to the required holding force at half of the maximum extension. Again an uncertainty factor of 0.8 was applied to the extension spring force.
4. The dyneema melt line strength was then chosen using a factor of safety of 3.

C. Stress Analysis

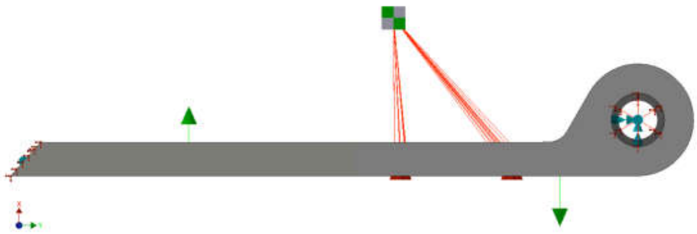

Fig. 5 - Door FEA loads and constraints

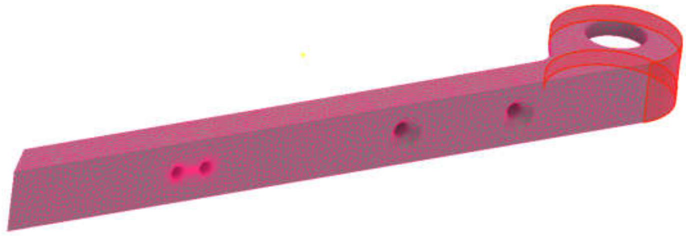

Fig. 6 - Door FEA mesh

Finite element analysis was employed to analyse the stress and displacement of the antenna doors under the applied loads. The doors will be subjected to loads from the torsion springs and two melt lines in the undeployed state as well as acceleration loads during launch. A representation of the applied forces is shown in Fig. 5. Simulations were carried out for zero acceleration and 18g acceleration in the +X and –X directions as marked in Fig. 5. A tetrahedral finite element mesh was created. The mesh was refined several times to ensure mesh independent results were obtained for maximum stress and displacement in the doors. The final mesh is shown in Fig. 5. The maximum Von Mises stress and displacement occurred for the case of acceleration in the negative X direction. Fig. 7 shows the distribution of Von Mises stress and displacement for this loading case. The maximum Von Mises stress is 21.5 MPa. This maximum stress occurs at the melt line attachment holes on the door as shown in Fig. 7. A Margin of Safety (MOS) [5] of 3.14 was calculated with respect to the yield stress of the PEEK material using Eq. 1.

$$\mathrm{MOS} = \left[\frac{\text{Design Allowable Stress}}{(\text{Design Limit Stress})(\text{Factor of Safety})}\right] - 1 \tag{1}$$

The factor of safety used was 1.1 as recommended in [6] and the yield stress of PEEK is 98MPa. The maximum displacement of the door was 0.47mm during acceleration and 0.38mm with no acceleration. These displacements are small enough so as not to interfere with the overall operation of the device.

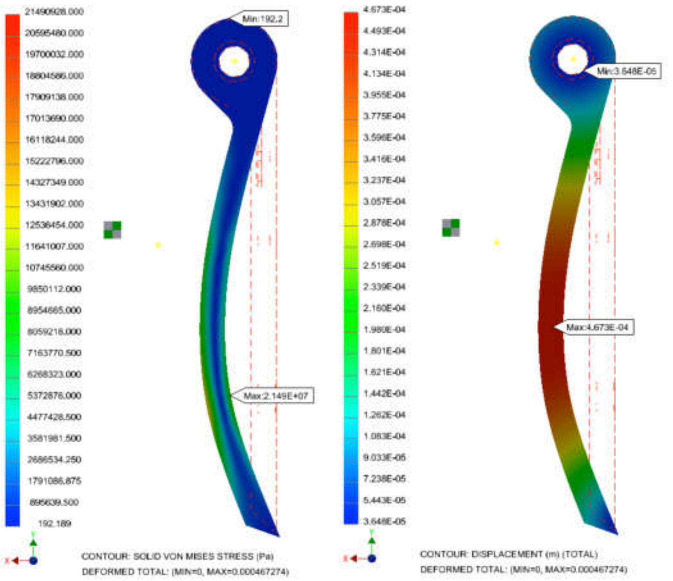

Fig. 7 - Door FEA Von Mises stress (left) and displacement (right) results

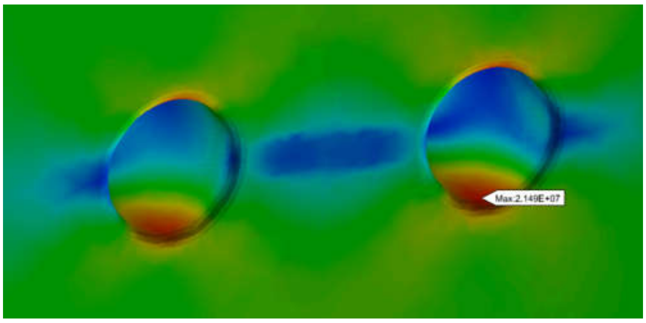

Fig. 8 - Maximum stress occurs at the melt line attachment holes

VI. Test Plan

A. Model Philosophy

As the ADM is a newly developed subsystem it will follow a prototype model philosophy as described in [6]. Three physical models of the updated design will be produced: a Development Model (DM), an Engineering Qualification Model (EQM) and a Flight Model (FM). Qualification level testing will be carried out on the EQM which will be identical to the flight model and after qualification and refurbishment may be used as a flight spare. Acceptance level testing will be carried out on the FM. The main tests that will be carried out on the ADM are listed below:

B. Development Tests

- These tests will be carried out at a components/part level and on the DM to ensure the proper function of the mechanism and confirm correct sizing and choice of components early on in development process.
- Melt Resistor Overload Test – In order get the melt resistor temperatures sufficiently high to melt the dyneema line, a current above that rated for the resistor must be supplied for a short time. This test will confirm that this process does not damage the resistors before they can complete the required task. A current will be passed through the resistors for a short time (5 seconds) and after cooling the resistance will be measured to confirm no internal damage has occurred. This process will be repeated for a certain number of cycles and for increasing lengths of time. Ideally the test should be carried out in a vacuum to ensure realistic temperatures are reached representing the space environment.
- Melt Resistor and Melt Line Selection – This test will confirm the choice of line and resistor by ensuring the melt line material can be successfully melted by the resistor at the lowest foreseen operating temperature. To achieve this the test will be carried out in a low temperature chamber.
- Door Opening Test – This test will confirm the correct choice of torsion spring by allowing repeated opening of the antenna doors. Because recoiling the elements and resetting the melt lines after each test would be

very time consuming this test will be carried out without elements attached and an alternative method of closing and releasing the door will be used. A suitable mass will be added to the doors to represent the element mass.

- Antenna Element Storage Test – This test will verify that the antenna elements will not be permanently deformed or damaged due to prolonged periods of time where they may be coiled up inside the ADM.

C. Functional and Performance Tests

These tests will confirm that the module can complete each required function and to the specified performance:

- Deployment Test Primary Resistors – This test will verify the correct operation of the complete deployment mechanism. Each melt line pair and resistor will be tested individually. The time taken for deployment, the door torque in the open position and the position of the deployed elements will be measured. To simulate as close as possible to microgravity the test will be carried out with the module attached to a large flat surface with a low coefficient of friction.
- Deployment Test Redundant Resistors – This is a repetition of the previous test using the redundant resistors instead of the primary resistors.

D. Mechanical Tests

Vibration testing will be carried out to ensure that vibrations during launch will not cause permanent deformations or damage to the module. This will also verify that the release-detection switches do not falsely state deployment due to motion and/or vibrations and that doors remain in the closed position when subjected to launch vibrations. Functional tests will be performed before and after vibration to ensure no change of behaviour has occurred. Mechanical tests will include:

- Static Acceleration
- Sine Vibration
- Random Vibration
- Shock

E. Thermal Tests

- Thermal Vacuum Test – This test is carried out to verify antenna reliability in a space representative environment by switching through two temperature extremes. During this cycling process functional tests of the antenna deployment will be carried out at the worst case conditions for deployment of the antenna. This is when the temperature is at its lowest.

Conclusions

The design of the antenna deployment module for EIRSAT-1, a 2U CubeSat has been described. Two versions have been designed, an initial design similar to many COTS units and an improved design, following from testing on an initial prototype, which addresses some shortcomings in the earlier design. Suitable materials were chosen for the module. Several analyses were performed to justify design choices including mechanism sizing analysis and FEA to assess stress and displacement in a critical component, the antenna doors. Finally a test plan has been outlined for the module including component level tests, functional tests, mechanical tests and thermal tests. The EQM and FM of the module are currently in production at UCD and the ambient test campaign will kick-off in September.

The educational value for students of following this design process is immense. Experience has been gained in an array of different space engineering disciplines including, Mechanical Design, Electrical Design, Mechanisms, Materials, Structural FEA, Testing and Verification. Extensive use has been made of ECSS Standards and Handbooks throughout the project. The FYS programme is an excellent opportunity for students to gain an overview and hands-on experience of every aspect of spacecraft design, manufacturing, testing and operations.

Acknowledgment

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The Langmuir Probe experiment (ESEO-LMP)

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***Abstract* – The paper gives an overview of the Langmuir Probe experiment for the European Student Earth Orbiter mission. The experiment is being developed by the Laboratory of Space Technology at Budapest University of Technology together with the Geodetic and Geophysical Institute of the Hungarian Academy of Sciences. In this paper the scientific basis, the implemented experiment structure, as well as student involvement are discussed.**

Keywords—ESEO-LMP, Langmuir probe, satellite onboard experiment, satellite, plasma properties

I. INTRODUCTION

The European Student Earth Orbiter (ESEO) is a satellite project jointly developed by students and teachers of multiple European universities. The primary purpose of the mission is to carry out scientific and technological experiments while providing an opportunity for student participation in satellite development. The Langmuir Probe experiment (LMP) is an onboard scientific experiment of ESEO, its mission is to study the ionospheric plasma environment with in-situ measurements. The experiment hardware and software has been developed by the team of the Budapest University of Technology. The scientific expertise is provided by the Geodetic and Geophysical Institute of the Hungarian Academy of Sciences.

II. SCIENTIFIC BASIS

A. Plasma environment

The ionosphere is an upper region of the atmosphere, where atmospheric particles ionized by solar radiation form a low-density plasma. The plasma parameters vary as a function of altitude, therefore the ionosphere can be divided into several layers. The orbit of ESEO is around 524 km altitude [1] which is situated in the uppermost F layer, more precisely in the F2 layer (the F1 layer only appears in daytime and merges with the F2 layer during the night). The plasma in the F2 layer primarily consists of singularly ionized oxygen atoms and electrons, and it is quasi-neutral. This means that the ion and electron densities are equal, and the net charge in the plasma is zero. Both the ions and the electrons are considered to follow the Maxwell-Boltzmann energy distribution and therefore the ion and electron populations can also be characterized by their temperatures. Since the energy exchange is significantly more efficient between ions and between electrons themselves, the ion and electron temperatures have different values. Electron temperature tends to be higher due to the lower mass of electrons [2]. The International Reference Ionosphere model [3] was used to estimate the plasma parameters at the altitude of ESEO. In this altitude the ion and electron densities are between 10^{10} and 10^{13} particles per cubic meter and the electron temperature ranges from 300 to around 3500 K. These estimates are supported by the initial results of the ISL (Instrument Sonde de Langmuir) experiment onboard DEMETER [4]. With the Langmuir probe the plasma parameters can be determined, with the exception of the ion temperature (see the explanation in the next segment). The data provided by LMP makes it possible to study of the ionospheric parameters. The plasma parameters in the ionosphere are sensible to a lot of spatial and temporal effects, like variations in the solar activity, including changes in the intensity of the solar radiation, coronal mass ejections (CME), solar flares, etc. [2] [5] [6] [7]. The orbit of ESEO during its six months operation will cover the ionosphere over the whole surface of the Earth and will provide a global view based on in-situ measurements of the temporal and spatial changes in the ionosphere. A special focus of the mission is toward the spatial and temporal anomalies of the ionosphere, like the winter anomaly, the equatorial anomaly and the South-Atlantic anomaly. The acquired data will be used to perform case studies and statistical studies as well.

B. Principle of measurement

The Langmuir probe has been chosen as the instrument of the experiment, a plasma diagnostic device used in various terrestrial and space applications. The Langmuir probe can be used to determine the ion and electron densities as well as the electron temperature of the plasma. It works by immersing one or more conductive electrodes (from now on detector) into the plasma and recording its current-voltage characteristic. In case of LMP a single cylindrical detector was chosen, and voltage is applied between it and the satellite chassis. A typical Langmuir characteristic is shown on Fig. 1. The curve can be divided into three regions. The first region is called the ion saturation region, where the negatively charged detector attracts the positively charged ions and repels the electrons.

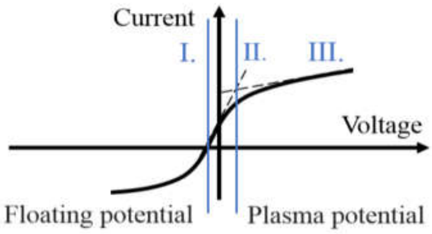

Figure 1: U-I characteristic of a Langmuir probe

The number of incoming electrons is negligible compared to the number of ions, and so the total current of the probe approximately equals the ion current. The exact opposite situation occurs in the third region (the electron saturation region), where the electrons are attracted, the ions are repelled, and the total detector current approximately equals the electron current. In between the two saturation regions lies the retardation region where both electrons and ions contribute to the detector current, the total current here is an exponential function of the bias voltage. The three regions of the U-I curve are separated by two notable voltage levels: the floating potential and the plasma potential. The floating potential of the probe is defined as the potential where the detector current is zero, or in other words where the ion and electron currents are of equal magnitude. Given enough time the potential of every non-disturbed conductor will approach this floating potential. Because the mobility of electrons is greater than that of ions the floating potential would be negative compared to an external point of reference. Fig. 1 shows such a U-I curve observable e. g. in a laboratory plasma. In space however the satellite chassis is charged to the floating potential, meaning that obtained characteristics must pass through the origin of the U-I plane and the floating potential cannot be measured directly. The plasma potential is the potential of the undisturbed bulk plasma, it is greater than the floating potential due to the higher mobility of electrons. At the plasma potential the movement of the plasma particles is unaffected by the electric field of the detector, and the incoming current is due only to their thermal motion [2] [4] [8].

An automated measuring instrument, such as LMP acquires the plasma characteristics by sweeping the detector voltage between the two saturation regions while recording the detector current. The recorded characteristics will be transmitted without further processing and the plasma parameters will be determined by subsequent analysis. The currents forming in the two saturation regions are called the ion and electron saturation currents and can be used to calculate the ion and electron densities respectively. This is complicated by the fact that in practice the current increases linearly instead of saturating at a constant value. In the retardation region the exponential increase of the current is affected by both the ion and electron temperatures, therefore the slope of the curve on a semilogarithmic scale could be used to obtain these parameters. However, in practice the contribution of the ions to the total current is so small, that only the electron temperature can be determined accurately [4] [8].

The plasma parameters important for designing the experiment are the following: difference between the floating and plasma potentials, saturation currents, dynamic range of the probe current and the Debye length. The potential difference was determined to be between 0.06 V and 0.95 V with the plasma potential being greater. The range of the bias voltage needs to be sufficiently large compared to this voltage difference, so the detector can enter the saturation regions deep enough for accurate measurement. A range of ±7 V was calculated to be sufficient (based on the results from the ISL even ±3.8 V might be enough [4]). The sweep can be set to any range between -8.7 V and +8.7 V to record the characteristic with different resolutions. The saturation currents range from microamperes to a few milliamperes, and the lowest current levels (around the floating potential) are estimated to be in the nanoampere range. The Debye length was determined to be between 1 and 40 mm.

III. Description of the Experiment

A. Overview

The implemented structure consists of the detector, abbreviated here as LDE (Langmuir Detector) and the necessary electronics contained within the Langmuir Control Box, or LCB. The LDE is composed of an electrode and a holding rod mounted perpendicularly on the nadir side of the satellite and its electrode is connected to the LCB via a triaxial cable. The LCB contains an analog amplifier (AMP), an on-board data handler (OBDH) and a power supply unit (PS) on three separate printed circuit boards, as can be seen on Fig. 2. The amplifier is responsible for controlling the detector voltage and converting the current signal of the detector to a voltage signal processable by the OBDH. The OBDH controls the measurement, records and sends the obtained data to the transmitter of the satellite. The panels are connected to each other by Teflon coated ribbon cables. All panels contain full copper layers which provide electric shielding and a thermal interface to the LCB structure. Card-Lok Retainers are used for fixation and for improving the thermal coupling between the electronic boards and the LCB.

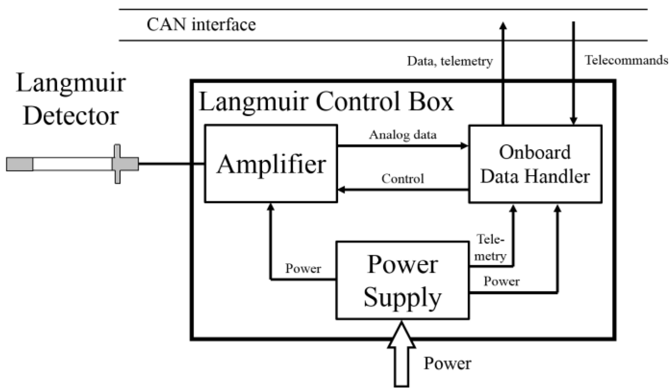

Figure 2: Schematic of LMP

B. Detector

The main challenge in designing the detector is to determine its surface area, as it needs to be a compromise between two important factors. Firstly, it is directly proportional to the current level of the detector, so it needs to be large enough for the amplifier to be able to sense the minimal current with sufficient accuracy. On the other hand, a too large detector would cause the potential of the satellite chassis to drift away from the floating potential, thus reducing the range of the sweep voltage. The final design of the detector is a cylindrical rod with a diameter of 13 mm and a height of 39 mm, making up a total area of 17.25 cm^2, which is around 1/600 of the surface area of the satellite. The material of the electrode is titanium, chosen for its durability and its ability to reduce the effect of photoelectrons. The holding rod has a diameter of 8 mm and a length of 90 mm, over two times the maximal Debye length. It is made of aluminium oxide ceramic capable of withstanding the eroding effects of UV and particle radiation [6]. The complete configuration of the detector and the electronic box is shown on Fig. 3.

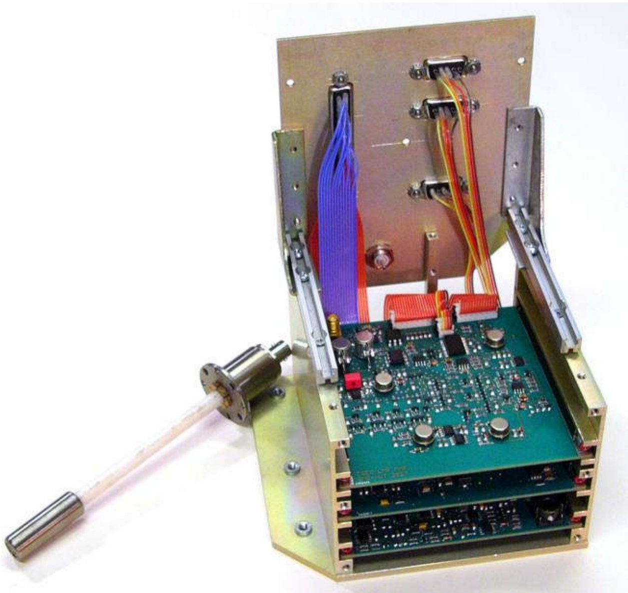

Figure 3: Langmuir Detector and Control Box. From top to bottom the three boards are the AMP, OBDH and PS.

C. Amplifier

The task of the amplifier is to convert the current signal to a proportional analogue voltage for the OBDH. The magnitude of this current may range from a few nanoamperes to milliamperes depending on the plasma properties and the bias voltage. To measure such very low-level currents indirect current sensing method was chosen.

The principle is implemented by a compensation amplifier circuit shown on Fig. 4. According to Kirchhoff's Current Law the sum of the currents in the inverted input node of the precision amplifier should be zero and therefore the detector current (I_{det}) and the compensation current (I_{comp}) are of equal magnitude. The output of the amplifier (U_{comp}), connected to the input through the feedback network, is proportional to the detector current. To minimize the error caused by the input bias current of the operational amplifier a low-bias model was selected. To maintain an adequate level of accuracy in the entire current range the amplifier can operate in multiple current classes. These classes are implemented by the feedback network, where resistors of different magnitude are connected in parallel, forming a resistance ladder. The resistors are being connected and disconnected by an automatic range control mechanism. The reference ground of the precision amplifier is the detector potential (V-DET), denoted here as the floating ground (F-GND). The voltage of the floating ground, thus the voltage of the detector is set by the on-board controller via a D/A converter and the bias amplifier located on the OBDH and AMP boards respectively. The AMP board houses a test network as well to monitor and validate the precision of the analogue circuitry. The input of the compensating amplifier can be switched between the detector and the test network by hermetically sealed relays.

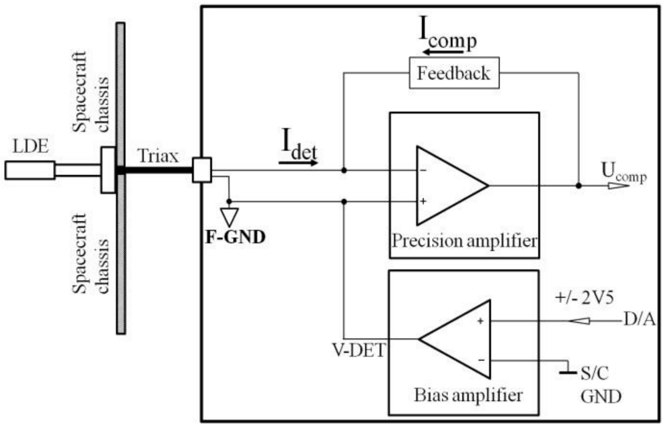

Figure 4: Schematic of the amplifier

D. Onboard Data Handler and software

The OBDH board houses the microcontroller and the necessary digital circuitry of the experiment. An Atmel AT90CAN128 microcontroller is used as a central processing unit complemented by an external flash memory to provide additional storage for scientific data. The amplified current signal, the detector voltage and various analogue telemetries are processed by the built-in A/D converter and sorted by analogue multiplexers. A separate D/A converter and supplementary analogue circuits produce the bias voltage, this unit is called the bias generator. The OBDH communicates on the payload CAN bus of the satellite (Controller Area Network) using CANOpen protocol. Scientific data is transmitted directly to the transmitter, while housekeeping information is being sent to the main computer of the satellite.

The microcontroller software operates according to the flowchart shown on Fig. 6. For the majority of mission time LMP will be in nominal operation mode, where scientific data is gathered periodically, once every second. The controller sweeps the detector voltage between +7 and –7 V in 200 ms and samples the U-I curve in 100 points. With an orbital velocity of around 7.6 km/s this rate of data gathering translates to a 7.6 km spatial resolution or about 0.064° in decimal degrees. The sweep profile of the bias voltage is shown on Fig. 5a. The profile was recorded during a test with a resistive dummy load. The activation of the automatic range control can be seen in the voltage proportional to the probe current, shown on Fig. 5b.

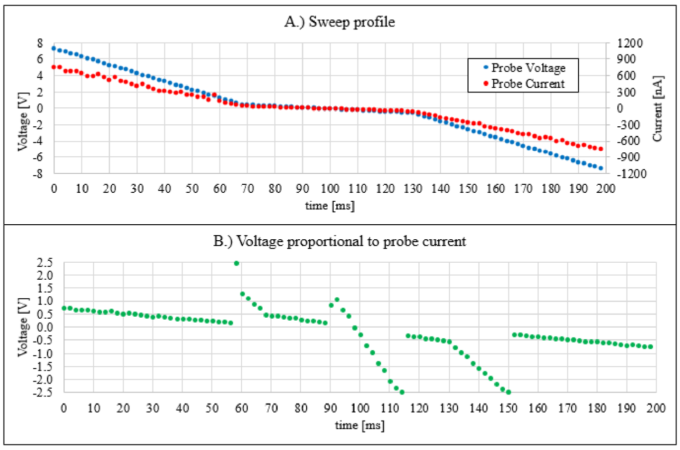

Figure 5: Preliminary test results showing bias voltage and probe current

The current and voltage values of the detector are sampled and stored in the internal memory of the controller, with the possibility of being pushed to the flash if necessary. If the sampling interval of one second is deemed too long, LMP can enter adaptive mode, where new sweeps can be triggered by a significant change in electron density. Adaptive mode can be activated automatically or by telecommand (TC), but due to the high data generation rate, the number of measurement cycles is limited. Self-test is performed periodically, the produced test datasets are transmitted to the ground for evaluation. Based on the results of the tests the automatic range control can be disabled by entering fail-safe mode via TC if necessary. Data collection can be stopped altogether by entering standby mode. Controlled supply voltage levels and board temperature are collected as housekeeping data in all modes of operation. Test operations 1 and 2 are used for testing the hardware during development.

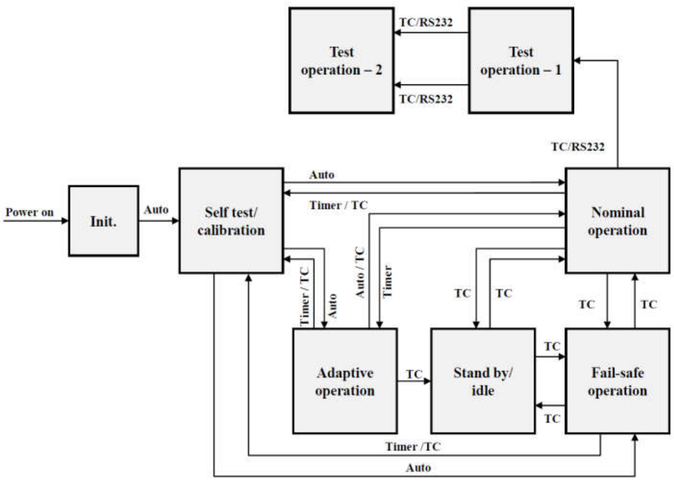

Figure 6: Schematic of the modes of operation

E. *Power Supply*

The third component of the LCB is the Power Supply unit. The PS ensures that the AMP and OBDH boards receive the power necessary for their operation and protects the experiment as well as the platform by blocking failure propagation. The high number of required supply voltages, the unregulated satellite power bus and the necessary galvanic separation of the payloads from the power bus were the primary motivation behind using a custom designed power supply.

LMP uses a switching-mode flyback converter. This topology sees common use for its high efficiency (around 70 to 80% according to tests) and relatively simple design even with a high number of outputs, especially in low power applications. The converter provides eight different power outputs with five separated grounds transmitted towards the various circuits of the experiment. The AMP and the OBDH require four different analogue and one digital power line (with the grounds being unified at the A/D converter), and the compensation current sensing technique needs three additional galvanically separated ones grounded to the detector potential (F-GND). The control method was chosen to be current mode control with fixed switch-off time for a sufficiently fast transient response. The PS provides its own auxiliary supply voltage, which also acts as feedback for the error amplifier of the control circuit, which helps to reduce power loss. The control circuit is implemented with discrete components instead of a single controller IC for increased efficiency. The extremely sensitive analogue amplifier and the relatively small power budget presented a unique set of challenges for the design of the power supply. Common and differential mode filters are included in the outgoing power lines to ensure that switching frequency noise does not affect the measured analogue data. Both types of filters are realized by LC circuits, but their implementation is different. While the differential mode filters use discrete coils and capacitors, common mode noise reduction is achieved by choke coils and by buried layers, creating a capacitive coupling between the power lines and the thermal layer. Additionally, the CAN communication line needs to be protected from overvoltage in every payload, in LMP this is provided by a dedicated protection circuit in the power supply, isolators on the OBDH board as well as layout considerations. The PS also contains an input current limiter, independent from the power subsystem of the satellite. A simplified model of the additional protective modules in the power supply is shown on Fig. 7.

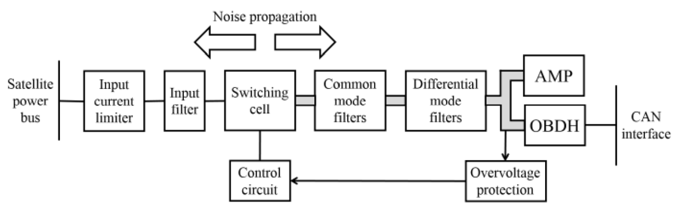

Figure 7: Noise and failure propagation in the PS

IV. Student Participation and Project History

The development of LMP began in 2006, when our university team joined the ESEO project. Currently the experiment is in the final stages of production with tests of the flight model scheduled for the spring of 2018. Student participation was active throughout the entire development process; thesis works, project laboratory reports and conference publications were and are still being submitted.

The basic structure, the decision to apply compensating current sensing and the physical basis of the experiment were already specified in the beginning, however, significant changes were made to the design due to the changing mission parameters. The original scientific goal was to study the plasma of the Van Allen belts taking advantage of the proposed geostationary transfer orbit. This was modified however in 2009 with the changing of the planned orbit to Sun-synchronous, as it only made possible to study the upper ionosphere. In these early years of development efforts were focused primarily on optimizing the detector for the plasma environment and work has begun on the breadboard models of the electronic boards. Between 2008 and 2012 four thesis works (two bachelors and two masters) were presented related to LMP, with three concerning the initial design concept of the three electronic boards respectively and one regarding noise reduction in the power supply. The project was represented at the 2011 Space Technology Conference in Athens [7], as well as at conferences of the Scientific Students' Association in 2009 and 2010 [5] [6]. All of these publications focused heavily on the scientific background and the obtainable scientific results. Posters and presentations were also prepared for the Seminar on Ionosphere and Magnetosphere Physics in 2010 and 2015 [9] [10]. A completely new satellite platform was introduced in 2013, smaller in both volume and mass and had a different solar panel arrangement and orientation, thus the position of the detector needed to be redesigned. The mechanical design of the LCB saw a large modification in 2014, when the connection of the boards had to be changed from a motherboard concept to ribbon cables due to the shrinking of available volume. Work continued on the electronic boards of the experiment, and technological models of the final hardware were produced in 2017. Five bachelors thesis works were presented between 2012 and 2017 concerning various aspects of development with the following topics: the redesigning and the testing of the power supply, transformer and inductive component design, development of the Earth Ground Support Equipment and the application of junction FETs in the automatic range control circuitry.

As of this writing the LMP project has concluded the critical design review and is now near the beginning of the test campaign of the integrated experiment. The hardware components of the flight and the engineering qualification models are ready for integration, and the software is also being finalized, delivery of the completed experiment is expected later in 2018.

V. Acknowledgment

The authors would like to express their gratitude towards Pal Bencze (1929–2016), professor of earth sciences and member of the Geodetic and Geophysical Institute of the Hungarian Academy of Sciences. He was the one who first envisioned LMP and guided its development for seven years. The project could not have been completed without his outstanding contribution.

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Lean Qualification of the AMSAT-UK Software Radio Payload

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***Abstract*— The European Student Earth Orbiter (ESEO) is a micro-satellite mission to Low Earth Orbit and is being developed, integrated, and tested by European university students as an ESA Education Office project. AMSAT-UK and Surrey Space Centre are contributing to the mission with a transceiver and transponder similar to that of FUNcube-1 with the addition of utilising an Atmel AT32 processor for packet software-redundancy, baseband processing, forward error correction, and packet forming; acting as a step towards software defined radio using automotive microprocessors [1]. As on the FUNcube-1 satellite, the telemetry formats and encoding schemes presented utilize a large ground network of receivers on the VHF downlink and conforms to 1200 bps and a new 4800 bps redundant downlink for the rest of the spacecraft. The uplink is on L-band using bespoke partial-CCSDS frames.**

This paper describes the lean satellite design approach introduced by Cho et al. [2] for hardware and software development and testing of the proto-flight model (PFM) payload computer. Furthermore, it assesses the compliance of the project to customer and ESA specifications and discusses the applicability of these standards. Finally, lessons learned are elaborated to provide guidance for future small satellite projects. Through multiple student projects, it was possible to successfully develop a proto-flight model using the lean satellite design approach which entailed an improvement of customer specification compliance from 81% to 86% comparing to the engineering model.

In software, utilising the Google Test Suite for verification of the SDR functions and FreeRTOS tools allowed students to optimize processor load margins to 30% when operating parallelized ADC and DAC, and CAN-open telemetry chains and exploring stable memory operations. A further finding was that in Summer 2017, there was an overall compliance of 82% to the CubeSat standard and 57% to the analysed set of ECSS specifications could be achieved. The poorer compliance in ECSS is due to the incomplete environmental testing at that time. The unfunded and student-based nature of the project places significant challenges when compared to conventional missions – but this was outweighed by the ESEO flight opportunity. Following this, we recommended to further the development of a new ISO standard for lean satellite design as initiated by Cho et al. [3] which eases the development process and reliability of small space projects that struggle to fully comply to ECSS or CubeSat specifications. ESA have since defined a subset of ECSS Specifications for educational and CubeSat missions.

Keywords*— *ESEO, Lean Design, AMSAT, Software Defined Radio, Education

I. Introduction

The European Student Earth Orbiter (ESEO) is a micro-satellite mission to low Earth orbit (LEO) being developed, integrated, and tested by European university students as an ESA Education Office project together with an industrial prime contractor called Sitael (formerly ALMASpace) in Italy. ESEO aims to provide student payload teams with unparalleled hands-on experience to help prepare a well-qualified space-engineering workforce for Europe’s future. The teams are expected to provide spacecraft subsystems, payloads and ground support systems as part of their academic studies; and AMSAT-UK have teamed with Surrey Space Centre at the University of Surrey to deliver an amateur communications payload which also acts as a redundant downlink.

The development of an amateur communications payload began in 2008 and, at the time, a 5.6 GHz transmitter and UHF receiver was proposed together with a laser beacon. However, the mission was re-evaluated by ESA at Phase B and the payload was revised to minimize spacecraft mass. As such, a VHF transmitter and L-band receiver was proposed which also avoided the primary UHF TMTC transceiver frequencies [4].

To fit the university calendar, the development was completed over a number of years. To meet interface baseband requirements of a transmitter and receiver, dual CANopen and I2C telemetry buses, the Atmel AT32UC3C processor was chosen. The main hardware and software control interfaces were built up for I2C, CANopen, and also a 1200 baud AFSK receiver using open source demodulator C code [5]. As a proof of concept, the initial student team collected APRS signals from the baseband audio output of an ICOM 910H radio and transmitted them over CANopen – demonstrating key parts of the chain. Further students worked on input and output filters for both hardware and software to receive 1200 baud AFSK and also transmit 1200 baud BPSK. The student engineers improved on the software too by understanding signal quantization, measurement, and phase error to understand where soft and hardware decisions are made in decoders – and by taking a windowed data approach to ensure correct decisions. These plots recorded sampled data and output bits throughout the decoding process for viewing and transferring to computers for analysis; see Figure 1. After this initial concept development, there were two further U.K. students that worked on the Engineering Model (EM) development PCB designs before a final set on the Proto Flight Model (PFM). This paper focuses on the ‘lean’ approach to qualification in two areas: environmental test and software verification. Two papers go into further technical detail [6] [7].

II. Environmental Testing

As part of the verification process, we require functional, thermal vacuum, vibration and EMC tests on the payload. The objective of the functional test is to confirm the overall functional performance of the payload electronics and covers aspects such as grounding, power consumption, CAN bus operation, carrier and modulation characteristics as well as commanding in the different operational modes. Moreover it contains procedures to test the transponder and the autonomous switching between modes depending on temperature. Sets of procedures with the payload designers conducted over time in parallel during assembly, calibration and environmental testing were taken to understand the behaviour of the payload. This highly intimate and risk-taking strategy allowed the team to parallelise the verification process with build and test to save time. Pragmatic best approaches were discussed and taken where deviation was required. However, this test philosophy may have led to non-compliance with ECSS testing requirements (discussed later).

A. Vibration

To ensure that the spacecraft can withstand the mechanical launch environment, a vibration test comprising sinusoidal and random vibration sequences was performed. Before and after those tests a low-level sine vibration was applied. This allows to compare the shock response spectrum of each low-level sine test in order to find any mechanical change on the test subject which would be indicated by a deviation in the spectrum.

Because of the PFM approach the test was conducted at qualification level at the request of the customer. This leads to higher risk of damage on the flight hardware but is in accordance with ECSS recommendations. Since the facility at Surrey Space Centre does not provide clean room conditions and thus violates ECSS requirements for testing, precautions had to be taken to protect the payload from contamination as much as possible. Before mounting, the entire machine was covered in a plastic sheet to protect the payload from the dust coming from the hydraulic system. Furthermore, all open venting holes in the payload enclosure were covered using Kapton tape in the cleanroom to minimise particle contamination inside the enclosure and on the PCB’s.

The tests were performed sequentially for each axis and although there were differences in the low-level sine responses, an inspection revealed no physical change or damage to the payload. In most aspects the test was done according to the procedures but there were deviations. The pre-vibration test on the adapter plate without payload was only performed as a low-level sine test and an acceptance test was skipped because the team and the trained facility staff came to the conclusion that is was not necessary and it would save time. A major deviation to the test procedures was that the payload was not functionally tested after vibrations for one axis was finished but only after all vibration tests were completed. The payload was only tested after all vibration tests were completed. The reason for this was the time pressures as well as the fact that a damage on the payload would have been fatal for the mission and jeopardise the ability to meet the delivery deadline regardless of which test it occurred. An inspection and extensive functional testing after the vibration test revealed no defects on the payload and enabled the team to proceed with the test plan.

B. Thermal Air & Thermal Vacuum

The thermal testing of the payload was intentionally conducted after the vibration which increases chances to detect any damage induced by the mechanical stress on payload. Because the thermal vacuum test will transition only between hot (70°C) and cold (−25°C) cycles, it is necessary to test the payload in smaller temperature intervals to calibrate the internal temperature sensors. The FUNcube Dashboard software was used to convert the measured ADC values in actual values.

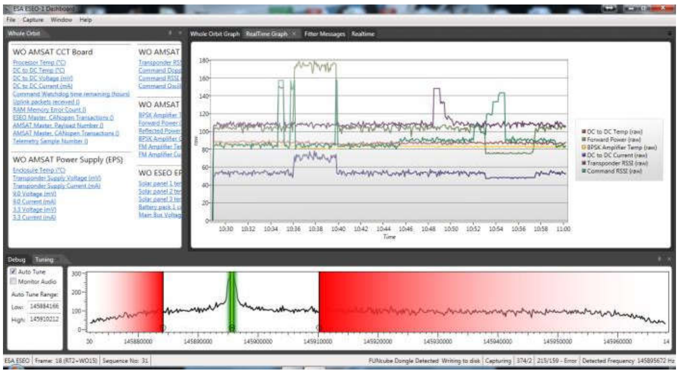

Figure 1. FUNcube Dashboard Image

A thermal air chamber at Surrey Space Centre was used to test temperatures from 0°C to 60°C in 10°C intervals and calibrate thermocouples at the same time. The temperature of the payload was measured with thermocouple sensors attached to the enclosure, the processor, and DC/DC converter. The data suggested that the sensors on the board were linear. Due to the large size of the thermal chamber and time pressure, the dwell time at each temperature interval was limited to around 10 minutes which violates ECSS requirements but can be justified by the non-critically of the calibration process for the mission and the fact that there were no customer requirements on calibration.

The full thermal vacuum test took place at a RAL Space in Harwell. The required cycle pattern took about 48 hours to complete and comprised 4 cycles between +70°C and −25°C to expose the payload to extreme temperature changes and verify its full operability at all times. In order to do this, the payload was electrically connected via the chamber interface plate. At +70°C and −25°C temperatures are kept for a dwelling time of 2 hours to allow the payload to reach equilibrium and take accurate measurements in cycles 1 and 4. A deviation during this test was to instead of having major dwell points, was to add a stabilisation criteria of 1K/h at each plateau instead of the 2 hr dwell times. Measurements from these cycles were compared later to identify any vacuum induced damage.

Functional testing during the tests revealed that the flight software still contained software constants for incorrect temperature limits that were set for the engineering model to switch into safe mode – this was not found in the thermal air tests. This anomaly meant the PFM could not be fully commanded by the GSE over 50°C and could be argued that the full ECSS approach would have allowed the functionality to be verified at the correct temperatures. The TVAC test was compliant to the test procedures in all aspects and further functional testing at SSC confirmed that the payload was not damaged and was still fully operational after completion. The test was in line with both customer and ESA specifications.

III. Software Challenges

A key objective for this project was that in order to meet ESA timing and resource management constraints [8], it would be necessary to utilise a real-time operating system (RTOS). Due to its small memory footprint and processor cycle overhead, combined with its free license, FreeRTOS was selected for use. This allowed for functional areas of the software to be split up into threads, thereby isolating discrete software functionality and allowing for best practice development techniques to be used. Therefore CANopen, uplink, downlink, telemetry collection, payload data transfer and satellite operations were split into individual threads.

A problem encountered due to the multi-organisational nature of this project was that of developing software to a strictly defined interface between organizations and proving the functionality before the two systems were coupled. An example of this was the application layer protocols operating on top of the CANopen communications protocol, allowing for communications between the AMSAT payload and satellite itself. An emulator with limited functionality was supplied by Sitael to ensure correct hardware configuration however this would not prove higher level software operations, as a trial a software development practice entitled Test Driven Development (TDD) was used throughout the project, the end result of this was that when the payload was integrated with the satellite it worked immediately – the value of TDD has been seen many times over during this development and should be strongly considered by anyone wishing to collaborate on a project successfully.

In order to validate the behaviour of our corrected Multimon implementation, a software test harness was created using C++ in the xUnit Google Test Framework [9], a bespoke AFSK encoder was then developed within the harness, this encoder took a binary input stream and created an AFSK signal at the correct rate for the Multimon decoder sampling frequency. The use of this test harness meant that the library functionality could be tested without having the hardware present and without an RF commanding chain to send AFSK packets to the payload, this allowed for the library to be tested in isolation from the rest of the system. The input and output of this encoder can be seen in Figure 2.

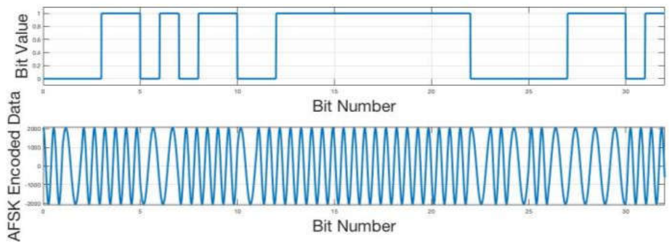

Figure 2. Test Harness for AFSK using xUnit Google Test Framework

With this tool, we were able to quickly construct and test signals for our baseband processing and hone the processing chain requirements suitable for a student project duration. Similar processes and tools are used in Surrey's CubeSat missions [10].

IV. PFM Compliance

Compared to the EM, the overall compliance achieved with the PFM increased significantly – and are reviewed from three points of view: the spacecraft (Sitael's, or the customer), ECSS, and ESA CubeSat Standards. In Summer 2017, the spacecraft requirements compliance increased from 81% to 86% while ECSS compliance was determined as 57% and compliance to the CubeSat specification as 82%. We reviewed the spacecraft requirements to find that full compliance is possible but ambiguous requirements led to non-conformity.

The compliance of the relevant ECSS standards and its tailored CubeSat versions is illustrated in Figure 3. In total, 519 ECSS requirements and their CubeSat equivalents were analysed and classified in five categories. Green indicates that the requirement is compliant in both the original and the tailored ECSS specification. Blue means that it is compliant with the original ECSS and not applicable in the CubeSat version. Yellow represents requirements that could not be met in the original ECSS but are compliant or not applicable in the tailored document. Orange indicates requirements for which the compliance status could not be determined clearly or a verification task is yet to be performed. Finally, the red colour signifies that requirements are not compliant in either of the two versions of the specification.

The bar chart shows that the flight model achieved a compliance of around 50 to 70% for this selection of relevant ECSS specifications. The fact that the compliance is better in the radio frequency and structure specification can be explained by the low number of applicable requirements to the project of 22 and 30, respectively. By adding the blue and yellow category, the compliance status for the CubeSat tailored version, we can interpret between 80 to 90% compliance could be achieved. This is not unexpected since the CubeSat standard tailoring relaxes many requirements that are more suitable for large space projects and makes them applicable for small scale amateur projects. In addition, the chart shows that up to 10% of original ECSS requirements are met despite a relaxation or making them not applicable in the tailored document. A possible explanation for this is that the ESEO satellite is bigger than conventional CubeSats and therefore could be located between professional satellites and CubeSats on a scale of design complexity and

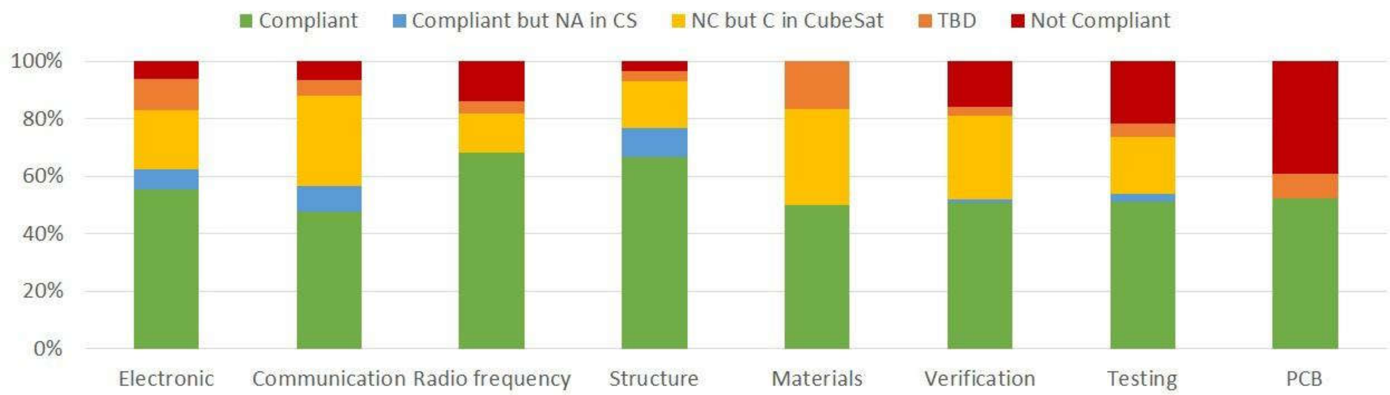

Figure 3. ECSS and CubeSat Compliance Assessment

quality which enables it to comply with more sophisticated ECSS requirements without tailoring.

Between 0 and 20% of requirements are not met in either specifications primarily because they require a much higher standard infeasible to a student based academic and amateur project. But also due to early compromises were taken during development and verification which led to ECSS non-compliance whilst still being compliant to the customer specification. Finally, several requirements could not be allocated to one the discussed categories because it is unclear if those requirements are met due to missing data (e.g. tests not performed) or ambiguous interpretation.

If only six requirements would be updated with tailored requirements that are suitable for the payload, a compliance of 94% could be achieved. In the event Sitael or ESA provides the necessary facilities for a full EMC test, additional three requirements could be verified which could results in a 96% compliance. Only a small selection of relevant ECSS documents were analysed here due to the limited time frame and focus on the PFM development, but gives nevertheless attempts to quantify the general ECSS compliance.

V. Project Discussion & Educational Value

The lean satellite design approach utilised for the PFM development entailed significant deviation from ECSS conformal design and verification but allowed to save time, cost and other resources. It was possible to parallel many tasks and conduct testing concurrently with assembly and flight preparation to discover errors and correct them as early as possible to avoid delays and cost increase. Hardware issues that occurred during this process were fixed quickly and efficiently by relying on the internal experience of the team and local experts towards developing reliable and cost-effective solutions.

A suitable risk management approach enabled the team to conduct environmental tests in a very short time frame with the payload passing all requirements successfully and gathering calibration data for the flight software and telemetry simultaneously. Nevertheless, care was taken to perform environmental testing in a very professional manner and in conformance to the test procedures since insufficient verification and immature workmanship are the most common reasons for failure in CubeSat projects [11]. The strategy to do continuous functional testing during the entire assembly and testing process turned out to be very valuable. Extensive testing with ground station equipment enabled the team to simulate near mission conditions, check the RF performance and to change resistors on the RF boards to adjust the filter characteristics immediately. In order to calibrate the internal temperature sensors, the vacuum test was combined with a thermal ambient test to collect data over a large temperature range of −25°C to +70°C in a very time-efficient manner.

Furthermore, the dense university calendar and time consuming preparation for several exams limited the available time that could be spent working on the project more than initially expected. In terms of team communication, the small size of the team had great advantages over traditional projects that involve many people. It was possible to synchronise the core team of five people through a common Skype group, regular face to face meetings and email while keeping the documentation effort low. However, this poses the risk that important knowledge gets lost if one team members leaves the project. The outstanding dedication of all team members that worked on weekends and several times during the night ensured that deadlines were kept and had significant influence on team building which mitigated the risk of team members leaving the project.

Furthermore, most team members worked on the project un-compensated in parallel to their daytime jobs which implies a strong dedication and commitment to the project and ensures excellent work ethics. Bartram [6] who was working on the same project identified that communication between different working groups is critical and project updates from the top level are able to provide continuing motivation for payload teams at lower level. He also points out that every student that was working on the project found real value and motivation in working with the experienced AMSAT team on a hands-on space project that will actually launch into orbit.

The team stayed in constant contact to the customer for synchronisation and to discuss and agree on any design changes and problem resolving or mitigation strategies in a fast way. In addition, comprehensive documentation was maintained to ensure common understanding among team members, Sitael and ESA. Internal delays due to technical issues were recovered by working overtime, on weekends or in night shifts [11].

The final unit is shown at Surrey Space Centre in Figure 4 and has since required further modification to ensure manufacturing and testing is applied with good practices that are expected for an ESA space flight hardware, keeping to ECSS standards as reference. A key lesson here is to pay closer attention to customer requirements and specifications rather than meeting deadlines – both ESA and Sitael have been pragmatic in helping the team move forward, and provided a unique opportunity for all students and staff involved.

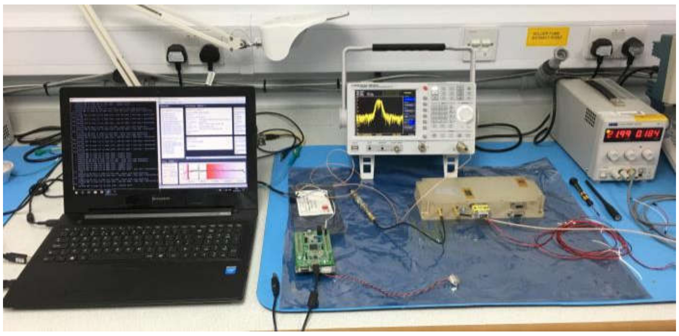

Figure 4. AMSAT Payload, Summer 2017.

Each student has found real value in working with the experienced AMSAT team in a real mission. We note the following feedback: "*it has been great to get the opportunity to work on something that is going to go into orbit, that fact has been really motivational throughout the year. It has also been good to be able to collaborate with AMSAT and Sitael as it gives an exposure that would otherwise have been missed.*" Each U.K. student involved in the project has gone on to PhD studies.

VI. Summary

By using a pragmatic lean satellite design and verification approach, it was possible to successfully build a payload proto-flight model that is highly compliant to customer specifications. It is a thorough recommendation that this process is followed by any similar projects in the future and to identify early ESA specifications and compliance processes.

The literature review on academic space projects revealed vital lessons learned that could be exploited for this project. By adopting a different design, manufacturing, mission and management philosophy than traditional missions the project achieved some significant advantages. Such a small project team has the ability to easily implement agile project management methods and to establish an efficient team communication. Because the AMSAT core team consisted of only 5 people that live in close proximity, it was possible to schedule face-to-face meetings regularly for important discussion or test campaigns. Using freely available software such as Skype allowed to establish a 24h group communication channel for discussions and to virtually participate in any testing activities over video conferencing.

The PFM could not achieve full ECSS compliance to customer specifications due to early review and ambiguous requirements. Despite having superior facilities, equipment and expertise compared to most academic CubeSat teams, only an overall compliance of 82% to the CubeSat standard and 57% of the analysed ECSS requirements could be achieved with the PFM. In addition, the EVT test campaign comprised of minor deviations from test procedures by working with Sitael and ESA.

Considering this, it is recommended to further promote the development of a new ISO standard for lean satellite design that could ease the development process and reliability of small space projects that struggle to fully comply to ECSS or CubeSat specifications. This approach seems to be a promising concept but further investigations to identify best practices of small satellite projects are required to assist in the development of such a standard.

VII. Acknowledgements

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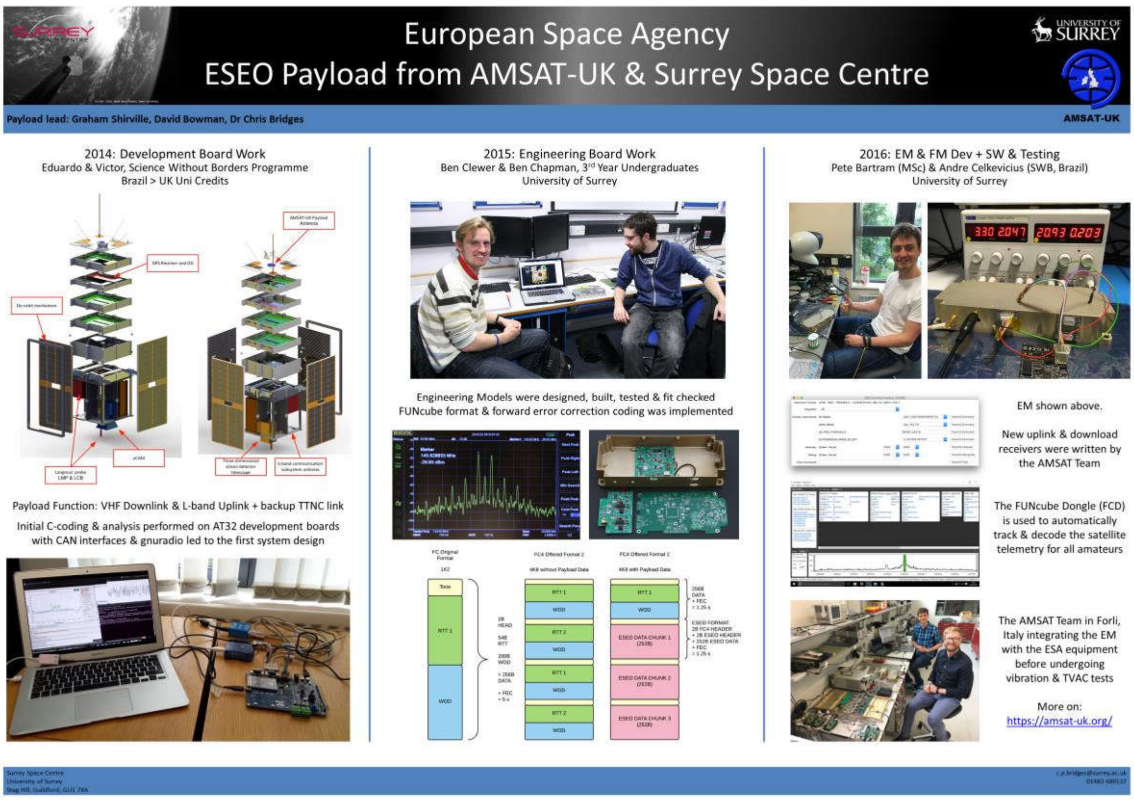

Fly a Rocket! – pilot cycle results

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***Abstract*—This paper describe the pilot cycle of a new European student rocket program that started with an online pre-course in late 2016, rocket campaign in March, 2017 at the Norwegian Center for Space Related Education (NAROM)/Andøya Space Center (ASC) and ending with the students writing a report in June, 2017.**

In this paper, the cycle is presented and the conclusions are given. Section 1 give an overview of the program including the educational objectives, and Section 2 describe the three different parts in more detail and in Section 3, the results are given.

Keywords—Student rocket campaign

I. INTRODUCTION

ESA Education has long experience with great resources for teaching students and pupils in space related education. Maybe the two best known is REXUS/BEXUS for graduate university students and Cansat for high school students. There has been a gap between the two, however, and with the Fly a Rocket! student rocket program we wish to fill this gap. NAROM has since 2000 had a student rocket program that fit very well to give students that has recently started on their university studies an introduction to a "real" rocket project.

The program is a collaboration between ESA, NAROM and the Norwegian Space Center (NSC), and all the three parties provided funding for the pilot cycle.

The pilot cycle was divided in to three parts in addition to the application process, which is described further in the next section: a pre-course where the students read up on the related subjects, then the campaign period with the students at Andøya, and a part where the students wrote a final report together.

II. EDUCATIONAL OBJECTIVES AND PROGRAMME DETAILS

A. Educational objectives

A very important part of the Fly a Rocket! programme is a practical approach. From experience, we find that mixing some lectures/theory in the classroom with much practical work works great and is very encouraging for the students involved. This is also important for showing the students how an actual, scientific project is, and at least the campaign period is very similar to an actual, "real" rocket campaign in every aspect, only more condense.

The condensed learning objectives are:

- Background information of the physics and technical aspects of rockets and rocket flights
- The use of rockets, balloons and ground based instruments as a technology platform to study processes in the atmosphere
- Basics of measuring with electronics onboard a highly accelerated platform and in low pressures and temperatures
- Work on a real rocket project as a team and interact with industry experts and other students from many different nations
- Data comparison with models
- Reproduce a scientific project: scientific objective, building and testing instrumentation, collecting data, analysis, and conclusions

International cooperation across different languages and cultures is also an important part of the learning outcome of the program. The students are expected to go to academia or industry after their studies, where this is often an important part to have experience of.

B. Application and selection process

A total of 493 applicants applied for the total of 20 openings at the pilot cycle of the program. The application from the students consisted of a single document where the student would describe his/hers motivation for joining the programme, what outreach would be done if accepted, a tie-breaker with a suggestion of the name of the rocket, and a technical task were the student had to suggest an additional payload on the rocket.

United Kingdom, Italy, Spain and Portugal were the countries with most applicants. The selection process was done by ESA, and though some students was studying at the same country and even university, they all came from different country of residence, including Canada, which is a cooperating state in ESA.

C. Online pre-course

For the pilot cycle, students from all fields were invited to apply to join. Since the students were not necessarily from a closely related subject, an online pre-course was developed. The pre-course was made to get all participating students up at a given academic level to make it easier for everyone at the campaign period. For some students already at a high academic level in the related subjects the online pre-course was expected to be quite easy and for others it would probably be more difficult and demand more work/time to complete. The pre-course consisted of two parts: an online text openly available for the public, and two exercises based on the content of the online text that the students needed to write a report of and hand in to NAROM, and both exercises was obligatory to be invited to the rocket campaign at Andøya.

The subjects of the pre-course was:

- Rocketry: rocket principle, types of rocket engines, rocket thrust equation
- Rocket dynamics: rocket degrees of freedom, forces acting on the rocket, simulations on rocket trajectories
- Satellite orbits: Kepler's laws, the six orbital parameters, detailed analysis of orbits in a plane
- NAROM student rocket (as a small introduction)

D. Rocket campaign

The largest part of the project was the student rocket launch campaign at Andøya. The students arrived on Sunday March 27, 2017, and on the next five days the students had introductory lectures for the week and did group work to prepare for launch. The NAROM student rocket is a 2.7 meter long Mongoose 98 sounding rocket with a carbon fiber body with an apogee of approx. 8.5 km altitude and a flight time of 90 seconds. The rocket is spin stabilized, and is not despun during flight. The impact area is at sea, and there is no recovery attempted.

The students were divided in to groups of 5, and each group had specific responsibilities as preparations. The different groups had these responsibilities:

1. Rocket System Design group: Large-scale rocket simulations (position, velocity, acceleration and all derived parameters during flight), including safety concerns and stability simulations
2. TM Readout group: setting up the data decoders and write/develop data analysis tools for data post processing after launch for all groups to use, in addition to make some of the sensor cards
3. Payload group: make sensor cards, make custom cables in the rocket and prepare the rocket itself before launch and test it
4. Telemetry group: Setting up all the telemetry equipment and test this prior to launch
5. Science group: balloon release prior to launch, and looking at the science behind the launch.

Together, all these groups go through all the preparations before a large scale rocket campaign, but again on a more condensed scale. It is clear that the students do all the work of the campaign, but is assisted with professionals from NAROM and ASC.

During the nominally 60 minute long countdown the students take an active part, including filling the positions as Head of Operation, Payload Manager, Head of Operation and all other positions, but again with the assistance/help from NAROM and ASC.

After launch, the students is again divided into the same groups as for the pre-launch work, and analyse the rocket data. On the last day of the campaign, the day after launch, the students have presentations for each other and NAROM/ASC to present the data analysis they have completed the day before.

Due to challenges due to wind the rocket launch was not launched while the participating students was at Andøya. The rocket, named Volare-1 by the students (*to fly* in Italian) was launched on May 31st, and the countdown and launch was filmed by ASC and streamed to all students online.

E. Student pilot cycle end report

After the launch campaign had ended the students started work on a project report which they all contributed on with one student taking the lead on the work. The report was first based on rocket data which was collected on an earlier launch not related to Fly a Rocket!. After handing the report in and feedback was given by ESA and NAROM, the students updated the report based on the feedback and the new data from the Volare-1, which then just had been launched (on May 31).

Figure 1: Launch of "Volare-1" on May 31st, 2017

III. Survey, Results and Conclusions

An extensive survey was done by ESA after the end of the pilot cycle, which showed that the students was very satisfied. Some improvements was noted from the survey and by ESA and NAROM throughout the cycle. Some of the results are discussed in this section.

The pre-course was considered an important reason that the program can have a high academic level even though the students had a varying background, and the students considered the online text contributed to the program. The feedback from the students showed, however, that some of the obligatory exercises during the pre-course was too hard. The intended reason to have a difficult pre-course was that the students, who was already then invited on a closed group on social media, would be "forced" to collaborate to solve the exercises, but this collaboration did not work in the intended way, which resulted in, at least for some of the students, struggles with completing all the exercises.

The campaign week got very good student feedback. Some of the students missed more advanced and in-depth discussion on some of the topics. This was not surprising to NAROM, as it is very difficult to teach the topics to students with very different academic background. For some students the level of talks and discussions was probably a bit difficult, for most fine and for some it was maybe a bit to easy and little challenging.

Improvements will be done on this if the program is extended to additional cycles.

The overall feedback from the students being “very high levels of satisfaction and [they] would recommend the project and ESA Education office activities.” The pilot cycle is now being reviewed by all parties, and additional cycles are being considered.

Removing Roadblocks from the UK space skills pipeline: A student and young professional perspective

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***Abstract*—This paper presents a student and young professional perspective on developing the space skills pipeline. Developing the space skills pipeline is critical in ensuring the government's space sector growth target, £40 billion by 2030, is achieved. The limitations of the current pipeline are identified, including places that government policy, industry and universities are falling short. These can be generally categorised as the lack of awareness of the space sector, lack of opportunities to develop experience, and the mismatch between teaching useful knowledge in universities and the skills employers need. Several methods for solving each of these issues are suggested, drawing from activities of UKSEDS, and examples from both national and international institutions and organisations.**

Keywords*—*skills; education; careers; growth; space

I. Introduction

The UK government's National Space Policy [1] recognises the potential benefits of space to society and the UK economy, and identifies that space is part of today's national critical infrastructure. It codifies the government's ambition to grow the UK space sector to £40 billion (~10% of the global market) by 2030 and sets the path to meet this goal. It lists four key principles that should be supported by the national space strategy, including "supporting the growth of robust and competitive commercial space sector".

A critical component of a growing and healthy industry is the availability of a skilled and educated talent pool. This has been repeatedly identified by government and industry alike as the number one issue facing the sector at present [2-3]. The importance of the availability of this pool cannot be understated. Silicon Valley's success demonstrates the vibrant entrepreneurial environment that can be attained with high numbers of skilled individuals and access to investment capital. Previous national space strategies [4] have stated the importance of ensuring the existence of a sufficiently large and diverse talent pool, and the UK Space Agency (UKSA) has created its own Education, Skills and Outreach [5] strategies to address the issue. However, only a few initiatives to improve the skills of graduates and promote interest in space among higher education students are identified in the UKSA's policy, such as the Space Placement in INdustry (SPIN) scheme and Higher Apprenticeship qualification.

This paper presents a new perspective of the skills pipeline issue, based on the experiences of students looking for career opportunities in the space sector and of young professionals working in the sector. This evidence has been gathered by UKSEDS (UK Students for the Exploration and Development of Space), the UK's student space society, and includes the results from surveys, interviews and experiences of the organisation's membership over several years. Potential roadblocks preventing the growth of the talent pool required for the government's targets are identified. Several potential solutions are described and evaluated based on their efficacy. Some, such as the SpaceCareers.uk website, are currently being implemented by UKSEDS, and others have been identified from the work of other organisations from the UK and around the world.

II. Approach To Data Collection

A. Aggregated UKSEDS event surveys

UKSEDS collects survey data as part of the registration process for all its events, including the annual National Student Space Conference, the largest event of its kind in the UK.

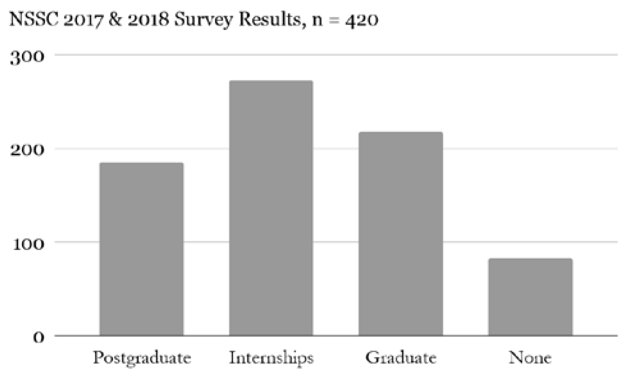

FIG 1 Results from survey question: What opportunities are you looking for?

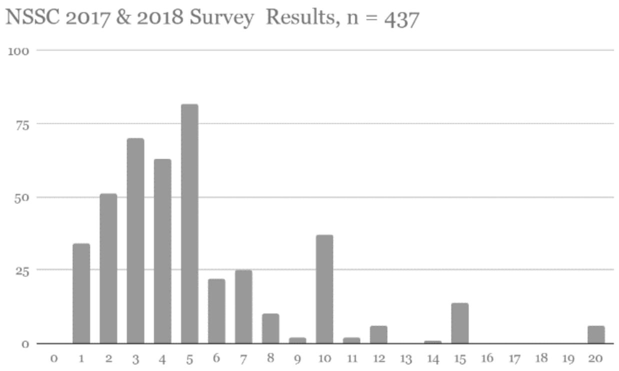

FIG II Results from survey question: How many UK space companies can you name off the top of your head?

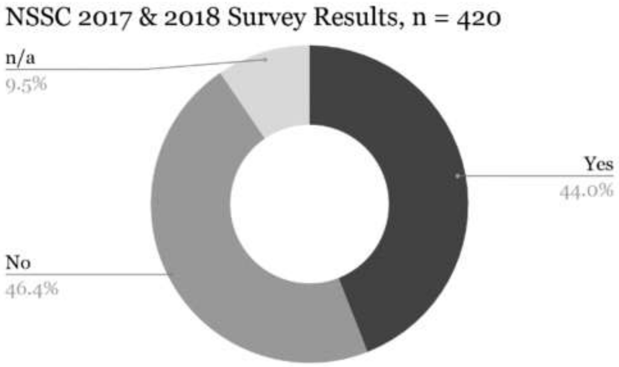

FIG III Results from survey question: Have any space companies exhibited/spoken to you at your university?

Note that these data are from a self-reported survey, which cannot be independently verified. They also represent a spectrum of students from first year undergraduates to PhD students, in a range of technical and non-technical disciplines (approximately 42% engineering, 25% physics, 19% other sciences/mathematics and 14% other or non-disclosed).

B. SpaceCareers.uk job postings and web traffic

The second main source of primary data is from the careers website, SpaceCareers.uk. This site was set up by UKSEDS in 2015 to provide a single place for students and young people to search for jobs and other opportunities in the space sector. The number of job adverts for various opportunity types, and the associated average views per post are shown in Table I. The jobs in question are primarily UK-based positions but include several European openings.

These data provide a useful source of information on the types of adverts that are most attractive to the students who use SpaceCareers.uk. There are a few caveats to the data, notably it is based on jobs that are either sent to SpaceCareers.uk to be advertised (currently a free service) or opportunities found by the SpaceCareers.uk team. Although it is likely to capture a good cross-section of the opportunities available, there will be some that have not been included. Additionally, several of the adverts will be a single advert for multiple opportunities.

	March 2017 - March 2018		
	Posts	Opportunities	Views per post
Internships	71	115	595
Direct Entry	95	33	492
Graduate	32	106	411
PhD	47	60	265
Post Doctorate	10	10	194

TABLE I Number of adverts per year of each category of job and viewing figures

C. Additional sources of data

Finally, some data used in this paper has been taken from 3rd party reports. Specifically, SSPI (Space & Satellite Professionals International) commissioned the *2016 Satellite Industry Workforce Study* [6], performed by recruitment consultancy Korn Ferry. The authors of this report used two main sources of information: 14 telephone interviews with HR executives at companies (including Arianespace, Airbus and SES) and an online employee survey distributed globally through SSPI's membership and other avenues, which received 1060 respondents. The report also notes that the survey is self-reported with no independent verification and should therefore mainly be used to identify trends.

II. ROADBLOCKS TO A LARGE TALENT POOL

A. Awareness of the space sector

The first roadblock identified is the lack of awareness of the breadth of activities of the space sector among further and higher education students.

From the UKSEDS survey data presented in FIG II, the median number of firms students know of is 4. These are generally government bodies and the largest upstream companies. The average number of attendees that knew of the downstream employers at the NSSC 2016 was 38%, but was 64% for upstream companies and 70% for government bodies. This does not represent the actual composition of the space sector, where the upstream segment accounts for only 12% of revenue [7].

There are several reasons why this lack of awareness is a roadblock. Firstly, it limits the pool of potential candidates to the small number of students who already know about the sector. While many tech companies such as Facebook, Google and Amazon have strong presences on university campuses in addition to being household names, the same cannot be said of space companies (see FIG III). The result is that many capable students do not consider applying to space jobs. For a sector that is competing for top science, engineering and computing talent this is a major obstacle to growth.

Secondly, one of the key areas of growth for the space sector is downstream applications, which overlaps with many other sectors. Many potential users of space data come from disciplines such as computer science and GIS, which are not traditionally associated with space, and as a result they are not typically made aware of the value the space sector has to offer to their speciality. The Space Innovation and Growth Strategy Skills Themes Report noted that "(sought after) graduates were not aware that they could seek specialist employment as space specialists within their own industry (for e.g. in the water industry)." [8]

B. Opportunities to develop experience

The second roadblock is the lack of opportunities to develop experience. The value of experience is obvious: it differentiates the veteran from the recruit, the professor from the student and is one of the key traits sought by employers. For example, SpaceX filters applications based on:

- *"Hands on hardware/software development exp - i.e. What problems have you actually encountered and solved?"*
- *"Experience with engineering competitions, and placement in top positions/ brackets at those competitions"*
- *"GPA/ SAT - other hard scores"*
- *"Drive/ Grit"*

SpaceX sends a recruiting mission to the Formula Student competition each year, competing with the automotive industry for the top performers [9].

For undergraduate students, opportunities to gain experience are limited. Readily available non-technical part time jobs are a good way of gaining 'soft' skills – teamwork, responsibility, timekeeping etc. – but it is the more valuable technical skills that are most difficult to come by. These are most easily obtained through hobbyist activities, summer internships/research placements and extra-curricular activities, such as engineering research projects run by student societies. However, most STEM courses have a large number of contact hours (15+h/week) [10], which leaves students with little spare time in which to pursue these extra-curricular activities for which they typically receive no credit. The most common reason cited for not volunteering with UKSEDS is lack of time. Additionally, many opportunities to gain experience are unpaid or low-paid, disadvantaging students from low-income backgrounds who cannot afford to work for free [11].

In this regard, the space sector compares poorly with other STEM sectors. For example, Formula 1 teams support Formula Student, while other sectors run challenges like Barclays Launchpad Business Challenge, Shell Ideas360, Babcock Telegraph STEM Awards, IMechE Formula Student and Unmanned Aerospace challenges for Mechanical and Electrical Engineering students. Though there are some similar competitions in the space sector, these tend to be lower profile (which reduces their attractiveness to students), and less well publicised.

Data collected from delegates to the National Student Space Conference in 2018 and 2017 (FIG I) shows that there is a large demand for internships and research placements. 56% (273) of attendees reported that they were searching for internship or research placement opportunities. This is a larger number than for both the postgraduate research/courses (i.e. master's or PhD programmes) or graduate roles (graduate schemes or direct entry). Additionally, the demand from delegates at these events alone far outweighs the number of opportunities that are advertised on SpaceCareers.uk (TABLE I), demonstrating the significant shortage of entry-level opportunities.

British degrees are significantly shorter than many other European countries, with the vast majority of courses taking 3 years for an undergraduate bachelor's, 4 years for an integrated master's, and 3 + 1 years for an undergraduate bachelor's and a postgraduate master's. A significant disadvantage of the speed of this system is that it reduces the time available for students to gain experience before starting work.

The serious impact of this issue is highlighted in the *2016 Satellite Industry Workforce Study* [6], which focuses primarily on North America. It identifies that the "industry relies heavily on a cadre of experienced workers ages 45-54, who make up 42% of employees". Many gained their initial experience in the military before moving to the commercial sector later in their careers, something which is rarer today due to a relatively smaller defence industry. The report additionally states that "the voluntary attrition rate - people leaving their jobs by choice - for employees with 1-5 years of service is a shocking 67%" and concludes that the "industry is failing to invest in careers paths that retain younger talent". If the UK's space sector grows as predicted, there will be a major shortage of experienced professionals in a few decades.

C. Mismatch between teaching and skills employers are looking for

The third roadblock we have identified is the mismatch between the specific skills employers are looking for and what is taught at universities. Many entry level positions available in industry require experience in a specific software package such as ESATAN, STK, and Catia, which are not readily accessible to students because of the high cost of licences.

Universities must teach a broad range of skills and knowledge to equip their graduates to work in many different sectors, and although there are space master's courses available to try to bridge this gap, they rely on students being able to afford the cost of an additional degree. Tuition fees for the International Space University's one-year MSc in Space Studies are €25,000 (£22,200) [12].

Additionally, many disciplines are multidisciplinary, often requiring a mixture of skills and knowledge normally available across different degree courses. This is particularly an issue in the field of space applications, where space data is applied to everything from agriculture to oceanography. It is important not only to know how to manipulate data, but also to understand the source of the data, such as the type of imagery, the orbit of the satellite and its revisit time, as well as the specifics of the problem that is being solved. As a result, applicants are expected to have well-developed programming skills, a good knowledge of Earth observation techniques, and domain specific knowledge for the application in question.

III. Removing the roadblocks

The following section contains several recommendations for government, industry and universities, along with examples of similar existing programmes from around the world.

A. Encouraging organisations to create internship or placement programmes

Internships and placements are the most valuable way in which students can gain experience before committing to a career. Until recently only the largest organisations had formal internship and graduate placement programmes. While opportunities were available at SMEs, these were typically on a more ad-hoc basis, and only accessible to those with connections in the sector. The UK Space Agency's Space Placement in INdustry (SPIN) scheme, launched in 2013, has helped encourage companies to take on students, and made placements with SMEs much more readily available to those without connections.'Spinterns' get 8 weeks of paid summer work experience at a space company, and host organisations are persuaded to host them on the basis that they bring an "injection of fresh ideas and enthusiasm" and a "chance to informally 'interview' a potential employee of the future" [13]. A greater expansion of this programme would further benefit the sector.

Perhaps the best examples of summer internship programmes can be found in the US. SpaceX, Blue Origin and ULA all have large paid internship programmes, and often recruit from within their intern graduate pool. They have found a way to benefit from providing experience-gaining opportunities, and this model should be adopted by more firms in the UK.

An alternative example is the longstanding Summer Undergraduate Research Experience (SURE) programme [14] at the University of Leicester, which provides funds for undergraduate students to undertake research within the department. In the past SURE students have used the programme to further research in extra-curricular projects, such as Leicester's CubeSat programme. There are similar approaches to this at several universities, including the Scotland-wide Carnegie Scholarships, and Imperial College London's Undergraduate Research Opportunities Programme (UROP) [15].

B. Encouraging self-organised technical projects

Rocketry, robotics and CubeSat projects provide excellent opportunities to develop experience and skills, and many students can perform novel and original technology development or research in the process. Many of these projects will be presented at the SSEA 2018 conference.

Despite this, many students are put off from organising such projects because of their perceived complexity. Competitions provide a good way of encouraging large numbers of students to start their own technical projects by providing a clear structure, technical support, and funding. Existing competitions include the Mars Society's University Rover Challenge, the UK Space Agency's SatelLife Challenge, ESERO-UK's CanSat competition, and UKSEDS' National Rocketry Championship (NRC) and Lunar Rover Competition (LRC). The latter challenges students to design, build and test small rovers based on a set of requirements, passing through an industry-led review process to progress to the competition final. Many competitions addressed at students, including the NRC and LRC, and undergraduate paper/presentation competitions such as those run by Airbus and the British Interplanetary Society have a relatively small number of applications from eligible students. There are two actions that could help to solve this:

1) Universities should encourage their students to engage with opportunities like this by offering extra credit or other benefits

2) Companies should emphasise in their recruitment materials how involvement with competitions makes students more employable

NASA and ESA have both created hackathon initiatives which encourage students and others to create a technical and/or business project in 24 hours. In addition to developing technical skills, hackathons help to bring awareness of the space sector and its activities to a different group of people: computer scientists, developers and entrepreneurs, a key recruitment target for space application SMEs. The NASA Space Apps Challenge 2017 saw hackathons in 160 locations with over 15,000 participants [16].

Industry should be providing more support for these projects and competitions. Offers of funding or resources, such as engineering advice or lab space are incredibly valuable for student-run projects. In many places, particularly in Europe, this is already being done. For example, the WARR Hyperloop team at TU Munich has significant financial support from Airbus, and dozens of other companies have provided expertise, components or facilities. CubeSat programmes in other nations are heavily sponsored by government (DLR, NASA programs), industry and universities. Similar financial support has simply not been available for UK projects. For companies, getting employees involved as competition judges or on review panels improves the learning experience for the participants and can help to boost a company's profile amongst its potential future employees.

To maximise the value and uptake of such competitions, it is important the tasks involved are:

1) relevant to the industry's needs

2) implicitly or explicitly supported by industry and universities

3) accredited or recognised with course credit, certification etc.

C. Outreach with higher education students

The space sector should have a greater presence on university campuses and at careers fairs in secondary and tertiary education. Not only will this broaden the talent pool, but it can help to find potential users of space data and technology. The UK's aerospace sector is about 95% SMEs [17], which typically lack the resources to exhibit on multiple university campuses and career fairs. An efficient way for such organisations to maximise their impact would be to combine resources to fund a general space sector stand at such events, perhaps under the banner of the UKspace trade association or another similar body. This would raise the profile of the sector, benefiting all the companies involved. Companies could also create and maintain links with local universities, providing support or guest speakers to relevant departments and societies.

D. Development of training courses for specific skills

The shortfall in skills, and to some degree experience, can be offset by introducing more paths for students to gain them. One method of doing this is to introduce specific postgraduate degree courses. For space engineering, several have existed for many years (Cranfield University's MSc in Astronautics and Space Engineering, and the University of Surrey's MSc in Space Engineering), whilst other have been introduced more recently (the University of Leicester's MSc in Space Exploration Systems). Universities have also identified topics where specialist courses may be required, with the development of master's courses in space data at the University of Strathclyde and in Earth observation at Leicester. However, committing to the financial and time cost of a postgraduate degree is not feasible for all.

The second method is to introduce short training courses. Industry-standard courses, such as the *Continuing Education: Space Systems Engineering* [18] course run by University of Southampton (£2100), or the *Space Missions Operations Course* [19] run by Catena Space at Goonhilly (£300 students rate) are prohibitively expensive for students [20]. The ESA Academy has introduced an excellent range of affordable training opportunities ranging from concurrent engineering to spacecraft communications [21]. However, these are primarily based in Redu, Belgium, and there is still a lack of courses teaching specific software packages or systems engineering techniques (such as CAE). In the UK, UKSEDS have worked directly with software companies to provide students with opportunities to learn and practice with industry-standard products (MSC Software). The most important consideration in providing workshops is to ensure that they are short, affordable and modular.

CONCLUSIONS

We have presented several roadblocks to the successful growth of the space sector, supported by a collection of primary, secondary and anecdotal data, as well as a summary of approaches to overcoming these roadblocks. The key takeaway is that the industry should be encouraged to engage with students through events, projects, and competitions, and for government and universities to enable students to gain further experience and skills.

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ROACH-RX – Experiment on Adhesion and Locomotion Technologies aboard REXUS

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Abstract— The experiment "Robotic in-Orbit Analysis of Cover Hulls", ROACH, examines the utilization of electrostatic adhesion as novel means of locomotion on spacecraft hulls in space. The experiment's goal is to maneuver a rover, that has a size of approximately 10 x 10 x 10 cm³, inside of a sounding rocket during its microgravity phase and in a relevant vacuum.

I. Introduction

ROACH is developed by members of the Small Satellite Student Society (KSat e.V.) and assisted by the Institute of Space Systems (IRS) from the University of Stuttgart.
The project is funded and supported by the German Aerospace Center (DLR), which provides students with the opportunity to launch experiments aboard REXUS (Rocket Experiments for University Students) sounding rockets in cooperation with the Swedish national space board (SNSB). The program's purpose is collecting scientific data and educating the participating students.
The project is inspired by solving the challenge of the threat posed to spacecraft by an increased population of space debris in orbit and the presence of micro-meteorites [1]. Hulls of spacecraft are additionally subject to fatigue, e. g. radiation and thermal cycles. This can damage or destroy spacecraft. Traditional countermeasures are limited to the use of additional protective material. This, however, increases the spacecraft mass, which drives the costs and limits the payload mass. Crewed space stations can be maintained by humans, but extravehicular activities are inherently risky for humans and a workload to be avoided. ROACH is a first attempt in the field of robotics to develop an overall system for the automated maintenance of spacecraft hulls. Based on the ROACH experiment, the development of future maintenance robots, able to act autonomously in damage assessment and potentially performing repairs, is possible.
The goal of ROACH is to validate the feasibility of such a system and assess the capability of such a rover system [2]. The locomotion and adherence of a rover to a hull in space-like conditions are challenging problems. To enable the movement on and the inspection of an arbitrary surface the wanted adhesion technology is required to provide to function in reduced gravity and vacuum. Electrostatic adhesion is expected to be such a methodology. By applying high voltage, a Kapton-coated metal foil adheres to most surfaces, electrically conducting or not. The adhesive force can be used to attach the rover to a surface and enable its movement. The adhesive connection can be created and removed without any residual traces. Various materials, designs and operating voltages were tested for their practical usability and adhesion performance. The rover and its subsystems' performance is determined by sensors aboard the rocket and the rover itself.
Those sensors include distance sensors, a rotational encoder, an acceleration sensor and a camera at the rover itself. Three additional cameras mounted inside the experiment compartment (see Fig. 1) give further information about the rover's behavior during the microgravity phase of the parabolic flight. The objectives of the experiment are:
Primary:
Validation of the functionality of electrostatic adhesion foils under space-like conditions.
Validation of the drive mechanism of the rover in reduced gravity.
Secondary:
The rover stays entirely in contact with the prescribed path and moves as planned. Investigation of the surface material characteristics along the prescribed path.
The launch campaign of ROACH aboard the REXUS 24 rocket is scheduled for March 2018 at Esrange Space Center in Sweden.

Keywords—Electroadhesion; Rover; Students; Sounding Rocket; REXUS

II. Experiment Design

The experiment is placed in a module of a REXUS sounding rocket [3]. This rocket consists of an improved Orion power unit and a payload section for up to five experiments with a total maximum mass of 95 kg. For each experiment a module,

with a diameter of 30 cm and a height of up to 30 cm, is available. It is also possible to place an experiment in the nose cone of the rocket. Power supply and several stop- and start-signals are given by the rocket's service module, which is connected to every single experiment module.
The locomotion of a rover on a metallic surface in vacuum and microgravity is the main challenge of the project. To meet this challenge, electrostatic adhesion was the chosen concept. This involves a Kapton-coated metal foil, which has high voltage applied. Due to this, the foil can adhere to nearly any surface. Particularly, it can adhere to electrically conducting and non-conducting surfaces. The adhesive force is used to adhere the rover to the surface and enable its movement on the surface with a mechanism with a fan belt and gear wheels. The electrostatic connection to the surface can be removed and reattached repeatedly without residual traces. The mechanical concept of the rover is that of a tracked vehicle. It consists of two fan belts, on which the electrostatic foils are mounted and the rover chassis carrying the electronics. These are a high voltage generator, an acceleration sensor as well as distance sensors and a rotational encoder to collect data about the locomotion of the rover during the experiment phase.

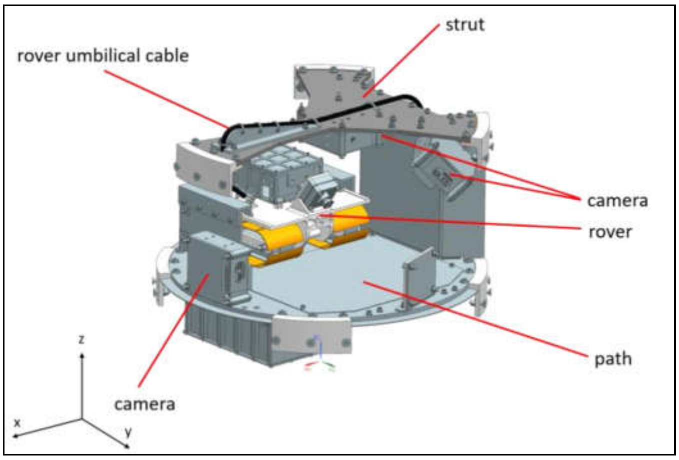

Fig. 1: Overview of the ROACH experiment set-up inside the rocket module

The chassis is a 3D-printed integral component made from ABS synthetic material. The rover electronics is accommodated in a separate box, whilst fan belts with pads are at the sides at the bottom side of the rover. Sensors are placed in between fan belts, see figure 2. In driving direction of the rover, a camera is placed on the rover and records the full experiment operation. It functions as a test payload and gives information about the path and the rover perspective.
Around the path, three cameras are placed and provide, together with a mirror, four external perspectives.
Power and experiment data are managed by the On-Board Control Unit (OBC). The OBC is placed in an aluminium box and mounted to the bulkhead of the module. The OBC Raspberry Pi manages the communication of the experiment with the service module of the rocket and the experiment's ground station. The Power Supply Unit (PSU) is provided by the service module with an input voltage between 24 V and 36 V and provides the rover a voltage of 12 V and the OBC with 5 V. The OBC receives and stores all data of the rover and generates all commands. If there are no data coming from the rover, the OBC tries to restart the rover and acts as a watch-dog.
The physical connection of the module to the rover is realized by an umbilical that should not affect the rover in its movement. The intended linear movement of the rover induces a torsion within the cable, which counteracts forces in the direction of movement.
During the launch of the rocket, the rover is fixated by the Rover Holding Mechanism (RHM) to tracks at the side of the casing. The RHM is realized by a double bolt pressed by two springs to the middle of the rover. Its purpose is to prevent mechanical contact of the adhesion pads and the path to prevent damages from launch vibrations. To release the rover from the RHM a wire rope is severed by a pyro cutter. By this, the springs pull the double bolt and leaf springs at each side of the tracks press the rover to the path. This ensures that the RHM has no further influence on the function of the rover, when exiting it.

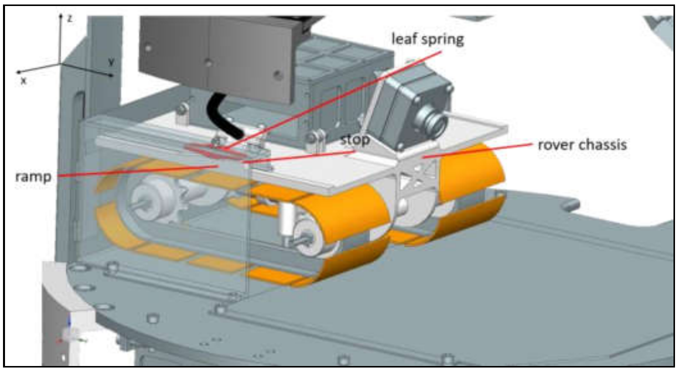

Fig.2: Rover Holding Mechanism of ROACH as a security fixture during launch.

The OBC, the RHM, the rover as well as its electronics are electrically and mechanically separated to avoid negative effects of loose items and to minimize the risks posed by the high voltage, which is generated on the rover. Electromagnetic interferences are reduced by using a milled aluminium box for all electronic modules. To avoid influencing other experiments in the rocket, the experiment module is separated to other modules by a bulkhead and a metal mesh as well as a sheet metal around the cable feedthrough.
The rover is equipped with its own PSU, which transforms current from 12 V to 5 V for the microcontroller and to 3.3 V for the sensors. Separated from the other electronics, DC/DC high-voltage converter provide 3 kV for the adhesion pads.

III. TESTING

Several tests were conducted before the campaign at the facilities of Thales Alenia Space and of the Institute of Space Systems (IRS) to ensure the functionality of the design under flight conditions. To simulate the load at launch, the experiment was mounted on a vibration table. The test parameters where predefined by the characteristics of the REXUS rocket (50 – 2000 Hz sinusoidal at 4.0 g and 20 –

2000 Hz random at 6.0 grms). Every run was performed in each axis. To be able to analyse changes due to the loads, before and after every load run a low-level resonance sweep was performed. The comparison of the resonance sweeps showed no unexpected changes and the RHM design to protect the tracks and rover was also verified.

In Addition, thermal-vacuum tests were conducted to provide data on the performance of the electronics and the high-voltage systems in the necessary temperature and pressure range (-20 °C to +60 °C and 10^2 Pa to 10^{-3} Pa), which were expected during preparation and launch of the experiment. While the electronics were not impaired by the temperatures, the high-voltage system caused some considerable problems during evacuation. Later video analysis showed, that in the pressure range from 10^1 Pa to 10^{-1} Pa the insulation of the tracks and pads was not sufficient and lead to corona effects on the tracks and arcing between the pads and the surface. These effects concurred with Paschen's law und lead to a redesign of the pads and tracks to improve insulation.

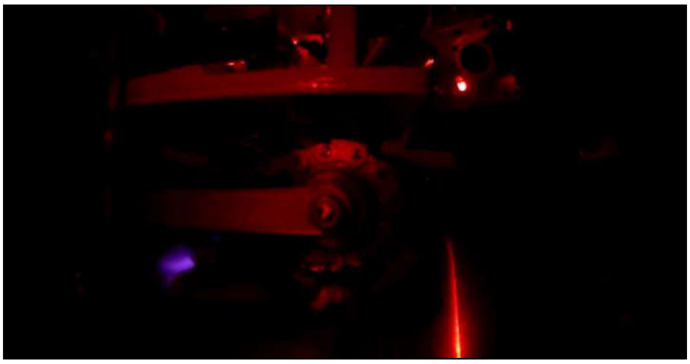

Fig. 3: Corona effect observed in vacuum chamber.

After these initial tests, further experiments in vacuum chamber followed to verify the new design. The finalized design is described in section III and Fig. 6.

IV. ELECTROSTATIC PAD DESIGN

The adhesion pads consist of a copper layer (9µm) and a polyimide layer (25µm). The copper is connected to one electrode with the other electrode being the aluminium surface to which the pad shall adhere. Electrical isolation is created by a polyimide layer. To insulate the edges of the pad, an etching process is used, removing the copper layer where needed. A similar etching process can be used to create meandering geometries in the copper layer to enhance adhesion to dielectric materials [4]. However, for adhesion to electrically conductive materials the adhesion force is higher without adding complex geometries.

Initial tests have been performed to evaluate the influence of numerous factors on the achievable adhesive force. Those factors are the shape and pattern of the pads, the thickness of the isolation and the applied voltage. The size constraints of the pads were considered by the design of the rover tracks, which are 35 mm x 50 mm for a single pad. This is needed to prevent the pads from kinking when the rover moves. However, deliberately kinking the front and rear side of the pad maximizes the usable copper area and therefore increases the total force.

The direction of the applied force as well as the attachment point are critical for the resulting adhesive force. Tangential forces are significantly higher than normal forces (a factor of 10 times has been observed), due to the tendency for the pad to peel off, when loaded in the normal direction. This can be counteracted by choosing an attach point in the centre of the pad with a small surface area.

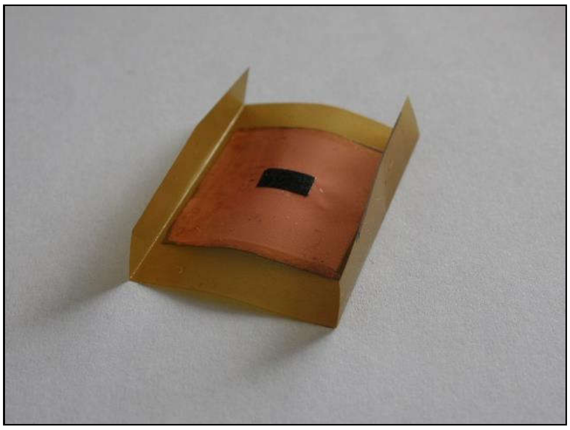

Fig. 4: Single adhesion pad from Kapton tape (brown), coated with copper (red brown) and attachment point (black)

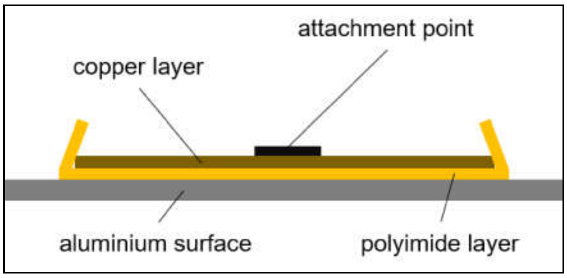

Fig. 5: Schematic cross section of single adhesion pad and its individual components.

The reachable voltage between the electrodes is approximately 2.1 kV. Higher voltages result in electrical breakdown of the polyimide layer. With this voltage the adhesive, normal force ranges between 0.8 and 2.2 N per pad of a size of 40 mm x 35 mm. The range of the force depends on the condition of the aluminium surface and whether the pad is slightly kinked. The adhesive pads must function properly in vacuum. Therefore, extensive tests in a vacuum chamber have been performed. The design vacuum environment for the ROACH experiment is equivalent to 70 km to 80 km altitude (Standard Atmosphere): 5.22 Pa to approx. 1.0 Pa. In this vacuum environment, proper high voltage insulation is of critical importance, due to the decreased breakdown voltage, of a so called Paschen-breaktrough, compared to sea-level pressure or high vacuum [5]. To ensure insulation, the top side of the adhesion pads must be covered with an insulator. Conformal coating spraying proved to be ineffective. This is most likely due to air traps inside the coating or due to damage to the coating when bending the pad. It is recommended that this is investigated further. An alternative method is to cover the pad with polyimide tape. This, however, decreases the flexibility of the adhesion pad, leading to lower total adhesive force. To avoid voltage breakthrough this is a suitable trade-off and the latter method is used, leading to a normal force of about 0.8 N per pad (2 kV). The polyimide tape, which insulates the electrodes, has a higher breakdown voltage, which have been tested up to 3 kV. With 2 kV of supply power the normal force equals approximately 1 N. The pads are mounted to a toothed belt using double sided, conductive carbon tape, which connects all adhesive pads to each other and to the voltage supply cable. This tape is then insulated using conformal coating spray and polyimide tape. Double sided polyimide tape is used to insulate the connection points. The supply cable rotates with the belt. With this setup, voltages up to 1 kV and forces up to 0.6 N at normal pressure) were achieved, which is likely to be increased with improved insulation.

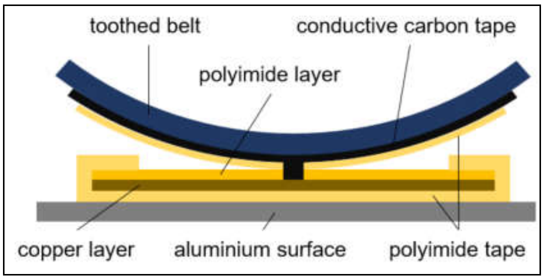

Fig. 6: Schematic cross-section of adhesion pad attached to belt in vacuum configuration

When manufacturing electrostatic pads, it is critical, that the pads are not bent or kinked to ensure reliable adhesion performance. Dust on the aluminium surface can reduce the adhesive force and is to be avoided.

V. Damage Control and Risk Mitigation

Spacecraft charging is a known problem in spacecraft engineering that has been intensively studied following the loss of DSCS 9431 in 1973, though common consequences are less severe [6]. The use of high voltage potentials to operate the adhesion pads of ROACH could cause a similar problem, even though ROACH is not capable to change the total charge of the spacecraft. The charge gathered by the rover is considered negligible since the time spent in an unshielded high-radiation environment is short.

The static charge buildup in structural components typically does not cause problems. However, electrostatic discharges (ESD) between components or to space do. ESD between components happen when the charge buildup of electrically insulated parts leads to voltages higher than the insulating materials' breakdown voltage. Surface breakdowns between conductors can easily be avoided by connecting them to a common ground. Generally, electrical conductors are almost neutral relative to the thin surrounding space plasma.

The current design of ROACH relies on electrostatic attraction and can be modeled as a parallel plate capacitor. The adhesion force of $F = \frac{\varepsilon \cdot A \cdot U^2}{d^2}$ diminishes with the distance square law between the copper layer and the underlying conducting structure. For uncharged dielectrics, only non-uniform fields create attraction forces of $\vec{F} = \vec{\nabla}(\alpha \cdot \vec{E} \cdot \vec{E})$. If the dielectric has gathered a total nonzero charge through surface charging, it resembles a capacitor and adhesion forces depending on the charge are achieved. Thus, ROACH works best on electrically conducting surfaces. Issues related to dielectric charging of the rover's path can be avoided by operating only on electrically conducting surfaces. The model of a parallel plate capacitor correctly indicates that the generated electric fields are almost entirely constrained to the dielectric foil between the conducting surface and the copper layer. Electric components on the other side of the structure are not affected. The surface charges rapidly dissipate after removing the pad. An electric circuit may be influenced, if there is no conductive shielding between the pad and the circuit and the distance is low. An example would be a PCB mounted inside the spacecraft on a non-conducting wall, where the rover is operating on the other side. It is recommended for a future user to define no-go areas for an electrostatic adhesion rover to avoid such issues.

Discharging of dielectric materials to space or to visible conducting parts can occur over larger distances. Generally, a built-up voltage of 400 V between dielectric surfaces and electrical conductors is considered the lower limit for this to happen.[1] The rover's adhesion pad operative voltage of 2 kV surpasses this limit. However, all parts of the rover connected to this voltage are insulated to at least 3 kV in the current design. A local discharge through the pads' insulation cannot be ruled out if the built-up surface charge reaches more than 1 kV. If such charges are expected, design changes with regards to insulation are required. Dielectric exposed spacecraft surfaces can build up considerable charges, which are the typical cause for ESD. Bringing a grounded object, e. g. the rover, into close proximity of such surfaces may trigger ESD regardless of the rover's design. Most at risk are thin dielectric coatings on conducting structures since the rover cannot operate well on pure dielectric structures.

As a capacitor, each pad can store up to 0.2 µC or 0.4 mJ[2]. If a discharge occurred it would thus be classified a minor discharge, though the used voltage of 2 kV may justify a classification as moderate discharge. The declaration of ESD sensitive areas may be advisable, so that the rover can avoid operating there [7].

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[1] "A published rule of thumb is that if dielectric surface voltages resulting from spacecraft surface charging are greater than ~500 V, positive relative to an adjacent exposed conductor a breakdown may occur. In this document, we have adopted a more conservative 400 V differential voltage threshold of concern for ESD breakdown.", Guide to Mitigating Spacecraft Charging Effects, H. B. Garrett and A. C. Whittlesey, JPL Caltech 2011, pp. 24-25

[2] Based on $Q = \frac{\varepsilon_0 \cdot A \cdot U}{d}$ and $W = Q \cdot U$

During initial testing, some discharges occurred. Mechanical damage to the insulation layer was found to make the pads much more susceptible to breakdowns. These were primarily seen in a low-density atmosphere and matched predictions by Paschen's Law [5]. The pressure found in typical orbits is significantly lower and Paschen breakdowns are therefore significantly less likely. Following these observations, the electrical insulation of all high-voltage parts was redesigned. The improved design was found to be unable to produce discharges under laboratory conditions. Any pad malfunction (i.e. damage) is easily detectable, and the power supply would be cut in such a case.

In summary, ESD pose a risk that needs to be assessed on a case-by-case basis but can generally be considered minor to moderate. Proper spacecraft design and testing, further research on the high-voltage system and defining safe operating conditions can mitigate most risks. It is necessary to further improve and test the design, especially under real operating conditions.

VI. Conclusion And Prospects

Electrostatic adhesion is a promising concept to create connections that are removable repeatedly and therefore enable the locomotion of robots on spacecraft. During the ROACH project as an experiment onboard a REXUS sounding rocket, this concept is investigated. Already conducted tests of the pads in vacuum chambers showed that plasma can occur in several pressure levels. This is most likely due to discharges at residual atmosphere pressure. The goal is to complete the understanding of this effect and to take countermeasures. It is also important to have sufficient even surfaces and an appropriate current and voltage progression. Besides the scientific gain, the focus of REXUS is educating students. Concerning the ROACH team, this objective has been achieved. The principally feasibility of electrostatic adhesion and its applicability to arbitrary surfaces makes it interesting for further students' projects as well as for practical operations.

Acknowledgment

We would like to thank all our supporters, especially the Thales Alenia Group and the Institute for Space Systems of the University of Stuttgart as well as the REXUS/BEXUS organizers.

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Student Perspectives on the 2017 ESA Concurrent Engineering Challenge

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***Abstract*—In September 2017, the first ESA Academy's Concurrent Engineering Challenge (CEC) was held, giving 88 Master's and PhD-level students from twelve ESA Member and Associate States a powerful platform to experience system engineering in an intense, fast paced, and real-world environment. Within four days, teams of physics and engineering students in Concurrent Design Facilities (CDF) located in Politecnico di Torino, Universidad Politécnica de Madrid, University of Strathclyde and ESA's European Space Security and Education Centre (ESEC) each developed a preliminary design for a satellite mission to map the Lunar south pole for water-ice as a precursor for the Moon village concept. Each team was divided into subsystem groups of two to three students each. As the subsystems design progressed, key parameters were regularly updated and shared within the team using ESA's Open Concurrent Design Tool (OCDT). The Challenge concluded with final presentations and critical discussion of the four satellite designs. Lessons learned during CEC were carried back by the students to their respective universities and projects and are discussed by the ESEC student team. The remaining co-authors are listed in the Acknowledgements section of the paper.**

***Keywords*—Concurrent Engineering, Open Concurrent Design Tool, Concurrent Design Facility**

I. Introduction

The Concurrent Engineering Challenge is organised by the ESA Education Office and the ESA Systems and Concurrent Engineering Section to introduce university students to the concept and practice of concurrent engineering and support universities in ESA Member and Associate States in the development of their Concurrent Design Facilities. From the 11th-15th of September 2017, twenty-two Master's and PhD-level students in engineering or physics disciplines from across twelve ESA member states gathered at the ESA Academy's educational CDF in ESA's European Space Security and Education Centre in Belgium. They were joined remotely by three similar participating student teams in other educational CDFs located in Politecnico di Torino in Italy, Universidad Politécnica de Madrid in Spain, and University of Strathclyde in the United Kingdom. In each CDF, students were divided into subsystem groups of two to three students each, supported by two system engineers with concurrent engineering knowledge. These professionals were there to guide the students but not to drive their design. The four teams were given the same mission to work on largely independently: using a concurrent engineering process, design a preliminary satellite mission to map the Lunar South Pole for evidence of water and ice, with a view to future Lunar village colonisation, at a resolution of at least 100 [m^2/pixel]. To make this task achievable in the four days given, teams were to assume using commercial-off-the-shelf components (COTS) where possible, no specific launch date, piggybacking on the Ariane 5 launcher, imposing a total mass limit of 300 kg. At the end of every day, student teams presented that day's progress with one another, allowing a wide exchange of ideas. The Challenge concluded with final presentations and critical discussion of the four satellite designs.

II. Background

A. Concurrent Engineering

Concurrent engineering is a system design practice that encourages immediate collaboration between groups working on interrelated subsystems, so that the whole system can be integrated seamlessly and quickly[1]. It requires all subsystem designers be together for several sessions using a tool such as the OCDT to share their relevant data with one another. By contrast, a typical system design process may begin with an objective, followed by an outline design; passed through various departments to fill in their specifics, until finally the system engineer must struggle to fit everything together, most likely requiring every subsystem to redesign their contributions several times before arriving at a functional end design. This process can be lengthy, whereas a concurrent engineering approach can reach the same stage in less time. Concurrent engineering is commonly utilised by ESA missions at their ESTEC facility, including the Mars Sample Return Carrier Mission, CLEP Assessment of a Europa Moon Penetrator, and SPADES Solid Propellant Autonomous Deorbit System assessment studies, to name a few[2]. The typical practice is to have eight sessions with all interested parties present, including representatives from the group commissioning the mission, spread out over the course of a month to allow the engineers involved to do any necessary additional research between sessions. A first iteration on the design often takes about three sessions, followed by a second iteration for improvements which takes around an additional two sessions. Further iterations are quicker, and will continue until the system engineers decide the changes between iterations are

[1] http://news.aucotec.com/5-benefits-concurrent-engineering/ — Visited on 12 September 2017
[2] http://m.esa.int/Our_Activities/Space_Engineering_Technology/CDF/Studies_Reviews — Visited on 12 September 2017

so incremental that another is unnecessary; usually no more than five iterations are required at the early stages [1].

B. Lunar South-pole Mission

The CEC's mission was based on ESA's announced intention to build a permanently manned lunar base by 2030, with robots sent up to begin construction in the next decade[3]. This would serve a primarily research purpose, similar to the Halley Research Station in Antarctica, but the lunar village could one day be used as a stepping stone for many space industries and colonising Mars. It is important to know how the human body adapts to low gravity in the long term for these future endeavours to be successful. The dark side of the Moon is an ideal place for ultra-sensitive radio-telescopes, as it is completely insulated from the noise coming from Earth. It would be vitally important that those stationed there will be able to supply their own food, water, and air continually, so efforts are being made to identify vital resources such as water-ice on the Moon in readiness for early colonisation.

III. Subsystem Designs

The following section will be detailing each subsystem a part of ESEC's team AMOONDSEN. All subsystems utilised the OCDT tool provided by ESA, and the following sub-sections will provide more in-depth information on what was learned.

A. Attitude and Orbit Control Systems

Attitude and Orbit Control Systems (AOCS) is required to select sensors and actuators to facilitate the monitoring and control the attitude of the satellite in low-Earth orbit from the launcher release, during transfer, lunar orbit, emergency situations, through disposal phase. The team's first step was to prepare worst-case scenarios and calculate the thrust required to position the satellite accordingly. Three iterations of actuator structures were implemented in cooperation with Structures, Power, and Propulsion. Four COTS reaction wheels in tetrahedral orientation combined with twelve 1N hydrazine thrusters were chosen for the final design iteration. The system ensures 100% momentum reserve and is fully redundant. For AOCS sensors, six sun sensors, two star trackers, and two inertial momentum units were chosen, with the driving criteria for this decision being price, mass, and accuracy, with accuracy requirements provided by the Instrumentation subsystem.

B. Communications and Data Handling

The role of the Communications and Data Handling subsystem was to enable the satellite to send and receive information to and from the ground station on Earth, as well as store instrumentation data onboard. During the daily updates between teams, it quickly became apparent that the initial requirements set during the early stages of the project greatly affected the overall complexity of the subsystem. The updates provided an opportunity to collaborate with the other university's and learn the reasons behind their design decisions. This collaborative effort allowed the ESEC's team to re-evaluate decisions made, and discover issues with their own design and other teams', thereby increasing the overall quality of the subsystem. For example, AMOONDSEN choose to utilise a patch antenna array for its satellite downlink. In contrast, other teams used higher frequency band transmitters, which greatly reduce difficulties that arise in the use of arrays, in spite of the minimal amount of COTS antennas and transmitters available for those frequencies. A key lesson learned by the team throughout this process was that trade-offs between complexity, COTS availability, and the ability to fulfil data budget requirements must be made for mission success. Additionally, it was crucial to have constant open communication between the subsystem and the Instrumentation and Mission Analysis teams, as Instrumentation required specific data rates to meet their mission objectives while Mission Analysis provided the windows of opportunity for satellite-to-Earth communication.

[3]http://www.esa.int/About_Us/Ministerial_Council_2016/Moon_Village — Visited on 12 September 2017

C. Propulsion

The propulsion team was responsible for finding a suitable propulsion system to transfer the satellite from its parking orbit to the moon, and to keep and correct its altitude and attitude in lunar orbit. Following trade-off studies, chemical propulsion was chosen. With regards to complexity and mass, a main engine consisting of six hydrazine thrusters of 20 N and an I_{sp} of 225 s was selected. Based on the delta-V for the mission, it was possible to compute the propellant mass for the system, which was found to be 158 kg of hydrazine. At first, a blow-down feeding system was initially chosen for the propellant, but due to structural considerations, a regulated tank pressure feed system was the chosen solution. Concluding the design is the choice of nitrogen as feeding pressurant, with a mass of 2.8 kg at an operating pressure of 276 bar.

D. Configurations

The responsibility of the Configurations team was to gather the subsystem designs of the other teams and combine them into a single SolidWorks model for analysis of the entire spacecraft. The inputs that drove the satellite configuration design were derived from the payload envelope, centre of mass, and moment of inertia requirements from the Ariane 5 launcher. Configurations worked closely with the Structures team early in the design process to help develop a consistent structure design that would accommodate all subsystems and the spacecraft design requirements. As the design phase progressed, the focus shifted to collaborating with the Instrumentation, Propulsion, and AOCS teams to determine optimal component placement. Ultimately, an octagonal satellite structure was chosen. Positioned at one end of the satellite is the mounting ring and thrusters. The other end, which is Nadir-facing during science operations, has the instrumentation apertures. The outer side panels of the octagon have seven solar panels mounted to them, with the remaining panel reserved for the patch antenna array. Inside the satellite is mounted the propellant tank, onboard computer, transceivers, electronic power system, and AOCS components.

E. Mechanisms

Mechanisms refers to the mechanical parts on the spacecraft that can move relative to others. Initially, the team focused its work on the mechanisms surrounding the solar panels. The requirements of the mission led to the initial hypothesis to use deployable, rotating solar panels with sun tracking capability. Progress on the project gradually reduced the power needed from the panels, and so a simplified architecture using fixed panels was chosen, negating the use of orientation mechanisms. During the early iterations of the project, deployable and pointing systems for communication antennas was also investigated, however an immovable array was chosen for the final design. In accordance with the final mass of the satellite and launcher selected, a deployment system was chosen. Although the depth of complexity of final design was not large, the team was able to experience and take-away the importance of communication with other teams, adapting work according to other teams' needs, and gaining knowledge about space systems requirements and standards.

F. Instrumentation

The instrumentation team was responsible for designing the scientific payload of the satellite. The primary science objective was to image the Lunar South Pole with a minimum resolution 100 [m^2/pixel]. The difficulty lay in confining such an imaging system to the space, power, and communication constraints of the satellite. As such, the team worked closely with the groups responsible for these subsystems. The model of concurrent engineering proved invaluable to the initial design stages as the requirements and specifications of the instruments often changed as the design progressed. It was found that ESA's team of students differed in approach from the others, in that the design of the imaging system was done in accordance with optical principles rather than finding specs of a COTS component, likely due to all three team members being physicists by training. The approach allowed greater flexibility when dealing with orbital height requirements, though proving to be challenging to implement. Ultimately, the design was successful and mission requirements satisfied. The CEC provided the Instrumentation team important experience in practical, real-world engineering. Lessons learned during CEC enabled a different thought process to be used for design and enabled students to better apply knowledge gained in the teams' physics training to engineering projects.

G. Power

The Power team was responsible for ensuring the satellite could generate and store sufficient energy throughout the mission. This included sizing the solar panels and batteries, and collating the power budget. The concurrent engineering process enabled the team to start from abstract notions of typical panel and battery performance and gradually arrive at a more precise design as other groups solidified their requirements. The power budget collates how much power each component would require during each mission phase, and was used to conclude that deployable solar panels would not be required for satellite mission success. Opting for body-mounted over deployable panels traded mass and complexity for the expense of redundant panels. From the CEC, the team learned how to design in a nonlinear way and how to use trade-offs to make important decisions, applicable to any engineering project.

H. Structures

The Structures team was responsible for designing the structure of the satellite to comply with requirements of the mission, including: fitting within the predefined dimensions, compatibility with the adapter ring surface, having a first natural frequency higher than 60 Hz, providing an interface between payload and fuel tanks, and complying with the mechanical load design safety factors. The proposed structural design was composed by an octagonal load bearing column made of CFRP with an aluminium core and trusses to link the load bearing column to the ring adapter and tank holders. The material choices were made by comparing specific mechanical properties to minimise the mass required to withstand the loads. The structural design was carried out by analysing the maximum stresses and displacements obtained in the different components for the most critical loading case, which is the maximum acceleration reached during the launch of the satellite. A simplified Fem analysis was performed in ANSYS for validation purposes. Buckling was considered during design in those components subjected to compression loads. At the end of the last iteration of the design, the structure fulfilled the structural requirements and weighed at around 20% of the dry mass of the satellite, 18.35 kg, which matched the typical value provided in Space Mission Analysis and Design [2].

I. Thermal

The task of the Thermal team was to make sure that the satellite could cope with the wide range of temperatures to be experienced throughout the mission. The first step for the team was to obtain the minimum and maximum allowable temperatures for each subsystem. The next step was to evaluate the worst case thermal scenarios. The hot case involved the situation where the satellite is receiving solar and Earth radiation, Earth Albedo, Moon Albedo, and dissipated power from the electronic equipment onboard. The cold case involves the satellite being in both Earth and Moon eclipse. Starting with a 1 m^2 satellite configuration assumption, the hot and cold case temperatures of 35 ^oC and 5 ^oC were found respectively. The thermal design was iterated as the concurrent engineering process continued and new information surfaced. This involved taking the dissipated power of all subsystems into account, the satellite configuration, the required surface areas for balancing equations, and monitoring the operating temperature of all components. The resulting design consisted of the satellite covered in a Kapton foil-type multi-layer insulation without a radiator. COTS heaters were chosen to ensure that components remained within required temperature range. The final satellite thermal range was found to be -7 ^{o}C to 23 ^{o}C respectively.

J. Trajectory Analysis

The Trajectory Analysis team was responsible for defining the overall scope of the mission. This involved determination and optimisation of launch opportunities, transfer windows, staging locations, transfer trajectory and operational orbit as well as disposal strategy at the end of the mission. Decisions were based on the mission statement and the derived mission requirements. The main outputs of Mission Analysis for the other subsystems include the delta-v budget, illumination and eclipse times, communication windows to Earth or relay stations as well as relative motion to target bodies for scientific operations. In this study, Mission Analysis performed a trade-off on the transfer capabilities from Earth to Moon, looking at direct, bi-elliptic, and low energy transfer options, of which the weak stability boundary transfer was chosen due to low delta-v requirements. Additionally, an orbit with the capabilities for observation and mapping of the Lunar South Pole had to be developed. After conducting studies of high elliptic, EML halo and LLO orbits, a quasi-frozen LLO was chosen due to the long-term orbit stability, resulting in low station keeping costs. Moreover, the Instrumentation team confirmed that the speed above ground and observation periods in the chosen orbit were within the feasible range for the mission's optical components.

IV. Completed Design

Team AMOONDSEN's satellite design presented on the final day of CEC 2017 consisted of a 286.40 kg wet mass satellite, equipped with a CCD camera, IR spectrometer, meteorite scanner, particle detector, and radiation detector as its payload. The satellite is powered by seven fixed GaAs solar panels which generates a total 240 Watts of power in the Sun. Two quadrifilar helix antennas, a four-patch antenna array, and two transponders make-up the Communications system's equipment. The satellite is an octagonal structure, with the final Configuration model shown in Figure 1 [3].

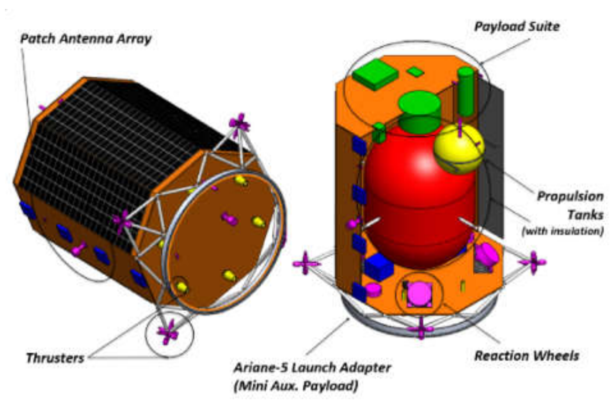

Fig. 1: AMOONDSEN Final Iteration

V. Learning Outcomes

A key take-away from the challenge regarding concurrent engineering is its increased communication capabilities. The CDF combined with the use of the OCDT enabled all subsystems to communicate on-demand with one another and update designs that would affect other subsystems in real-time. This made it easier, and possible, to complete a preliminary design of a satellite in such a short period of time. Utilising concurrent engineering to increase communication abilities between the team is a directly transferable lesson that members can take with them throughout their current education and future projects. For example, the University of Western Ontario, of which CEC alumnus Kelsey Doerksen is a Masters student, is looking to begin a final-year project for undergraduate students to design a CubeSat in eight months' time, to be run and assisted by Ms. Doerksen. Utilising the OCDT and employing concurrent engineering techniques such as hosting design meetings in a classroom-style CDF on campus, will produce better communication between members of a large team with various engineering backgrounds and ideas.

In addition, the experience of working with individuals from a wide-variety of educational and cultural backgrounds provided a unique opportunity for every member to learn something from one another. Projects within the space industry are inherently a collaborative effort, whether that be between varying disciplines such as scientists and engineers, or between nations. Opportunities to better hone and develop ones' teamwork and interpersonal skills is valuable and CEC was no exception to this. Very few of the members entering the challenge knew one another prior, and by the end of the week strong bonds had been developed through successful teamwork practices, facilitating new networks between peers.

ECTS credits were also provided to ESEC team members whose universities could accept them. Rohan Chotalal and Adam Dabrowski both received two ECTS credits, and Darian van Paridon received one ECTS credit towards their degrees.

In summary, CEC has shown that a concurrent engineering design process proves to be beneficial for many space system design projects. This process can be applied in a strictly academic format in the form of a course, and involves the possibility of implementing a concurrent engineering facility for project work at the university level. Discussions and shared experiences from attendees, detailed in the Post Challenge section of this paper, assures that not only the participating students from the 2017 CEC will benefit from the experience gained, but that future students will as well.

VI. Post Challenge

Following the CEC, a participant, Maxime Valencon, was driven by what he had learnt throughout the week and proposed presentations and hands-on activities on concurrent engineering methodology and software at Cranfield University. The development of a partnership between the major Concurrent Design Facility of CNES and Cranfield University was also favoured following the Challenge, initiated by

Maxime Valencon, proposing lectures and conferences with professionals on-campus, as part of the MSc in Astronautics and Space Engineering. This outreach resulted with professors, teachers, and students becoming interested in the CEC and various concurrent engineering hands-on projects proposed by ESA Education Office. From this gained interest and partnership, it was proposed to use concurrent engineering tools such as the OCDT in a design project, a key component of the MSc at Cranfield, to provide a good background in concurrent engineering for students' future careers in Space Engineering. Adam Dabrowski, a PhD student and alumnus of CEC 2017, has been running concurrent engineering seminar exercises as a part of the Space and Satellite Technologies course at Gdask University of Technology. Four of the students whom attended the seminar participated in ESA Academy's CubeSat Concurrent Engineering Workshop 2018. Moreover, the methodology was picked up by a student research group in their CubeSat project, in which the students described the approach as very helpful and empowered their work.

In addition, Kelsey Doerksen curated a presentation about the challenge for undergraduate students at Carleton University in Ottawa, Canada, that were a part of a 4th-year satellite design project. Following this, two students, Lucas Brewster and Bryan Southwell, expressed great interest and applied to be a part of ESA Academy's CubeSat Concurrent Engineering Workshop 2018 and participated in January 2018. Similarly, William Ferguson delivered a presentation on his experience of the CEC to some of his fellow PhD students in the Centre for Doctoral Training in Metamaterials at the University of Exeter, prompting several of them to apply to future ESA Academy training sessions.

Furthermore, at the faculty of Aerospace Engineering at Delft University of Technology, an initiative has been made to establish a concurrent design facility. This is useful for the final year bachelor thesis project, as design decisions, trade-offs, and preliminary designs can be made with greater efficiency.

VII. Conclusion

The Concurrent Engineering Challenge taught the ESA student team a creative, holistic approach to designing the components of a space mission, while maintaining awareness of all members' work. In four days, starting from largely theoretical understandings of the different spacecraft subsystems, the team designed a preliminary satellite mission to locate water-ice on the Lunar South Pole. Following CEC, students returned to their respective universities with newfound skills, applicable to many areas, and could offer valuable experience to others; promoting students, professors, and members of their community to engage in future ESA Academy training sessions. The Concurrent Engineering Challenge facilitated a deep and practical understanding of the key benefits and applications of concurrent engineering, enabling the participants to apply their knowledge to a unique problem, whilst encouraging a rich exchange of ideas across various disciplines. Through doing so, students enhanced their skills in teamwork and open communication in a novel and engaging way, which are applicable to their future career and educational projects.

Acknowledgements

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Behavior of Polymers in Microgravity

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***Abstract*—The future of space structures can be summarized into a single word: Deployables. The need for extensive research on the field of deployable structures has arisen in recent years, with intended use in solar panels, satellite antennas, spaces trusses and even space habitats in space or planetary settlements.**

Pneumatically actuated deployables, is a distinct category of deployable structures, which deploy using the pressure of a fluid (usually a gas). They generally impose a low risk during deployment, have complex geometries and a high compaction ratio. However, their greater disadvantage is the low stiffness and damage tolerance. The lower stiffness could be countered with the use of a thicker shell for the inflatable structure. The damage tolerance however, would require the structure to retain a significant proportion of its initial stiffness and shape even at a case of internal pressure loss, which could occur due to a micrometeorite or space debris impact and puncture of the outer shell.

The AML – Applied Mechanics Laboratory and the AML Space Group aim to solve this problem, by researching the idea of deploying pre-impregnated polymer fibre fabrics into space and curing them, thus creating a lightweight, high-stiffness, thin-shelled structure in space. Such structures could easily tolerate a pressure loss and even an impact scenario and still retain a significant proportion of their initial stiffness, shape and strength, solving the most important impediment of inflatable structures.

The AML Space Group shall research the behavior of various polymer resins in a micro-gravity environment, by participating in the ESA Fly Your Thesis 2017 campaign. In the experiment, uncured glass fibre reinforced polymer tubes would be stowed before flight, then deployed, and cured during the micro-gravity intervals of the parabolic flights, using a UV light-source. In a complementary experiment, small uncured polymeric samples, as well as fibre reinforced polymer laminates would be also cured during the micro-gravity intervals. Identical reference specimens shall be produced on Earth with the same equipment at 1g gravity acceleration. The goal is to test and compare the mechanical properties and microstructure between these two batches of specimens produced in the two different gravity acceleration levels.

Keywords—Deployable structures; UV polymers; composite structures, materials, manufacturing

I. Introduction

The idea of using UV polymers for space application is not new. It was first conceived, and prototype tested during the Space Race in 1963, for use in space inflatable structures by the Hughes Aircraft Company [1]. Inflatable booms were deployed by pneumatic or foam-driven techniques and then cured using internal UV Ledstrips or solar radiation. The inflatable booms were made of fibre cloths pre-impregnated with UV Polymers.

Extended research is being performed in novel fast curing polymers in many academic and industrial fields. However, a few researches have been performed on the behavior of polymers, especially the curing procedure, in the space environment – vacuum and microgravity. Research on the behavior of materials in vacuum chambers measuring outgassing has been performed for a wide variety of materials by NASA [2]. On the other hand, research on the behavior of polymer materials cured in microgravity has not been extensively performed. The main difficulty for research on that field is that the curing of polymers requires time ranges that measure to hours for polymerization and the only lab capable of providing that long micro-gravity time ranges is the International Space Station. However, experimenting on polymerization requires high-temperatures which are a critical concern in the ISS. However, UV polymerizing polymers could be cured in a matter of seconds and without high-temperature need or generation, thus making them capable of being experimented to in a parabolic flight campaign [3; 4; 5].

There has been investigation of the idea of deployables previously in literature, and also in the Fly Your Thesis! campaign. "Spaghetti Tubes", a project participation in the Fly Your Thesis! campaign in 2003 investigated the use of inflatable deployable tubes [6]. Additionally, in 2004 a project named "Composite Photopolymerization for Teeth Repairing" flew on the campaign [7], which was focused on the effects of microgravity on photopolymerizing medical polymers. Finally, the 2011 ESA REXUS project “FOCUS” experiment [8] flew on a suborbital rocket flight, where a deployable structure was inflated and cured, to investigate the feasibility of space manufacturing.

II. Scientific Background

In recent years, the use of polymers in space structures is being investigated, in order to extent the list of space-graded materials for space applications [9]. Polymers are ideal space materials as they are lightweight and can be reinforced with fibre cloths, manufacturing composite materials that can reach mechanical properties higher than of metals [10].

A typical UV polymer material is a single component system requiring no mixing, consisting of polymers in the families of epoxies, acrylates, urethanes, and thiols and a photoinitiator. The photoinitiator plays a key role in UV-curable systems by generating the reactive species, free radicals or ions, which will initiate the polymerization of the multifunctional monomers and oligomers. To be efficient, a radical-type photoinitiator must fulfill a number of requirements [11], namely: a) strong absorbance of the UV-radiation emitted by mercury lamps, b) short lifetime of the excited states to avoid quenching by atmospheric oxygen, c) fast photolysis and bleaching which generate the free radicals, d) high reactivity of the free radicals evolved toward the monomer function, e) good solubility of the photoinitiator in the formulation and f) formation of non-colored and odorless photoproducts [11].

The advantages of UV polymers as matrices in composite materials is primarily the curing time which could take place within seconds and using the solar radiation as the curing agent which eliminates the need of an energy source. Additionally, UV polymers are cured in lower temperatures than convectional polymers used as composite matrices, which significantly lowers thermal stresses in fibre reinforced composites. Finally, UV polymers are environmentally friendly, since they avoid the use of solvents [12].

Main disadvantage is the limited thickness of laminates that can be cured due to the small penetration depth of UV radiation combined with the photo-masking of the UV polymer by the reinforcement. Furthermore, high strength and modulus fibres such as carbon fibre enhance this problem, as they heavily obstruct UV transmission [13].

III. Manufacture

The specimens were prepared and manufactured in the Applied Mechanics Laboratory. The dimensioning of the specimens was decided after careful consideration of the manufacturing constraints, the acquisition of materials and similar research performed in literature [14; 15; 16; 17].

A. Specimen Preparation

Two main type of specimens were produced: (a) single and (b) double layer woven glass fibre specimens. The glass fibre sleeve used was S-glass 34tex, had a base dimensioning of ±45° at 45 mm diameter and a thickness of 0.4 mm. The polyethylene sleeves had also a diameter of 45 mm and a thickness of 0.1 mm. Both glass fiber and PE sleeves were provided by Fibermax Composites (Volos, Greece). The resin used was mainly acrylic based (>98% wt) with Phenyl bis(2,4,6-trimethylbenzoyl) phosphine oxide Photoinitiators and was provided by 3D ink, (Kansas City, USA) without any further purification.

The Glass-fibre sleeves as well as the two polyethylene sleeves per glass-fibre sleeve were cut at the length of 800 mm. The edges of the glass-fibre sleeve were fixated using tape, so as to minimize attrition and loose fibre strands. The tube laminate was created, by enclosing the glass-fibre between the two polyethylene sleeves. The tube laminate was placed on top of a metallic tube mould, so as to stretch the laminate into tubular shape. The circular metallic disk was apposed at the base of our structure, inside the inner bag and fixated with a metallic clamp. The specimen bottom plate was apposed above the circular disk, with the interjection of an O-ring, so as to achieve air-tightness at the bottom interface. The specimen bottom plate was apposed with the circular disc through a bolt dressed in Teflon tape. The top plate differentiates in that the circular disk bears a one-way valve.

Fig.1a-d. Specimen preparation process. a, b) glass fiber sleeves between PE sleeves. c) mounting of the lower metallic disc and clamp. d) Installation of the bottom plate after O-ring placement

Finally, the specimens were filled with UV resin up to a v_f of 0.5, folded using the zigzag folding method [14] and packed for transportation. During transportation and resin filling, the specimens were kept in light-tight storage, to ensure that no polymerization occurred before curing in the parabolic flight.

B. Specimen Curing

The device used for the curing procedure was designed and manufactured in the Applied Mechanics Laboratory, at the University of Patras, and fulfilled the requirements set by Novespace for the participation in parabolic flights [18]. The device was mainly partitioned by a UV-light LED source for curing and an oil-less air compressor for the inflation and deployment of the specimens. Inside the curing chamber, a batch of 4 specimens could be inflated and cured at the same time. Prior and after curing, the specimens were stored in light-tight storage, to ensure no polymerization occurred outside the curing chamber.

The curing sequence for the specimen manufacture would take place during the 0-g phase of the parabolic flight that spans a timeframe of 20 seconds. The air compressor would provide an overpressure of 0.5 barg inside the specimens, deploying them via inflation over a timeframe of 5 seconds and providing the desired cylindrical shape for the curing phase. Afterwards, the UV-light source would be switched on, providing 80 W/m2 quasi-uniform irradiation at 395-405 nm of wavelength for the remaining of the 0-g phase of the flight. After the first parabola, each batch would remain inside the chamber for an additional 4 parabolas (80 secs), for additional curing only during the 0-g flight phase. To prevent deflection of the deploying end of the tube specimens during deployment, a sliding plate mechanism was used to fixate the deploying end, as shown in Figure 2.

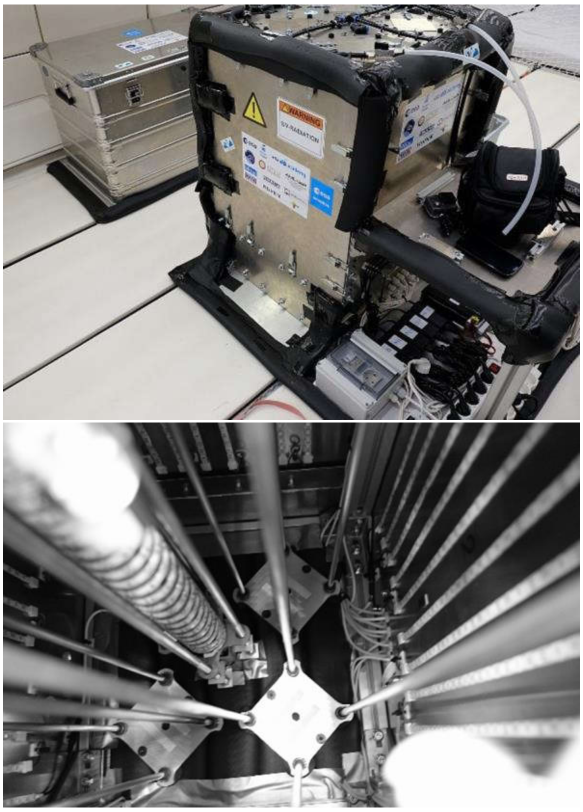


Fig 2a-b. a) (front) curing device and (back) storage rack where cured specimens were stored during the flight. b) Curing chamber shown from above, with the sliding plate mechanisms prominent.

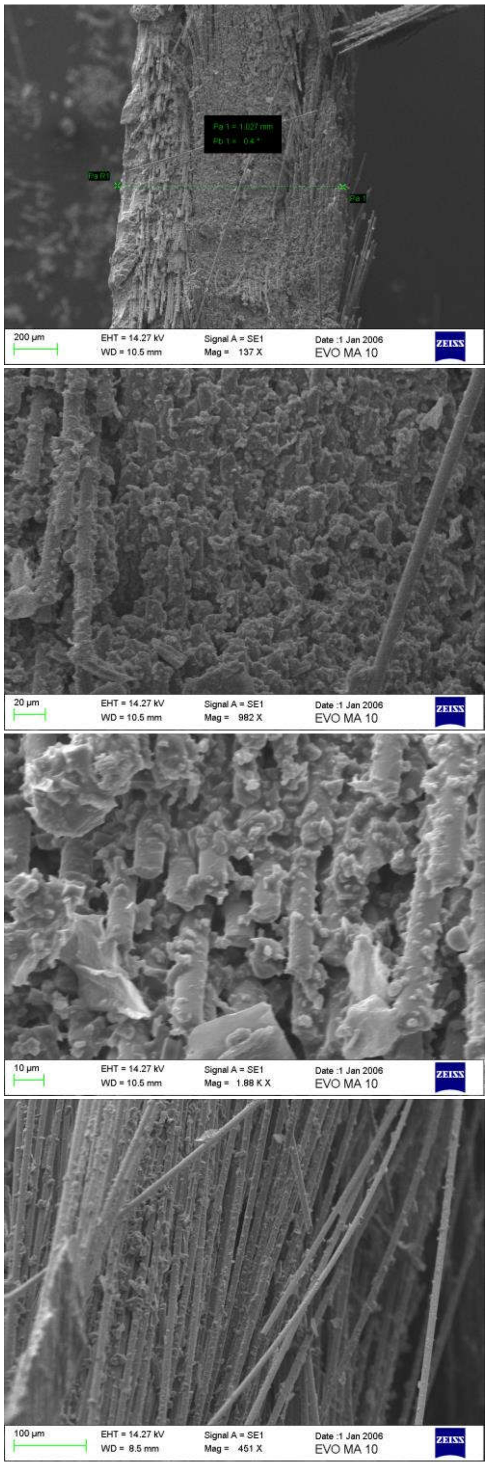
IV. Experiments and Testing

After the parabolic flight campaign, the 0-g specimens were carefully packed and shipped in light-tight storage back to the laboratory, where they were processed together with the 1-g specimens, machined and tested, following the standards where possible.

A. Microstructure

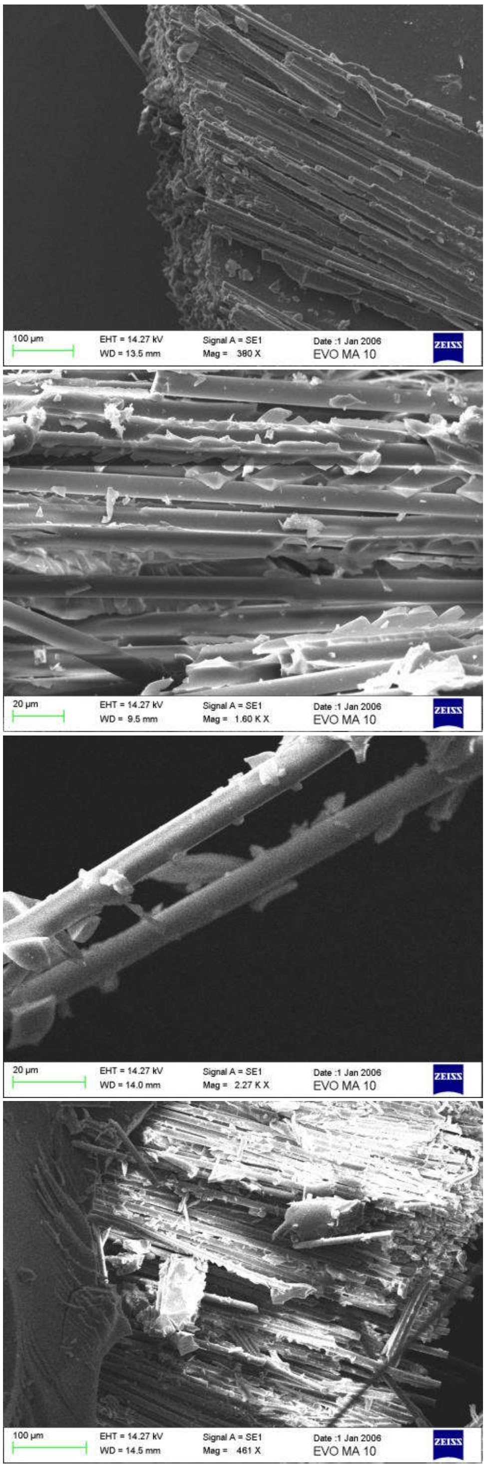
The microstructure of the 1-g and 0-g specimens was observed through SEM. The morphology of the UV-cured composite deployables was investigated by SEM observations on the cross-sections of the composites.

In figure 3, the cross-section of a deployable manufactured in 0-g conditions appeared to have a uniform structure, with the resin being attached to the fibers surface throughout the overall thickness. However, at the edges of the sample, the resin was proven susceptible to cutting and left fibers exposed.



Figures 3a-d. Top to bottom. Cross-section of the 0-g tube specimen wall, images of cut edges.

In figure 4, the cross-section of 1-g manufactured deployable specimens is shown. The reinforcement appeared to have been uniformly wet by the resin as the one in 0-G condition. Nevertheless, fibers in 1-g composite deployable appeared to be more exposed than the 0-g sample with much less resin residues left on them.



Figures 4a-d. Top to bottom. Cut of the 1-g tube specimen wall. Fibers with resin remaining on their surface across the cross-section.

B. Coupon Tensile Testing

For the mechanical tensile testing, the ASTM D 3039/D 3039M-00$^{\varepsilon 1}$ standard [19] for tension testing of composites was used. The coupons were cut from several double layered tube specimens in the axial direction at 200x15 mm dimensions. The tests were performed at an INSTRON 8872 with a 25 kN loadcell, under controlled temperature and ambient moisture conditions and a rate of grip separation of 1.5 mm/min.

The results from the 1-g control specimens showed a maximum stress of 7.07±1.27 MPa, ultimate strain of 3.71±0.58 % and toughness 326.9±58.0 kJ/m^3. On the other hand, the results from the 0-g specimens performed better, showing a maximum stress of 11.59±1.60 MPa, ultimate strain of 4.81±0.48 % and toughness 741.5±168.2 kJ/m^3.

Comparing the 0-g specimens with the 1-g control, an increase in maximum stress of 63.9% is observed. Moreover, the tests displayed an increase of 29.6% in the ultimate strain and 126.8% in toughness.

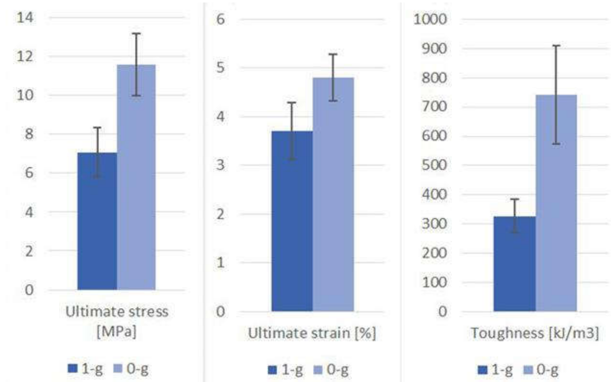


Figure 5. Tensile properties comparison of the 1-g and 0-g coupon specimens.

C. Coupon Compression Testing

For the mechanical compression testing, the ASTM D 3410/D 3410M-03 standard [20] for compression testing of composites was used. For the cutting of coupons, a bandsaw was used to cut several double-layer tubes in the axial direction at 90x15 mm coupon dimensions. The same testing and loading conditions were used as the tensile tests.

The results from the 1-g control specimens showed a maximum stress of 19.96±9.51 MPa, ultimate strain of 1.51±0.48 % and toughness 923.6±757.9 kJ/m^3. On the other hand, the results from the 0-g specimens performed better, showing a maximum stress of 24.21±4.33 MPa, ultimate strain of 1.38±0.19 % and toughness 1398.1±473.4 kJ/m^3.

When the 0-g specimens are put to comparison with the 1-g control, an increase in maximum stress of 21.3% is observed. As for the ultimate strain, a reduction of 8.6% is observed and the toughness is increased by 51.4% compared to the control.

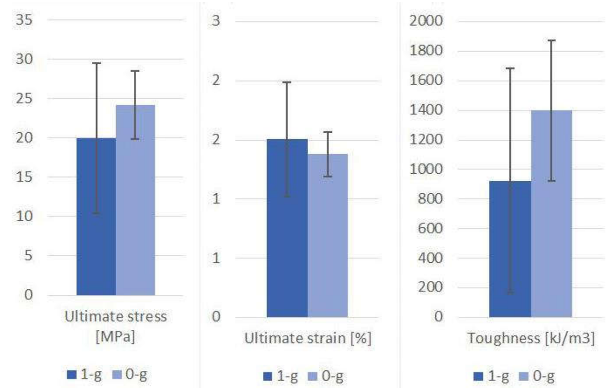


Figure 6. Compression properties comparison of the 1-g and 0-g coupon specimens

D. Tube Specimen Testing

A total of 2 double layer tube specimens were tested in single point bending as a single cantilever beam, using grip displacement loading at a rate of 5 mm/min. Prior to testing, the tube specimens were stripped of their polyethylene covers and from both edges 50 mm length of material was cut and removed due to imperfections. The final tubes tested were 360 mm in length, which corresponds to a L/D beam ratio of 8. Finally, the tubes were fixated on the testing apparatus with adhesive and then with hose clamps tensioned at 10 Nm.

Figure 7. Tube specimen single cantilever test setup.

The tube specimens were loaded until failure. The two specimens respectively displayed a maximum torque of 7.65 and 13.76 Nm at the base of the beam and displacement equal to 24 mm and 64.7 mm at the tip. The failure mode for the first tube was matrix failure due to defections and buckling of the fibres at the base of the beam. As for the second specimen, the failure observed was also matrix failure and fibre buckling, but at a distance of 54 mm from the base of the beam. In this case also, the failure was due to imperfections at that area.

Figure 8a-b. Failure mode of the tube specimen 1 (a) and 2 (b).

V. Results and Discussion

Experimental testing showed difference in the microstructure and properties of the composite, comparing the 0-g to the 1-g specimens, with the behavior of the 0-g specimens displaying better results compared to the 1-g.

In the microstructure, the wettability of the fibres has improved in the 0-g specimens in comparison with the 1-g control. This finding could support the hypothesis that in microgravity the surface tension of the liquids (resin in this case) dominates over gravity, thus providing better wettability of the fibres. Moreover, this effect could also be hypothesized to be caused from better and more uniform dispersion of the photoinitiator particles in the liquid resin during microgravity, thus providing a more uniform distribution of nucleation points during polymerization.

For the mechanical testing, the results displayed a large scatter in all cases and the conclusions reached are not definitive. The general trend shows that the mechanical properties of the 0-g coupon specimens are higher when compared with the 1-g control. However, the large number of imperfections, such as voids, fibre misalignment, variations in thickness and in shape, produced large scatter in the results. The tube specimen tests showed that no valid results could be drawn, due to the large number of aforementioned defects intervening with correctly assessing the properties of the structure. More testing and investigation is foreseen in the future.

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Sounding Rockets to Revive Passion for Space Exploration

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***Abstract*— Cosmic Research is a student association aiming to launch a rocket into space to revive passion for space exploration. The group is dedicated to the development of sounding rockets and making knowledge more accessible. This paper presents the association's milestones and their projects to reach space.**

Keywords—rockets; sounding; space; students; opensource; education

I. Introduction: Context

Space exploration poses extreme technological challenges that help push the boundaries of human knowledge. Multiple tangible benefits stem from this activity, reaching numerous areas of society. Such are telecommunications and aviation, but also medicine, agriculture and many more.

Because of the apparent long-term effectiveness of these benefits, space exploration is often regarded as an unreasonable expense by a big group of people. Neither do world authorities perceive it as a relevant issue anymore – let us take as an example NASA's budget reduction since the Space Race ended [1]. The uninterest for this activity might be caused by a collective short-term vision, induced by omnipresent social, political and war tensions over the last 30 years.

Obviating the development of space exploration could have tragical consequences for humans in the mid and long term. Such might be the lack of resources – as that of growingly used scarce metals [2] – and ultimately, overpopulation and extinction.

In this context, Cosmic Research was founded to change people's perception – especially that of the young – about space exploration. Created as a non-profit, this team of university students has set itself the objective of sending a homebuilt rocket into space. Their ultimate goal with this project is to generate enthusiasm about space exploration.

II. Foundation (June 2016)

The project was started in 2016 autonomously by four engineering students from Universitat Politècnica de Catalunya. Three of them were aerospace engineering students at the School of Industrial, Aerospace and Audiovisual Engineering of Terrassa (ESEIAAT). The fourth was a software engineer student at the Barcelona School of Informatics (FIB).

Cosmic Research was constituted as a non-profit association in June of that year. The vision of the association was stated as *"To reignite passion about space exploration and offer space-related education openly to the public"*. The members decided to build rockets to draw people's attention to the topic of space exploration. Developing rockets from scratch also provided a way of making knowledge about rocketry more accessible.

III. Early steps (Summer 2016)

In June 2016, the team purchased and assembled a high-power rocket kit as a way to get familiar with amateur rockets. The rocket was named Valentina in honour of the first woman in space. Valentina was successfully launched twice from an aerodrome in Alcolea de Cinca, Spain. The second time, it reached a peak altitude of 900 m, carrying inside a custom altimeter made from an Arduino board. These first launches gave the team vital experience in the matter [3].

In November 2016, the team designed and static-fired its first homebuilt rocket motor. It consisted of a solid mixture made of potassium nitrate – the oxidizer -, and sorbitol – the fuel. The test was a success, paving the way for future research on solid propellants.

IV. First fully self developped rocket (March 2017)

A. Introduction and Mission Objectives

In December 2016, the team members proposed a new mission. Its main objective was to develop and launch an experimental rocket into 2 km. The design phase concluded in January 2017, and the rocket was built during February. It was named Resnik, in honour of the first Jewish woman in space. The team decided to name their rockets after female astronauts to pay tribute to women dedicated to space.

B. Airframe Construction

The rocket airframe was built on two one-meter commercial phenolic tubes sold by Public Missiles Ltd using a carbon-fibre skinning process. This process consists in adding a layer of carbon fibre to a basis through several layers of epoxy. This method is known to substantially increase the strength of the original structure without adding too much weight.

The ogive was also bought commercially and it is made from high-strength polyethylene. This allows radio signals to pass through the rocket's airframe. The fins were laser-cut from high-quality aircraft plywood and attached to the to the airframe using epoxy.

The rocket used a conventional dual-deployment system for its recovery. It consisted of two nylon parachutes, deployed using an electronic system that triggered a pyrotechnic charge.

C. *Propulsion*

Resnik was powered using an experimental solid mixture made of potassium nitrate and epoxy. The formula for the propellant was inspired by a similar one developed by Richard Nakka, a mechanical engineer versed in experimental rockets [4]. This combination is known to offer unrivalled reliability and an acceptable specific impulse – a measure of the engine's performance. Sugar-based formulas were discarded due to their instability.

The combustion chamber consisted of a 60/60-aluminium cylinder, two metallic closures and the nozzle. The nozzle was designed and machined in-house from a cylindrical steel piece.

D. *Avionics*

Resnik carried a telemetry and tracking system. The rocket had 2 independent raspberry pi zero acting as independent OBC. The first one was recorded and stored an onboard video through a CMOS camera. The second one (main computer) was used for the recovery, telemetry and tracking systems.

The second raspberry read data from an 9-DOF IMU, a temperature sensor, a barometer and some GNSS signals. After performing some calculations, the main computer sent orders through an amplification circuit that deployed the drogue parachute (when apogee reached) and the main parachute (at 150 m above the ground). The coordinates, height and Euler angles were sent through an UHF link using the RFM69 transceiver, LoRa techniques and a monopole antenna.

On the ground, data was received using a 5-element Yagi-Uda antenna, connected to the same transceiver described before. Then, the data was sent to a laptop through an Arduino Uno.

It was possible to visualize the rocket position in real time. A commercial electronic mini Alti-Duo was also added as a redundant system.

E. *Launch Day and Data Summary*

The rocket was launched in March 11, 2017 from Alcolea de Cinca, Spain. It rose to an altitude of 1930 m, probably setting a new record for non-professionals in Spain. It reached a maximum speed of Mach 0,8 – 1000 km/h. Onboard avionics provided relevant data during its trajectory and deployment mechanisms worked as expected. The rocket described a narrow parabolic flight and was recovered using two parachutes. The mission was considered a success.

Fig. 1. GPS view of the rocket trajectory. Map source: Google.

V. PUBLIC OUTREACH AND CANSAT PROJECTS (SUMMER 2017)

Following the success of Resnik, the Cosmic Research project was officially presented to the public. The team grew from less than 10 to more than 20 members.

During the summer of 2017, Cosmic Research participated in various educational activities. A remarkable one was the launch of a CanSat developed by local high school students [5]. A CanSat is a can-sized device mimicking a small satellite.

The team of Cosmic Research gave advice to the students and performed two launches. A small rocket named Ansari was assembled for this purpose. The first launch served as a test, containing a mock-up CanSat. The second one deployed a real CanSat at an altitude of 1439,1 m above the ground of Alcolea de Cinca. The CanSat obtained consistent lectures of pressure and temperature. This mission was considered a success and it opened the door for future CanSat launch campaigns.

VI. A ROCKET INTO THE STRATOSPHERE (2018)

A. *Introduction and Mission Objectives*

In September 2017, the members of Cosmic Research set themselves the goal of sending a rocket into the stratosphere before 2019. The corresponding mission was named Bondar and its main objective is to launch an experimental rocket into 15 km. Bondar has been conceived as a prototype of a rocket that could reach space within 2022.

B. *Launch Site*

To minimize the risk this mission might pose to other beings or properties, Cosmic Research is in negotiations with INTA, a Public Research Organisation that depends on the Spanish Ministry of Defence. Cosmic Research would make use of INTA's El Arenosillo facilities for their launch campaign. This site is located in a safe area in the south coast of Spain.

C. *Stability, Aerodynamics and Trajectory Studies*

In order to analyse the rocket's flightpath, an important part of the team has been working in the development of a computerized simulator. The intended apogee was fixed at 15 km above sea level. To achieve this, different research lines were opened.

The first one was linked to the rocket propulsion, as the simulator contains the predicted instantaneous thrust that the rocket will be subjected to.

The second research line regarded aerodynamics and stability. This part of the simulator can predict the rocket's apogee and lateral deviation, as well as the external forces that affect it [6].

The final research line studied the roll, as it is known that inserting a certain amount of roll in the rocket flight can help to stabilize it and diminish its lateral deviation. This part has yet to be implemented in the simulator.

The following image illustrates how this simulator operates.

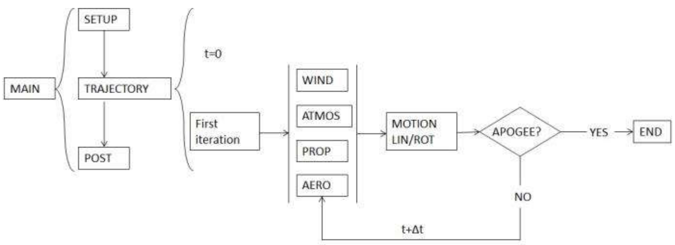

Fig. 2. Rocket simulator functioning overview.

D. Research on Propulsion

It was found that the development of a solid motor capable of bringing an average total impulse of at least 30 kNs was necessary for Bondar [7]. The propellant formulation uses Ammonium Nitrate (AN) as oxidizer and a metallic charge combined with burn rate enhancers and other additives to propitiate the ignition of the motor. The current objective is to develop and characterize a formulation that gives a specific impulse greater than 200 s.

It is known that using AN has important drawbacks, one of them being the change of the allotropic structure form at 32 ºC. This change produces a 4% increase of volume that significantly affects the mechanicals properties of the grain. An experimental process is being developed to stabilize the phase of the AN and test its efficiency.

Other technologies developed by Cosmic Research include: the propellant manufacturing process, the ignition system, the union elements and choosing the proper configuration of insulating materials to protect the combustion chamber structure from the adverse combustion conditions and as well obtaining the desired thrust profile.

E. Structural Studies

As to ensure the rocket's integrity during the flight, all stresses acting on the rocket were modelled into the global simulator. The simulator is able to calculate the dimensions of the motor casing, as well as those of other structural components. It uses the inputs of the trajectory simulator.

It has been found that the structural capabilities of the materials used are highly dependent on its working temperature. As a consequence, a heat transfer analysis of the combustion chamber has been performed. The analysis considered: the heat transferred by the combustion gases by convection, the aerodynamic heating and the heat transferred by conduction.

Vital was the development of an algorithm that computes the heat transferred inside the propellant – which acts also as a heat insulator. The result is that the sizing of the main structural parts of the rocket, including the insulators, has already been completed.

Additionally, a motor test bench was built in order to test experimental propellant formulas.

F. Avionics System

The Bondar's avionics system is divided in three independent parts: the flight termination system (FTS), that will destroy the rocket when ordered from ground, the video computer, that will record in video and stream the entirety of the flight, and the main computer.

The main computer has been built using a Texas Instruments MSP430 microcontroller. It is connected to several sensors such as a GNSS receiver, a barometer and an inertial measurement unit (IMU). It will be in charge of triggering the recovery systems. It will also act as a flight recorder and will send data to the ground systems about the flight progression.

To achieve real-time performance, the main computer will use a real-time operative system. This allows asynchronous and event-based programming. A firmware that exploits both patterns has already been built.

Two different protocols and two antennas will be used for the communications between ground and the rocket. The data link will employ a frequency of 869 MHz. The onboard emitter will be a monopole antenna and the receiver, a helix-shaped one. It will work under the LoRa protocol, that allows for long range and low consumption communication.

The video link will be possible through a 2,4 GHz frequency and a motorized parabolic antenna. The standard IEEE 802.11 protocol – commonly referred as Wi-Fi – will be used.

G. Recovery System

The rocket is meant to be launched from a ground-based launchpad and splashdown in the ocean.

At apogee, the rocket avionics will trigger a CO_2-based system. This will split the fuselage in two, the booster part being jettisoned in the sea. The nosecone containing the avionics will descent using the pilot. The main parachute will be deployed at a safe altitude close to sea level to reduce the rocket recovery radius. The main will remain folded in a deployment bag and attached to the nosecone until the avionics fire two cable cutters.

H. Mission Current State and Expectations

As this paper is being written, the simulator is considered to be almost completed. Validation using a commercial software is yet to be done. Initial simulations seem consistent.

The avionics and the recovery system are yet to be flight-tested but some preliminary ground tests indicate good results. A full-scale motor test will also take place before summer 2018.

If the Bondar Mission is accomplished successfully, the team will most certainly centre its attention to the "Spaceshot" Mission. This will consist in developing a rocket aiming to the Karman Line, set at 100 km. This limit is considered to be the frontier between Earth's atmosphere and outer space.

Cosmic Research believes this endeavour will cause great media impact and help attract people's attention to human space activities. An achievement like this will most likely serve as an inspiration for students and young people in general. Besides, it is the commitment of the team to share what they learn through this process openly with the public.

ACKNOWLEDGMENTS

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Challenges for European Hands-on Education Projects in the Field of Rocketry

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Abstract — **Germany's student sounding rocket programme "STERN" (Studentische Experimental-Raketen) is a nationwide education programme initiated by the German Space Administration DLR (Deutsches Zentrum für Luft- und Raumfahrt) in 2012. The project's objective is to promote young professionals for launcher systems and to establish a practical education of students in the field of aerospace engineering. In this context, eight university teams began to design, build and qualify their own experimental rockets including all subsystems from propulsion to payload. This wide approach makes the programme the biggest and most ambitious student sounding rocket project in Europe.**

After giving an update about the programme status and the conducted launch campaigns from ESRANGE (European Space and Sounding Rocket Range) in Sweden in 2015 and 2016, this contribution focuses on examining the challenges and benefits of this endeavour from the perspective of a participating university. References and comparisons are made to foreign rocketry programmes such as PERSEUS (Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique) in France.

One particular characteristic of the strategy of STERN is to give the student teams the freedom to develop and test the rocket engines themselves. The ethanol / liquid oxygen bi-propellant engine of TU Dresden might be the most complex rocket engine within the programme. The lessons learned from developing and verifying such an engine in a university environment are discussed. The paper rather concentrates on the operational and management aspects of the education project than on the technical characteristics, which have been described in detail in previous publications.

Keywords—student; sounding; rocket; education; programme

I. INTRODUCTION

In recent years, several hands-on activities in the field of rocketry have evolved in Europe's tertiary education domain. Some of them are national endeavours, like the programme "Studentische Experimental RaketeN" (STERN) in Germany or the programme "Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique" (PERSEUS) in France, others are local or regional initiatives, e.g. Delft Aerospace Rocket Engineering (DARE) at TU Delft. These projects show great differences in how they are organised and conducted. This goes along with varying resources. Although their technological and scientific objectives distinguish from each other, they all try to improve education in rocketry by giving students the possibility to not only learn the theory, but to turn it into practice by working on their own experimental and sounding rockets. While the importance, benefits and challenges of hands-on activities in general have been discussed in previous work [1], this paper will concentrate on the specific requirements and challenges of rocketry projects. Therefore, section 2 will outline STERN as an exemplary rocketry programme including its objectives, participating teams and scope. Section 3 will detail how a specific project within STERN is conducted: the SMART Rockets project at TU Dresden. This is followed by a discussion of the main challenges for student rocketry in Europe in section 4. Finally, a conclusion is given in section 5. The main goal of this contribution is to raise awareness of the importance of practical education in rocketry and the challenges that need to be resolved in order to enable upcoming generations of professionals to gain the skills they need to ensure Europe's access to space in the future.

II. STERN

Since the STERN programme has been described in detail in previous work [2], this section will focus on its overall scope and give an update on its current status. The programme is initiated and conducted by the German Space Agency (DLR) and funded by the Federal Ministry of Economic and Technology (BMWi). The main objective is to raise a new generation of well-educated and skilled young professionals, who will ensure Europe's autonomous and cost-effective access to space in the future, especially within the Ariane programme. To achieve these objectives, DLR provides financial and administrative support for participating universities, which develop individual rocket systems. One key characteristic of STERN is that the student teams have the freedom to design full experimental rockets, particularly including propulsion systems. So far, the programme has launched two cycles. Since they have no dedicated names, they are simply referred to as "STERN 1" and "STERN 2" as outlined in the following subsections.

TABLE I. MISSION RESULTS IN STERN 1

University Team	*Rocket*	*Engine*	*Propellant*	*Thrust [N]*	*Envisaged Apogee [m]*	*Reached Apogee [m]*
HS Augsburg	HyCOMET	Hybrid	HTPB + N_2O	1,000	5,000	-
HS Bremen	Aquasonic	Hybrid	PE + N_2O	1,000	6,000	6,500
ZARM / Uni Bremen	ZEpHyR	Hybrid	Parrafin + LOX	1,800	10,800	1,500 [5]
TU Berlin	DECAN	Solid	AL + APCP	3,000	7,500	5,500 / 5,700[a]
TU Braunschweig (ERIG)	Leonis	Hybrid	HTPB + N_2O	1,300	5,400	5,700
TU Dresden	SMART	Bi-Liquid	Ethanol + LOX	500	4,100	-
TU München (WARR)	Cryosphere	Hybrid	HTPB + LOX	8,000	15,000	-
Uni Stuttgart	HyEnD	Hybrid	Paraffin + N_2O	10,000	46,000	32,300

[a] *DECAN performed two flights with two individual rockets*

A. *STERN 1*

The first round of the STERN programme was launched back in 2012. Eight universities participated in the programme with individual rocket systems [2]. Although most of the teams have already launched their rockets successfully and thus concluded their projects, the programme is still ongoing with at least one remaining university team. In the original schedule, a total project duration of three years for each team, who had individual kick-off dates, was foreseen. However, all projects have been extended to account for the high organisational and technical complexity.

Three launch campaigns have been conducted at the European Space and Sounding Rocket Range (ESRANGE) near Kiruna in northern Sweden. No further launch campaigns are planned within STERN 1. The results of the first two launch campaigns, comprising 6 rocket launches by 4 teams in total, have been presented previously [3]. They took place in October 2015 and April 2016, respectively. The third and final campaign took place in October 2016 with two launches of equal rockets with the names HEROS 2 (Hybrid Experimental Rocket Stuttgart) and HEROS 3 by the Hybrid Engine Development (HyEnD) student group from the University of Stuttgart. The rocket has already been launched in the first launch campaign of STERN, but experienced a technical malfunction of the engine, which led to a non-nominal flight. The team made an extensive analysis of the failure and optimised the system for another launch attempt one year later. It turned out to be a very successful launch campaign, because HEROS 3 reached and apogee altitude of 32,300 m. “This set a new altitude record for European student and amateur rocketry and a world altitude record for hybrid rockets built by students” [4]. 0summarises the results of all teams and the launch campaigns that have been conducted within the STERN programme up to now.

It can be seen that most teams achieved a successful flight. In average, the apogee altitudes reached during the flights were lower than the apogees that have been estimated in the beginning. The main reason for this is the elevation of the launcher at ESRANGE, which has been limited to 80° or, in the case of the ZARM Experimental Hybrid Rocket (ZepHyR), even to 75° by the authorities from the Swedish Space Corporation (SSC) due to the experimental nature of the rockets, which might impose a higher risk to the launch range.

B. *STERN 2*

The second edition of STERN started in 2017. While eight teams have been supported in STERN 1, only 3 teams are supported within STERN 2 up to now. However, there has not been any official statement regarding STERN 2 from the DLR, so the technical goals of the programme remain unclear. The three teams of STERN 2 comprise HS Bremen with their rocket AQUASONIC II (project start 01.06.2017), TU Braunschweig with the rocket Leonis II (project start 01.08.2017) and Uni Bremen with their rocket ZepHyR 2 (project start unknown but the launch is envisaged for 2020). The duration of each projects is 3 years as it was planned for STERN 1. Instead of developing new rocket systems, the teams focus on enhancing and optimising the rockets flown in the previous projects. For instance, ZepHyR 2 will feature larger diameter and length as well as an increased thrust of 5 kN (compared to 1.8 kN), while the basic layout and propellants remain the same.

III. TU DRESDEN’S SMART ROCKETS PROJECT

The SMART Rockets project at TU Dresden features a biliquid propellant combination with ethanol as fuel and liquid oxygen (LOX) as oxidiser and is thus the only one of its kind within STERN. Figure 1 gives an overview of the rocket design and subsystems.

However, the project comprises much more than the rocket itself. To verify the complex propulsion subsystem, a suitable test bench needed to be developed, respective test plans had to be drafted and risk analyses had to be performed. Due to the particular complexity of this ambitious project, the objective was adapted and a stepwise approach applied. TABLE II. presents the timeline of the project. Moreover, it represents the extensive efforts in verifying the design of both the thrust chamber and the test bench itself. Significant delays result from manufacturing, which is further discussed in the subsequent chapter. Since testing is an iterative process and design changes are necessary before the next test campaign can begin, those delays add up drastically during the course of the project.

TABLE II. TIMELINE OF THE SMART ROCKETS PROJECT AT TU DRESDEN

Date	*Event*
End of 2007	Initial student theses on the test bench
August 2012	Begin of funding within STERN
September 2012	Start of rocket engine test bench setup
March 2013	Employment of two PhD students
December 2013	Rocket engine test bench operational
May 2014	Preliminary Design Review
July 2014	Initial test campaign, open combustions
August 2014	Test campaign on ignition
September 2014	First combustion chamber tests campaign
November 2014	Focusing project goal on engine development
March 2015	Second combustion chamber test campaign
May 2015	First flight combustion chamber test campaign
November 2015	Combustion chamber tests on full thrust
January 2016	Delta-Preliminary Design Review
February 2017	First flight thrust chamber test campaign
November 2017	Combustion chamber tests for increased thrust

IV. CHALLENGES FOR STUDENT ROCKETRY

The manufacturing of rocket components, especially considering complex parts for the propulsion system (e.g. cryogenic tanks suitable for LOX) is not just a technological, but also a management challenge. Usually, university teams have three options. The first is to purchase Commercial-Off-The-Shelf (COTS) parts. However, most products on the market are not suitable because they are either space qualified and therefore too expensive or they derive from another industry and do not meet lightweight design requirements. Another drawback of this option is that the students do not have the chance to design their own components. Thus, the learning effect is relatively low. The second option is to manufacture components in-house, i.e. in workshops run by the university. This is often the cheapest solution, since the material generates the only costs in most cases. However, the manufacturing times are usually quite high and frequent delays occur. This could be avoided by outsourcing of manufacturing processes, which represents option three. Yet this approach goes along with higher costs, for which there is often not enough budget. Therefore, each project has to make a trade-off between these options and either plan resources accordingly or chose a design in which COTS parts can be implemented. The latter option might not be desirable for any educational project.

Of course, the question of manufacturing is dependent on the source and amount of funding. The acquisition of funding is a challenge on its own. It seems that basically two approaches exist. On the one hand, there are student teams like DARE, who invest a lot of effort to reach out to sponsors and build a network of supporters over the years. This means that they also have to implement outreach as a mandatory activity in order to

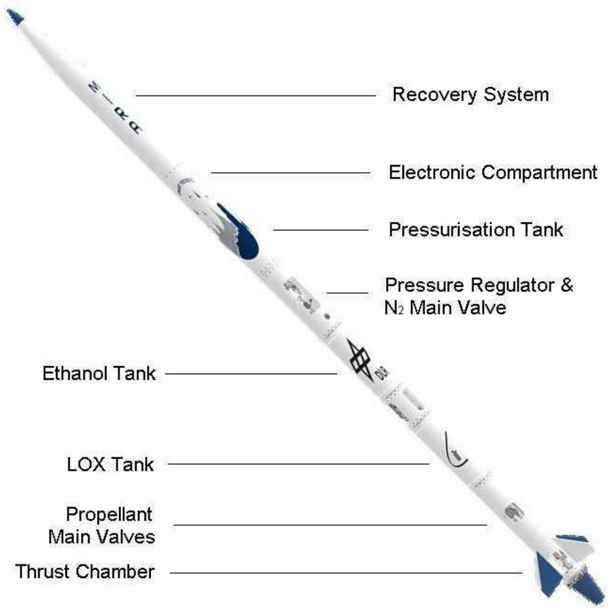

Fig. 1. Design and Subsystems of TU Dresden's rocket

represent their sponsors. Unless there is no existing network, finding sponsors has to be considered a time and workforce-consuming task. In general, the success rate is uncertain and allows only partial funding by each sponsor. Other activities rely on governmental funding, such as STERN and PERSEUS, which are programmes conducted by the respective national space agencies of Germany and France. Usually, they provide full funding for the projects. Still, there are many countries where such programmes do not exist and even the established programmes seem to struggle. As presented in section 2, the number of university teams funded in the STERN programme dropped from eight in the first round to only three in the second. One reason might be that even though budgets for education exist within the agencies, educational initiatives have to compete with other programmes. This competition can be tough, because such initiatives do not seem to fit to classical funding policies. While the outcome and success of a research project can be measured easily, e.g. by the amount of published papers, the success of educational projects can only be measured indirectly and over a greater time scale, e.g. by comparing the careers of participants to those of non-participants. Thus, it is harder to demonstrate the impact of such programmes. Consequently, it is more difficult to obtain and establish research budgets.

However, the need for funding is immanent for hands-on activities. This applies to rocketry in particular, as dedicated infrastructure is necessary for the conduction of verification tests, e.g. engine test benches, and for the launches themselves. Depending on system complexity, this can easily extend the scope of similar activities like CubeSat or payload developments. Even if this infrastructure is built, test and launch sites still have to be found, because they usually not rank among university standards. Existing ranges like Trauen, operated by the DLR, are accessible, but the test benches have to be provided and staff has to be paid. The DLR has built a test stand dedicated to student projects in Lampoldshausen. However, it is not suitable for any propulsion systems that require cryogenic fluids and is limited to solid and hybrid engines [6]. Therefore, some student teams try to find and establish their own test site, e.g. at their home university. Although this is potentially the cheapest solution, it is difficult to achieve due to the inherent emissions of noise and exhaust gasses as well as safety regulations. While this is limited to an extremely narrow time period, usually in the order of some seconds per month, the responsible persons are often overly concerned when they hear the words rocket or combustion. Moreover, appropriate space is hard to find within existing university estates. Consequently, conducting the obligatory verifications is challenging, time consuming and contains a high risk of causing delays.

But even if all verification has been done and everything is set for take-off, the right launch site still has to be found. This is considerably more challenging in Europe than in other parts of the world. While there is enough space to launch experimental rockets in the USA, even to higher altitudes, it is very challenging in Europe to find a place to launch at all. There are two launch sites north of the polar circle, ESRANGE in Sweden and Andøya Space Center in Norway. All rockets within STERN and PERSEUS are normally launched from ESRANGE. It is efficient to combine launch campaigns of several rockets. The main advantage of those sites is the experienced staff, whose support is particularly valuable for student teams. On the contrary, this makes launch campaigns relatively costly, adding to the high logistic costs due to the remote areas of the launch sites. Further challenges are the limited operation conditions as discussed in section 2 and that the launch site personnel has to be integrated in the development process from an early project phase on. It is advisable to let them participate in the preliminary design review and all subsequent meetings, to make sure that the rocket meets the requirements of the launch site. These requirements can be very different from range to range. For example, DARE launches frequently from the El Arenosillo base in southern Spain, where the implementation of an abort system that can be activated from ground is mandatory. Yet at ESRANGE, no active control or data uplink is desired. Thus, a rocket developed for a certain launch range might not be able to launch from other sites. Within public space in Europe, no further launch sites are known where flights to a reasonable altitude above some hundred meters are allowed and accessible for student teams. The only other option might be to launch from a restricted area. However, this goes along with its own challenges, because the military is not used to serve as a launch site provider for any type of civil research rockets. Further bureaucratic hurdles are imposed by the fact that most of these restricted areas are simultaneously nature protection areas. This might not apply for military activities, but any civil activity within the area has to comply with the respective regulations. This could prevent a rocket launch completely.

Finding a place to test propulsion system or the right launch site are not the only common challenges that student teams have to overcome. There are other issues, ranging from documentation to the procurement of specialised parts, that most of the teams have to face. Some of them are part of engineering itself, so it might be justified to train them, but others might just be seen as another cause for delays while not adding any value to the project. Such issues could be minimised by establishing a close exchange between the teams, so that one team can benefit from the solution another team already found and vice versa. This could accelerate the overall progress within student rocketry. However, this requires a platform, which also needs to be moderated. Despite the possibilities of the digital age, it seems that no tools have been established, neither by individual teams nor by an agency.

Another challenge for educational activities is the availability of students. As discussed in detail in previous work [1], students often do not get any credit for additional hands-on activities. Thus, they tend to focus on mandatory courses to complete their studies in time. This limits the participation in fields like student rocketry, even though such participation is considered to be highly appreciated by employers.

Even if sufficient participation can be ensured, it is hard to conduct projects due to conflicting schedules. Participating students still have to attend lectures and pass exams. Therefore, their commitment to the project might be very limited. In general, a cyclic behaviour of commitment can be experienced, which is closely connected to the year's study schedule. While commitment is high at the beginning of a semester, it decreases towards the exams, potentially forcing whole projects to pause. For longer projects, like in STERN, this means that progress cannot be planned easily and might be much lower than it would be for a continuous operation. In fact, this partly explains the delays discussed in section 2. For shorter projects, like the one-year-projects within PERSEUS, the challenge is to prevent any delays since the project cannot be extended, because the students will not be available anymore after the scheduled period. As for longer projects, new students would need to be recruited, creating further delays. This might be evident to students, but has to be communicated carefully to all stakeholders from the very beginning, since they might not be aware of these issues, which are not present in other research projects.

Nevertheless, not only the student participation is a challenge. To enable a close and continuous supervision by university staff can be also an issue. Since most contracts of scientific researchers, particularly PhD students, are not permanent, there is always the risk to lose key personnel, which would heavily affect the project's progress.

V. CONCLUSION

There is no single solution to the challenges that have been discussed in the previous chapter. It is also not the objective of this paper to present solutions, because any sustainable approach should be discussed by all stakeholders. Therefore, this paper wants to raise awareness for the challenges of student rocketry and give a starting point to spark such a discussion. It is evident that we have to foster future generations of space professionals and that hands-on activities do a great job in both motivating young people to pursue a certain research field and to better prepare the students for their professional careers. However, even established programmes like STERN and PERSEUS seem to struggle recently. This is not only unfortunate for the quality of space education, but imposes a threat to the future of the space transportation sector in Europe, which is already challenged by rising competition from North America and Asia. In this situation, student rocketry is not a risk but an opportunity. If it gets the right support, it can play a vital role in Europe's space strategy and allow cheap and easy research on novel technologies. But to do so, Europe needs to find a way to step forward. Obviously, the student teams cannot solve all problems on their own. National space agencies could help, but they usually operate within their country or the frame of bilateral agreements. Thus, an international entity is needed. A European student rocketry association could concentrate the ambitions across Europe, but it is questionable how such an institution could be created and funded. The European Space Agency could take a leading role here, but would need an increased budget for education and thus, the consensus of its member states. It seems that the Europe's future in space depends on how they will acknowledge the value of education.

Acknowledgment

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The ESEO Power Distribution Unit

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***Abstract*—In this paper a high-reliability satellite subsystem, the distribution unit of the onboard power system is discussed. Those design, construction and manufacturing methods are presented which ensure that the subsystem is able to provide operation, according to strict requirements, as a main unit of a satellite mission. The principles of developing and manufacturing was carried out by the group of Laboratory of Space Technology with contribution of students, based on the professional heritage of the ESA Rosetta Lander and implemented in the European Student Earth Orbiter (ESEO) mission which is the ESA's Education Satellite program.** SSEA-2018-

Keywords—ESEO-PDU, satellite, power distribution, cross-strapping, latched current limiters

I. About the ESEO

In the European Space Earth Orbiter mission, several European universities are involved and take part in the development of a subsystem element or a payload for the ESEO spacecraft or in the operation of the ground segment. This educational project provides outstanding opportunity for university students and young professionals to participate in a challenging space project which gives well-applicable and practical experience for the next generation of space workforce. The ESA takes part as the founder and supporter of the project and according to the new tender, ALMASpace and later SITAEL is included as the company that coordinates the assembly process and the final integration of subsystems and payloads to the new ESEO mission.

The ESEO project is a microsatellite mission, placed on Low Earth Orbit (LEO) and aims three main objectives during its 2 years long lifetime. One of them is to take images of the Earth's surface and other celestial bodies for educational outreach purposes. Another is to measure the radiation and plasma properties of the environment in Earth orbit, and the last is to test technologies for further educational satellite missions [1].

The satellite uses sun-synchronous near circular target orbit with 524km altitude and 97.4° inclination. The orbit procedure identifies 15 orbits per day in order to provide an appropriate coverage of the inspected area [1].

The new concept of the spacecraft has two main changes over the previous principles. The new ESEO has a mass of ~45kg, and a size of 330x330x630mm which means significant reduction in both parameters. The two modules of the satellite (the bus and payload module) contain all the subsystems and payloads which are physically isolated from each other. The main bus is also separated from all the payloads and in order to enhance the overall reliability level, redundancy is implemented for most of the units [1].

In the final phase of the mission, a special De-orbiting Mechanism function will start that provides the end of deployment of the satellite by re-enter it to the Earth's atmosphere [1].

II. The Power Distribution Unit

The main objective of the Power Distribution Unit (PDU) is to supply electrical power to the subsystems and payloads of the satellite and to prevent the overload of the main power bus. The PDU consists of two identical units (the main and the redundant) that are interfaced with each other in order to provide the required redundancy [2].

Both motherboards are interfaced with the Power Management Unit (PMU) of the satellite by redundant synchronous serial Low-Voltage Differential Signalling (LVDS) lines using a full cross-strapping redundancy scheme.

In order to manage the power distribution and prevention functions each payload and subsystem has a dedicated Latched Current Limiter (LCL) circuit which connects them to the main power bus. An individual current limit and undervoltage protection level is defined for every LCL as referred by the requirements of the payload or the subsystem.

The control function of the PDU is managed by an FPGA, using CRC protected communication interfaces and combinational logic network in it. The FPGA controls the LCLs with individual ON and OFF command interfaces, furthermore collects and processes their telemetry by reading the telemetry interfaces of the LCLs (see Fig.1.). Since the main and the redundant PDU unit are interfaced with each other every single LCL, including the command and the telemetry interfaces, can be accessed and managed by both PDU section so the prevention against any single-point errors can be realized.

The applied LCLs can be classified according to the used design principles into two categories, the BME-LCL and the ESA-LCL. The ESA-LCL contains a newly developed current limiter IC (RHFPMICL1) so the secondary goal of the PDU is to test this IC by involving it into the design.

The PDU utilises a control circuit called Fire and Select with which it is able to activate the Non-Explosive Actuator (NEA) units by providing an isolated command line to the Telemetry and Telecommand (TMTC) subsystem of the satellite. At the end of the mission, the PDU will be responsible for the power support of the De-Orbiting Mechanism, controlling it via the Fire and Select.

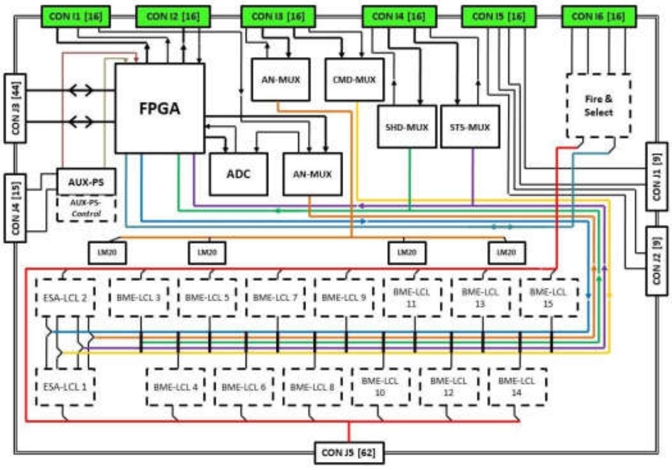

Fig.1. PDU block diagram

Both of the motherboards possess an individual power supply circuit called the AUX-PS which is a switching-mode power supply that has an own control board, with the task of providing electrical power to the FPGA, ADC and to the multiplexers (see Fig.1.).

The Fire and Select circuit, the AUX-PS control, and both type of LCLs are called as daughterboard because their functions are realized on separated PCB boards that are vertically assembled to the motherboards (see Fig.2.) with a unique assembly method.

III. BME-LCL

The BME-LCL is an overcurrent protection circuit. The circuit contains two redundant input command lines (ON and OFF command) and three output lines as status and overload digital telemetry and analogue current telemetry.

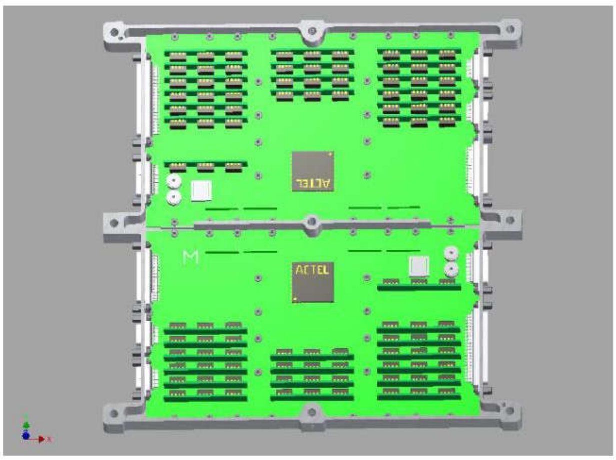

Fig.2. PDU configuration

During normal operation, the LCLs turn on and off the payloads and subsystems of the satellite. When an unit is malfunctioning the LCL prevents the overload of the main power bus by limiting the input current of the unit at a maximum level. This maximum level of the current is the trip-off current. In order to avoid overheating the LCL the continuous current limitation mode shall be terminated by turning off the faulty unit after a specific time that is the trip-off time. After an overload trip-off it is essential to wait enough until the limiter can release the heat that was accumulated during the limitation. During this period the LCL cannot be turned on again. This time is called the on-reject time. Both times were chosen considering ECSS (European Cooperation for Space Standardization) derating recommendation. Additional the LCLs limit the inrush current of the unit therefore it provides a very controlled profile for all inrush parameters at switch ON [3]. By the trip-off current the LCLs can be distinguished into three current classes specified by the energy needs of the loads.

Each LCL contains an undervoltage lockout circuit (UVLO) that disconnects the unit or prevents its connection to the power bus when the bus voltage is under a certain level. The aim of the UVLO is to reserve energy of the main power bus for the essential units by disconnecting the loads in a predefined sequence. There are four different LCL classes specified by the threshold voltage level called shedding class, which represents the importance of the unit.

The two redundant command lines are unified with a galvanically isolated pulse command interface. This receives the commands from the FPGAs directly from the main and through multiplexers from the redundant side. With the galvanically isolated pulse command interface if one of the command lines is short circuited to the high or low voltage level the other command line is still functional.

IV. ESA-LCL

ESA LCLs are based on rad-hard integrated current limiter controllers (RHFPMICL1). Some of the parameters of the integrated circuit like the UVLO threshold, trip-off current, trip-off time and operational modes can be programmed with external components. ESA-LCL provides analogue current and digital status telemetry.

On the ESEO satellite the ESA-LCLs are protecting the main systems. These systems are essential to the operation of the satellite and should be always powered when the voltage level of the energy bus is sufficient.

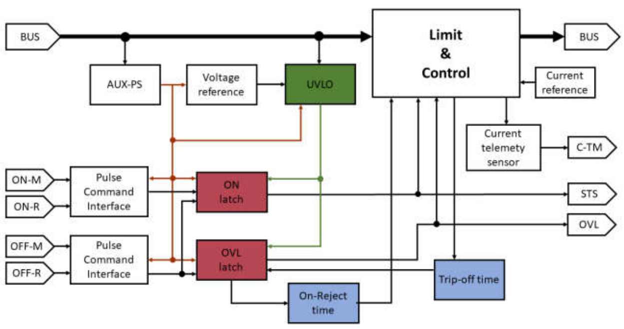

Fig.3. BME-LCL block diagram

ESA-LCLs are operating in re-triggerable (R-LCL) mode. This means that following an overload trip-off the limiter automatically turns on again after a specified time that is called recovery time. When the LCL shuts down after an overload it writes its digital status telemetry register to indicate that a trip-off event occurred. This status can be cleared with a command from both main and redundant side through pulse command interface to detect further trip-off events. This overload status does not affect the operation of the R-LCL. The recovery time can be set with external components as well.

The LCL is configured ON by default at power up. As consequence of the re-triggerable mode of operation the R-LCL do not have ON and OFF command interfaces.

V. Fire and Select

The unit of Fire and Select plays an important role which is to provide power for the Micro Propulsion System (MPS) and for the De-orbiting Mechanism (DOM) at the end of the mission. The circuit is accommodated in a daughterboard so both the Main and the Redundant motherboard have a Fire and Select circuit board. The Fire-event refers to the actuation of the pyro lines to the DOM and MPS. The pyro line actuation is triggered by the Fire-signal which is given by the TMTC system as a response to a high-priority command.

The command sequence consists of three main steps which ensure the high-reliability of the activation method for the pyro lines. The first is to turn on the dedicated LCL, thus powering the Fire and Select, by a normal ON command on the LCL Control Register. Then the bit in the position of the DOM or MPS in the LCL Control Register will be set so the selected pyro line can be activated by a Fire-signal from the TMTC. The last step is when the Fire-signal, from a direct, high-priority telecommand, activates the selected pyro line, dedicated to DOM or the MPS.

The actuation of the selected pyro line can be monitored in two dedicated status registers that belong to DOM and MPS. These registers can be cleared by the FPGA through common pulse command interface.

VI. AUX Power Supply

The AUX-PS is responsible for supplying the FPGA and all the digital components on the motherboard (Analogue-Digital converters, multiplexers, and temperature sensors). It is realized as a switching-mode power supply with a Buck-converter. The control method of the converter is implemented as current-mode control as it contains a "current-sensor" resistor, a comparator with hysteresis and an error amplifier with reference. These three main parts of the control function and the Buck converter can be seen in the middle of the block diagram (see Fig.4.).

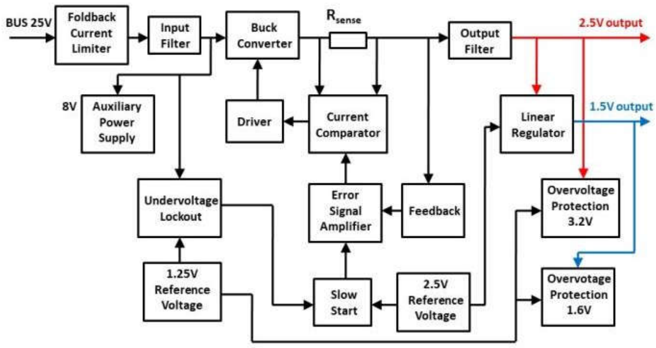

Fig.4. AUX-PS block diagram

The power supply uses the main power bus as an input (18V-25V) and provides two outputs with 2.5V and 1.5V supply voltage. Those components which belong to the converter power block or the input and the output filter are located on the motherboard while the components of the control circuit can be found on a separated daughterboard.

AUX-PS contains a Foldback Current Limiter (FCL) circuit before the input filter in order to prevent the overload of the main power bus. Additionally, an internal linear power supply takes place in the AUX-PS whose function is to provide 8.5V voltage for the blocks of the control circuit.

The power supply possesses two protector circuits with different goals. The first one is the Undervoltage Lockout (UVLO) which disables the converter when the voltage of the main power bus decreases below a specified value. The converter turns off below 15V and starts to operate above 16V. The other is the Overvoltage Protection (OVP) circuit that uses two shunt regulators to prevent the overvoltage on both outputs. The protection method is to limit the output voltages to a certain value. These specified voltages are 3.3V and 1.65V.

The control circuit and the OVP operate with independent voltage reference so that avoiding output overvoltage caused by a single point failure.

VII. Controlling Method of the PDU

The operation of the PDU is controlled by Microsemi's high reliability, industrial grade FPGAs that were tested also by ESA for radiation [4]. There is one FPGA on the Main and one on the Redundant board. The FPGAs are responsible for the controlling of the ON and OFF commands and reading the statuses of the LCLs. In addition, the PDU Control operates the analogue digital converters and reads the telemetry lines.

The PDU is commanded by the PMU using synchronous serial communication protected by an 8bit CRC. Various command lengths are applied between 16-40 bits including CRC bits. The error detection has a Hamming Distance of 4 or 5, depending on the data length.

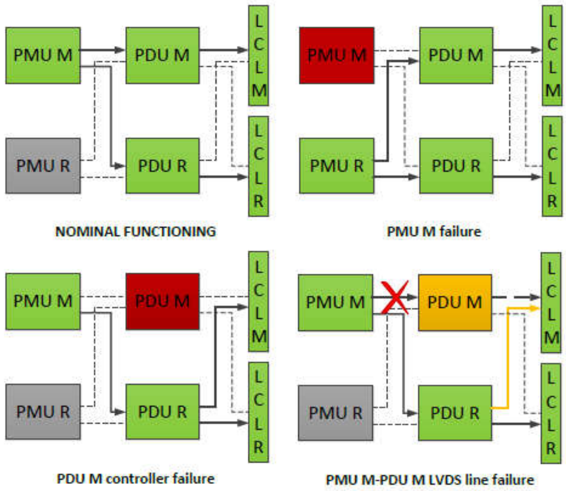

Fig.5. Failure mode examples

In normal operation one FPGA only controls the daughterboards placed on its motherboard with direct command lines. However additional command lines connect the two motherboards. Thereby the cross-control of the daughterboards and reading the telemetry lines becomes available. This means if the direct communication fails anywhere or one of the FPGAs stops working the daughterboards are still controllable from the other side. Some examples can be found on Fig.5.

The cross-strapping lines do not provide direct connection from – for example – the main FPGA to the daughterboards of the redundant PDU panel. The interfaces of the daughterboards are accessible through multiplexers – one at a time. This robust design increases the fault tolerance of the PDU.

VIII. MECHANICAL DESIGN AND TESTS

The concept of PDU can be described as a unique way of power distribution on small satellites. The solutions that used in the design and in the assembling progress are unique such as the accommodation and fixation of the daughterboards onto the motherboard. The daughterboards are assembled to the motherboard vertically and supported with specially shaped, surface treated aluminium struts in order to prevent failures occurred by vibration. To verify the pertinence of the principles of developing, several tests were carried out with the manufactured EBB2 (Elegant Bread Board 2) model (see Fig.6.) which is the same as the PFM (Proto Flight Model) (see Fig.7.).

The EBB2 was subjected to vibration test on qualification level. Full Functional Tests (FFT), Reduced Functional Tests (RFT) and Performance Tests were carried out on -25°C, 25°C and +70°C during the thermal environmental cycle tests and EMC tests was conducted with the combination of RFT. Before the integration of the ESEO platform the PDU is assembled into its frame which is opened from the top side therefore only conducted EMC tests were required. The radiated emission and radiated susceptibility tests will be performed after the integration of the platform when the frame of the unit above closes the top of PDU frame.

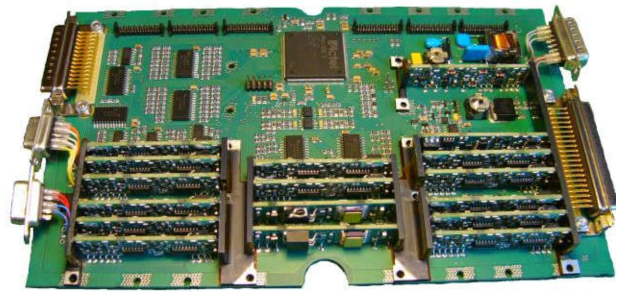

Fig.6. The manufactured EBB2 model

IX. EDUCATIONAL RETURN

This project has given an outstanding opportunity for university students to contribute in the system-side development of the ESEO. During the years of development the project was opened for enthusiastic students because involving young people in the space industry and guiding the next generation of space workforce have always been an essential principles of the Laboratory. They could have acquired lots of useful theoretical and practical solutions and the distinguished point of view of space projects. To construct the distributional part of the power subsystem, students have obtained and also have utilised the requirements of ECSS harmonizing with the design philosophies of the PDU to provide the good practice of the construction. Beside the acquirement of the knowledge of the system-side point of view, manufacturing the PDU unit has been a useful hands-on experience as students have been participated in the design and manufacturing process alongside with endorsing supervisors meanwhile completing their project subjects.

To mention some important hands-on aspects of the project among many others, active participants could have learnt how to perform measurements with complex measurement instruments -for example with thermal chamber-furthermore all the external bread board based test setups have been constructed by them. Moreover they could have got an insight into the approach of the documentation process concerning a real space project. Thanks to that useful knowledge many of past students, who has been working on the PDU unit, now is working at space related companies.

Educational curriculum has also been influenced by the PDU project as the operational principles and the practical applications of the LCLs have been involved in the thematics of two university subject such as the Space Technology and Space Technology Laboratory.

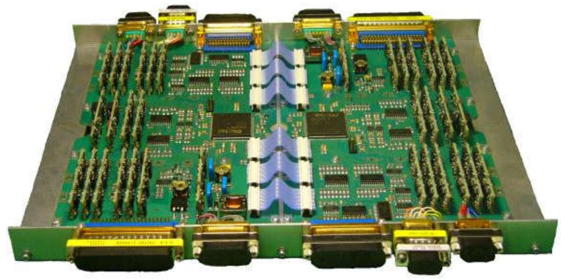

Fig.7. The PFM unit

X. Conclusion and Student Participation

The design and implementation were constructed with the involvement of several active university students who worked in the Laboratory of Space Technology during the history of ESEO (2006-2018) and who took part in the internship programs, training courses and in the design and in the test campaign.

With the former prime contractor, by the end of the PDR closure, at the beginning of 2011, the task of our laboratory was the development of the complete Electrical Power Subsystem (EPS) of the ESEO. After the continuation of the ESEO program in 2013 our contribution to the platform was reduced to the Power Distribution Unit. The conceptual change in the power management scheme required a complete reconsideration of the former design thus giving the opportunity to involve new students with new tasks into the program by the framework of project laboratory, thesis work or summer internship programme. Students were regularly attended at conferences and seminars presenting their results in form of oral presentation, posters and papers in conference proceedings [5][6][7].

The complete design and the inductive components of AUX-PS, moreover the whole set of adjusted LCLs are also products of work of students [8][9]. The EMC and FFT tests were also carried out with the significant contribution of students of the laboratory.

Tests on PDU were finished at the beginning of 2018 so the flight model could be delivered in the first half of this year.

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Wave-based attitude control of EIRSAT-1, 2U cubesat

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Wave-based control is a relatively new way to design controllers for under-actuated mechanical systems. It has several attractive properties, including robustness to un-modelled system dynamics, robustness to non-ideal actuator behaviour, reduced sensing requirements, and an ability to cope well with system flexibility and resulting vibrations. It has been successfully applied to flexible robots, cranes, and materials handling, for example. But it is also particularly well-suited to space applications, including attitude control of large space structures and debris control using elastic tethers. Currently a wave-based toolbox is being developed under a contract with ESA where the main application is robust control of launchers with significant structural flexibility and sloshing of on-board liquid propellant.

It is now planned to have the first in-flight, space-test of wave-based control on EIRSAT-1, which is a 2U cubesat being developed under ESA's Fly Your Satellite! programme by a team of students from University College Dublin. With ESA's significant support, and subject to meeting ESA's stringent requirements, the project is to design, build, test, launch and operate a satellite with three payload experiments, where wave-based control is the third experiment. The plan is that EIRSAT-1 will use a space-qualified, commercial, off-the-shelf attitude determination and control system for the first part of the mission. Later a command from ground will switch attitude control from the commercial board to wave-based control, to test and evaluate its performance in this application. Because of design constraints, the actuation is by two-axis magnetorquers, which restricts the magnetic dipole to a plane, rather than the preferred 3-dimensional space. Furthermore, the inclination of the ISS orbit means the satellite experiences a continuously changing geomagnetic field. Thus, the space of available control torques is quite limited. Furthermore, the available torque magnitudes are minuscule in the context of the moments of inertia of the 2U cubesat.

Extensive computer simulations have been carried out in modelled space environment which predict good performance even within these strong constraints. Changes in attitude are slow, but workable. Shortly hardware testing will begin. A challenge here is that the torque from the magnetic actuators are so small that complete experimental testing on the ground is very challenging.

Keywords—CubeSat, Wave-based control, Attitude determination and control, Fly Your Satellite!, EIRSAT-1

I. Introduction

EIRSAT-1 is a 2U cubesat being developed under ESA's *Fly Your Satellite!* (FYS) programme by students from University College Dublin. This cubesat will carry three experiment payloads: a novel gamma-ray burst detector, an array of samples of new thermal coatings designed for spacecraft, and software implementing a control algorithm. This control algorithm is wave-based control (WBC) and will be used to control the satellite's attitude for a portion of the mission. The algorithm is designed to give good control of flexible or under-actuated mechanical systems [1].

Flexible structures offer many advantages over their rigid counterparts. They can be much lighter, making them easier to accelerate and cheaper to manufacture. Minimising mass is crucial for spacecraft, and resulting structures are often flexible, making it much more difficult to control their motion. Motion can cause long-lasting vibrations, limiting manoeuvre speeds and position accuracy. Such limits are undesirable in many space applications such as spacecraft attitude control and robotic arm control.

WBC is a novel method for controlling flexible, under-actuated mechanical systems. It has been shown to be very suitable for controlling flexible robot arms, launch vehicles with sloshing propellant, and large space structures [2-4]. The idea behind WBC is that motion within the flexible system can be described in terms of mechanical waves which can travel through the system in two directions; one travelling away from the actuator (outgoing), the other travelling towards it (returning). The actuator launches waves into the flexible system and then absorbs returning waves. When all the launched waves have been absorbed, the system will have undergone the desired reference motion and vibrations will have been damped and removed from the system.

It has been proposed that WBC be used to control the attitude of the EIRSAT-1 cubesat. This satellite has a rigid structure with flexible antennae. However WBC's vibration damping properties are secondary to this application. Control of EIRSAT-1's attitude presents new some challenges. The first is that WBC will need to control the attitude of the cubesat about 3 axes. WBC has mainly been used for 1-D or 2-D systems. The second challenge is that the cubesat actuators will be magnetorquers, which are novel to WBC. Their control authority is very strongly limited.

This paper outlines how WBC will be used for the EIRSAT-1 mission. It describes how WBC will be carried as an additional software payload, when will it be used on the mission, and how will it be tested. Then, a method for using WBC to control EIRSAT-1 is presented. Results from simulations will then be presented. These are simulations in which WBC is being used to control the attitude of a cubesat model in various scenarios. Finally, a summary of future plans will be discussed.

II. WBC PAYLOAD

It has been planned that WBC will be used to control the attitude of EIRSAT-1 for some of its mission. This is done to help qualify WBC for use in other space applications and to evaluate its ability to control the attitude of a cubesat. Since WBC has not been space-tested, there is some risk. Therefore, for most of the mission, EIRSAT-1 will use a space-qualified, commercial, off-the-shelf (COTS) attitude determination and control system (ADCS). WBC will be considered as an additional experimental payload with no extra mass. It will comprise software running on the satellite's on-board computer. At some point in the flight, control over the satellite's magnetorquers will be handed over to WBC. The WBC payload will still use the attitude determination function of the COTS ADCS hardware. The WBC system will then be tested by commanding it to carry out a series of manoeuvres. After the tests, or if some significant problem is detected during a test, control will be handed back to the COTS ADCS.

This strategy removes the need to develop custom ADCS hardware for EIRSAT-1. To test its performance, WBC will be given a series of tasks, of increasing difficulty, which an ADCS should fulfil. The tasks will include making step changes in attitude (both small and large), detumbling, and trajectory tracking. Each WBC test will be monitored by supervisory software on the on-board computer. If the system starts to behave unexpectedly (e.g. excessive power consumption or delays in completing manoeuvres) control will be given back to the COTS ADCS to return it to nominal attitude control (zenith/nadir pointing).

III. WBC FOR CUBESATS

There are some challenges in using WBC for attitude of EIRSAT-1, which will be described below. First we give a brief outline of traditional WBC.

WBC is most easily understood with 1-dimensional lumped flexible models with a position input as shown in Fig 1. The actuator takes in a position command and moves to that position, x_o. In other published works on WBC, the idea of mechanical waves is described [3-5]. The actuator moves and launches a "wave", or propagating motion, into the chain. The wave travels down the chain, moving each mass. The wave is reflected of the end and travels back to the actuator, again moving masses. At the actuator the wave can either be absorbed or reflected back into the system.

WBC uses the idea that the displacement of each mass and the actuator can be divided into two components. A part of their displacement is caused by the outgoing waves, and the other by returning waves. This is described in (1) where x_i is the displacement of the ith mass, a_i is the component of this which is the result of outgoing waves, and b_i is the component due to returning waves.

$$x_i(t) = a_i(t) + b_i(t) \tag{1}$$

In [3] there is a derivation of wave transfer functions, G(s), which relate the outgoing / returning components between two adjacent masses, as described in (2) and (3).

$$A_{i+1} = G(s)A_I \tag{2}$$

$$B_i = G(s)B_{i+1} \tag{3}$$

where A and B are s-domain equivalents of a and b. The subscripts i and $i+1$ denote the ith and i+1th masses. The WTF $G(s)$ is difficult to implement exactly but is reasonably well approximated by a second order transfer function with half critical damping and parameter $\omega \approx \sqrt{k/m}$.

$$G(s) \approx \frac{\omega^2}{s^2 + \omega s + \omega^2} \tag{4}$$

Using equations (2), (3) and (4), the controller in Fig 2 can be implemented.

This controller however, is for a plant with a position input. Often practical systems have force or torque inputs, so WBC must be adapted. This can be done rather simply using the idea of a notional actuator. This is an imaginary position-actuator connected to the first mass in the chain by an imaginary spring. The notional actuator has been used for other versions of WBC [2,5], but a new version is presented which is intended to remain as similar as possible to the original version of WBC in Fig 2. It is presented in Fig 3. The displacement of the imaginary actuator is controlled and measured, as the real actuator position was in Fig 2. The position of this actuator is used to calculate the deformation of the notional spring. Using Hooke's law, the force in the notional spring is calculated. This force is given as a command to the system's real force actuator. The measured force applied to the system and the measured first mass position are used to calculate a measured position of the notional actuator. Again, this is done using Hooke's law. If the actuator behaviour is ideal (output saturation, rate limit, etc) the measured and commanded position of the notional actuator will be equal, but in general they will not.

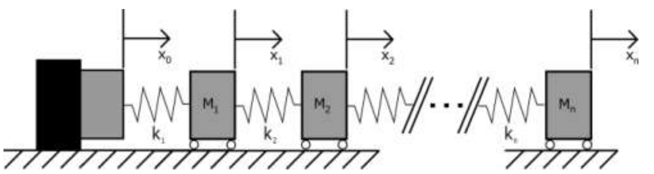

Fig. 1. A lumped model of a 1-D flexible system, comprising a chain of mass and springs connected to a position actuator. The position of each mass is x_i.

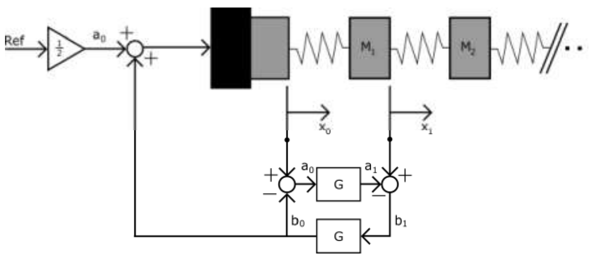

Fig. 2. A mass-spring chain controlled by WBC. The signals a and b denote outgoing and returning wave components of the actuator and the first mass in the chain. The transfer function G can be Eq.(4), with $\omega = (k/m)^{1/2}$, k and m are representative spring stiffness and mass values of the chain close to the actuator.

This covers how WBC is adapted to systems with force/torque inputs for single-input-single-output (SISO) systems. To control the attitude of a 6-DoF satellite, three independent WB controllers are used simultaneously. Each controller controls the torque about one satellite axis. For pointing control, this trio of controllers take in the measured attitude of the satellite in the form of a unit quaternion. The measured and reference position inputs for the three controllers are the three imaginary components of the reference and measured attitude quaternions. For detumbling or spin control, the controllers will take in the measured and reference angular velocity of the satellite about its three body-frame axes.

Outlined so far is a WB controller which gives a torque command to an actuator which can be used to control the attitude of a cubesat. This must be adapted to give a magnetic dipole command for EIRSAT-1's actuators. The same approach will be used as in other works on cubesat control [6]. The torque generated by the magnetorquers will depend on the local geomagnetic field vector and on the magnetic moment generated by the satellite's magnetorquers. Some method is needed to calculate the magnetic moment which will produce the desired torque, or as close to it as possible. This can be calculated using (5) by assuming that the output torque vector, T, the local geomagnetic vector, B, and the magnetic moment, m, are all perpendicular to each other. Note, T will always be perpendicular to the other two vectors. There is also no benefit to not having m perpendicular to B. Note that all vectors are expressed in a body-fixed reference frame.

$$m = (\mathrm{B} \times T_{\mathrm{cmd}})/|B|^2 \tag{5}$$

$$T_{out} = m \times B \tag{6}$$

Equation (6) is an expression for the actual torque

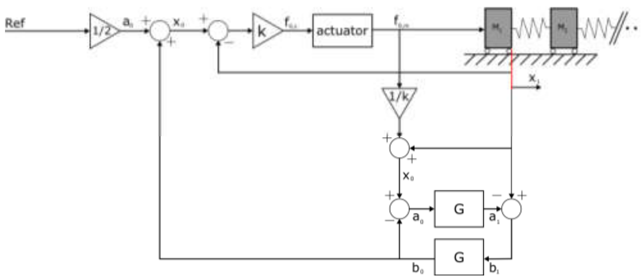

Fig. 3. WBC used to control the force applied to a mass-spring chain. The notional spring stiffness, k, is representative of that of the chain springs close to the actuator.

generated by the magnetorquers. This torque, T_{out}, will be a projection of the commanded torque, T_{cmd}, onto a plane perpendicular to B. This outlines the challenge in using magnetorquers; the output torque will always be on a plane perpendicular to the local geomagnetic field vector. This vector, B, is also a function of the satellite's current attitude and its position in its orbit. To add to this problem, the magnitudes of B, m and hence T_{out} are very small. So the torque available is very limited.

IV. Simulations

Results from simulations are now presented. These are simulations of an EIRSAT-1-like satellite in a circular polar orbit, using magnetorquers to adjust its attitude and to detumble the satellite. The cubesat was modelled as a 10cm × 10cm × 20cm block with a mass of 2.6 kg, evenly distributed. In all simulations, gravity gradient and atmospheric disturbing torques were applied. It was assumed the satellite had access to ideal attitude data, so the satellite's exact attitude is available to the controller. The first set of results in Fig 4 shows the satellite making small rotations about its roll, pitch and yaw axes. The cubesat is initially at rest with respect to an earth centred inertial (ECI) reference frame. The satellite is commanded to rotate by 10°, -5° and 5° simultaneously about the roll pitch and yaw axes. The satellite has a 3-axis magnetorquer. Fig. 5 shows the torque applied by the magnetorquers onto the satellite. Fig. 6 shows the same satellite with the same initial conditions, performing a large rotation about one of its short axes. Fig. 7 shows the magnetorquer force for this simulation. Fig 8 shows the results from a simulation where WBC was used to detumble the satellite using a 2-axis magnetorquer. The satellite had an initial tumble rate of 30°/s about each axis.

V. Conclusions and Future Work

The Method for using WBC to control a model of EIRSAT-1 sat has been described. A brief discussion of how WBC will be used to control the attitude and spin rate of the satellite about three axes is outlined. Also, it is shown how this

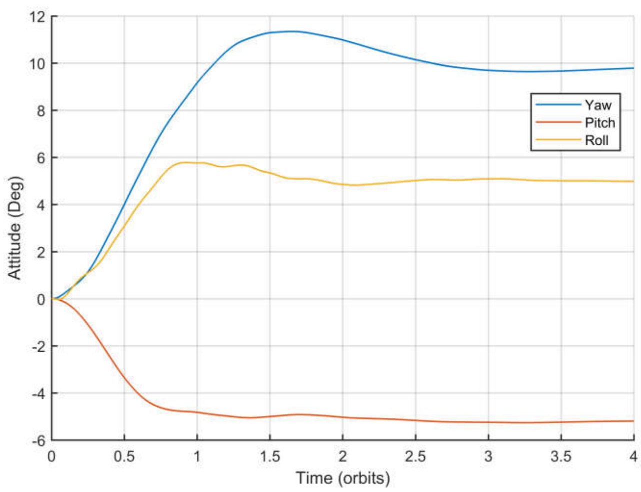

Fig. 4. The Attitude of a WBC controlled cubesat in Euler angles. The cubesat is commanded to rotate by 10°, -5° and 5° about yaw pitch and roll axes respectively.

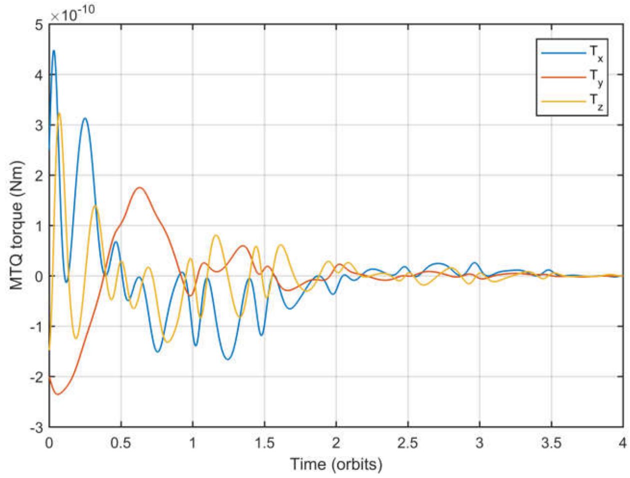

Fig. 5. The torque generated by the cubesat's magnetorquers (MTQ) when making the three small rotations

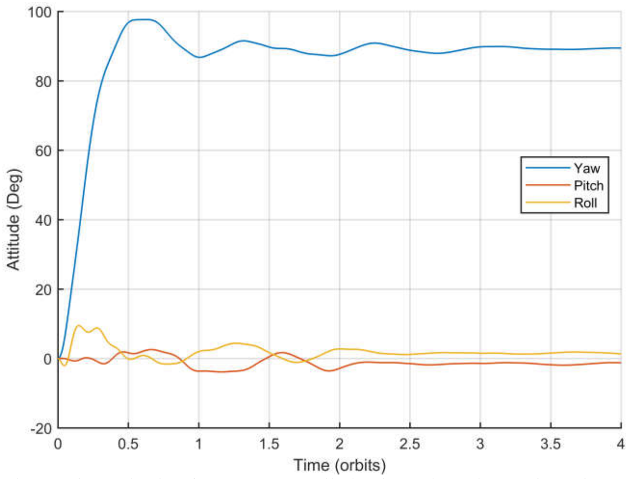

Fig. 6. The Attitude of a WBC controlled cubesat in Euler angles. The cubesat is commanded to rotate by 90° about the yaw axis

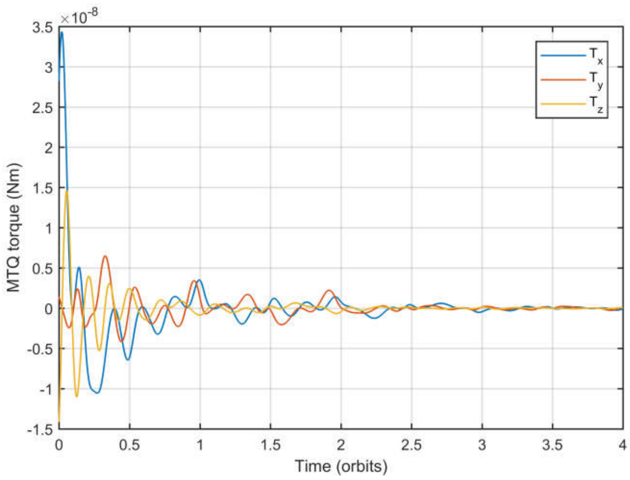

Fig. 7. The torque generated by the cubesat's magnetorquers when making the three small rotations

controller has been adapted to work with magnetorquers; the type of actuator which EIRSAT-1 will use. An overview of how WBC will be used over the course of the EIRSAT-1

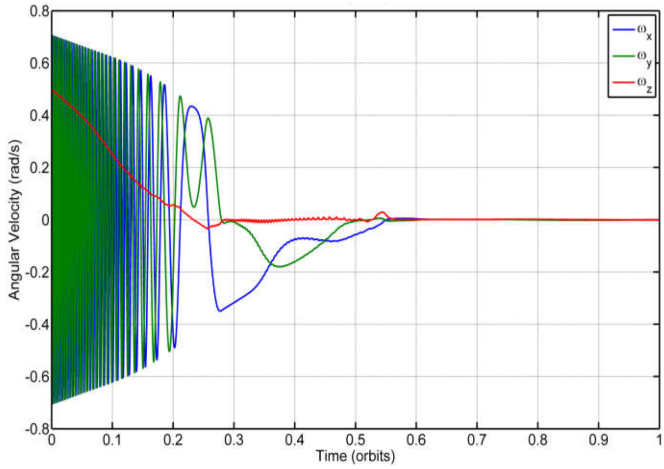

Fig 8. The Angular velocity of a WBC controlled cubesat relative to an ECI frame. Velocity components are expressed in satellite fixed components. The satellite has an initial angular velocity of 30°/s about each axis. The WBC controller is commanded to bring the satellite to rest.

mission is also given. Using WBC for only brief test periods and using an off-the-shelf attitude control system means that testing WBC poses little risk of the rest of the EIRSAT-1 mission. The results in Fig. 4 to 8 show that WBC is capable of controlling the satellite using magnetorquers to perform these simple manoeuvres. For pointing control, changes in attitude are slow, but not impractical. Given the small torques that can be generated using magnetorquers, short settling times are not expected. For detumbling WBC was much more successful, arresting a relatively large spin rate within a single orbit.

In the coming months, testing and verification of ADCS hardware will begin. A part of this will be to design the WBC software for EIRSAT-1. The created cubesat attitude model will be for useful for designing the controller implemented in this software.

The experience of developing this cubesat model has been a very beneficial educational experience for the students involved. It has given students an understanding of the challenges involved in satellite attitude control and has provided useful data on expected levels of performance of the attitude control system for the EIRSAT-1 team. The EIRSAT-1 project and the FYS programme has given the students invaluable experience in working on the many areas involve in satellite design.

ACKNOWLEDGMENTS

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The DAEDALUS Project

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***Abstract*—Atmospheric research is essential for further developments in a variety of scientific fields, space examination being one of the numerous examples. Project DAEDALUS introduces a self-stabilizing, free-falling unit, capable of measuring and distributing atmospheric data during descension. Incorporating the usage of composite materials, robust electronics, an aerodynamic wing and body structure and live data transmission, the DAEDALUS team has developed an approach to atmospheric investigation, potentially applicable for earth and outer space measurements.**

***Keywords*—free-falling unit; atmospheric measurements; proof of concept; student project; demonstrator; reentry; parachute**

I. INTRODUCTION

Newer and safer prospects for the collection of atmospheric data are necessary, especially in times of a rising interest in space exploration and occupation. Technologies suitable for measurements of the Earth's atmosphere might be insufficient for an application under unknown circumstances, as is often the case in outer space missions. Therefore the members of the DAEDALUS team, consisting of students from the University of Würzburg [1], the University of Applied Sciences Würzburg-Schweinfurt FHWS [2] and the TU Vienna [3] aimed to build a proof of concept for a free falling unit (FFU), inspired by the gentle descension of maple seeds, which measures atmospheric data and sends it to an own ground station, thereby decelerating towards the nearest mass centre. The aim was a successful project realization, showing the applicability of this alternative descent mechanism and motivating other students to implement their project conceptions.

II. PROJECT ENVIRONMENT

A. REXUS / BEXUS Programme

The project was part of the REXUS Programme's 24th launch campaign [4], consisting of a 5.6 m long rocket with a diameter of 0.356m (Fig. 1), providing place for five experiments developed by students. Having started with an application in October 2016, the project cycle ends in March 2018 with the start of the rocket and the subsequent analysis of the data obtained during flight.

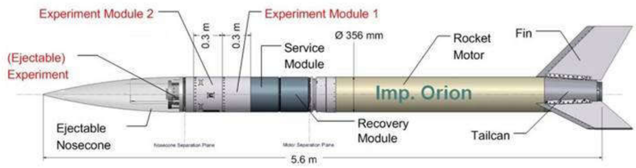

Fig. 1. REXUS Rocket composition

B. Launch Campaign

1) Setup

The DAEDALUS group built four operative FFU's, called Space Seeds, with the intention of placing three of them in the rocket's nosecone (Fig. 2). Starting at the SSC Esrange Space Center [10] near Kiruna, Sweden, the rocket reaches an altitude of 80 – 90 km, at which the Space Seeds will be ejected, marking the start of their free fall.

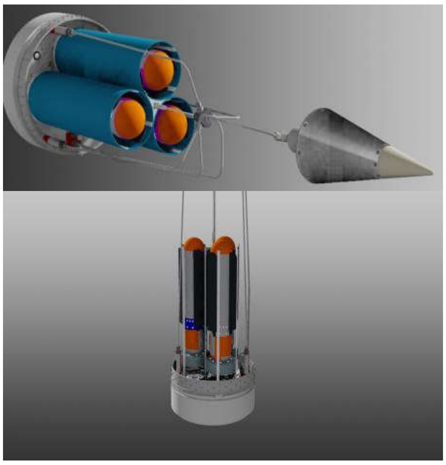

Fig. 2. Seed placement in the rocket's nosecone

2) Recovery

After landing, the FFU's will send heartbeat signals, making it possible for a recovery team to find them with a special search device.

III. The Space Seeds

A. Outer Structure

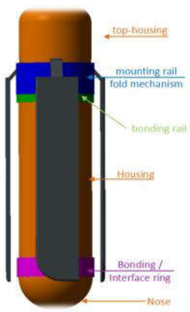

Fig. 3. *Outer Structure Components*

The majority of the Space Seed's outer structure components, namely the housing and the top-housing as well as the ejection tubes (Fig. 6), consist of glass fibre composites, with the interface ring and bonding rail being made up of aluminum and carbon fibre composites used for the wings and the nose.
These choices on materials were made considering all requirements and the expected course of the flight, including possible velocities of up to 800 m/s and high stagnation temperatures on the FFU's nose tip.

B. Wings and Fold mechanism

The wings have a length of 250 mm and a profile depth of 50 mm. The chosen MH-78 profile is pictured in Fig.5. They will stay folded at the beginning, with a mechanism consisting of a tension spring unfolding them after ejection.

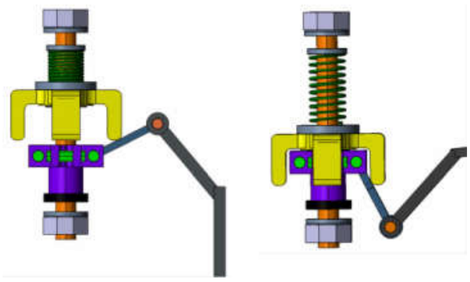

Fig. 4. *Folding Mechanism concept*

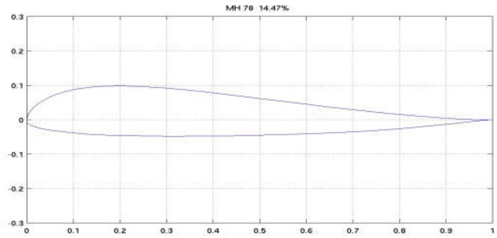

Fig. 5. *MH-78 profile [5]*

C. Ejection Mechanism

The Seed-Launchers, built by students from TU Vienna's Space Team [6], are derived from a standard CubeSat deployer (Fig. 6). They are comprised of a rigid glass composite tube, an aluminum metal stand, a lower rubber-cushioned seat acting as a piston and a foldable carbon composite spring. The Space Seed's ejection is caused by line cutters, cutting the steel cables tensioning the springs.

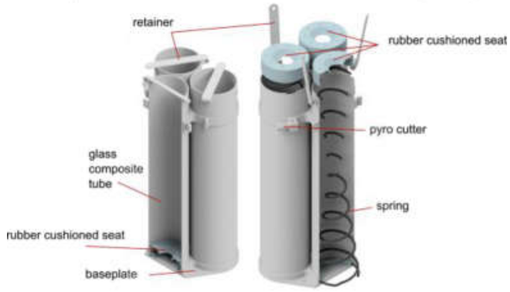

Fig. 6. *Seed-Launcher in stored/deployed condition*

D. Inner structure

The inner structure is divided into four stages, each of them being separated by stiff sticks from the above one.
Paying attention to the requirement, that every experiment should provide the possibility of being dismantled and reimplemented into the rocket at any time, it is precisely fitting into the Space Seed's cleading. Furthermore, additional stages can be added.
Fig. 8 illustrates the placement of the most important parts, their functionality being described later on.

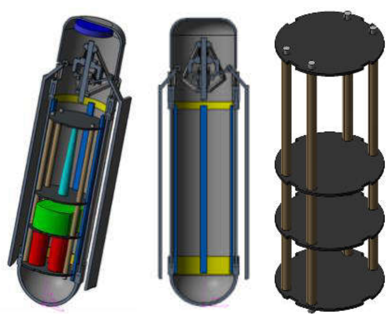

Fig. 7. *Overview of the Inner Structure*

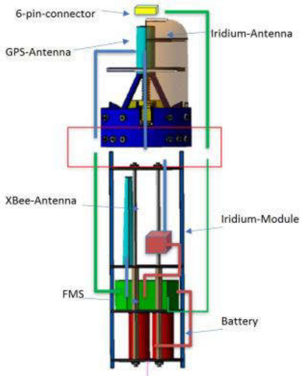

Fig. 8. *Inner Components*

IV. Electronics and Dataflow

All data we receive from our experiment will be sent to the ground station by the REXUS Service System (RXSM), therefore we have to provide a connection to it during the course of the experiment. The data transmission can be divided into two major cases: the dataflow whilst our experiment is connected to the rocket and the transmission after ejection.

A. Measured Data

The data we measure will be of different types, including the current acceleration, height, battery voltage, current and temperature, as well as the current pressure and seed position. The sensors needed for these measurements are part of the seed's Flight Management System (FMS), which is discussed in section C.

B. Rocket Components

- The main intelligence on the rocket side is an Arduino Mega, being the main part of the On-Rocket Board Computer (ORBC) and responsible for saving all incoming data from the seeds and passing a certain amount to the RXSM.
  The communication with the Space Seeds is made possible by an XBee module, connected to the Arduino.
- The interface between the ORBC and RXSM is represented by a Com – Board, including an isolated DC converter and power distribution parts.

C. Flight Management System

The centrepiece of the seed's inner components is the Flight Management System (FMS), provided by the Technical University of Vienna's Space Team. It is mounted onto the second stage of the inner structure and combines a powerful micro-controller with up-to-date sensor technology, power supply electronics and standard communication interfaces. User interaction is possible through a seven-segment display, an acoustic feedback system and XBee - / USB - Interfaces.

Fig. 9. *View of the FMS board*

D. Before Ejection

While being in the rocket's nosecone, all data from the Space Seeds will be transmitted to the ORBC via a direct UART connection with a baud rate of 115200 Bd.

E. After Ejection

After ejection, the data transmission to the ORBC has to be wireless. This is accomplished by using XBees.
An XBee 868LP module, which is connected to the FMS, will continuously send data to the ORBC's XBee module, providing a communication channel until the distance between the descending Space Seeds and the REXUS rocket is too high.

F. GPS Data

The seed's GPS data will be obtained and processed in two different ways. On the one hand, we will gather such data from the FMS' CAM-M8Q - GNSS module, which is additionally connected to an external active antenna for a better signal receiving from the GNSS satellites.
On the other hand, to improve chances of recovery of all Space Seeds, we will make use of the Iridium Satellite Network. Therefore, an Iridium module, containing an antenna, will be placed in the top housing, having a UART connection to the FMS. In that way, we can send position data to the Iridium network, which will be sent to an own server via a TCP/IP connection. The whole dataflow regarding the Iridium network is shown in Fig. 10**.**

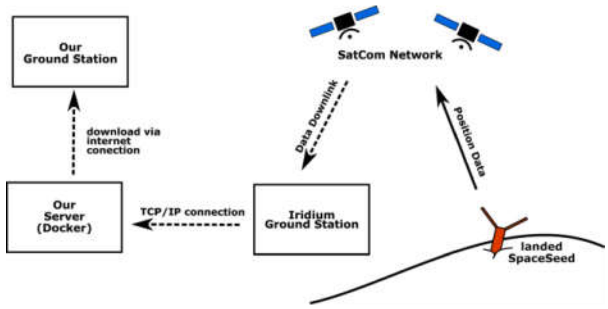

Fig. 10. *Dataflow of the Iridium SBD Service*

G. Data Saving

Saving all data measured throughout the descension of the Space Seeds is mandatory.
For safety reasons, the data will be stored twice:
on an onboard flash module, soldered onto the FMS as well as on an SD card on the ORBC.

H. Camera

A GoPro Hero 4 will be used as an external device to observe the ejection of the Space Seeds. With its battery pack being removed, it will be powered by the DC – Converter and switched on and off by the Arduino.

V. Power Supply

A. Estimated Power Consumption

Displaying the power consumption of all components, we have to take a look at the parts inside the REXUS rocket (Table 1) and the ones inside the free-falling units (Table 2) separately.

TABLE I. POWER CONSUMPTION BY COMPONENT (ON-ROCKET)

Component	***Quantity***	***Standby Power*** [a]	***Power*** [a]	***Peak Power*** [a]	***Estimated run-time*** [b]
Arduino	1	0.50	2.00		600
Camera	1	2.00	5.00		600
XBee	1	0.00010	1.70	2.60	400
Com/Power Board	1	0.10	0.10		600

a. Power in W

b. Run-time in s

TABLE II. POWER CONSUMPTION BY COMPONENT (ON-SEED)

Quantit y	***Component***	***Standby Power*** [a]	***Power*** [a]	***Peak Power*** [a]	***Estimated run-time*** [b]
1	FMS	0.70	1.60		1950
1	Sat-Com	0.17	0.30	7.50	1800
1	XBee	0.00010	1.80	2.60	1950

c. Power in W

d. Run-time in s

B. Supply

The power supply of the components mounted on the rocket (Table 1) is provided by the RXSM. The incoming unregulated 28V are reduced to 5V with the help of a 15 W isolated DC-converter on the Com-Board. The FFU's inner components (Table 3) will be supplied by an NiMH Saft VHT Cs Battery, which will be charged with a 28 V charging voltage before the start. Having a working temperature range of -40°C up to +85°C, it is able to provide a maximum current of 15 A. However, we expect about 3.50 A peak current for a seed's hardware components. The batteries will be preheated with a wire heater to enable their maximal power output.

C. Component Overview

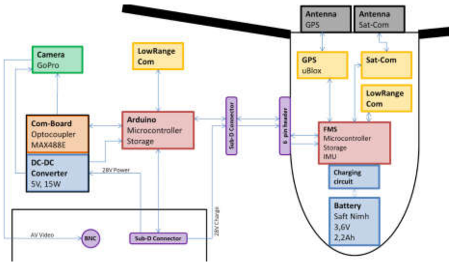

Fig. 11. *Overview of the electrical components*

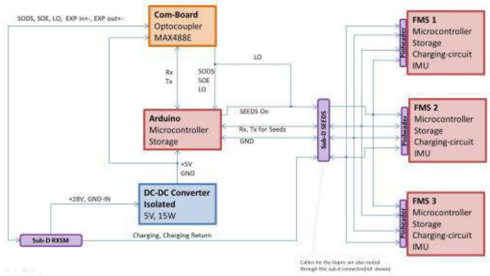

Fig. 12. *Overview of the electrical components*

VI. Conclusions

The DAEDALUS Team managed to build the Space Seed as described, according to its own goals and with respect to the REXUS programme's frame conditions and is currently undergoing the last tests with the REXUS rocket's start following soon. Subsequently, the FFU's and all data will be analyzed in order to see, if all predictions were correct and the Seeds were able to meet the requirements.
A successful campaign will hopefully give reason to the development of advancements of this technology and atmospheric measuring in general.
Future missions, inspired by our approach, may contain a different configuration, a more complex electronic assembly or other additional features, enhancing the Space Seeds' status from a proof of concept to a versatile measuring unit, applicable under various surrounding conditions in outer space.

VII. Acknowledgement

There are a lot of people and institutions that helped us in various ways throughout the project and who deserve our gratitude and a mentioning here. Regarding institutions, we begin with thanking the German Aerospace Center DLR [7], the Swedish National Space Board SNSB [8] and the European Space Agency ESA [9] as the main organizers of the REXUS/BEXUS programme. In addition, the campaign would not be possible without the Swedish Space Corporation SSC [10]. The Center of Applied Space Technology and Microgravity ZARM [11] also deserves special thanks for constantly helping the team to improve and successfully conclude the project cycle.

Further, we want to thank the Julius-Maximilians-University Würzburg, especially the Chair for Aerospace Information Technology [12], represented by Prof. Hakan Kayal, and TU Vienna, thereby mentioning the Automation and Control Institute of the Faculty of Electrical Engineering and Information Technology ACIN [13].

We want to accentuate the support by Prof. Dr. Walter Baur of the FHWS, Dr. Jürgen H. Fecher, Aerodynamics Engineer at Zeppelin NT and OUV, and Mag. Manuel Schleiffelder, Supporting Engineer working at PT Scientists, who continuously helped us to overcome problems and provided advice when ever needed.

The DAEDALUS team is grateful to all the sponsors, who made the project possible: The Austrian Research Promotion Agency FFG, Austrian Ministry for Transport, Innovation and Technology, U-BLOX, CADSOFT, PREH, GLENPRO, Mouser Electronics, AST Systems, all ahead composites, Digi Key, KSat Stuttgart e.V. and MReuss. An overview of all helpers and sponsors can be found in [14].

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ESA/ELGRA Gravity-Related Research Summer School

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Abstract— **The European Low Gravity Research Association (ELGRA) and the European Space Agency (ESA) Education Office co-organise at the ESA Academy's Training and Learning Centre in ESA-ESEC, Belgium, a Summer School on gravity-related research since 2016. This Summer School explains the fundamentals of performing research at different gravity levels and offers an overview of current research activity under microgravity and hypergravity conditions in life and physical sciences. Over four and a half intensive days, 22 Bachelors or Masters students from ESA member and associate states attend stimulating lectures, and work within small groups to devise project ideas for prospective experiments. Gravity-related research is introduced to these future scientists and engineers by experienced professionals from across the European space and research sector. These professional trainers are ELGRA and ESA experts, freely sharing their experience and know-how with the students, including their day-to-day work and research experience in biology, human physiology, and physics. Many different scientific topics are addressed during the school including: solidification, fluid dynamics, heat and mass transfer, spaceflight analogues, animal models, cell biology, growth of plants, artificial gravity for astronaut countermeasures and space adaptation. Each year the programme incorporates new elements to enhance the experience for the students based on their feedback.**

Keywords—microgravity, hypergravity, research

I. Introduction

The European Low Gravity Research Association (ELGRA) [1] and the European Space Agency (ESA) [2] co-organise an annual Summer School on gravity-related research which takes place at the ESA Academy´s Training and Learning Centre in ESA's European space Security and Education Centre (ESEC) in Redu (Belgium) over four and a half days.

The main objective of the Summer School is to promote gravity-related research amongst future scientists and engineers. These young minds are introduced to the benefits of performing research at different gravity levels and offered an overview of current research under microgravity and hypergravity conditions in both life and physical sciences. Other related objectives are:

- Transfer of knowledge and expertise,
- Inspire and network with the future generation,
- Encourage students to participate in hands-on opportunities,
- Attract future scientists and engineers into the space sector.

Each year, ELGRA contacts their members to offer them the opportunity to participate in the Summer School by submitting an abstract to propose a lecture in life or physical science. Three lectures in biology, human physiology and physics are selected. The selected ELGRA members join the Summer School for a minimum of one day and along with some additional ESA experts provide a background to their topic area, examples of gravity-related research and share their experience and expertise. Supporting the summer school is the student arm of the ELGRA association, SELGRA. SELGRA have created an active association for student members to communicate and share opportunities in gravity-related research, support conference attendance and communicate member activities. These experiences are shared at the Summer School and participating students offered the opportunity to join to provide further points of contact.

Fig. 1. Group picture at ESA/ELGRA Gravity-Related Research Summer School 2016

After the selection of the 15-20 experts and the finalisation of the programme of the Summer School, a call for student applications is launched by ESA Education Office. The Summer School is opened every year to 22 Bachelor and Master students in science or engineering disciplines from ESA Member and Associate States not yet involved in the space sector. Interested students apply via ESA Education website [3] by filling-in an application form and providing a motivation letter, a CV, a recommendation letter from a university professor or academic supervisor and an official copy of academic records. Selected students are informed at least one month before the Summer School starts.

The participating students and experts (Fig. 1) are sponsored by ESA and ELGRA to cover their travel, accommodation and meals.

II. SUMMER SCHOOL CONTENTS

The Summer School programme includes lectures in the following topics:

- Gravity-related research and gravity-related platforms (ESA)
- Hands-on opportunities for university students (ESA)
- Introduction to project management (ESA)
- Gravity-related experiment development (ELGRA)
- Experiment life cycle (ESA)
- Physical sciences at different g levels - 3 lectures (ELGRA)
- Life sciences at different g levels - 3 lectures (ELGRA)
- Human physiology at different g levels - 3 lectures (ELGRA)

For example, for the Summer School 2017 the scientific lectures covered the following topics:

- life sciences: plant and cell biology in space; gravity machines; and animal models.
- physical sciences: solidification; blood flow; heat and mass transfer under microgravity conditions.
- human physiology: space adaptation; brain in microgravity and artificial gravity for astronauts.

These lectures are complemented by three testimonials from university students who have designed, built, tested and performed a scientific experiment or technology demonstration in the ZeroG airplane [4], the Bremen drop tower [5] and ESA's Large Diameter Centrifuge [6] in the frame of ESA Academy's hands-on projects [7]. These three university students present their projects as well as their lessons learned and give tips to the participating students for their potential future projects.

Throughout the Summer School, the students are asked in groups of four or five to generate an idea for a future gravity-related experiment. During the time allocated for this group exercise, they are asked to come up with a scientific or engineering objective, to choose a gravity-related platform and propose a preliminary experimental setup and procedure. Students take advantage of the continuous presence of experts in the room to discuss their ideas. In the

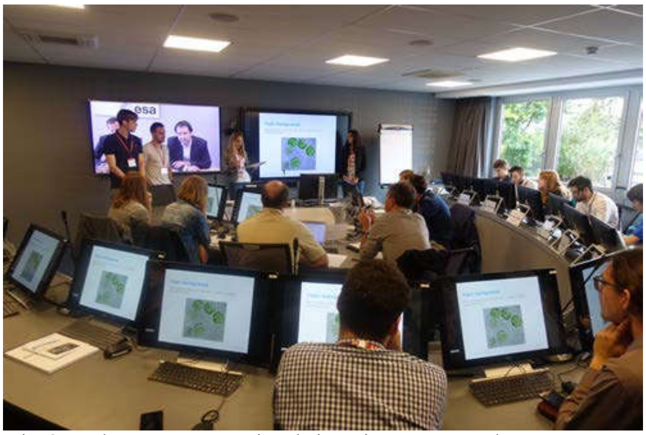

Fig. 2. Student group presenting their project to ESA and ELGRA experts during the ESA/ELGRA Gravity-Related Research Summer School 2017

final day of the Summer School, as shown on Fig. 2 the student groups get the opportunity to present their project and are evaluated by experts from ELGRA and ESA. Upon completion of this process the students are presented with a certificate of participation and a course transcript including their score to allow them to claim ECTS credit(s) for their participation to their respective universities.

Aside from the lectures and team work, students have the opportunity to visit space-related centres in the region. In 2016 and 2017, the students visited:

- ESA's European space Security and Education Centre (ESEC) [8] and learned about ESA operations activities, as well as the Proba and Galileo programmes.
- The Euro Space Center (ESC) [9], a science museum and educational tourist attraction devoted to space science and astronautics where they had the opportunity to perform moon or mars walk and test the 3-axis rotating chair.
- The Centre Spatial de Liège (CSL) [10], an applied Research Centre owned by the University of Liège, focused on design, integration and calibration of space observation instruments. Students had the opportunity to hear about their diverse activities and to see their cleanroom and test facilities (Fig.3).

III. STUDENT STATISTICS & FEEDBACK

The ESA/ELGRA Gravity-Related Research Summer School has been organised twice and each time involved 22 university students and 18 experts. The 44 participating students were 39% females and 61% males, 45% at Bachelor level and 55% at Master level, 52% in a scientific discipline and 48% in an engineering discipline. They were citizens of 12 ESA member states and studied in 36 different European universities. The feedback from the participating students was very positive, as shown on Fig. 3, they gained knowledge and increased their interest in gravity-related research. They consider that their participation will be useful for their future career. After the Summer School 80% of the students are envisaging to apply for an ESA Education gravity-related hands-on opportunity.

Fig. 3. Student and experts visiting the Centre Spatial de Liège (CSL) during the ESA/ELGRA Gravity-Related Research Summer School 2016

IV. CONCLUSIONS

The ESA/ELGRA Gravity-Related Research Summer School is a unique opportunity for university students to acquire new understanding on different topics of space research, work on a group exercise and network with experts in gravity-related research. With this Summer School ELGRA and ESA aims at complementing what future scientists and engineers learn at university, inspire them and attract them into the space sector and its multiple research opportunities.

The third edition of the Summer School will be organised from 25 to 29 June 2018 and the call for applications is opened until 7 May 2018.

The atmosphere during the summer schools has always been very pleasant not only for the students but also for the experts and organisers, with relaxed conversations intertwined with scientific and technical discussions. The comments from students of the two first editions reflect the success of the school:

"It has been easily the most inspiring week of my life. I have learned so many different things about performing experiments in altered gravity platforms and I believe this has been an important milestone in my education in Physics. I also loved the multicultural environment as I think I have made some friends for life and I have now made contacts that I am sure will be crucial in the future!", from a Portuguese student from the University of Porto, Portugal.

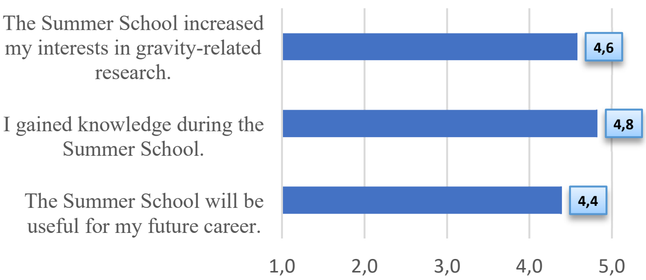

Fig. 4. Feedback from the university students who participated to the ESA/ELGRA Gravity-Related Research Summer School in 2016 and 2017

"I could not be happier that I took part in ESA/ELGRA Summer School. The opportunity to listen and talk to people that are working in space sector and spending time with other students with different backgrounds from all over the Europe was an amazing experience. During this week I learned a lot and expanded my horizons. With a clear conscience I can recommend it to every student.", from a Polish student from the Warsaw University of Technology, Poland.

"The ESA/ELGRA Gravity-Related Research Summer School has been a fantastic experience that I could not recommend more highly to anyone with an interest in research and the space sector. Hearing about cutting-edge microgravity research from the experts in each field has been a wonderful opportunity that has not only increased my interest in the subject but in a career within the space sector in general. It was also great to be able to meet highly motivated students with such a range of backgrounds and interests. I am very grateful to have been given such an amazing opportunity and would like to thank everyone involved in the organisation and running of the summer school!'', from a British student from University of Surrey, United Kingdom.

"A once-in-a-lifetime opportunity to discover the fascinating science behind space experiments, meet with top experts in the space sector and connect with passionate individuals from all over Europe.", from a Greek student from Aristotle University of Thessaloniki, Greece.

ACKNOWLEDGMENT

We would like to thank ESA and ELGRA experts who developed and delivered lectures during the two first editions of the Summer School and shared their knowledge and enthusiasm with the university students.

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The SEEDS International Post-Graduate Masters Programme: Training for our Future in Space

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***Abstract*— The SpacE Exploration Development Systems (SEEDS) postgraduate International Master programme provides young engineers and scientists with an opportunity to prepare for the future in space, both within and beyond Europe. Initially conceived by Politecnico di Torino and Thales Alenia Space-Italy in 2005, the programme now includes three academic partners (Politecnico di Torino, Italy; ISAE-Supaero, France; and University of Leicester, UK) all of whom have a long heritage of space activities at industrial and academic level. In addition, there is significant industry and agency involvement, through the participation of Thales Alenia Space Italy and ESA-ESTEC in the programme. The course is designed to equip students with the knowledge and technical abilities required by industry, agencies and academia in the space sector, producing the skilled graduates that will be required to sustain and grow the new wave of space exploration and commercialization which is being driven by initiatives in the private sector.**

Nine years of activities have passed and nine project works have been successfully completed, dealing with various space exploration themes. The tenth edition of the course is currently under way, with a project related to the Lunar Orbital Platform-Gateway. In this paper we describe the course and some of the projects undertaken to date, along with lessons learned.

Keywords*— *Masters; Space Systems Engineering; Employability; Skills

I. Introduction

The SEEDS (SpacE Exploration and Development Systems) initiative was conceived by Politecnico di Torino and Thales Alenia Space Italy in 2005. Its objectives were to establish a Post-Graduate International Master programme to enable young scientists and engineers to prepare for Europe's future in space – although today, the course also welcomes students from countries outside of Europe, including the United States and India. SEEDS was originally shared with Supaero Toulouse (France) and University in Bremen (together with ZARM) in Germany [1 - 6]. Since 2013, the consortium comprises Politecnico di Torino, Supaero, and the University of Leicester, (UK). All three institutes have a long tradition of space activities at both the industrial and academic level.

In Turin and Toulouse, the course starts in November and lasts ~11 months; students in Leicester begin a month earlier and the duration is 12 months. Students are recruited by all three institutes. They spend approximately the first half of the course attending courses at their home institute, thereafter merging as an integrated team to accomplish the project work, spending two months per location. Students apply to SEEDS through a Master of Science programme in France and UK, and to a Post-Graduate Master at Politecnico di Torino. SEEDS is funded and supported by aerospace companies, space agencies and students' tuition fees. Significant support, in terms of teaching hours, tutoring and funding comes from one of the major European Space Companies, Thales Alenia Space in Italy, France and UK. The course is supported by the European Space Agency, ESA, which hosts at the final presentation of the course at ESTEC, Netherlands, as well as a Concurrent Design activity in the early phases of the project.

In order to meet the demand for skilled personnel in space related subjects, the number of space-related post-graduate education programmes is growing, particularly in Europe [7]. Existing programmes differ widely in scope and characteristics, coverage and focus, quality and organization, as well as entry qualifications and required time effort. Unlike other post-graduate programmes, SEEDS focuses on human space exploration with emphasis on the major project performed through three successive internships in three different European locations under the supervision of company and university personnel.

II. STRUCTURE, METHODS & ORGANISATION

The course structure is summarized in Fig. 1. During the initial taught phase of the course, students attend classes and perform exercises covering basic concepts, the fundamentals of space systems engineering design, and specific space-related disciplines. This is followed by the project phase, which lasts about six months, during which students work on the conceptual design (Pre-Phase A/Phase A) of a human space exploration mission. Both phases pursue a multidisciplinary approach, where all specialized disciplines are integrated to allow students to acquire the system view and then to complete the conceptual design of a case-study, applying Systems Engineering tools, methods and processes. At the beginning the basic design techniques and criteria pertaining to various engineering disciplines are introduced; later, the focus is on the development of an integrated system-level design, where the attention is primarily on adequacy and coherence of proposed solutions. Students are therefore supported along a technical education path where individual capabilities are progressively incremented through acquisition of new learning, then enhanced and tested through intensive team working sessions. System-level sensitivity towards design objectives is developed and engineering best practices are applied to the case-study.

The Project includes preparatory work and conceptual design activities. During the preparatory work the students focus on the motivation and requirements of space exploration, definition of the mission statement, mission objectives, and top level (system-of-systems) requirements through the application of top level Functional Analysis and top level Concept of Operations (ConOps). Major functions at this level are allocated onto discrete building blocks, and the final result is the identification of the complete architecture of the system of systems (i.e. the collection of single systems that pool their resources and capabilities together to create a more complex system, which offers more functionality and performance than simply the sum of the constituent systems).

Conceptual Design activities carried out at each site further develop the design of a selected subset of building blocks, which represent innovative concepts, both in terms of functions performed and technological challenges. They are highly characterizing elements, which constitute an added value for the whole system of systems. Every space system is developed through a process with phases and reviews. In Pre-Phase A the system engineering approach is used to develop initial concepts, as well as a preliminary set of key high-level requirements; to realize these concepts through modeling, simulation, or other means; and to verify that these concepts and products meet the high-level requirements. During Phase A, the iterative use of the system engineering approach continues, taking the concepts and draft key requirements developed during Pre-Phase A and developing them to become the baseline system requirements and ConOps. During this phase, key areas of high risk are investigated to ensure that the concepts and requirements being developed are appropriate, and to identify verification and validation tools and techniques that will be needed in later phases [8]. Starting from system requirements, the conceptual design methodology evolves through system architecture definition and mission definition.

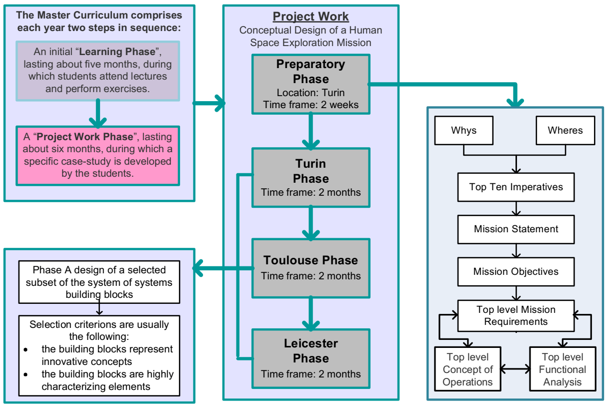

Fig. 1. SEEDS master course structure

After the list of systems requirements has been completed, Functional Analysis begins. Results of this analysis are first the functional tree and then the physical (or product) tree: the former identifies the basic functions which the system must perform to meet requirements, while the latter maps system functions onto products which carry out those functions – i.e. the subsystems and equipment which generate the system. Once the Functional Analysis is complete and the elements of the product tree have been identified, it is possible to determine how these elements are connected to form the system. It is thus possible to draw the functional/physical block diagram of each subsystem, and eventually, of the whole system.

In order to complete the system definition, the system budgets (mass, power, thermal etc.) have to be determined. This requires the system modes of operation to be established. However, this task can be fulfilled only after subsystems and their relative equipment have been identified. The definition of the system modes of operation is a crucial activity that, together with the ConOps, helps accomplish the definition of the Mission. Typical analyses contained in ConOps include evaluation of mission phases, operation timelines and scenarios, end-to-end communications strategy, command and data architecture, operational facilities, integrated logistic support, and critical events [8] [9]. With the preliminary definition of mission and system completed, it is important to verify that all system requirements have been satisfied. A process of refinements and iterations may be necessary before being able to perform the system design synthesis, which enables freezing of the system configuration. Typically, each conceptual design activity lasts about six weeks and is subdivided into three different phases:

1. First Phase (two weeks): all students work together on the definition of system requirements and system functional analysis. During each design activity at the three sites, one or two building blocks can be designed, depending on system complexity. Throughout this phase all students work on the building blocks in series, to enhance consistency of results.

2. Second Phase (three weeks): students form smaller groups to define subsystems requirements and architecture at main equipment level, with the identification of system modes of operation, subsystem sizing and system budgets for the building blocks, performed in parallel to shorten design times. As well as forming groups to consider specific technical areas

(e.g. avionics, environmental control, mechanical), coordination groups are also formed to verify the consistency of system and subsystems solutions. These roles rotate through the project.

3. Third Phase (one week): all students work together to finalize reporting.

III. Project Work Activities

SEEDS project topics are carefully chosen to align with current and/or strategically important themes in space exploration, and although each course lasts for only one year, successive years can build on work performed in the earlier sessions. For example, the classes of 2012 – 2015 worked on a sequence of projects dedicated to a rational and thorough long-term vision of Mars exploration. The projects followed a logical sequence of steps, covering: (2012) Exploration of Mars from the proximity of Phobos; (2013) Exploration of the Mars Surface; (2014) Precursor missions aimed at in-situ resource utilization (ISRU), and (2015) development of Mars Permanent Outpost.

As an example of the work which can be conducted in the project, the sixth class to be enrolled in SEEDS considered a mission which the team named *ORPHEUS* (Orbital Reconnaissance and PHobos Exploration by hUmanS) whose objectives were "To perform human exploration of Mars from its proximity; to execute a manned landing on Phobos, including a sample return; to develop and validate techniques to lay the framework for future manned exploration and exploitation of Mars". A mission to Mars involves challenging mass budgets due to the high ΔV requirements; the level of safety implies additional mass for redundancy. Hence, the mission concept was designed to reduce the initial spacecraft masses by sharing the payload between two. The smallest, called the Mars Automatic Transfer Vehicle (MATV) is unmanned and its payload mass has been maximized to send to Mars those payloads not linked with human activity or human safety. Its payload consists of the following: scientific, robotic landing packages to be deployed on the surface of Mars; the Phobos Lander (PhL); and the Laboratory (LAB). The latter two are used by the crew once in Mars proximity, to land on Phobos and to analyse regolith samples. Fig. 2 shows a schematic produced by the students to summarise the architecture of the mission.

The manned spacecraft (the Crew Interplanetary Vehicle or CIV) has all the subsystems necessary for sustaining humans for the entire mission duration, as well as the required habitable volume and the necessary propellant. The advantage of using an unmanned transport spacecraft is the use of a high-efficiency, low-thrust solar-electric propulsion system. On the CIV however, due to human presence, strong transfer time constraints are imposed. Hence, the CIV uses short trajectories with a less efficient propulsion system. A docking manoeuvre in Mars orbit is necessary for the exchange of modules between the two spacecraft. In case of failure of docking, the scientific mission fails, as the crew cannot access the PhL; this is an acceptable risk due to fault tolerance. However, the risk of loss of the crew in this case is not acceptable and it imposes the requirement to equip the CIV with all the necessary propellant

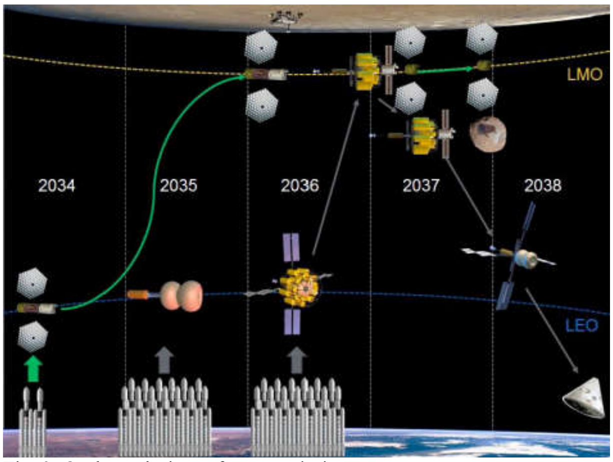

Fig. 2. Orpheus design reference mission.

for the entire manned mission, rather than the MATV carrying fuel for the CIV's return trip. This decision is less effective from the mass point of view, as the CIV propellant is carried by the CIV itself, which has a propulsion system with lower efficiency.

The Orpheus mission was designed as a short stay mission in which the crew did not reach the surface of Mars. The following project, Mars Initial Landing ExpeditionS TOward a New Era (MILESTONE) had the objective of delivering humans to the Martian surface; to ensure their survival through the establishment of a long permanence outpost; to conduct in situ scientific operations and exploration; and to allow for their ascent from the Martian surface. MILESTONE is an early stage mission, which creates an outpost on Mars for further human exploration by subsequent missions. A 500 day transit is assumed for the crew, with the intention of residing on the surface for 60 days. As a pre-cursor to exploration missions, MILESTONE is focused on the establishment of a habitable environment to ensure the supply of resources to sustain human life. The analysis starts and ends in Low Mars Orbit with a detailed design focused on the surface modules and vehicles required to achieve this goal.

The MILESTONE surface outpost is formed of a number of components: a habitable module, a laboratory, a greenhouse, an ISRU system and a power plant (see Fig. 3).

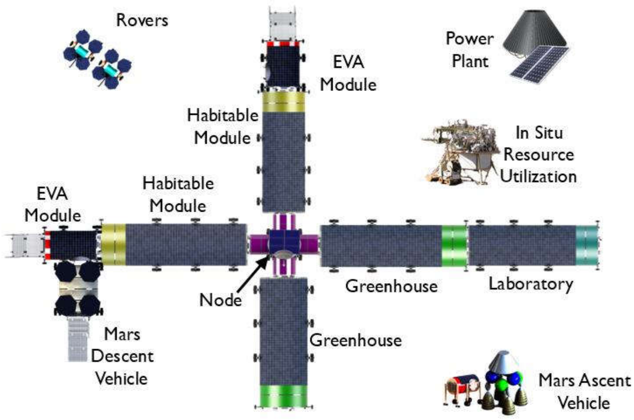

Fig. 3. Milestone outpost layout.

A pressurised rover allows for exploration in future missions, and three communications satellites and an Earth return vehicle are placed in Martian orbit. The outpost is sized for future 500 day scientific and exploration missions that will consist of a crew of six people. While the outpost is intended to be largely self-sufficient, there will be some reliance on Earth resources, with each crew bringing certain consumables. During this first manned mission to the Martian surface, there will also be technology demonstrations, increasing technology readiness levels for future missions.

The programme is responsive: should an interesting or urgent project work theme be proposed by an Agency or by industry, the next project can be re-focussed on this topic – to the benefit of the community, and also of the students who gain in-depth training in a topic relevant to current themes and priorities, enhancing their employability as a consequence. In keeping with this philosophy, project work for the 2016 and 2017 intakes was/is directed towards lunar exploration, due to the emergence of concepts including the Lunar Village, and the importance of the Lunar Orbital Platform - Gateway as an international priority for future space exploration. The 2016 project consider MUSE: Moon Utilisation for Science and Exploration, the objectives for which were to "exploit the Moon and its resources for sustaining a cislunar station, enhancing its utilisation for scientific and technological progress, and paving the way for future Mars exploration".

Fig. 4 shows a timeline for part of the mission, illustrating the primary vehicles and critical subsystems designed by the students during the project: each meeting a well defined set of requirements, and defined through the careful application of the scientific and engineering competencies developed in the earlier parts of the course. For example, Fig. 5 shows an analysis of the ΔV vs transfer time for a family of transfer trajectories from the surface at the lunar north pole, to a near-rectilinear halo orbit (NRO) around the moon. The transfers and NRO were studied and designed by the students in response to top level mission requirements, and this analysis was used to inform the design of subsystems such as the lunar ascent vehicle propulsion unit. This lunar theme continues in the present (2017-18) project, focusing on the requirements for ISRU that form part of the Lunar Orbital Platform-Gateway, and the design of precursor systems such as the Heracles lunar lander [10].

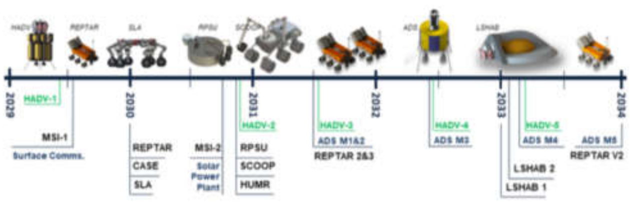

Fig. 4. Concept of operations for Phase II of MUSE.

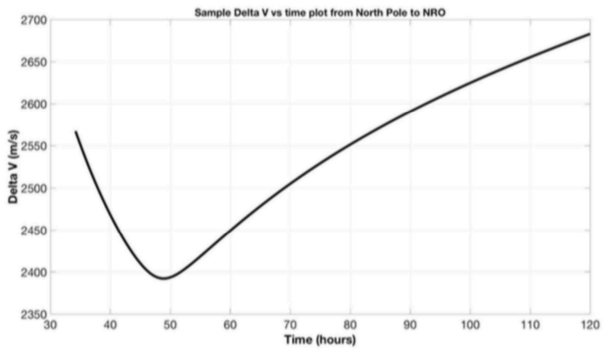

Fig. 5. Analysis of ΔV vs transfer time from lunar north pole, to a Near Rectilinear Halo Orbit.

IV. FUTURE SPACE WORKFORCE

Since the first SEEDS edition in 2005 each year the number of student applications in Turin ranged from about 20 to 40 for a maximum number of 15 places. Students have also been selected at ISAE (Institut Supérieur de l'Aéronautique et de l'Espace)-Supaero in Toulouse (French, Spanish, Italian and German students) to join the team recruited in Italy during the Project Work phase. Since the sixth edition a considerable number of students from the University of Leicester has also joined the team to accomplish the Project Work. A total of 45 students are participating in the 2017-18 session.

Unlike in Turin where, only students with an MSc or 4-year BSc (or equivalent) in an Engineering or Physical Sciences discipline are eligible to admission, in Toulouse and Leicester students can choose SEEDS as an internship during the last semester of space-related MSc courses offered at those institutes. Generally, about 20% of applicants are female. No special measures have been taken so far to improve the balance of gender ratio. Applicants' average age ranges between 24 and 28, with a few exceptions.

Taking into account the first seven editions of the SEEDS Master course, seventy-five students have attended SEEDS. The majority of students to date have been Italian with contributions from other European countries, specifically UK, France, Germany, Spain and Romania, and also from non-European countries including the USA, India, Argentina, Uganda and Venezuela.

Almost 65% of the students have been employed in aerospace industries just few months after the end of SEEDS. This result testifies the success of the programme. The remaining 35% of the SEEDS students have been partly employed in other fields, in space agencies or are now working in universities, pursuing PhD projects or other research-related activities, demonstrating the value of SEEDS to the academic research community as well as the aerospace industry.

V. CONCLUSIONS & LESSONS LEARNED

The first year of SEEDS started in November 2005, with a Plenary Opening, which took place at ESA's European Space Technology Centre (ESTEC) in Noordwijk (NL), with the full support of ESA. In the period since then, several important lessons have been learned:

- The Project Work, where the students play the role of systems engineer or system specialist, is a fundamental step in the programme, helping students to develop their skills through the accomplishment of specific design activities.
- The enhancement of team working capabilities through dedicated lessons and practical applications during the Project Work is vital to prepare students for the real working environment they will encounter in the industry.
- Blending academic learning with case studies from industrial experience is essential in equipping students with the tools, methodologies and knowledge required in the field, along with an understanding of the design and operation of real missions, and how these techniques have been applied.
- Exposure of the students to the use of modern tools, such as Concurrent Engineering, is invaluable preparation for future employment and narrows gap between academia and their eventual working environment.
- Multidisciplinary teams of students improve the quality of systems engineering work, even though communication between team members may be difficult at the beginning because of the range of educational backgrounds in the team (for instance, a mixture of science and engineering as the student's first degree); support is often needed from the academic team to ease anxiety and foster team coherence in the early project phases…
- …however, the diversity of background and approaches provides students with exposure to the working environment they are likely to find themselves in after graduation, and enables them to function efficiently in that situation
- Lectures during the Learning Phase, dealing with technical topics as well as personal skills development and team building, are particularly useful as they help students share a common language and common understanding of space systems.
- The international background of both tutors and students has to be strongly enhanced to foster the exchange of knowledge, educational methods and design solutions.
- The opportunity for the SEEDS students to visit as part different university, industry and agency sites (including the facilities at ESA/ESTEC), is highly appreciated by them, and facilitates their subsequent introduction to the professional space sector.
- Project work which is of genuine relevance to industry and academia is highly motivating for students and provides excellent preparation for the next phases in their careers. It also opens the possibility for publications to be written, enhancing student CVs and employability prospects. Several papers have been presented by SEEDS students at major international conferences such as IAC.
- A good and well-maintained contact and interaction between the SEEDS academic team, and the industry and agency partners, has been essential in guaranteeing the effectiveness of the education, the responsiveness of the Master's content to current professional needs, access to facilities and instruments, and opportunities for visits and contacts, in preparation for the start of their future professional careers.

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PACMAN experiment: a Parabolic Flight Campaign student experience

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Abstract - *Presently, no competitive or commercial solution is available to perform autonomous rendezvous and docking between small-satellites. Therefore, in the last years there has been an increasing interest in developing different technologies, addressing the main issues of fuel consumption and the strong impact of close range navigation subsystems on satellites mass budget and complexity. One promising solution is represented by relative magnetic navigation, where the chaser relative position and attitude can be controlled thanks to magnetic interactions with the target vehicle.*

PACMAN experiment is a technology demonstrator that has been developed by a team of university and PhDs students in the framework of ESA Education Fly Your Thesis! 2017 programme and supported by the University of Padova. The experiment has been selected to fly during the 68th ESA Parabolic Flight Campaign, that took place last December 2017. The main goal of the project is to develop and validate in low-gravity conditions an integrated system for proximity navigation and soft-docking based on magnetic interactions, suitable for small-scale spacecrafts. This will be accomplished by launching a miniature spacecraft mock-up towards a free-floating target that generates a static magnetic field; a set of actively-controlled magnetic coils on-board the spacecraft mock-up, assisted by dedicated localization sensors, will be used to control its attitude and position relative to the target.

The realization of PACMAN experiment will also allow to validate the theoretical/numerical models that describe such interactions.

This paper presents an overview of the experiment concept and design. Particular attention will be given to the problem solving.

Keywords - CubeSat, Autonomous Rendezvous and Docking, Relative Magnetic Navigation, Parabolic Flight, Low-gravity

I. INTRODUCTION & BACKGROUND

Autonomous rendezvous and docking was hardly addressed in space, with few important exceptions like European ATVs and Russian Progress spacecraft; considering small satellites, no competitive or commercial solution is currently available. Recently, the advent of CubeSat modules has greatly encouraged international aerospace companies and agencies to invest in the development of technological demonstrators or scientific payloads using these platforms, thanks to their reduced cost for accessing space. Various technologies have been already tested in space using CubeSats, but only few experiments have been performed on docking systems [1-9], even if the development of such mechanisms could expand enormously the possible mission scenarios. Therefore, in the last years there has been an increasing interest in developing different technologies: above all, one promising solution is represented by the relative magnetic navigation exploited for both close range rendezvous manoeuvre [10-11] and formation flight [12-14].

The Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) aboard the ISS [1] represent the state of the art of small docking interfaces. The Autonomous Microsatellite Docking System (AMDS) [2] represents a connection system for small-scale spacecraft. The docking system within this experiment is composed by an extendable probe which is captured by a drogue and then retracts, allowing the two vehicles to mate. The Autonomous Rendezvous Control And Docking Experiment (ARCADE), was a docking system very similar to AMDS and composed of a conical probe, captured by an electromagnet placed at the end of the drogue. The most important contribution on electromagnetic navigation is the RINGS (Resonant Inductive Near-field Generation System) project in the framework of MIT SPHERES program aboard the ISS, in which the vehicles were equipped with large coils to generate electromagnetic coupling actions for both power transfer and relative navigation [3]. In parallel, in the framework of the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) program, a simplified technology was designed and tested in ground laboratories by Underwood & Pellegrino [4] on low friction tables. A very similar technology has been developed and tested in ground laboratory also by Chen [5]. Recently, the Surrey Training Research and Nanosatellite Demonstrator (STRaND) programme have been developing and testing in laboratory STRaND-2, a nano-satellite able to perform visual inspection, proximity operations and docking using a series of tuned magnetic coils [6]. Another relevant work was realized in the FELDs experiment (*Drop Your Thesis!* 2014), that tested the self-alignment capabilities of a tethered soft docking system based on a ferromagnetic tethered probe launched towards a target electromagnet [7].

Finally, the CubeSat Proximity Operations Demonstration (CPOD) plans to perform with two identical 3-U modules several on-orbit tests of rendezvous, proximity operations and docking by means of low-cost off the shelf components [8]. Similarly, the On-Orbit Autonomous Assembly from Nanosatellites (OAAN), a collaboration between NASA's Langley Research Center and Cornell University, plans to study autonomous control algorithms for rendezvous and docking manoeuvres, low-power reconfigurable magnetic docking technology, and precise relative navigation using carrier-phase differential GPS [9].

II. ESA Education *Fly Your Thesis!* programme

ESA Education *Fly Your Thesis!* Programme is a unique opportunity for University students to conduct their experiments in low-gravity conditions through a series of parabolic flights on the Airbus A310 Zero-G operated by NoveSpace. The programme launches a call for proposals once a year. Up to 4 teams are selected and given the opportunity to participate in a 2 weeks Parabolic Flight Campaign (PFC) that takes place in Bordeaux.

In a parabolic flight, the aircraft climbs with a high angle before dramatically reducing its thrust and falling along a parabolic trajectory. During the manoeuvre, three main phases can be identified and characterized by different gravity levels: the low-gravity phase, during which weightlessness is achieved, lasts about 22 s. The PFC consists of a series of three flights of 30 parabolas each and it ensures different and unique testing conditions.

III. PACMAN concept

PACMAN (Position and Attitude Control with MAgnetic Navigation) experiment is a technology demonstrator whose main goal is to develop and validate, under low-gravity conditions, an integrated system for proximity navigation and soft docking based on magnetic interactions, suitable for small-scale spacecraft.

The main objectives of PACMAN experiment were: 1) the development of a system for proximity navigation and soft docking based on magnetic interactions, 2) the development of a dedicated low-range navigation system based on markers-camera system and 3) the validation of the whole PACMAN system in the relevant low-gravity environment.

These were achieved by launching a miniature spacecraft mock-up (CUBE) and a Free-Floating Target (FFT): a set of actively-controlled magnetic coils aboard the CUBE, assisted by dedicated localization sensors, were used to control its attitude and relative position with respect to the FFT, which produced a static magnetic field. The relative pose between the CUBE and the FFT reference frame was determined by means of a camera vision system aboard the CUBE and an external reference camera for post-processing. The closed-loop system evaluateed the desired control torques from the position/attitude error information collected by a set of sensors and the magnetic field model of the FFT.

IV. PACMAN experiment evolution

A. *PACMAN proposal*

Even though PACMAN experiment conceptual idea was appreciated by the *Fly Your Thesis!* committee, leading to the selection as a participating team to the 68th ESA PFC, its design went through profound modifications.

The original design, initially thought for a *Drop Your Thesis!* campaign, was supposed to be an evolution of FELDs experiment [7], introducing an active navigation control and the leash removal. Therefore, the experiment was firstly designed considering the launch of a CubeSat towards a fixed large electromagnet, with subsequent active control on the attitude, inside a secured environment, namely a plexiglass CHAMBER.

Shortly after the selection, detailed analyses pointed out that, inside a plane performing a parabolic flight, the displacement of free floating objects with respect to a structure fixed to the plane itself was excessively large, in relation to the original PACMAN design, i.e. to the CHAMBER dimension. In addition, the displacements were highly unpredictable and analysed data showed no particularly advantageous conditions that could result in a successful rendezvous manoeuvre. This meant that the probability of the CUBE to hit the walls of the CHAMBER before being able to perform a docking manoeuvre, or even the probability of the CUBE to exit the magnetic field region relevant to consistent interactions, was extremely high.

To bypass this problem, a simple, yet ingenious and very effective solution was developed: the use of two free floating objects, namely the CUBE and the FFT, instead of a CUBE and a fixed target. In this way, the displacement of the free-floating objects with respect to the plane was still an issue, but since the target electromagnet was no longer bound to the CHAMBER, the available volume for the experiment could be dramatically increased up to values that the probability for the CubeSats to hit surrounding objects during the microgravity phase could be neglected. Furthermore, in this configuration the two CubeSats represented a closed system, hence there was no reason for them to exit from the relevant magnetic field region if the initial motion was correctly provided and the control scheme was properly working.

B. *PACMAN simulations*

The whole PACMAN experiment was based on the results obtained from a dynamical model simulation implemented in Matlab-Simulink. In the model, the mass characterization of the system, the initial velocities, positions, orientations of the CUBE and the FFT, as well as geometrical and electrical characterization of the coils were used as input. The mutual magnetic interaction between the free-floating modules were then calculated by a subroutine, based on a semi-analytical formulation for the magnetic force calculation between inclined circular loops [15]. The forces were integrated over the whole coil discretized domain, and then referred to the centre of mass of the CubeSat, while the torque was calculated by considering the total forces as applied in the centre of the coils. The evaluation of the forces and the torques applied to the CUBE was therefore divided into two separate calculations.

The forces and the torques applied to the FFT were simply calculated by considering the sum of the two CubeSats as a closed system. The coils currents were provided as an input for the forces calculation subroutine and were defined by a PID controller which compared the misalignment of the vectors normal to the front face of the modules with the direction of motion. Once the forces and the torques were calculated, the integration module updated the position and the orientation of the CubeSats. This process was repeated until the modules got in contact.

The information collected from the simulations did not only demonstrate the theoretical feasibility of this concept, but also was used to drive the experiment design towards the best configuration, i.e. defining the sizing parameters of the CubeSats such as geometry and position of the coils, as well as the magnetic field required to have a stable and smooth attitude control. Moreover, the CUBE/aircraft motion in free floating was investigated, using the data provided by NoveSpace for the g-jittering and the aircraft motion, to understand the range of displacements of the CUBE during the parabolas, hence the definition of the operative volume of the experiment.

C. PACMAN Testing

One of the most demanding steps of this experience was the testing campaign before the flight. Several tests were performed both to comply with NoveSpace safety requirements and to guarantee an experimental environment suitable to achieve the intended objectives. Every sub-system of the experiment was tested in order to identify off-nominal conditions that could have been neglected in the theoretical assumptions. Therefore, testing was necessary to spot possible unwanted operational conditions and gather information on how to restore the nominal behaviour of the systems. A brief description of the main sub-systems tests is given in this paragraph.

1) Magnetic Actuators

PACMAN experiment was based on magnetic interactions between coils. To validate the Matlab-Simulink model, comparisons with benchmarks needed to be performed. After the code validation, also the behaviour of the actual coils needed to be tested. Hence, a simple magnetic interaction test was performed to measure forces between different coils and to compare them with simulation and analytical results. The main drawback of this test was related to the low magnetic field produced by the coils, resulting in small forces. After considering several testing configurations, the final adopted solution consisted in the evaluation of the weight force through a precise scale (accuracy 0.0001 g, Fig. 1).

Two coils were used for these preliminary tests: one was positioned over the scale while the other was held up by a structure over the first coil. A weight variation was measured because of the mutual repelling force.

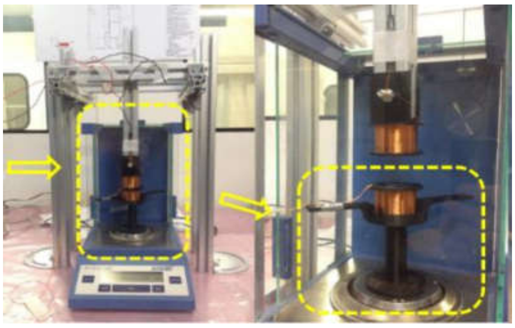

Fig. 1: Experimental setup. The repellant force is measured as a weight variation.

The measurements were then compared with the data obtained from the model. The obtained results revealed a good correlation between the experimental and theoretical data. The average error was below 1% [16].

2) Hold & Launch

The Hold & Launch subsystem aimed at keeping the CUBE and the FFT in position during the ramp-up phase, as well as providing them with a predefined initial velocity immediately after low-gravity was reached. The Hold system was composed of one holding electromagnet, while the Launch system featured a linear guide controlled by a servo-motor. The electromagnet was used to hold the CUBE and the FFT in position prior to the low-gravity phases and during the hyper-gravity phases, allowing an easy and fast repositioning of the CubeSats during the horizontal steady phase. Static load tests were successfully carried out to estimate if the release interface would have been able to sustain 8 kg, which was the maximum expected CubeSat weight multiplied by a safety factor equal to 4, according to NoveSpace requirements. Despite its conceptual simplicity, the Hold and Launch subsystem turned out to be one of the most challenging issues of the experiment, because of the intrinsic difficulty of having both a strong electromagnet holding force and a clean release of the CubeSats. This happened because the residual magnetism on the CubeSat increased as the holding capabilities of the electromagnet increased. A long trial and error session solved the issue and the best solution employed a feature of the current control scheme of a bench power supply and a non-ferromagnetic gap between the electromagnet and the plate on the CubeSats. The progresses during this process were monitored using an experimental setup on a low friction table.

3) Vision subsystem

The camera for visual relative pose (position/attitude) determination was located at the centre of the top CUBE face, with its optical axis oriented along the motion direction. The board was responsible for the image acquisition, analysis and pose estimation. Several tests were executed to assess the performances of the vision subsystem. To achieve this objective, an experimental plotter was used to impose translational and rotational displacements to the target mock-up. The plotter consisted of two high precision motorized linear stages and a rotary stage, as shown in Fig. 2. The linear stages, driven by stepper motors, allowed to impose planar displacements to the CUBE mock-up, while the rotary stage was equipped with a graduated scale, allowing rotations about the normal to the operative plane.

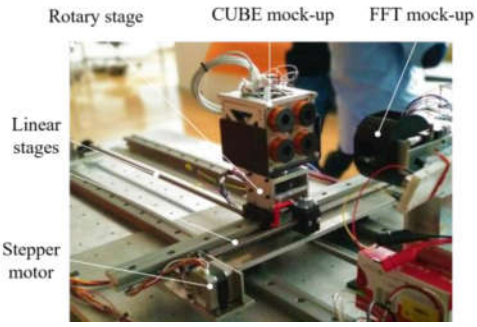

Fig. 2: Photo of the experimental setup.

The maximum error obtained from the comparison between the imposed target trajectory and the reconstructed one obtained from the image analysis algorithm was limited to a range of about 3.5 mm, ±1 mm and ±5 mm along the x, y and z-axis respectively. The standard deviation of the measures, with respect to the imposed attitude, was 4.61° for Roll, 2.69° for Pitch and 0.29° for Yaw angles. Therefore the tested algorithm proved to be capable of real-time pose estimation [16].

4) Driver circuit

Operational tests on CUBE power board were performed to guarantee the correct current supply to the coils and to size the battery pack. The selected driver circuit was an A4990, which could be easily connected to Arduino UNO microcontroller. Arduino UNO used two pins to drive each coil: the first pin carried the PWM signal while the second one established the current direction. Each driver could supply two coils; thus, two drivers needed to be used in the CUBE. They were assembled on a custom board that enabled the connection to Arduino UNO in a shield-like configuration, thus reducing the occupied space. The H-bridge of the driver could be controlled through the Arduino UNO PWM signal. Arduino UNO could handle four PWM signals at a frequency of 32 kHz, compatible with the driver specifications. The 32 kHz PWM guaranteed a negligible current ripple during the switching phase, highlighted also by operational tests carried out in laboratory monitoring the voltage across a shunt resistor with an oscilloscope and the internal voltage drop in the Pololu Driver at 100% duty cycle. The setup consisted in a simple DC current measurement on the coil @ 100% duty cycle, because the focus was on the magnetic field magnitude. Given the number of turns of the coils and the maximum required magneto-motive force, it was easy to establish the input voltage needed to be supplied to the driver. The regulation of the input voltage on the driver allowed obtaining the required load current, thanks to which the sizing voltage for the main load of the CubeSat was defined and important considerations about the battery pack sizing were drawn.

5) Temperature

Several tests were carried out on the CUBE and the FFT to verify the strict compliance with NoveSpace safety requirements. The temperatures of the CUBE and FFT coils and structures were monitored, by applying the typical operative conditions of a parabolic flight. This means that the coils were supplied with the maximum current for 20 seconds and, after that, the whole module was put in stand-by conditions for 2 minutes. This process was consecutively repeated 30 times, to simulate precisely the flight operative conditions. After these cycles, the temperature of the CUBE coil did not exceed 32.5 °C and the overall temperature of the module stayed below 29.5 °C (with a room temperature of 25.5 °C). The temperature of the FFT coil did not exceed 34°C and its structure temperature remained below 27°C (room temperature ~23°C). Moreover, an additional test was performed to demonstrate that, even if the coils were powered throughout the whole low-gravity phase (worst case scenario), the temperature of both the FFT and the CUBE would not have exceeded the allowable limit of 49°C.

D. PACMAN final design

The final configuration of PACMAN experiment was the result of a thorough analysis of the simulations that provided a sensitivity analyses on the sizing parameters. This was followed by an intensive experimental session, leading to the choice of some practical solutions and to discard some others. As already mentioned, the full experiment consisted of a CHAMBER, a CUBE and a FFT.

The CHAMBER (Fig. 3) was a safe environment for the CUBE and the FFT to float, as it avoided the risk of hurting other people or damaging the experiments. It also contained the Hold & Launch systems.

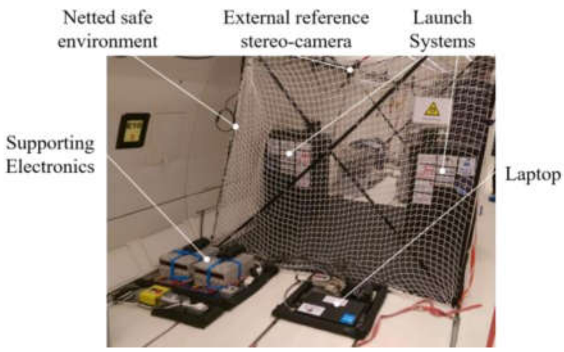

Fig. 3: Photo of the CHAMBER inside the aircraft.

The CUBE represented the real core of PACMAN experiment (Fig. 4). It was equipped with an integrated system for proximity navigation and soft-docking, i.e. a set of coils, which magnetic field was controlled by two microcontrollers: the Raspberry PI 3 performs the PID control, based on data received by the onboard camera and the IMU. The collected data were then sent to Arduino UNO, which performed the control action through the driver circuits.

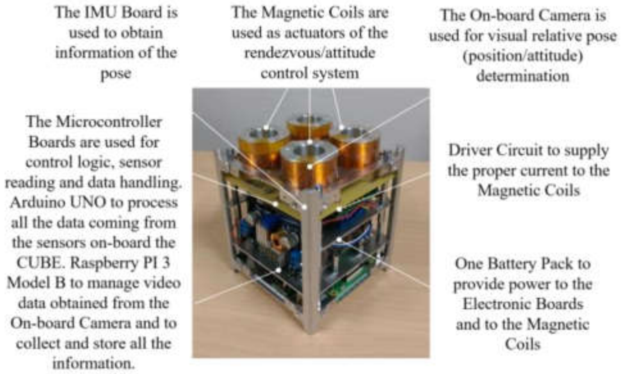

Fig. 4: Photo of the CUBE with its subsystems.

Furthermore, Arduino UNO checked the operative conditions by processing the signals coming from the temperature sensors, turning off the device if the temperature went above a defined threshold. Arduino UNO was also responsible for the initiation and interruption of the acquisition and control routines, by using a proximity sensor for the former and its internal clock for the latter. These last two features were implemented both on the CUBE and the FFT.

The FFT (Fig. 5) design was much simple, with respect to the one of the CUBE, since the coil did not need an active control, but it was simply supplied with a constant, nominal current for the whole duration of the operational interval. Similarly to the CUBE, also the FFT was equipped with an IMU board useful for post-processing analyses.

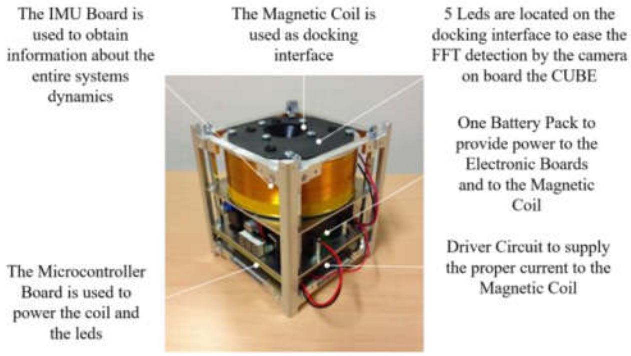

Fig. 5: Photo of the FFT with its subsystems.

After the realization of the first mock-up modules the team realized that, due to the large amount of electronic devices utilized, most of the space was occupied by cables. Therefore, in the final design, a custom Printed Circuit Board (PCB) was produced, which allowed to solve the space issues and also to embed several components directly in it, such as the protection circuits and the switching circuit for the FFT coil.

V. CONCLUSIONS

This paper presented the design and testing phases of PACMAN experiment, a technology demonstrator of an integrated system for proximity navigation and soft-docking based on magnetic interactions. Every single subsystem and detail of the experiment has been considered and designed by the team, facing with perseverance all the issues emerged throughtout the whole project development.

Working side by side with ESA and NoveSpace engineers was an amazing experience and a priceless occasion to improve the technical knowledge. At the conclusion of the programme, all the hard work was transformed into a working experiment that made this an invaluable and unforgettable experience.

ACKNOWLEDGMENT

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Educational activities in development and testing of the Cranfield De-Orbit Mechanism for the ESEO satellite

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Abstract— **Within the frame of the ESA European Student Earth Orbiter (ESEO) educational programme, Cranfield University has developed a De-Orbit Mechanism (DOM) payload, which has provided a valuable learning opportunity to its students. ESEO is a microsatellite mission to Low Earth Orbit (LEO), which will carry a suite of university student-built payloads. The Cranfield DOM payload has been developed as a low-cost solution to allow small LEO satellites to comply with space debris mitigation guidelines, which require removal of satellites from protected orbit regions (including LEO) within 25 years of the end of the operational mission. The DOM achieves this by increasing the aerodynamic drag acting on the host satellite, by means of lightweight Kapton drag sails that are deployed at the end of the mission, enhancing the natural orbital decay and reducing the lifetime until the satellite re-enters and burns in the atmosphere.**

The DOM payload has been designed and developed by Cranfield MSc and PhD students, and the flight model is currently fully assembled and tested. This paper describes the design, development and testing activities performed by the students. These activities included requirements analysis, reference to ECSS standards, producing technical documentation, prototyping, defining and performing functional and environmental tests, flight hardware manufacture and assembly, and participating in formal ESA milestone reviews. The paper also discusses the learning experiences achieved within this project, and further educational benefits that are anticipated for the remainder of the ESEO programme.

Keywords—ESEO; satellite; education;de-orbit; space debris

I. Introduction

Cranfield University, a wholly postgraduate university in the UK, has been engaged in space teaching and research for over 30 years, with its MSc in Astronautics and Space Engineering running since 1987. In 2012, Cranfield joined the ESA ESEO (European Student Earth Orbiter) programme [1]. ESEO is a micro-satellite mission to Low Earth Orbit, with payload instruments being developed, integrated and tested by European University students as an ESA Education Office project. The satellite bus is being designed and built by SITAEL (formerly AlmaSpace, Italy), and is shown in Fig.1.

Fig. 1. The ESEO satellite. (Image courtesy AlmaSpace/SITAEL)

Cranfield was invited to provide a De-Orbit Mechanism (DOM) payload, as a result of its previous development of a de-orbit drag sail (Icarus 1) flown on the UK's TechDemoSat-1 satellite in 2011 [2]. At time of writing, the flight model of the DOM is currently fully assembled and tested, and awaiting final delivery for integration with the ESEO satellite. Over the course of the project, a number of MSc and PhD students have been involved in the development and testing of the DOM payload, and benefited from associated educational activities; these are described in the following sections.

II. The De-Orbit Mechanism

A. Preliminary Design

Design of the DOM payload began in the 2012-13 academic year, with four MSc students working on the project for their Masters theses. The students were provided by AlmaSpace with an Experiment Interface Document, which described the mission, and detailed the technical requirements,

[1]Former Cranfield PhD student

interfaces, and resources for the ESEO payloads. The students then had the task of defining a suitable candidate design of a de-orbit mechanism compatible with the ESEO mission. The main requirements for the payload were as follows:

- Pose no significant risk to the host satellite; probability of accidental deployment shall be <1%
- Meet the Inter-Agency Space Debris Coordination Committee guidelines (de-orbit within 25 years without attitude control, deployment success > 90%)
- Mass shall be less than equivalent propellant mass for a deorbit manoeuvre (Isp = 320 s)
- Compatible with Cranfield build and test facilities
- Compatible with the ESEO satellite
- Project budget shall be less than £10k

The initial reference baseline was a design similar to the previous Icarus-1 de-orbit sail from 2011. This mechanism was configured into a frame, which fitted around one of the satellite panels, and contained folded lightweight booms and thin Kapton sails. The booms had tape spring hinges which effected the deployment via stored strain energy. The design of Icarus 1 is described in [3] and shown in Fig. 2.

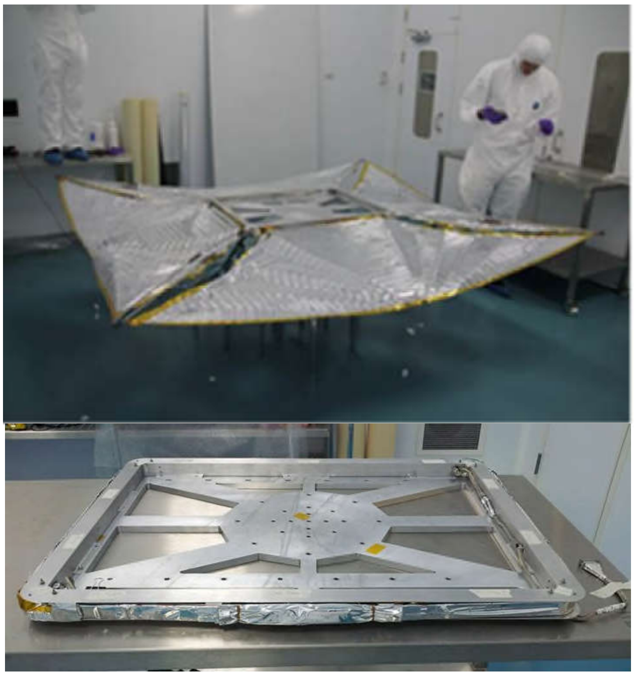

Fig. 2. Icarus 1 deployed (above) and stowed (below).

A study of different alternative concepts was then performed by the MSc students, which identified a range of solutions including motor-driven and inflatable deployment, different tape-spring-based approaches, and use of bi-stable composites, alongside the original Icarus design. A trade-off was performed which resulted in the selection of a compact tape-spring based design. This design is shown in Fig. 3 and Fig. 4.

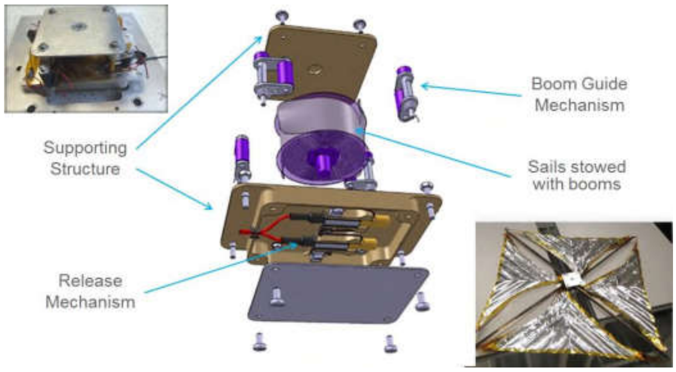

Fig. 3. Design of the DOM. Shown stowed (top left), exploded view (centre) and deployed (bottom right).

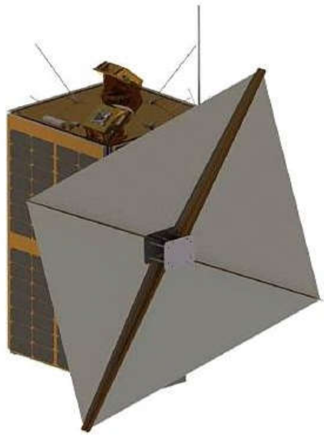

Fig. 4. The DOM shown deployed on the ESEO satellite. (Image courtesy AlmaSpace/SITAEL.)

This design utilises coiled tape-spring booms, which, along with the folded Kapton sails, are wrapped around a central hub which rotates around a spindle. Rotation is prevented by a securing Kevlar cord, until deployment is actuated by cutting of the cord by small CYPRES™ pyrotechnic cord cutters. Release of the stored strain energy in the tape spring booms causes the hub to rotate and the booms and sails to deploy.

A Preliminary Design Review was held in March 2013, after which the four MSc thesis projects then focused in detail on specific aspects of the payload and mission:

- Mission analysis and systems engineering – this focused on the end-of-life de-orbit simulations, aerostability of the drag sail, and thermal analysis
- Mechanical engineering and detailed design of the selected tape-spring concept – this included manufacturing considerations and identification of suitable materials and components
- Mechanical engineering and detailed design of the alternative inflatably-deployed concept – this also covered testing requirements and approaches for the payload, and evaluation of the atmospheric entry and burn-up of the satellite

- Structures and kinetics – this focused on the design and analysis of the tape spring booms and the deployment processes

During this stage of the project, the students produced several physical prototypes and performed preliminary functional testing. The student team also developed detailed requirements and design specification documents, which were shared with ESA and AlmaSpace. This provided excellent educational opportunities for the student team, particularly in ESA project procedures, review processes and use of ECSS standards documents. To add to this, ESA and the University of Bologna also offered an ESEO Training Course consisting of lectures and in-company training at Almaspace, which some of the Cranfield students attended on ESA scholarships in September 2013.

B. Detailed design and testing

In the following academic year, 2013-14, further MSc student projects continued the design and development activities. This included 3 students working on the DOM as a Group Design Project, and one for a Masters thesis. A PhD student also started in late 2013 with a research project on drag augmentation systems for space debris mitigation, which included a strong responsibility for development of the DOM payload.

An Interim PDR was held with ESA in February 2014. The design was refined and an engineering model built, with students producing the manufacturing drawings and liaising with the Cranfield workshops for manufacturing. Detailed test plans were developed by the students and a number of test activities undertaken with their involvement:

1) Rapid decompression testing at the Open University

This test was performed to verify that the stowed sails would not be affected by the rapid pressure drop during the launch ascent phase. The test set-up, showing the vacuum chamber, is shown in Fig. 5.

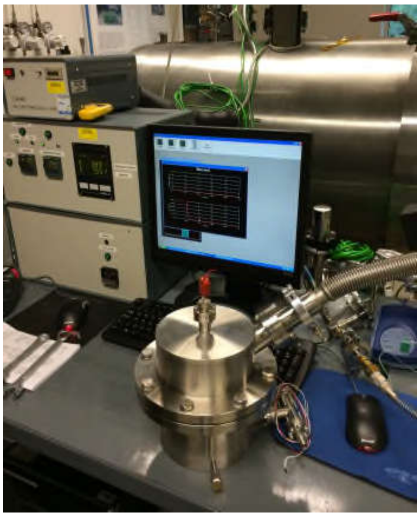

Fig. 5. The DOM engineering model undergoing rapid decompression testing at the Open University.

2) Mechanical vibration testing at RAL Space

The sine and random vibration test specifications were defined in the ESEO project documentation, and enveloped the expected environments for several launch vehicles, as the launcher for ESEO is still to be confirmed. Preparation for this test also required the design and manufacture of a mechanical interface plate, to allow the payload unit to be attached to the shaker. The test set-up is shown in Fig. 6.

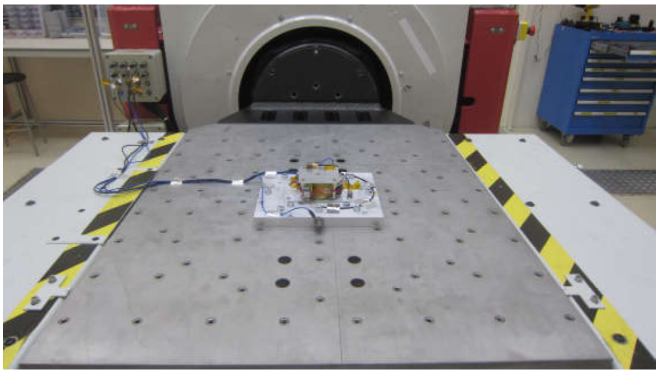

Fig. 6. The DOM engineering model undergoing vibration testing at RAL Space.

3) Functional testing

Multiple deployment tests were performed, to verify the correct and repeatable behaviour of the mechanism. The students made reference to ECSS standards to define the necessary number of deployment tests required for the different payload models (qualification and protoflight). A deployment test configuration is shown in Fig. 7.

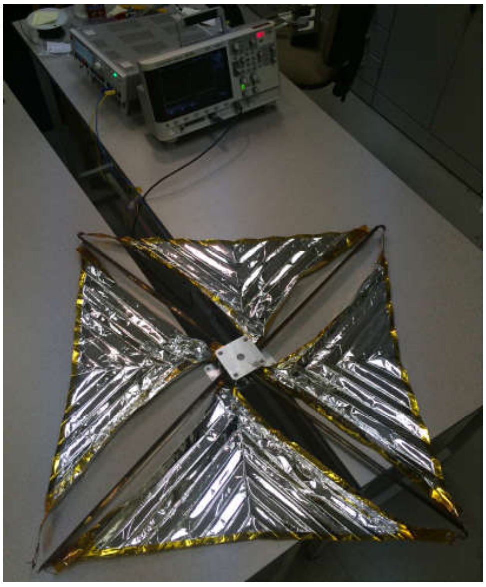

Fig. 7. DOM deployment test. This shows a test performed with deployment triggered via the pyrotechnic cutters. To reduce costs involved in consuming these cutters (which are one-shot devices), some deployment tests were performed by manual release of the retaining cord.

4) Characterisation tests of the actuators used to release the sails and booms

These tests evaluated behavior of the actuators with temperature, identified the no-fire current, and confirmed the speed of the actuation. This provided input for design of the electrical interface to the satellite, and definition of the deployment operations and commanding.

C. Critical Design Review

The students prepared the test reports, with the supervision of academic staff. These were delivered to ESA and AlmaSpace for the Critical Design Review (CDR) in July 2014. Following this milestone, a more physically representative Elegant Breadboard Model (EBB) of the DOM payload was built. This could be considered to be the Qualification unit. This model used copper-beryllium alloy tape spring booms, which were manufactured in Cranfield, and representative parts and materials. It was subjected to functional and environmental testing, in a similar way to the previous engineering model.

The satellite-level CDR was held in May 2015, and the DOM EBB model delivered to AlmaSpace in November 2015. During 2016 the focus was on production of the satellite. A fit-check with the satellite panel, and testing of the EBB with the ESEO satellite power and control units was performed in January 2017, with the payload being successfully deployed via command to the satellite control interface (Fig. 8).

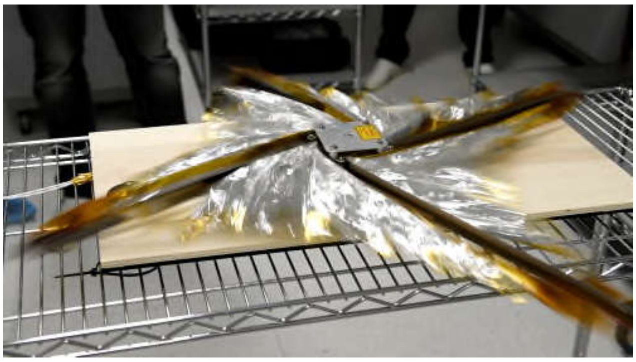

Fig. 8. The DOM EBB mid-deployment at AlmaSpace premises. (Image courtesy AlmaSpace/SITAEL.)

D. ProtoFlight Model

Assembly and testing of the ProtoFlight Model (PFM) was performed during 2017. The flight model had some slight differences from the EBB model, in particular:

- The machined aluminium primary structure had to be given an Alodine surface coating
- A flight-grade electrical connector had to be procured
- Minor modifications to the flight harness had to be made, to ensure compatibility with the satellite power subsystem (insertion of resistors)

The PFM was assembled in the Cranfield clean room, which provided experience of working in clean conditions and following appropriate practices for such conditions. The mechanical parts were machined in the Cranfield University workshops and the copper-beryllium booms manufactured using heat-treatment in an oven on campus. The Kapton sails were manufactured and folded by hand, and the flight electrical harness was also hand-made in Cranfield. The manufacture and assembly process was documented and reviewed by ESA and AlmaSpace.

After assembly, the PFM was subjected to the following test campaign during spring 2017:

- Mechanical vibration testing (RAL Space, UK)
- Functional testing (Cranfield, UK)
- Thermal Vacuum Testing (SITAEL, Italy)

Test reports were again prepared and the project documentation updated and reviewed by ESA at the Delivery Review Board in June 2017.

The payload flight unit is currently in storage in the Cranfield clean room (Fig. 9), awaiting final delivery and integration with the ESEO satellite.

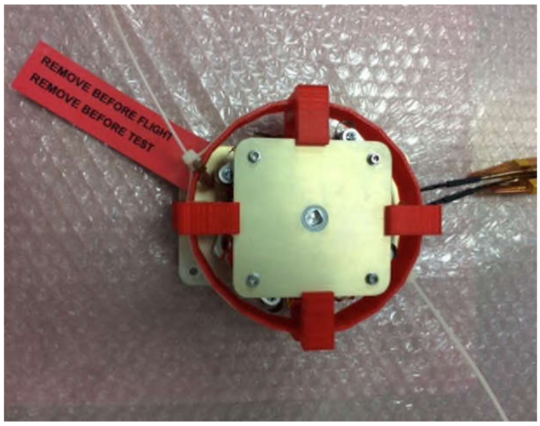

Fig. 9. The DOM PFM in storage, awaiting delivery. Note the Remove Before Flight protective cover, which also prevents accidental deployment.

In parallel with the PFM activities, several further MSc projects were undertaken in topics related to the DOM:

- Development of an evolution to the DOM design – this project investigated the lessons learned from the Icarus and DOM drag sail designs, and ways in which the design could be refined to improve its adaptability and commercial scope. This was directly linked to an ESA CleanSat study performed at Cranfield.
- Investigation of accelerated life testing requirements to simulate extended pre-deployment storage on-orbit and confirm survivability.
- Examination of alternative de-orbiting methods, and the potential for combining different techniques for effective end-of-life strategies.

Research continues in Cranfield in the area of de-orbit mechanisms and drag-augmentation systems for space debris mitigation, building on the experience of the ESEO project.

III. EDUCATIONAL OUTCOMES

Participation in the ESEO project has provided extensive and valuable space engineering and project management education for a significant number of students at Cranfield University. The principal educational outputs are summarized below:

- Masters theses: 12
- MSc Group Design Project reports: 3
- PhD theses: 1
- ESEO Training Course participants: 5
- Other students and researchers involved: 3

The ESEO project activities have also resulted in multiple conference and journal articles, e.g. [4], [5], [6], [7] and directly contributed to the successful participation of Cranfield in the ESA CleanSat Building Blocks study in 2016-17.

In addition to the specific engineering and design tasks within the development of the DOM payload, the key learning points (for both students and staff) within the ESEO programme have been:

- Experience of project management and understanding the ESA review processes
- Development of professional technical communication skills: preparing detailed technical plans and reports, maintaining version control
- Access to facilities such as cleanrooms, vibration testing, vacuum testing, satellite manufacturing
- Opportunity to interact with and learn from experienced space engineering professionals
- First-hand experience of the practical issues involved in producing flight hardware; for example recognising the additional lead-times introduced when procuring flight-grade parts was a very useful lesson for the team.

With the one-year duration of UK MSc courses, it was generally very easy to fit thesis projects into the ESEO schedules, although it was sometimes difficult for students to attend the ESEO training, which took place in September, after the course had finished and some students had already started jobs. The involvement of a PhD student was extremely beneficial, as this provided excellent continuity across multiple years, and invaluable depth of expertise that could be shared with successive rounds of MSc students.

Cranfield's involvement in ESEO, and the work of its students on a flight hardware project, definitely enhanced the attractiveness of the MSc course and helped in the recruitment of high quality students at both MSc and PhD level.

IV. CONCLUSIONS

The ESA ESEO programme can already be considered to have achieved excellent educational benefits for the students involved, even before the satellite is launched. The opportunity to design, build and test flight hardware is very rare as a student, and provides an unmatched and inspirational experience. Many of the students involved have gone on to careers in the space sector, including at ESA, and they are sure to be eagerly awaiting the successful launch and operation of the ESEO satellite.

ACKNOWLEDGMENT

Cranfield University gratefully acknowledges the support of the ESA Education Office, SITAEL (formerly AlmaSpace), The University of Bologna, The Open University, RAL Space, and all the Cranfield staff and students who have contributed to the design and development of the DOM payload.

(Please contact the corresponding author to obtain copies of the theses referred to in this paper.)

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Ferrofluid Dynamics in Microgravity Conditions

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***Abstract*—Ferrofluids are colloidal suspensions of magnetic nanoparticles in a carrier liquid. It is beneficial, for both fundamental research and future applications of ferrofluids in space, to obtain reliable measurements of the dynamics of ferrofluids in microgravity. This field remains unexplored since experiments in microgravity are expensive and the access to associated facilities is limited. In this ongoing project, the free surface displacement of a ferrofluid solution was measured in microgravity conditions in the ZARM Drop Tower in Bremen as part of the Drop Your Thesis! 2017 programme run by the ESA Education Office. The ferromagnetic solution is subjected to a controlled magnetic field while an initial percussion is imposed. Preliminary results point to significant contributions to the analysis of ferrofluid dynamics and sloshing dynamics in microgravity.**

Keywords—Ferrofluids; Sloshing; Microgravity; CFD; Reflectometry

I. INTRODUCTION

Ferrofluids are colloidal suspensions of magnetic nanoparticles in a carrier liquid [1]. Because of the high concentration of strong magnetic dipoles, their magnetic susceptibility is high compared to paramagnetic and diamagnetic substances. As a consequence, only moderate magnetic fields are required to control ferrofluids [2], which makes them interesting for a variety of different applications.

Despite the growing interest in ferrofluids, there is no clear consensus about the correct volume force expression that governs their dynamics in the presence of an external magnetic field [3,4]. Thus, an experimental comparison between the different proposed approaches would be a useful contribution to this debate [5].

Additionally, the sloshing dynamics of ferrofluids in microgravity are hardly known. This topic has been studied analytically [6] and numerically [7]. The latter study highlighted the importance of the shape and strength of the external magnetic field to the reorientation of the ferrofluid. The validation of model predictions is hampered by the lack of experimental measurements. To the best of our knowledge, only the NASA MAPO experiment [8] successfully gathered measurements of ferrofluid dynamics in microgravity, but visualization was obscured by coating of the inner container walls by the ferrofluid. Measurements of ferrofluid dynamics in microgravity with a better quality are required to improve the lack of experimental data. This would be of great interest for both fundamental and applied research.

In order to address the debate on the correct expression of volume force and the lack of experimental data of ferrofluids in microgravity, two containers with 475 ml of a ferrofluid solution were catapulted five times in the ZARM Drop Tower of Bremen. Under the influence of a constant magnetic field, a percussion was given to start an oscillatory movement in microgravity. Complementary detection systems were employed to quantify the free surface displacement and relevant variables were recorded.

This paper describes the experimental set-up which was designed, built and finally employed to execute the experiment as part of the Drop Your Thesis! 2017 programme run by the ESA Education Office. A short description of the physical model under development is also offered. The discussion about the preliminary results concludes with the identification of the most promising avenues of research.

II. METHODOLOGY

A. Experimental set-up

The experimental set-up (Fig. 1) is designed to impose an initial acceleration and magnetic field to a given ferrofluid volume and quantify the fluid response in microgravity. It consists of two linear sliding modules fixed to the capsule platform that hold two aluminium bases, each on which a plexiglass cylindrical container is mounted. The plexiglass containers hold the ferrofluid solution, which was produced with a commercial water-based ferrofluid. Around each container a copper electromagnetic coil is placed that generates a constant magnetic field. The intensity of the current through the magnetic coil is varied between 5 and 20 A for each launch. The construction materials were selected to minimize the electromagnetic perturbations. During microgravity, the linear modules accelerate the aluminium platforms up and down, exciting the ferrofluid in the plexiglass containers. After the percussion, a servo locking mechanism prevents further movement of the moving structure. A monoscopic fringe reflectometry detection system and a complementary lateral visualization are employed to measure the position of the free ferrofluid surface. From the video data, a 3D representation of

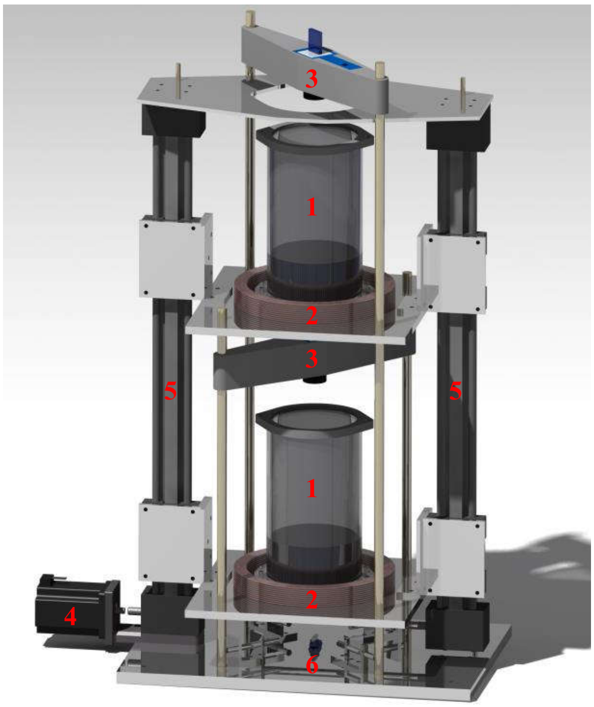

Fig. 1. Experimental set-up render: 1) Ferrofluid container; 2) Copper coil; 3) Visualization system assembly; 4) Stepper engine; 5) Linear modules; 6) Servo locking mechanism.

the free surface of the ferrofluid and relevant dynamical parameters are extracted.

Five catapult drop experiments were carried out in the ZARM Drop Tower of the ZARM Center of Applied Space Technology and Microgravity in Bremen, as part of the Drop Your Thesis 2017 programme run by the ESA Education Office. The ZARM Drop Tower has a vacuum chamber of 120 m. A catapult launch is used in which drop capsule is first launched upwards before it drops down again, resulting in a period of 9.3 s of microgravity conditions with a highest quality residual of 10^{-6} g. The catapult drop capsule has a weight of 165 kg and a payload area height of 953 mm. The capsule contains a battery pack with a power supply of 24 V DC, a capsule control system (CCS), radio telemetry and telecommand system, and an inertial measurement unit. The experiment payload is mounted on a capsule platform. The capsule is balanced before every launch to ensure high-quality microgravity conditions. For further specifications of the ZARM Drop Tower the reader is referred to the ZARM Drop Tower Bremen User Manual [9].

1) Percusion mechanism

A NEMA-23-XL servo-engine was employed to accelerate the ferrofluid containers along two IGUS ZLW-1040 sliders. The system performs a linear movement of ideally 4 cm with an acceleration of 12.6 m/s^2. The percussion is programmed to initiate 4.5 s after microgravity is reached. Due to internal friction the achieved amplitude of the percussion varied for each launch, and the acceleration profile resulted to be noisier than expected. The percussion was measured by an accelerometer in order to describe the observed behaviour of the ferrofluid.

2) Plexiglass containers

The plexiglass containers have an inner diameter of 11 cm, and a height of 20 cm. The containers are mounted to the aluminium base with brass bolts. The top part of the containers is skewed under a small angle of about 3º, in order to avoid adverse effects of laser reflections on the lid of the cylinders. A small hole is drilled in the top site of the containers to avoid condensation because of ambient temperature fluctuations. The inner surface was treated with Aquapel, a hydrophobic coating to avoid stains, which obscured the detection in a previous experiment [8].

3) Electromagnetic coils

Custom copper coils were designed and manufactured with dimensions and power requirements appropriate to the available space in the catapult capsule. The coils have 200 windings of a 1.8 mm wire diameter, an inner radius of 80 mm, a mean radius of 94.25 mm and a width of 25 mm. The total resistance of the coils at 20ºC is about 0.86 Ω. During the operation temperature increases and copper resistivity is modified, so in order to keep the magnetic field constant a PicoLAS LDP-CW 120-40 constant current power source was employed. The coils were wired in series, and a capacitor was connected in parallel to remove signal noise and stabilize the system.

4) Ferrofluid solution

The high-end EMG-700 ferrofluid (Ferrotec Corporation) was acquired for the experiment. We used a water-based ferrofluid rather than an oil-based one since this avoids coating effects of the container walls. A 1:10 volume solution of the EMG-700 ferrofluid in demineralized water was made with a ferrofluid volume concentration of 0.58 %. The physical properties of the solution were measured and can be consulted in TABLE I. Each container is filled with 475 ml of the solution, corresponding with a filling height of 5 cm.

TABLE I. PHYSICAL PROPERTIES OF THE FERROFLUID SOLUTION

Concentration (% vol)	***ρ* (g/ml)**	***μ* (cP)**	**σ (mN/m)**
0.58	1.020 ± 0.003	1.448 ± 0.007	61.70 ± 0.95

5) Visualization system

A monoscopic fringe reflectometric system [10] is used to quantify the displacement of the ferrofluid. Twenty centimetres above the surface of the fluid a Photron Fastcam MC2-10K is placed, with a SKR KMP-IR CINEGON 8 mm lens working at 60 fps, a shutter speed of 1/60 s and a resolution of 512x512 px^2. While the cameras are placed in the symmetry axis of each container, the DD635-5-24(16x62)-DOE laser projectors are pointing to the ferrofluid surface under an angle of 14º with respect to the vertical. A deformation of the ferrofluid surface is perceived as a lateral displacement of the pattern lines. The subsequent reconstruction process: (1) removes the noise from the original video image, (2) applies a Windowed Fourier Transform, (3) analyses and unwraps the result and compares it with the reference image (rest position of the fluid), and (4) calculates the phase shift and correlates it with the fluid height.

The previous system is complemented with a lateral visualization of the container using GoPro Hero 5 Session cameras working at 60 fps, 1920×1080 px^2 resolution and Wide FOV. Two GoPro's monitor each ferrofluid container with a relative angle of 180º. The distances between the symmetry axis of the container and the lens of each GoPro are d_1 = 191 mm and d_2 = 197 mm, respectively. The ferrofluid containers are covered with circumferential see-through grid rulers in order to derive the displacement of the ferrofluid from the GoPro videos, which are: (1) processed to correct the fisheye effect, (2) tilted to compensate the vertical inclination of the camera, and (3) analysed to compute the position of the region of interest. The height of a given point inside the container measured by the camera *i* with respect to the bottom of the cylinder, l_i, is approximated as

$$l_i = h_i \cdot \xi \cdot (d_i + d) / d_i + FP_i , \tag{1}$$

where h_i *[px] is* the height of the point of interest with respect to the focal point, ξ *[m/px]* the conversion factor from pixels to meters of the container scale (constant after tilting the image), *d [m]* the depth of the point of interest with respect to the middle plane and FP_i *[m]* the height of the focal point of the camera *i* with respect to the bottom of the container. The depth of the point of interest is estimated by imposing the equality between the height l_i measured by both cameras. The tracking process is done manually frame by frame.

B. *Physical and numerical model*

This section describes the physical and mathematical model used to simulate the behaviour of the ferrofluid.

1) Magnetic system

The magnetic system is composed by the following elements: (1) two electromagnetic coils, located around each ferrofluid container; (2) the ferrofluid itself, which behaves as a magnetic core when magnetized; and (3) the rests of ferrofluid in the free space.

The magnetic field generated by a circular ring is given by

$$\boldsymbol{B_{ring}} = \nabla\times\boldsymbol{A} , \tag{2}$$

where $\boldsymbol{B_{ring}}$ *[T]* is the magnetic flux density generated by the ring, and $\boldsymbol{A}$ *[Nm/A]* is the vector potential, which for a cylindrical reference system described by the unitary vectors $\boldsymbol{e_r}$, $\boldsymbol{e_\phi}$ and $\boldsymbol{e_z}$ adopts the expression

$$\boldsymbol{A}(r,z) = \frac{\mu_0 I}{2\pi r}\left(\frac{\eta}{\xi}K\left(\frac{4Rr}{\xi^2}\right) - \xi E\left(\frac{4Rr}{\xi^2}\right)\right)\boldsymbol{e_\phi}, \tag{3}$$

where $\eta(r,z) = r^2+R^2+z^2$, $\xi(r,z) = (r^2+R^2+z^2)^{1/2}$, μ_0 *[N/A²]* is the permeability of free space, *I [A]* is the current intensity, *R [m]* is the coil radius, *r [m]* and *z [m]* are the radial and vertical coordinates in the ring-centred reference system, and *K(x)* and *E(x)* are the elliptic integrals of first and second kind [11]. The resulting magnetic field is axisymmetric.

The real magnetic field is modelled as the superposition of the one generated by *n* circular rings located in a rectangular grid that covers the volume of the real coils. A value of $n = 64$, for which the variation of the magnetic field components with *n* at the nearest points of the ferrofluid volume is below 0.1%, is chosen.

The ferrofluid itself behaves as a magnetic core when magnetized and superposes its own magnetic field to the external field. This contribution requires a careful modelling of the ferrofluid volume shape, usually with a finite elements method. If the ferrofluid adopts a constant cylindrical shape and the external magnetic field is approximately uniform in the volume, then its magnetic contribution can be approximated as the one of an equivalent coil with the same geometry and a lateral surface current distribution $\boldsymbol{K_m}$. Mathematically,

$$I \cdot n_c\, \boldsymbol{e_\phi} = \boldsymbol{K_m} = \boldsymbol{M} \times \boldsymbol{e_r} = M\boldsymbol{e_\phi} , \tag{4}$$

where n_c is the number of loops per axial length and *M [A/m]* is the average magnetization vector module inside the ferrofluid volume. Following a similar procedure as before, it was decided to set $n_c = 20$, a value for which the magnetic field variation at the region under study is below a 0.03%.

The magnetization curve of a given material represents *M* against the magnetic field module *H*, and is usually measured experimentally. For a preliminary estimation, it was decided to interpolate the curve that corresponds to our ferrofluid solution with the basis of the Ferrotec water-based ferrofluid EMG-805 data available at Martin and Holtz [8] and Oldenburg et al. [12]. The magnetization curves of the EMG-700 and EMG-805 solutions are supposed to depend only on their magnetic particles concentration, which is the same for both (10 nm). The experimental data was fitted with functions of the form

$$M = 2/\pi \cdot (A \cdot atan(B \cdot H) + (M_s - A) \cdot atan(C \cdot H)) , \tag{5}$$

where *A*, *B* and *C* are the fitting parameters and M_s is the saturation magnetization. To obtain the magnetization curve of the studied solution, a linear interpolation of the fitting parameters was done. The result is detailed in TABLE II.

TABLE II. INTERPOLATED MAGNETIZATION CURVE DATA

Conc. (% vol)	M_s (A/m)	χ_{ini}	A (A/m)	B·10⁴ (m/A)	C·10³ (m/A)
0.580	2277.80	0.28	1138.90	0.31410	0.35378

2) CFD Model

A 2D axisymmetric Matlab CFD Model for capillary fluid systems [13] is employed to analyze the ferrofluid free surface displacement. The model solves the Navier-Stokes equations with an extra term in the momentum conservation equation. This term is calculated in a separate module and corresponds to the magnetic force. The acceleration data feeds the model, which reproduces the ferrofluid behavior during the experiment. The output was employed for dimensioning purposes and will be of high interest for the validation of the dynamic model.

III. RESULTS & DISCUSSION

The formulation of the local magnetic force over a ferrofluid has been a subject of discussion in recent times [5]. Although Kelvin's Law [6], expressed as

$$\boldsymbol{f_K} = \mu_0 (\boldsymbol{M} \cdot \nabla)\boldsymbol{H}, \tag{6}$$

where $\boldsymbol{F}$ $[N/m^3]$ is the attractive force per unit volume, has been extensively employed on previous works [8,12], Liu and Stierstadt restrict its validity to electromagnetically diluted systems, where the magnetic susceptibility becomes small [14]. Experimental evidence shows that this expression can only be considered valid for $\chi < 0.2$; for larger values, the alternative

$$\boldsymbol{f_V} = (\boldsymbol{M} \cdot \nabla)\boldsymbol{B}, \tag{7}$$

being $\boldsymbol{B}=\mu_0 (\boldsymbol{H}+\boldsymbol{M})$ $[T]$, was suggested by Odenbach and Liu [3]. This result was soon contested by Engel to highlight some theoretical weaknesses of the related study [4], suggesting instead this expression for a system in equilibrium

$$\boldsymbol{f_E} = \mu_0 (\boldsymbol{M} \cdot \nabla)\boldsymbol{H_0}, \tag{8}$$

where $\boldsymbol{H_0}$ is the applied magnetic field due to free currents and equivalent magnetic loads, sometimes named "external". It is important to note that $\boldsymbol{H}=\boldsymbol{H_0}+\boldsymbol{H_d}$, being $\boldsymbol{H_d} = -D\boldsymbol{M}$ the approximate demagnetization field and D the demagnetization factor. It is useful to note that the previous expression is related to (7) through $\boldsymbol{f_E} = (1+D\chi)/(1+\chi)\boldsymbol{f_V}$. For a spherical drop, the demagnetization factor is approximately equal to $1/3$ [15].

The magnetic field and magnetic forces field are calculated on an evenly spaced rectangular grid. This grid is then interpolated in the space to integrate the total force over the ferrofluid.

The initial magnetic susceptibility of the solution under study falls in the range on which the differences between the previously described dynamic approaches begin to be significant. With a careful modelling of all the magnetic contributions, the microgravity environment offers a unique benchmark to discriminate between them. The opportunity appeared during the fourth launch of the experiment, when a ferrofluid drop with a radius of 5.7 mm was unexpectedly formed after the percussion, as presented in Fig. 2. The drop floated during 2.5 seconds under the influence of the magnetic force produced by the coils, the ferrofluid cylinder and the rests of ferrofluid that sticked to the walls of the container. The inertial acceleration of the capsule was of the order 10^{-6} m/s^2, and the coils current intensity was kept constant at 15.9 A. By employing the lateral visualization system, it is possible to extract relevant kinematic parameters, such as the drop acceleration. Preliminary results show that its comparison with the output of the previous dynamic models may result in a valuable contribution to the ongoing debate about ferrofluid dynamics.

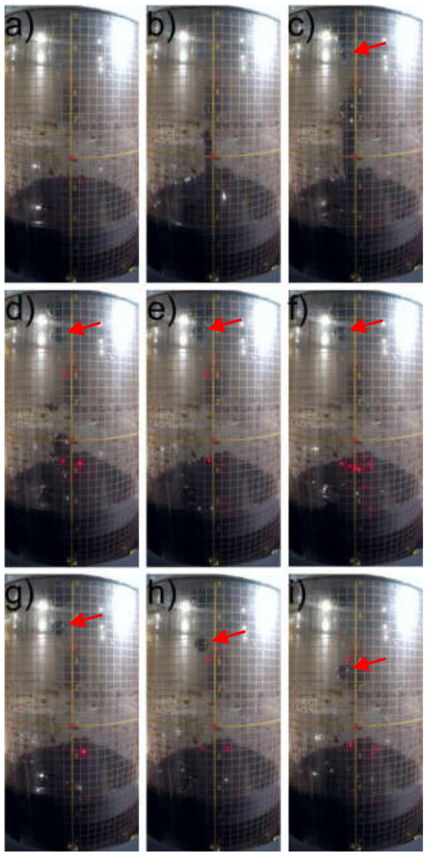

Fig. 2. Series of images captured by the lateral cameras showing the ferrofluid drop formation and evolution. a) t=-2.5 s; b) t=-1 s; c) t=-0.5 s; d) t=0 s; e) t=0.5 s; f) t=1 s; g) t=1.5 s; h) t=2 s; i) t=2.5 s.

While the last is a relevant event that will be part of a future work, it only represents 1.5% of the video record. The rest of the data, where the pattern fringe reflectometry detection system plays a key role, is expected to offer relevant information about ferrofluids oscillatory dynamics in microgravity as a function of the external magnetic field. During the experiment campaign it was observed that the oscillation of the free surface was mainly axisymmetric. Fig. 3 shows a video frame captured by one of the Photron cameras where the symmetry of the problem and the pattern lines deformation is clearly observed. Shadows and reflections were minimized, but their effects could not be completely removed.

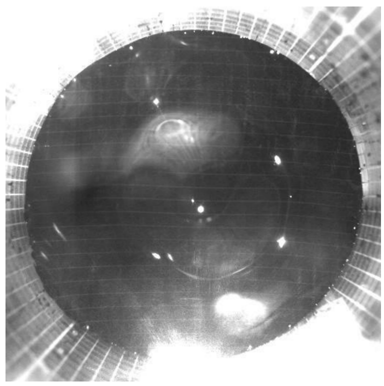

Fig. 3. Surface deformation observed from the top of the ferrofluid container.

The pre-processing phase then becomes critical to clean and prepare the video data, which is subsequently employed to reconstruct the fluid surface. Further steps involve the validation of sloshing models and the study of magnetically-damped systems.

IV. Conclusions

A preliminary analysis of the ESA Drop Your Thesis! 2017 – The Ferros results has revealed two main applications for the campaign data. Firstly, the microgravity environment and the characteristics of the ferrofluid solution resulted in the unexpected event of the generation of a ferrofluid drop, which can be used to compare the different models of a volumetric magnetic force over the ferrofluid. This objective requires a careful modelling of the magnetic system. Secondly, the quasi-axisymmetric deformation of the ferrofluid free surface measured by the monoscopic detection system will be compared with the simulations of our CFD Model. The removal of the video frames noise has been revealed as a critical step towards the collection of relevant dynamic parameters. Both topics will be addressed in a future work.

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PRIME: a REXUS project to demonstrate a miniature free falling unit for plasma measurements

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***Abstract*— PRIME (Plasma Measurement with Micro Experiment) is a student experiment, to be launched on REXUS25 sounding rocket in 2019 as part of the REXUS/BEXUS programme. The project aims to develop a miniature recoverable Free Falling Unit for plasma parameter measurements in the lower ionosphere. Two identical Free Falling Units are ejectable from the Rocket Mounted Unit. The geometry of the Free Falling Units is designed to be compatible with future 'DART' rockets, from the company T-Minus Engineering. A Free Falling Unit consists of an Experiment and a Recovery Unit, which share a common battery and an umbilical. The Recovery Unit consists of a parachute with its deployment mechanism and a localization system. The Experiment Unit includes the deployable, cylindrical Langmuir probes with a data acquisition system. The measurements will be validated against model and independent observations of the ionospheric parameters.**

Keywords*—*cylindrical Langmuir Probes; Plasma Parameters; REXUS/BEXUS; Free Falling Units

I. INTRODUCTION

Communication and navigation systems are dependent on signal propagation in the ionosphere, which is affected by space weather. Observations of plasma parameters under various conditions are important for improving models of this region. This gives a motivation to study the ionosphere [1]. Information about the properties of plasma in the ionosphere is limited by the amount and frequency of the measurements that can be performed. The measurements can be either in-situ or remote ones, with in-situ measurements usually giving better accuracy and resolution. In-situ measurements require the use of sounding rockets, and hence cannot be performed regularly.

Currently, the 'Improved Orion' is one of the standard sounding rocket launch vehicles used for atmospheric and ionospheric measurements, bringing tens of kg payload up to about 100 km altitude. It is the launch vehicle used in the REXUS/BEXUS programme, The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through the collaboration with the European Space Agency (ESA). Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. EuroLaunch, the cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. T-Minus Engineering [2] a company based in the Netherlands is developing a smaller 'DART' launch vehicle, providing an affordable alternative for bringing small payload (about 1 kg) to altitudes of over 100 km, which would enable more frequent measurements of the upper atmosphere. The volume available for payload of the DART is constrained by its inner diameter of 30 mm.

The purpose of the Plasma Measurement with Micro Experiment (PRIME) is to validate a miniature free falling payload complying with the dimensions of the DART rocket, in a flight on board REXUS25 sounding rocket. Two Free Falling Units (FFUs) with Langmuir probe based measurement system, see Fig. 1, will be ejected from the rocket module. The FFUs will continue in the ballistic flight, reaching an apogee of about 85 km, and record the currents collected by the probes. These measurements will enable us to obtain altitude profiles of electron temperature and density and compare the results with incoherent scatter radar data (EISCAT), ionosondes, and compared to models.

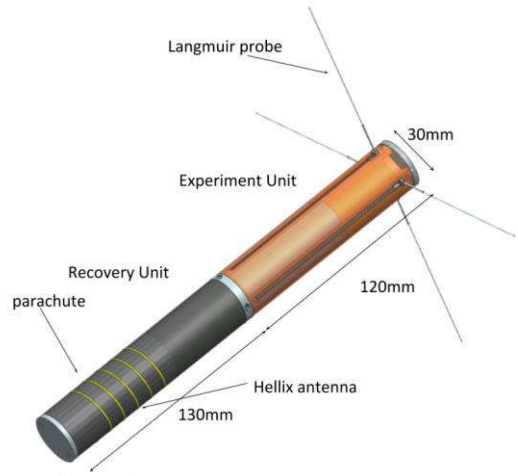

Fig. 1. Free Falling Unit

This paper presents the status of the PRIME experiment development after the Preliminary Design Review. Details of the Experiment are given in Section II, Section III introduces the Electrical Design followed by the Section IV for Mechanical Design. The paper is concluded with an outline of the project plan.

II. Experiment

A. Langmuir Probes

The PRIME experiment uses four cylindrical Langmuir probes, Fig. 2. Measuring current collected by the probes for known bias voltages is used to reconstruct the electron density and the electron temperature by analyzing the current-voltage curve. The analysis is dependent on assumptions about the plasma, such as the magnetic field strength, frequency of collisions and photoelectric currents. The probes deploy from the FFU in a symmetric configuration in the plane perpendicular to the FFU axis. An angular rate sensor, magnetometer and sun sensors provide data for reconstruction of the orientation of the probes with respect to the magnetic field of the Earth and the sun direction [3].

As the launch of the REXUS rocket is usually during the day, photoelectron emission will contribute to the current balance of the probes. The value of the photelectric current depends on material of the probe and the illumination conditions. The values of the maximum photoelectric current density in full illumination by the solar UV radiation for stainless steel (2.4 nA/cm^2) and gold (2.9 nA/cm^2) are lower than for aluminium (4.8 nA/cm^2), making them suitable for the probe surface [4].

The expected value of the electron density in the altitude range of 60 km to 90 km is between 10^4 m^{-3} to 10^{11} m^{-3} [5]. The expected temperature will be in the range of 170K to 300K [6]. The Debye length resulting out of these parameters is maximum 2 mm [7]. Given the experiment dimensions, the Langmuir Probe will operate in the "thick sheath collisionless regime" [3]. Thus, the radius of the probe shall be much smaller than the Debye length and the length of the probe to much larger than the radius of the probe

B. Similar Experiments

Our arrangement is similar to the design of the Multi-Needle Langmuir Probe [8]. The Multi-Needle Langmuir probe was flown up to an altitude of 300 km above ground level. It had a length of 41 mm and radius of 1 mm. The analysis started from the "thick sheath collisionless regime". Although the geometry and dimensions of the probe relating to the plasma is similar for the PRIME and Multi-Needle Langmuir probe experiment, we may not necessarily use the same analysis due to the differing conditions in which the probe will be flown, in particular with respect to higher collisionality and solar UV irradiation. The KTH SPIDER experiment used four spherical Langmuir Probes with a radius of 12.5 mm to measure plasma parameters in the E region of the ionosphere [9]. The interpretation of the data was intended based on "thin sheath collisionless regime", although it may not be fully applicable to it. For the PRIME experiment, we intend to investigate the refinements of the basic Langmuir probe theory that can improve the results of the analysis.

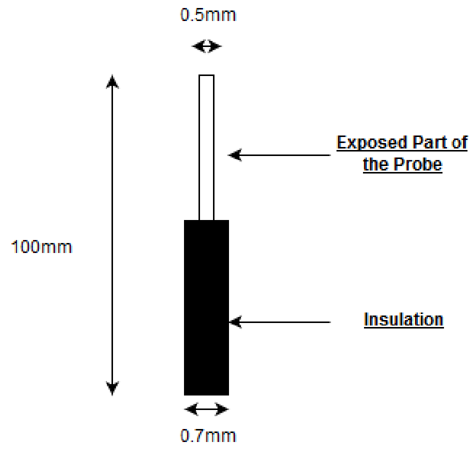

Fig. 2. Cylindrical Langmuir Probe

III. Electrical Design

The FFU consists of an Experiment Unit and a Recovery Unit, which will share a common battery and an umbilical connection to the RMU. The top level block diagram of the electronics is shown in Fig. 3. The umbilical connection is used for communication to the Rocket Mounted Unit (RMU) and charging the internal battery of the FFU.

The Experiment Unit is the Langmuir probes data acquisition system. It consists of a Data Hub PCB and an Experiment PCB. The Data Hub PCB contains the control and data storage circuitry. The functionality is implemented in a combination of an FPGA and a microcontroller, with data saving onto an SD card. The Langmuir probe circuitry is based on the design used in the SPIDER experiment, see Fig. 4. It consists of a transimpedance amplifier, for biasing the probe and converting current to voltage and a difference amplifier, which subtracts the bias voltage and further amplifies the signal. The transimpedance amplifier uses a high input impedance OP-amp OPA129, to reduce the current measurement error.

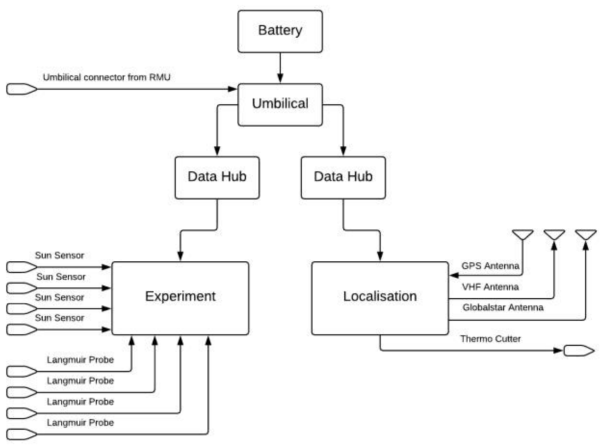

Fig. 3. Top Level Block Diagram

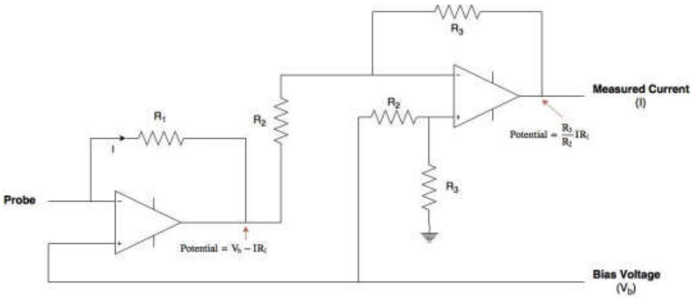

Fig. 4. Langmuir Probe Circuitry [9]

The Recovery Unit is used to ensure recovery the FFU after its ejection. The FFU deploys the parachute and transmits its position, so that it can be retrieved in the terrain. The Recovery Unit is implemented in two PCBs. The Localization PCB carries a GPS receiver and two different transmitters sending the data with the position of the FFU: one using a VHF frequency modulation for reception on the ground, and another using a higher frequency for sending the data through the Globalstar satellite constellation. It also contains a GPS front end receiving the GPS L1 signal for post-flight reconstruction of the flight trajectory using a software GPS receiver. In the Data Hub PCB, the raw GPS data and housekeeping data are stored on an SD card. The hardware of the Data Hub PCB is identical to the one in the Experiment Unit, but different software is used. The parachute release mechanism is activated at an altitude of 5 km, as deduced from a pressure sensor.

The miniature dimensions of the FFU require careful consideration of the antennas. The recovery uses two transmitting antennas, an omnidirectional Globalstar antenna operating at 1615 MHz and an VHF antenna operating at 173 MHz. A receiving GPS L1 antenna operates at 1575.42 MHz. A conformal antenna design is investigated for implementing custom GPS and Globalstar antennas. The VHF antenna will be a whip antenna attached to the parachute.

IV. Mechanical Design

A. Rocket Mounted Unit

The outer RMU structure is a cylinder with a diameter of 355.6 mm, a thickness of 4 mm and a height of 120 mm [10]. The RMU includes the ejection mechanism of the FFUs. Two FFUs are ejected simultaneously in opposite directions from the rocket. Use of two FFUs provides two sets of measurement data for cross-validation and minimizes the effect on the rocket by symmetric ejection. The two FFUs are held in place by hatches covering the ejection holes of the RMU skin. The hatches are constrained by a tensioned wire and hook set up. When the wire is cut by a pyrocutter, activated by the REXUS service module, the FFUs are ejected, see Fig.5. A camera for recording the ejection is also included in the RMU.

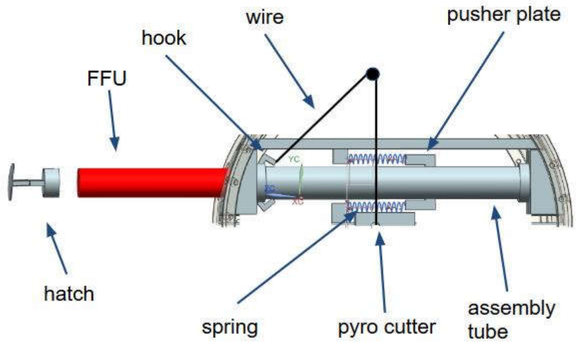

Fig. 5. Ejection System

B. Free Falling Units

The FFU structure is shown in Fig. 1. The recovery unit, surrounded by the custom antenna assembly, includes space for its PCBs, the parachute and its deployment mechanism. The deployment mechanism is constrained by a nylon string placed along the guiding cut outs on the parachute container and then is attached to the lid. The parachute cords go through the piston holes and the compression spring and are attached at the bottom of the container. The parachute is packed in the container on top of the piston. The two nylon string constrains the container lid, holding the parachute in place and compressing the spring. The parachute deployment is by the thermal cutter melting the nylon string, releasing the piston. The electronics of the recovery unit are located between the parachute container and the battery. The connection to the antennas is provided in the Localisation PCB.

The Experiment Unit hosts the Experiment PCB and Data Hub PCB, as well as the Umbilical PCB. The four Langmuir probes are mounted in separate individual probe beds mounted inside the casing of the FFU. The probes are hinged in their beds and are preloaded with a torsion spring. The probes are held down against the walls of the ejection system while the FFU is inside the rocket and are deployed as the FFUs eject.

V. Project Plan

The REXUS cycle 25/26 started with a proposal submission, in October 2017, and a selection workshop at ESTEC, Netherlands in December 2017. Currently, the design is developed further, including manufacturing and testing different prototypes, until the Critical Design Review, at DLR, Germany in June 2018. There will be a test flight for the Free Falling Unit in May 2018, with its goal to have a working recovery system. The Integration Process Review will take place in August 2018, at the Experimenters site, before the final testing phase starts, including also a Bench Test and a Spin Test. The launch campaign for REXUS25 is set to take place in March 2019 and will be followed by analyzing the data to publish our results.

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Assembly Integration and Testing of the ESEO Flight Model

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***Abstract*—The ESEO mission, European Student Earth Orbiter [1], is based on a 50kg microsatellite bus equipped with 7 payloads developed by different universities across Europe. ESEO should be inserted in a sub-600 km SSO LEO and its nominal mission is due to last 6 months with a possible extension period of additional 12. The project started in 2013 with a training period for the students of about 2 months and it is now on its final stage. Major achievements on platform side are related to the completion of a large set of tests foreseen on the initial ESEO EBB set and on the PFM set, both functional and environmental. A similar philosophy was implemented by the payload teams; they initially performed a series of tests on their EBBs which were installed inside the ESEO flatsat in a later stage; the flatsat is currently used for software integration testing, validation and to run mission scenario prolonged tests at system level. This paper will describe the MAIT phase of the ESEO satellite up to the upcoming system level environmental test campaign (April – August 2018)**

Keywords*—*microsatellite, multi-payload, cold-gas propulsion, LEO

I. INTRODUCTION

The ESEO S/C is a scientific demonstrator platform for payloads provided by European Universities, ranging from Earth imaging to space radiation measurement. The platform itself is the evolution of a smaller one developed in the past by SITAEL team, therefore the necessity to propose a smart approach to design and (delta-) qualification for both the platform and the payload, coherent with the mission budget and schedule.

According to the previous assumptions, an AIV/AIT plan capable to minimize the cost and the system development schedule has been proposed, based on a limited number of models. At P/L and unit level, the following models will be used:

For units and P/L:

- Elegant Bread Board (EBB), for electrical qualification testing of design, functionality, software and interfaces separately and by means the Avionics Test Bench (ATB, or ”flatsat”), for mechanical and structural testing and for use after launch with ground verification of on-board software updates prior to upload;
- Protoflight Model (PFM), for mechanical qualification and mechanical/electrical acceptance testing prior to system integration, and for functional verification after their integration into the ESEO FM.

For OTS components:

- Flight Model (FM), for electrical acceptance testing and mechanical fit check prior to system integration, and integration into the satellite FM.

At system level, the following models will be used:

- ESEO Avionics Test Bench (ATB, or “flatsat”) for electrical/data/software qualification of units and P/L, using elegant bread boards (EBB);
- ESEO Flight Model (FM), with flight structure and with all units, P/L and COTS flight models (FM) built to flight standard and integrated for acceptance testing.

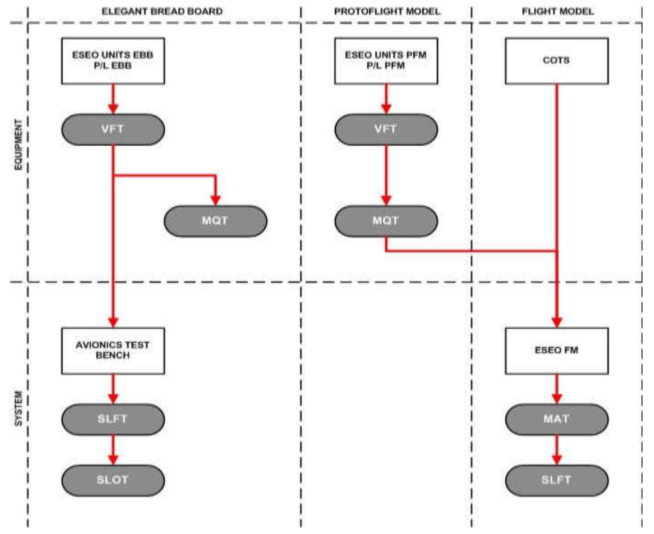

Fig. 1. ESEO Model philosophy.

All the units, the payloads and the subsystems shall undergo a set of tests aimed to verify their functionality, performance and operating capabilities. For each element, the dedicated set of

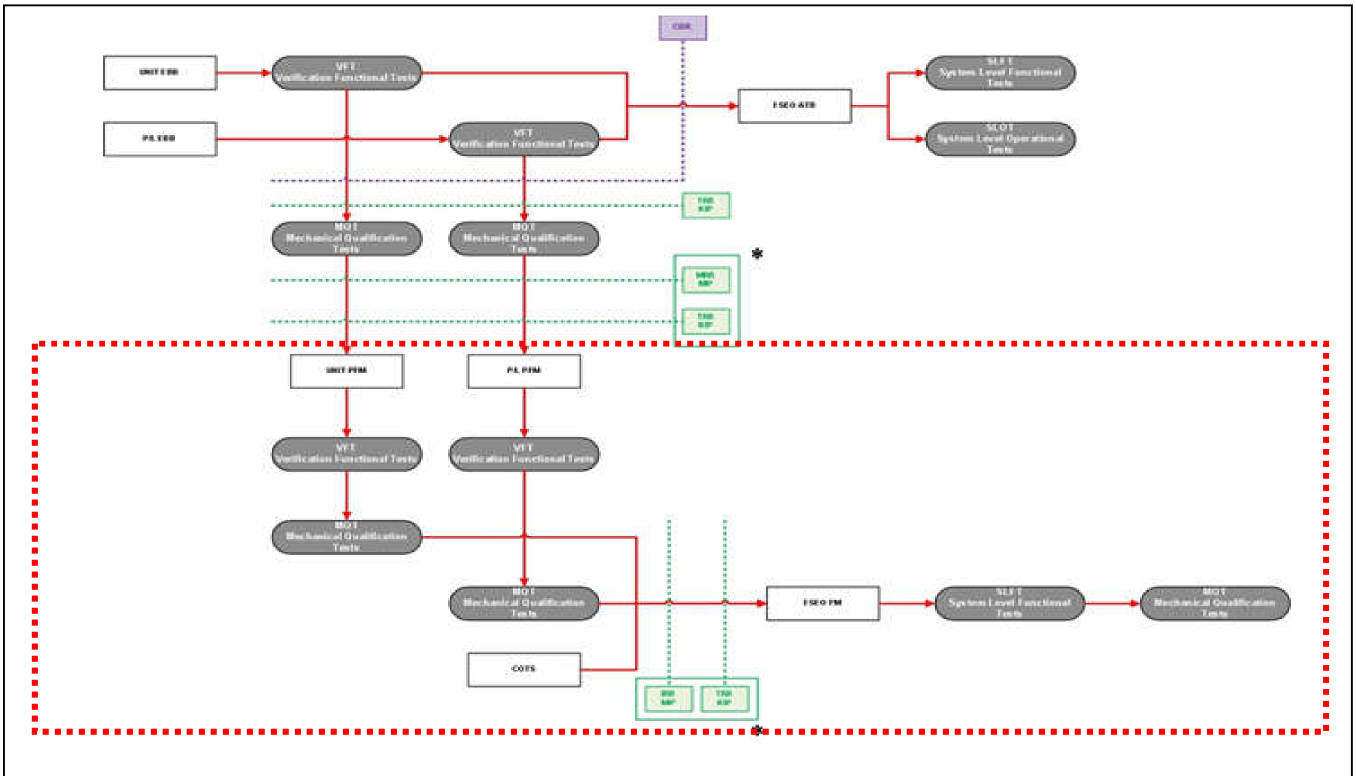

Fig. 2. ESEO AIV Plan. The circle highlits the stage of the AIV workflow reported in this paper

tests shall be specifically tailored to verify the requirements imposed on each of them.

The AIV program at equipment/subsystem level aims to the fulfilment of the following purposes:

- To verify the units and the P/L integration in the ESEO satellite;
- To verify the units and the P/L compliance with the ESEO mission requirements and their operability;
- To achieve the proto-flight qualification for the units and the P/L at equipment level;

The following verification tests are introduced in the proposed model philosophy:

- VFT (Verification and Functional Tests);
- MQT (Mechanical Qualification Tests), including vibration, thermal vacuum and EMC testing;
- MAT (Mechanical Acceptance Tests), reproducing the MQT test with proto-qualification approach;
- SLFT (System Level Functional Tests), including integrated system tests, EM compatibility, functional tests, system validation tests.
- SLOT (System Level Operational Tests), including mission simulations and FDIR tests.

The test specifications and the proposed EBB-PFM approach are in accordance to the ECSS E-ST-10-03C (Testing) and E-ST-10-02C (Verification)

II. High Pressure Tank

The high-pressure tank of the ESEO cold-gas micro propulsion system has been developed according to the same EBB and PFM approach. In accordance to the ECSS E-ST-10-03C, the vessel EBB has undergone full environmental testing up to completion of its own qualification cycle with the required burst test.

The Vessel PFM, manufactured in the same batch of the previous EBB, has undergone acceptance test campaign at unit level before being integrated at system level.

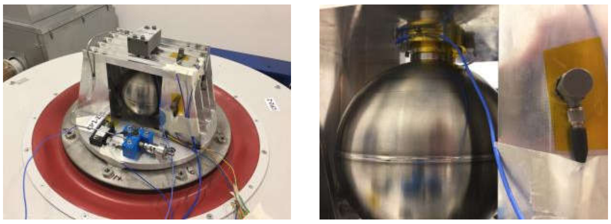

Fig. 3. ESEO Pressure Vessel Testing.

III. VIBRATION TESTS

The integrated ESEO SM has undergone vibration testing In 2016 to correlate the numerical models at system level and to provide integrated vibration testing for all those payloads requiring complex mounting or with tight schedule. The ESEO SM was populated with dummy masses apart the micro propulsion fluidics and the RF distribution unit.

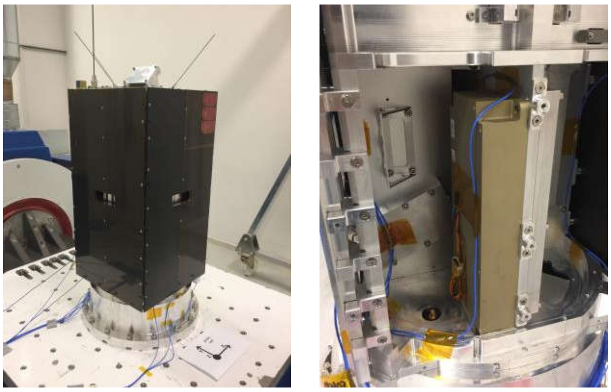

Fig. 4. ESEO SM Vibration Testing.

IV. SUBSYSTEMS PFM TESTS

Based on the results of the ESEO SM vibration test campaign, that allowed to confirm the vibration levels distributed to all the units and the payloads in the supporting documentation, all the PFMs have undergone the proto-qualification test campaign, including both environmental (MQT) and functional testing (VFT). With respect to the previous EBB testing, all the units have been vibrated stand-alone and then integrated in their own mechanics for thermal vacuum and EMC testing. Thanks to the ESEO structural break-down, the PFM mechanics is composed mainly by the S/C trays, as shown.

Fig. 5. ESEO PFM units testing.

For a more representative approach, the EMC testing ad unit level has been performed by stacking up all the spacecraft trays with the integrated PFMs, composing the final ESEO bus module. All the units have been moreover switched on and off by the on board Power Management Board. The two solution allowed realistic test conditions for both autocompatibility and conducted susceptibility, testing the all the PFMs within a flight scenario

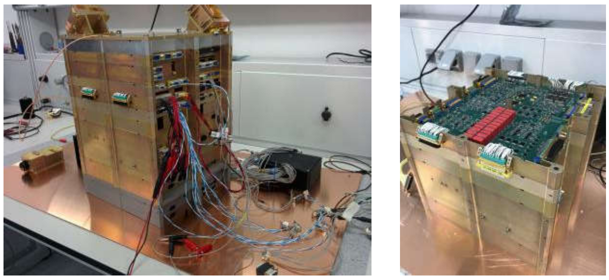

Fig. 6. ESEO PFM units EMC tests.

V. FLATSAT TESTING

In parallel to the ESEO PFM units and payloads acceptance test campaign, all the EBBs at the end of their qualification cycle have been integrated within the ESEO Avionic Test Bench, basically a flatsat model used to validate the on-board software iteratively and to simulate real mission scenarios on ground. The ESEO flatsat is currently running SLFT test aimed to validate the on board software to be installed on board the PFMs before the ESEO FM integration.

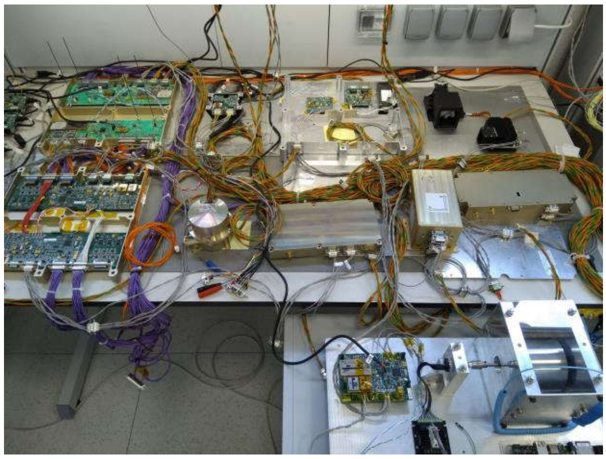

Fig. 7. ESEO ATB

VI. POWER SYSTEM

A. Solar Arrays

Solar arrays have been entirely designed and manufactured by SITAEL, involving a great effort in demonstrating the correct substrate preparation and solar cells installation processes. The solar panels test campaign has been performed both at SITAEL and ESA-ESTEC facilities, in accordance again to the ECSS E-ST-10-03C standards. A test panel, fully representative of the carbon fiber-Al honeycomb substrate plus the kapton layer has been prepared and cured in thermal-vacuum chamber, then the solar cells have been glued to the substrate. The gluing procedure has been tuned in order to achieve the best adhesion to the substrate without inclusion of air during the process.

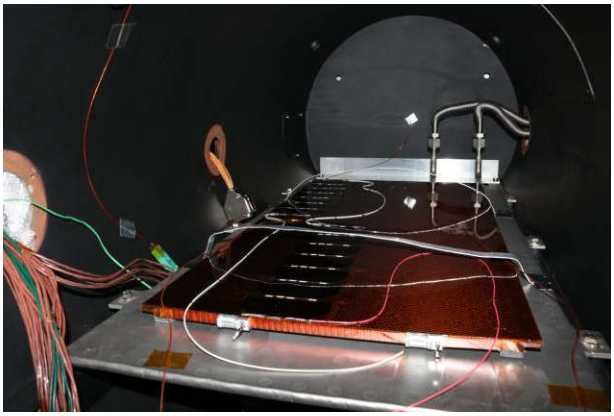

Fig. 9. ESEO Solar panels assembling tests

At the end of the solar panels manufacturing, thermal vacuum tests, in addition to pre- and post- ELM and flash tests, have been performed to demonstrate the lack of workmanship defects.

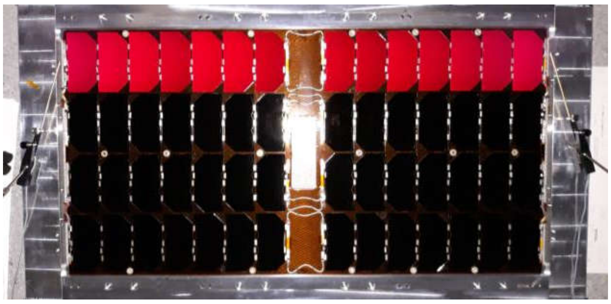

Fig. 10. ESEO Solar panels ELM tests

B. *Battery packs*

ESEO battery packs are composed of 36 commercial Li-ion cells, boxed in an aluminum housing integrating thermal sensors for on-ground and in-flight monitoring.

Both single battery Li-Ion cells and assembled battery packs underwent a series of functional end performance tests.

The performance tests started with a characterization cycling of all the PANASONIC NCR18650B cells procured, aimed at assessing the real voltage-capacity characteristic of the cells in comparison with the datasheet performance. A full charge-discharge cycle has been performed for each cell, using the nominal datasheet C-rate and temperature conditions, and the actual V-Ah curves have been compared to the nominal one. Internal resistance was also recorded. Both these measures have been used to screen and reject cells drifting too far away from datasheet values.

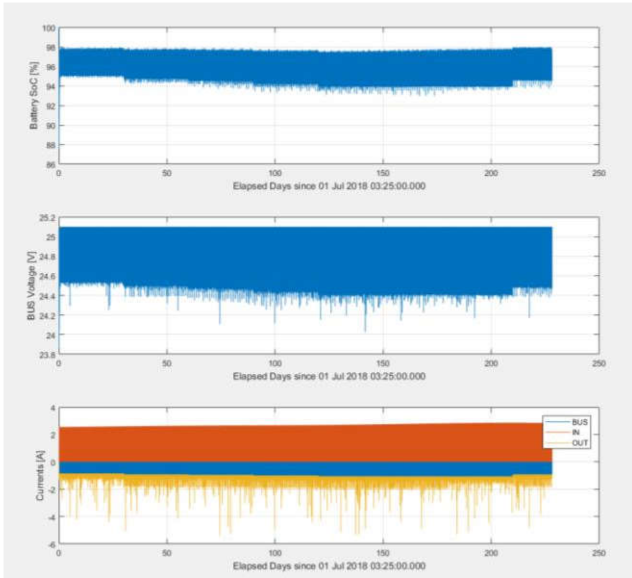

Fig. 8. ESEO Power Budget simulation results, showing the full time history of the battery State of Charge (top panel), voltage (mid) current (bottom) for the six-month nominal mission.

For a small subset of cells, a long-term cycling has been performed, in order to define the impact of ageing on cells performance. The test showed a good behavior of the batteries, outperforming even the cycle life guaranteed by the manufacturer.

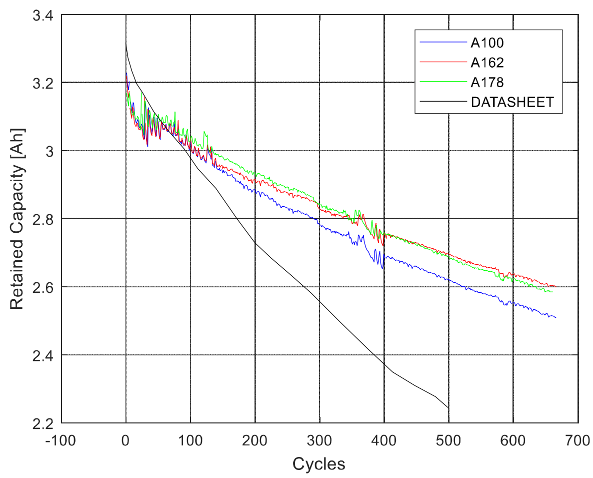

Fig. 11. Actual cycle life of three ESEO Panasonic cells (red-green-blue) vs datasheet nominal performance (black)

Additionally, several abuse tests have been carried out on a sample population of cells and on the assembled PFM battery pack, i.e. overcharge/overdischarge, short-circuit, drop/shock, high temperature heat-to-vent.

C. *Power Budget simulations*

The measurements from battery characterization and ageing cycles have been used to test and validate a numerical model, that was then integrated into a power system simulator.

The simulator has been run to assess the capability of the onboard electrical system to power the platform and the payloads during all operational phases of the mission.

Each platform subsystem and payload has been modelled through its power consumption and activation duty cycle, along with the power intake and storage granted by the solar arrays and the battery packs, respectively.

The simulations showed that the power system is adequately sized and capable of operating the mission.

VII. SOFTWARE VALIDATION

The development of ESEO software is based on an incremental approach. The functionalities defined in the software requirements will be implemented in successive steps. Consequently the activities related to the verification and validation will be also executed incrementally. The ESEO subsystems software is RTOS based. RTEMS operating system has been selected to provide the application the required support in terms of multi-threading standardized access to the hardware resources. For all the subsystem, static analysis and requirement verification have been take place. Moreover functional test at subsystem and system level have been performed. Once completed the functional tests at system level on the ESEO ATB, the EBB units and all the developed test benches will be made available for the operational tests in order to verify:

- ESEO S/C operability according to foreseen mission scenario;
- ESEO fault detection isolation and recovery algorithms;
- ESEO S/C compatibility with ground station.

The scenario test shall demonstrate the ESEO S/C capabilities to operate correctly according to the different simulated mission.

VIII. CONCLUSIONS

The ESEO S/C is now approaching the system level environmental and functional test campaign, that will be anticipated by the following steps in the next two months:

- Accomplishment of all PFM payloads acceptance test
- Integration of both ESEO Bus Module and Payload bay
- Verification of the mission scenario compatibility and related software validation (in parallel on the ESEO ATB)

The vibration test campaign shall be performed on the same TIRA 55kN electrodynamic shaker used for the ESEO SM verification, at SITAEL facilities, while the thermal vacuum and EMC testing shall be performed at ESA-ESTEC premises, being then ready for the shipment to the launch site.

[1] D. Bruzzi, P. Tortora, P. Galeone, “European Student Earth Orbiter: ESA’s educational Microsatellite Program”, 27th Annual AIAA/USU Conference on Small Satellite 2013

WOLF: A REXUS STUDENT EXPERIMENT TO DEMONSTRATE AN ACTIVE WOBBLING CONTROL SYSTEM FOR SPINNING FREE FALLING UNITS

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ABSTRACT

WOLF (WObbling controL system for Free falling unit) is a student experiment developed in the frame of REXUS/BEXUS programme, launched in March 2018 on board of the REXUS24 sounding rocket. The primary objective of the project is to demonstrate a system to suppress the wobbling of Free Falling Units (FFUs) ejected from a spinning rocket. Multiple FFUs ejected from a single carrier provide means of multipoint measurements in the upper atmosphere, where spin stabilisation is a common attitude control scenario. Lateral rates introduced by rocket coning, ejection tip-off or other effects result in wobbling of FFUs, while for many missions flat spin is required. A reaction wheel based control system was proposed to suppress the wobbling. A single reaction wheel, with rotation axis perpendicular to the nominal spin axis of the FFU, actuated with a control law based on the phase of the FFU wobbling is effective in reducing the lateral rates during limited flight time of the rocket. An analytical model of the motion of a cylindrically symmetric FFU is put forward, and verified by numerical simulation and a prototype test with a gravity-offloaded system. Due to a non-nominal and a short flight of the rocket, there are no data recorded during the flight to validate the objectives. The experiment to demonstrate the system in flight was based on two identical FFUs, launched inside a rocket module. Both FFUs carried the wobble control system, a parachute based recovery system and a wire boom deployment system. After dewobbling the FFUs, the wire booms with spherical probes would had been deployed and the deployment process would had been recorded. The electrical characteristics of the probes would had been monitored and compared with models of photoelectric current from various probe surfaces.

Key words: WOLF; Free Falling Unit(s); REXUS; Wobble control.

1. INTRODUCTION

Since aircraft and balloons are limited to altitudes of typically less than 40 km and orbital spacecraft have a minimum altitude of above 100 km, the only viable solution to access the middle atmosphere and lower ionosphere is the use of sounding rockets. Free flying payloads ejectable from sounding rockets can be used to make multi-point in-situ measurements, e.g. [1, 2, 3].

A series of student rocket experiments with free-flying payloads have been conducted at Royal Institute of Technology, KTH, Sweden [4]. Based on the concept of ejectable FFUs developed and demonstrated in the REXUS programme, a research sounding rocket was realised in the Swedish national sounding rocket and balloon programme. The experiment, Small Payloads for Investigation of Disturbances in Electrojet by Rockets (SPIDER), aimed at characterisation of Farley-Buneman turbulence in the E region of the ionosphere on multiple scales. Ten FFUs, conceptually similar to the ISAAC FFUs [5] were ejected from the same carrier, reaching an apogee of over 130 km. The SPIDER sounding rocket was launched on February 2, 2016 from Esrange Space Centre. The payloads were successfully ejected, and most of them were recovered.

However, the FFUs experienced a wobbling motion, probably induced during ejection (see Figure 1). The wobbling motion of the FFUs complicates the attitude reconstruction of the units, and compromises the electric probe measurements on the spinning payloads.

The WOLF REXUS experiment set out to address the issue of payload wobbling, aiming to demonstrate a system to suppress the wobbling and to ensure flat spin motion on cylinder-shaped FFUs. The experiment alsodevelops a more robust recovery and localization system to be used on FFUs of this class.

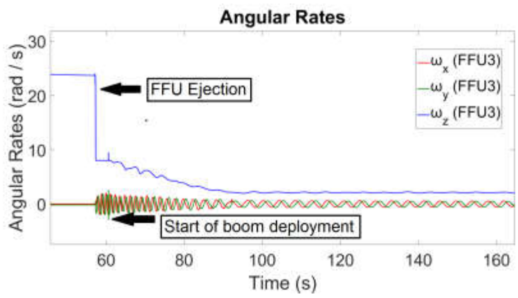


Figure 1: Components of angular rate vector in the FFU body frame recorded by a SPIDER FFU.

This paper presents the status of the experiment after the launch campaign. We start with presenting an analytical model of the FFU rotational motion with a reaction wheel, formulate the concept of active control for reducing the lateral rates, which is then simulated numerically. The setup and results of a prototype test with a gravity offloading system are presented. The secondary objectives of the experiment (characterizing of the probe photoemission, characterizing of the probe dynamics during and after deployment) are presented as well.

2. MODEL AND NUMERICAL ANALYSIS

The dynamics of a rigid body is described by Euler's equations. For an axially symmetric body (with moments of inertia about two principal axes equal), the motion is a combination of spin and coning (see e.g. the presentation in [6]). We consider an FFU with a controllable reaction wheel perpendicular to the spin axis, and describe its dynamics, formulating a simple control law.

2.1. Analytical model for rotation of an FFU with a reaction wheel

We consider an FFU with an axisymmetric moment of inertia. A reaction wheel with an axisymmetric moment of inertia is part of the FFU, mounted with its spin axis perpendicular to the spin axis of the FFU. If gravity torques and drag forces are neglected, no external torques are assumed to act on the FFU, then the total angular momentum is conserved. Represented in FFU body frame, the Euler's equations [7] are

$$\dot{\vec{L}} + \vec{\omega_{\mathrm{FFU}}} \times \vec{L} = 0, \tag{1}$$

where $\vec{\omega_{\mathrm{FFU}}}$ is the angular velocity of the FFU and $\vec{L}$ is the angular momentum of the FFU, given by

$$\vec{L} = I^{\mathrm{TOTAL}} \cdot \vec{\omega}_{\mathrm{FFU}} + I^{\mathrm{RW}} \cdot \vec{\omega}_{\mathrm{RW}} \tag{2}$$

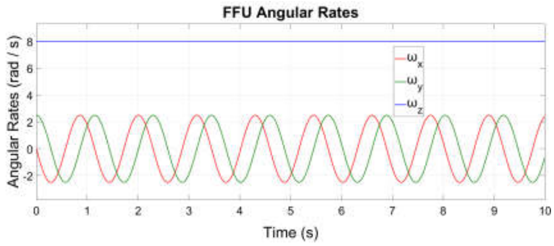
Here, I^{TOTAL} is the moment of inertia of the whole FFU, including the reaction wheel:

$$I^{\mathrm{TOTAL}} = \begin{bmatrix} A & 0 & 0 \\ 0 & A & 0 \\ 0 & 0 & C \end{bmatrix} \tag{3}$$

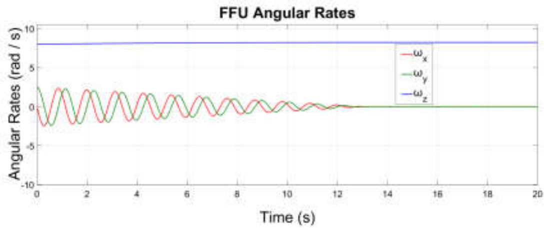
and I^{RW} is the moment of inertia of the reaction wheel in its principal principal axes (parallel to the FFU parallel axes by assumption):

$$I^{\mathrm{RW}} = \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \alpha \end{bmatrix} \tag{4}$$

The second term in equation 2 describes the contribution of the rotation of the reaction wheel with respect to the FFU to the total angular momentum (the contribution of the reaction wheel rigidly rotating with the FFU is included in the first term). While the angular velocity of the FFU can have arbitrary orientation, $\vec{\omega}_{\mathrm{FFU}} = (\omega_{\mathrm{x}}, \omega_{\mathrm{y}}, \omega_{\mathrm{z}})$, the reaction wheel is constrained to rotate about its axis fixed in the FFU frame, and $\vec{\omega}_{\mathrm{RW}} = (0, \omega_{\mathrm{s}}, 0)$.



(2a) Numerical simulation of torque-free precession of a thin disk.



(2b) Time history of the FFU angular rates with dewobbling control

Substituting equation 2 into equation 1 yields

$$\begin{aligned} I^{\mathrm{TOTAL}} \cdot \dot{\vec{\omega}}_{\mathrm{FFU}} + I^{\mathrm{RW}} \dot{\vec{\omega}}_{\mathrm{RW}} + \\ \vec{\omega}_{\mathrm{FFU}} \times (I^{\mathrm{TOTAL}} \cdot \vec{\omega}_{\mathrm{FFU}} + I^{\mathrm{RW}} \cdot \vec{\omega}_{\mathrm{RW}}) = 0 \end{aligned} \tag{5}$$

Using equations 3 and 4 this can be written in components:

$$\begin{aligned} \begin{bmatrix} A\dot{\omega}_{\mathrm{x}} \\ A\dot{\omega}_{\mathrm{y}} \\ C\dot{\omega}_{\mathrm{z}} \end{bmatrix} + \begin{bmatrix} 0 \\ \beta\dot{\omega}_{\mathrm{s}} \\ 0 \end{bmatrix} + \begin{bmatrix} (C-A)\omega_{\mathrm{y}}\omega_{\mathrm{z}} \\ (A-C)\omega_{\mathrm{x}}\omega_{\mathrm{z}} \\ 0 \end{bmatrix} + \\ \begin{bmatrix} -\beta\omega_{\mathrm{z}}\omega_{\mathrm{s}} \\ 0 \\ \beta\omega_{\mathrm{x}}\omega_{\mathrm{s}} \end{bmatrix} = 0 \end{aligned} \tag{6}$$

This can be re-arranged as

$$\dot{\omega}_{\mathrm{x}} - \frac{(A-C)}{A}\omega_{\mathrm{y}}\omega_{\mathrm{z}} = \frac{\beta}{A}\omega_{\mathrm{z}}\omega_{\mathrm{s}} \tag{7a}$$

$$\dot{\omega}_{\mathrm{y}} - \frac{(C-A)}{A}\omega_{\mathrm{x}}\omega_{\mathrm{z}} = -\frac{\beta}{A}\dot{\omega}_{\mathrm{s}} \tag{7b}$$

$$\dot{\omega}_{\mathrm{z}} = -\frac{\beta}{C}\omega_{\mathrm{x}}\omega_{\mathrm{s}} \tag{7c}$$

This set of three non-linear coupled differential equations describes the time evolution of the angular velocity of the

FFU, if the angular velocity of the reaction wheel $\omega_{\mathrm{s}}(t)$ is known. If the reaction wheel is disabled, equation 7 reduces to the known torque-free motion of a spinning top with constant ω_z. The perpendicular component of the angular rate rotates about the FFU z axis:

$$\omega_{\mathrm{x}}(t) = |\omega_{\mathrm{FFU}}^{perp}| cos(\lambda t + \phi_0) \tag{8a}$$

$$\omega_{\mathrm{y}}(t) = |\omega_{\mathrm{FFU}}^{perp}| sin(\lambda t + \phi_0) \tag{8b}$$

$$\omega_{\mathrm{z}}(t) = \Omega = const \tag{8c}$$

where ϕ_0 is the initial phase. The angular velocity λ is

$$\lambda = \left(\tfrac{C-A}{A}\right)\Omega. \tag{9}$$

For an oblate body with $C > A$, as is the case for disk-shaped FFUs, the lateral rate vector rotates in the same sense as the spin.

If the reaction wheel rotates, it will affect the dynamics of the whole FFU through the terms on the right hand side of equation 7, which contribute to the component of angular acceleration $\vec{\alpha} = \dot{\vec{\omega}}$ of the FFU:

$$\alpha_{\mathrm{RW}} = \begin{bmatrix} \frac{\beta}{A}\omega_{\mathrm{z}}\omega_{\mathrm{s}} \\ -\frac{\beta}{A}\dot{\omega}_{\mathrm{s}} \\ -\frac{\beta}{C}\omega_{\mathrm{x}}\omega_{\mathrm{s}} \end{bmatrix} \tag{10}$$

The y component of α_{RW} is related to spin acceleration of the reaction wheel, while the other two components are related to torque needed to rotate the spinning reaction wheel with the FFU.

To reduce the lateral rates, α must be directed opposite to $\vec{\omega_{\perp}} = (\omega_x, \omega_y)$. While this is not possible to achieve precisely in general case, based on the free motion of the FFU, the control law is proposed as

$$\omega_s(t) = -S\,\cos\phi, \tag{11}$$

where S is the maximum and $\phi = \tan^{-1}(\omega_y/\omega_x)$ is the phase of the lateral rate vector. As the FFU is dewobbled, its spin rate will increase slightly, so the phase should be updated based on observed angular rate components in the body frame.

2.2. Numerical simulation

The model defined by equations 7 was built up in Matlab/Simulink interface, which is used in modeling of dynamical systems and control problems. The input of the model is the velocity profile of the motor and the outputs are the angular rates of the FFU. The parameters of the FFU and the reaction wheel enter the model as the coefficients (gains). The result of a simulation of force-free precession of a thin disk with $C = 2A$, and an initial condition of $\vec{\omega} = (0, 2.5, 8)$ rad/s is shown in Figure 2a. The precession of the FFU is reproduced, with ω_z being constant, and $\vec{\omega_{\perp}}$ rotating in the xy plane in the positive sense, as the analytical model shows.

To evaluate the effectiveness of the proposed control law, a SIMULINK model was created. The inertia of the cylindrical FFU is estimated as $A = 0.0128$ kg m^2 and $C = 0.0216$ kg m^2, assuming a mass of 3 kg, radius of 0.12 m and height of 0.09 m.

The effectiveness of actuation is linear with the ratio of the reaction wheel moment of inertia about its axis, β, to the FFU moment of inertia about its spin axis A. For a representative reaction wheel the ratio β/A was assumed at $1.8{\cdot}10^{-3}$. The maximum spin rate of the reaction wheel was set to 300 RPM. Figure 2b shows the response of the FFU to the applied control. The lateral rates are reduced during the actuation, while the spin rate of the FFU is slightly increased, due to angular momentum conservation.

3. PROTOTYPE TEST

Evaluating the dewobbling system requires supporting the FFU prototype in a way allowing free rotation in all three axes with low friction. Suspension based systems provide a simple way of removing the gravity effects (e.g. [8]). A prototype, see Figure 3, was suspended on a 1.85 m long string (Savage-Gear Silencer SPE 8-Braid fishing line of 0.09 mm thickness, with 4.7 kg rating). The mass of the prototype was 0.355 kg, of which 0.047 kg is the reaction wheel. The moment of inertia A was $13{\cdot}10^{-4}$ kg m^2, and the wheel moment of inertia β was $5{\cdot}10^{-6}$ kg m^2.

A Faulhaber 0824006B brushless DC motor with integrated spur 21.9:1 gearhead was used for actuation, operated by a dedicated Faulhaber SC2402P motor driver. The control algorithm is performed by a PJRC Teensy3.6 microcontroller board, based on measurements of a STM L3GD20H angular rate sensor. All electronics were powered by a SAFT MP144350 3.75 V Li-ion battery, boosted to 5 V by a POLOLU U1V11F5 regulator board. Angular rate readings were stored in a SANDISK 8GB microSD card.

The prototype was spun up by a spin table with adjustable

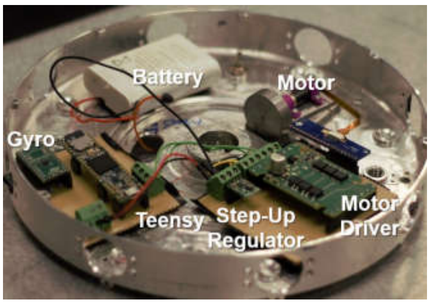


Figure 3: Prototype implementation.

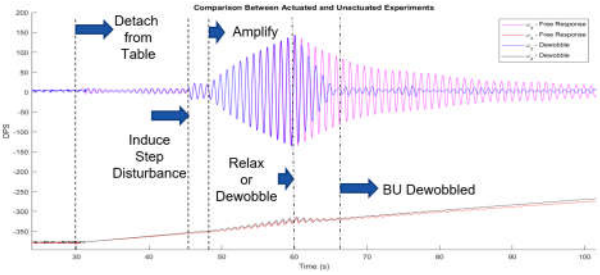


Figure 4: Time history of natural damping and active dewobbling tests.

height. By ramping up the spin rate to the desired value, and lowering the spin table, the suspended prototype was left in a state close to flat spin.

To demonstrate dewobbling of the prototype, lateral rates were induced by the reaction wheel. A short disturbance was introduced, followed by a period with the positive feedback control law, increasing the wobbling amplitude. Two scenarios were run at this point: disabling the reaction wheel or operating with the negative feedback control. The former scenario includes air drag damping of the prototype rotation, while the latter scenario demonstrates the effect of the actuation. Figure 4 presents a comparison between the runs, with the main experimental steps annotated. Until 60 s the two time histories overlay, indicating high repeatability of the test. With actuation, the lateral rates are reduced after 6 s, while with the damping of the unactuated system is considerably slower, taking over 40 s to achieve the same amplitude.

4. EXPERIMENT OVERVIEW

The primary objective of the WOLF experiment is to demonstrate a wobbling control system based on the concepts above. The layout of the experiment largely follows the solution from the REXUS experiments, starting with the ISAAC experiment [5], and the SPIDER experiment, here we briefly describe the WOLF set-up.

4.1. Experiment concept and timeline

The experiment hardware consists of one Rocket Mounted Unit (RMU) and two Free Falling Units (FFUs). A spring-based ejection system in the RMU keeps the FFUs constrained inside the FMU, and releases them at 65 km altitude. The dewobbling system is activated immediately after ejection, followed by the deployment of the wire booms. The FFUs deploy a parachute at 5 km altitude, and land for subsequent recovery. Each FFU consists of three modules: the bottom unit (BU), the Boom Deployment Unit (BDU), and the Common Unit (CU). The BU contains the dewobbling system and the electronics for deployment of the wire booms and for measurement of the electric probes. The BDU contains the wire boom deployment system, probes and miniature cameras for recording the process of the boom deployment. The CU records the general flight data including accelerations, angular rates, and atmospheric pressure. Each of the units has a diameter of 240 mm and a height of 30 mm, the total height of the FFU being 94 mm.

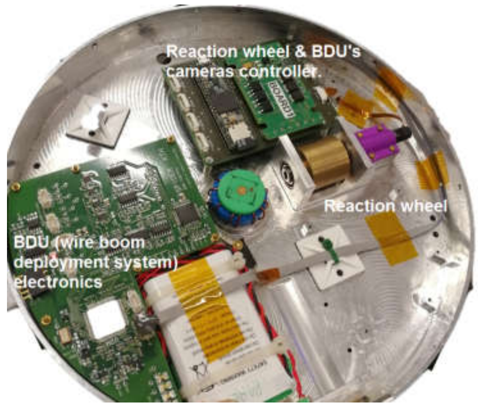


Figure 5: BU flight implementation.

4.2. Dewobbling system

The system to suppress FFU wobbling closely follows the prototype setup described in Section 3. The flywheel is supported by a steel shaft, mounted in both ends in ball bearings press-fitted in the support structure, see 5 The motor is attached to the structure by means of a cap and screws, and is connected to the reaction wheel by a coupler. The mass of the reaction wheel is 94 g and its moment of inertia is $9{\cdot}10^{-6}$ kg m^2.

4.3. Wire booms and probes

The wire boom deployment system is heritage from the SPIDER experiment, with spherical probes of 25 mm diameter at the tips of thin wire booms. While the relatively low altitude of the REXUS flights combined with launch not related to any specific geophysical conditions limit scientific value of the data to be collected on the Langmuir probes, they could be used for a measurement technology experiment. As REXUS rockets are flown during day-time, the probes onboard WOLF FFUs could be utilized to record the photoelectron current induced by solar UV radiation and its dependence on altitude and probe surface material. Estimating the photoelectron current is important in case of particle detectors, e.g. the Meteror Smoke Particle Detector, for which a model of the photocurrent as a function of altitude and material coating was developed [9]. WOLF spherical probes had surface of several materials (gold, graphite, nickel and aluminium) and it could provide useful measurements to test this model of photoelectron current.

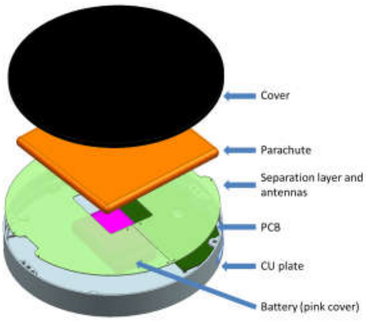


Figure 6: CU overview.

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4.4. Localisation and recovery system

While the recovery system has been reliable in the experiments with smaller FFUs [10], it has not performed equally well on experiments with larger FFUs and SPIDER. The electronics in the WOLF design are mechanically separated from the parachute by a flat lid (see Figure 6). The rim of the CU structure extends as a cylindrical wall, to which the lid attaches. The parachute is placed between the lid and the ejectable cover, held onto the CU with a polymer filament. The filament is cut by a thermal cutter, releasing the spring-loaded cover and exposing the parachute to the air flow.

The FFUs store all measurement data onboard so, RF systems are used for localisation of the FFU. During the parachute descent phase, a commercial GPS module provides the position of the FFU, which is transmitted during a VHF link and sent to Globalstar satellite network.

Thus, the CU utilizes two radio frequencies, Globalstar (1615 MHz) and GPS L1 (1575.42 MHz) As the range of commercially available small L1 antennas is yet very limited, and the antennas must comply with the space limitation of the CU, it was decided to pursue a custom antenna solution for WOLF. Patch antennas were chosen due to their flat design and easy integration on the lid that separates the parachute from the electrical components underneath.

5. SUMMARY

The demonstration of a wobbling suppression system would help to improve the performance of future experiments with spinning FFUs, in particular those involving the electric double probes. Such a system can be implemented with a single reaction wheel mounted perpendicular to the FFU spin axis. Here we exhibited the effectiveness of the system by numerical simulation and a prototype test. Due to a non-nominal flight, the rocket reached only 7 km altitude, instead of 80km, and the system could not had been validated.

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MULTITROP: an educational project on root tropism interactions

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***Abstract— MULTITROPism: interaction of gravity, nutrient and water stimuli for root orientation in microgravity*, is the educational experiment selected by the Italian Space Agency (ASI) to be performed on the International Space Station (ISS) during the third mission of astronaut Paolo Nespoli (VITA mission, Increment 52/53). It meant to promote young people interest to space sciences putting together: a) three scientists with long experience on the effect of space factors (as microgravity and radiation) on plant morphological and functional traits, b) three university students with interest in plant biology and c) nine high school students. The MULTITROP experiment aimed to investigate the role of the three main external stimuli (gravitropism, hydrotropism and chemotropism) on root tip orientation. The experiment reached the ISS with the SpaceX 13 mission. The three university students and the project scientific coordinator went to Kennedy Space Centre for late access activities. Seeds germinated in microgravity and seedlings were chemically fixed on board the ISS. The flight hardware was uploaded on Flight SpaceX 13 Return and successfully delivered to the scientific team. Post flight analyses are in progress. All students were much involved not only in training activities but also in dissemination events. They stimulated people interest to space science and technology with a significant coverage by media including local and national newspapers, TV and radio programs.**

Keywords— plant tropisms; root orientation; altered gravity; microgravity

I. INTRODUCTION

The advancement of International space programs relies on highly qualified scientists, engineers and technicians lifelong dedicated to Space science and technology. To achieve such goals much attention is being paid to actions aimed at motivating young people, and encouraging them to choose space related careers. Within this framework, the Italian Space Agency (ASI) is supporting educational projects as LISS (Lesson on the ISS) carried out in collaboration of astronaut Samantha Cristoforetti in the course of the FUTURA 42 mission on the International Space Station (ISS) in 2014 and also EXPLORA in collaboration of astronaut Paolo Nespoli in the course of the VITA mission on the ISS in 2017. Specific aim of these initiatives was not only to attract the interest of a significant number of students towards space and space-related themes, but also to create at the same time a relevant impact on their families and the general public in terms of news coverage, social-media interest and stakeholders' involvement. In 2017, ASI also promoted YiSS (Youth ISS Science), a call for educational/scientific experiments to be performed on the ISS during the third mission of astronaut Paolo Nespoli. Among the 13 University-School teams participating to the competition, the DALiSS team was the one awarded by proposing the experiment MULTITROP (MULTITROPism: interaction of gravity, nutrient and water stimuli for root orientation in microgravity). The project was conceived by botanists at the Department of Agricultural Sciences of the University of Naples Federico II and developed by a PhD and two Master students from the University of Naples and nine students from the High School 'Liceo Scientifico Filippo Silvestri' located in Portici. All activities were planned, coordinated and supervised by a university professor, the principal investigator (PI) of the project; two teachers acted as tutors of the school students. In this paper we describe the MULTITROP experiment focusing on the educational activities carried out by the team.

II. SCIENTIFIC BACKGROUND ON ROOT TROPISMS

On Earth, plants experience a large number of environmental factors influencing root growth and orientation. The movements of plant roots are mostly attributable to tropisms, that are a directional growth response guided by a directional stimulus [1]. Tropisms allow plants to adjust their growth as a function of environmental stimuli aiming at growth optimization and stress avoidance. By deepening our knowledge regarding root growth strategies and tropism interactions, good prospects in optimizing plant cultivations in Space and also on Earth can be achieved. Gravity is the principal factor guiding root orientation ever since plants colonized the land. However, several different tropisms have been identified for plant roots. The most extensively studied tropisms include gravitropism, phototropism, hydrotropism, chemotropism, halotropism and thigmotropism [2]. However, evidences suggest that other environmental factors influence root growth, such as electric fields, magnetism and sound [3]. In most cases, tropism functioning is documented to a certain extent but the remaining parts of the pathways still remain unknown. Although most research focuses on isolated tropisms and cut out interactions between different tropisms, it is clear that in natural circumstances the final growth strategy relies on the integration of proportional influences of all tropic signals. The MULTITROP academic team has long experience in research on the effect of microgravity on seed germination, seedling development and plant reproduction [4-11].

III. MULTITROP EXPERIMENT

The experiment aims to investigate on the interactions between gravitropism, hydrotropism and chemotropism in root orientation by eliminating the dominant action of gravity. More specifically, the experiment aims to verify if in microgravity the hydrotropic stimulus and / or the chemotropic stimulus are sufficiently intense to attract and guide the development of the root tips and, in the positive case, which of them exerts the greatest attraction. MULTITROP has three main goals: a) education, to enhance secondary school students' interest in space biology; b) scientific, to disentangle the role of gravity from the other stimuli for root growth; c) applied, to address technical issues in the design of growth chambers for plant cultivation in space. Results are expected to give insights for basic scientific questions on root development processes, to be used to develop new facilities for space missions and to define new sustainable agriculture practices on Earth. The experiment reached the ISS during the SpaceX CRS-13 mission and was performed using the hardware YING-B2 EU in BIOKON developed and set up by KAYSER ITALIA. Experiment was activated at launch site sowing 32 carrot seeds in the growth chambers (Fig 1). Deactivation occurred after seed germination and root development on the ISS by injecting a chemical fixative in the growth chambers. Activities were organized in three phases: pre-flight phase, in-flight phase and post-flight phase. The pre-flight phase included the species and substrate selection, according to inflight environmental conditions, and set up of the experiment container. The in-flight phase consisted of seed germination and sample storage in chemical fixative. The post-flight phase (still in progress) includes a ground reference experiment, processing of plant samples and data analysis.

IV. EDUCATIONAL ACTIVITIES

The whole team has been actively involved in each project phase. A video clip and a logo were mandatory for project submission. As requested, students recorded a video clip aimed to introduce the team, describe the project idea and highlight student's feedback on expected results. It is available at the following link:

https://www.youtube.com/watch?v=RK_pn38dFPc

The team conceived and realized also the logo (Fig. 2). It represents a seed germinating on the ISS (recognizable by the solar cells that replace the two cotyledon leaves). The seedling root, attracted by gravitropism, embraces the Earth. The symbolic message is that the space experiment is not limited to space biology science but results can give insights to take care of Earth by identifying new sustainable agriculture practices aimed at the reduction of the amount of water and fertilizers generally required for plant cultivation. Upon project approval, students from high school were involved in seminars, laboratory activities and dissemination events. They conducted these activities outside the regular school environment, making use of university laboratories, educational centers or public exhibitions.

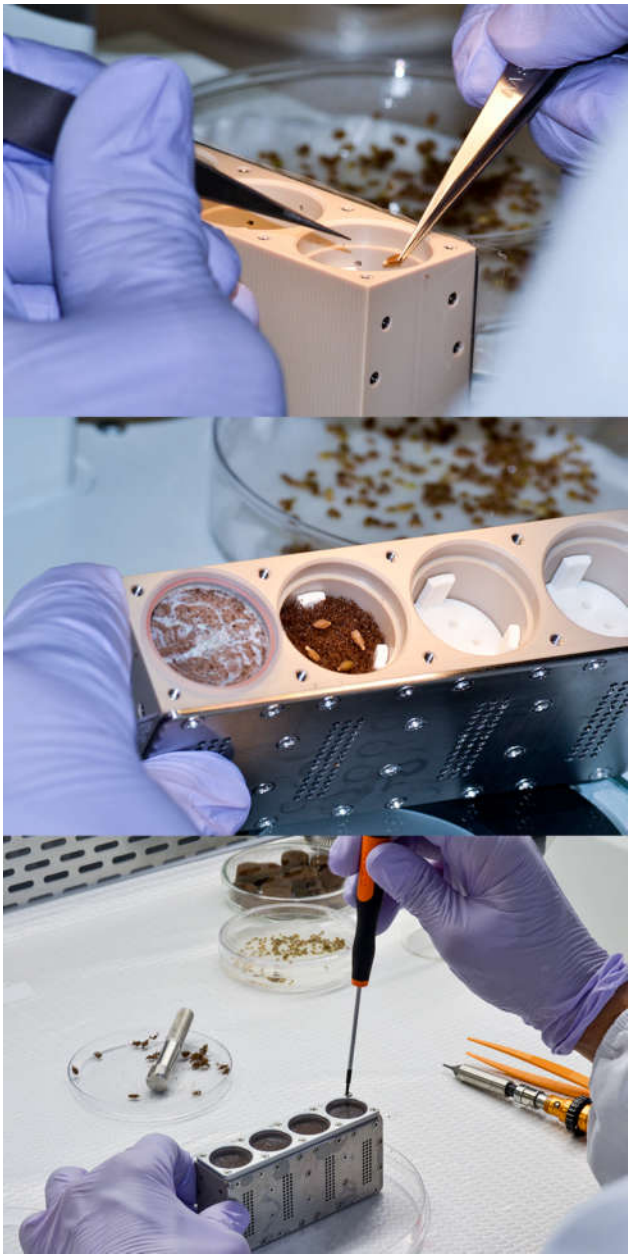

Fig. 1. YING-B2 Experiment Unit during implementation with carrot seeds at Space Station Processing Facility, NASA Kennedy Space Centre, Florida (USA)

Seminar regarded several topics including a) morpho-functional traits of seed germination and seedling development, b) root tropisms, c) how to plan a scientific experiment, d) methods for biometric data gathering, e) methods for statistical analysis of data. Laboratory activities were much appreciated by the students. They performed seed germination tests, recorded and edited time-lapse videos, used software for microscope digital image analysis and biometric measurements. Students participated to numerous local and national events aimed to promote space and space-related subjects to a significant number of young people, their families and the general public. During the events, to be more effective in the dissemination of the gravitropism phenomenon, they used to show young people the results of simple experiments performed using common materials, such as a glass jar, a sponge and a few beans or lentils. To galvanize and push people (especially children) to perform a similar test at home, they gave them a gadget consisting of few seeds wrapped in a small envelop reporting the “protocol” of their experiment and few more information on the project and the team.

Fig. 2. MULTITROP logo

University students in addition to the above mentioned activities were involved in the writing of the protocols for the experiment implementation at launch site. The three university students together with two highly motivated school students were involved in the Experiment Simulation Test (EST) in collaboration with the Payload Developer team. The EST was aimed to prove the correctness of the experiment planning but also to improve the understanding and harmony between the teams to be involved in the activities at launch site. An additional goal was to prepare the teams to potential critical situations. The university students together with the PI went to Florida (USA) at the Kennedy Space Centre to perform the late access activities for MULTITROP launch. Throughout the project the whole team was very active to achieve a significant coverage by media. Details on the project and frequent updates were reported on local and national newspapers, TV reports and radio news programs.

The MULTITROP project is still in progress and the team is approaching the post flight activities. So far the whole experience contributed to building long-term partnerships between peoples from different cultural backgrounds and research in the space domain. The interest of high school students was already captured and some of them are planning to focus their future education paths in the fields of science, technology and engineering.

ACKNOWLEDGMENTS

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Design of a Cost-Effecive Robotic Manipulator for an Educational Mars-Analogue Rover

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***Abstract*—The BEAR manipulator is a small, multi-functional robotic arm for the Berlin Educational Assistant Rover (BEAR), developed at the Department of Space Technology of the Technical University of Berlin. Besides providing an alternative application for the Department's research activities in space hardware miniaturization and autonomy, BEAR and several other Space Rover Projects serve as a platform for educating future systems engineers.**

Deriving requirements from student challenges such as the DLR SpaceBot Cup and the European Rover Challenge, the BEAR manipulator is primarily intended for object manipulation and visual inspection tasks. The arm's five degrees of freedom are instrumented for closed-loop control and allow versatile, be it slow, interaction with the field robotics environment. Moreover, the manipulator's simple mechatronic design and control architecture streamlines integration onto BEAR while enabling the system's reconfiguration for other tasks. The manipulator is currently configured for teleoperation, but it is fully instrumented for future autonomous activities.

This paper traces the BEAR manipulator's development from a conceptual link model to ongoing AI&T activities. We describe its structural and mechatronic design, as well as its control architecture. The impact of challenging programmatic constraints typical of student projects is examined throughout the development process, with a particular emphasis on cost-effective design using limited manufacturing capabilities, and high personnel turnover.

Keywords—manipulator, planetary rover, robot, education, student research

I. Background – Rover Projects at the TU Berlin

The Chair of Space Technology of TU Berlin has engaged in planetary robotics projects for several years for educational and research purposes. Major activities began in April 2013 in preparation of the DLR SpaceBot Cup, for which the Small Exploration Assistant Rover (SEAR) was developed. The system was to autonomously explore an unknown planetary surface on a competition field, find different objects and conduct an assembly process. The SEAR team of TU Berlin successfully participated in the competition in 2013 and its iteration in 2015, as one of the only three teams to pass the official qualification process during the latter [1].

The BEAR (Berlin Exploration Assistant Rover) project was initiated in 2016 in preparation for the European Rover Challenge [2]. A competing student-developed rover system has to accomplish several tasks during the competition, ranging from navigational challenges to various manipulation tasks. The diversity of the given tasks require the rover to interact with various objects, such as switches, handles, knobs and power sockets. Different samples ranging from loose soil to small rocks have to be collected [3]. Furthermore, a robotic arm for these tasks still had to fit the overall system architecture, respecting given budgetary, power, space and weight constraints. Thus a versatile device had to be designed which can be utilized in different mission scenarios and allows the robot a range of interactions with its environment, while making use of complementary system parameters in order to minimize the manipulator's complexity and cost.

II. Design Considerations

The BEAR manipulator is a lightweight, 5 degree-of-freedom tele-robotic manipulator arm designed for the BEAR rover. It is primarily intended for object manipulation and visual inspection tasks in planetary-analogue competitions. The manipulator was developed by graduate students over the course of several semesters as part of a lecture series about planetary exploration and space robotics.

A. Tasks and End-Effectors

The primary tasks of the BEAR manipulator consist of inspecting and manipulating objects in the field. The initial design called only for tele-robotic operation, with the development of autonomy foreseen for a later point in time. One archetypical task driving the design consists of grasping a small rock sample – up to 30 mm diameter, 300 g and an irregular shape – and placing it in a receptacle on board the rover. Another involves grasping and rotating an electrical switch on a piece of heavy equipment.

To that end, a preliminary end-effector selection was made with plans for later refinement. The mechatronic gripper of the SEAR manipulator was selected for its demonstrated performance of this class of tasks and relatively straight-forward procurement. Since all tasks would need to be completed using only the on-board sensors for feedback, a webcam interfacing with the rover's On-Board Computer (OBC) would be integrated into the end-effector, complimenting instrumentation of individual joints.

For the archetypical tasks described above, the manipulator needed to exhibit 3-dimensional repeatability on the order of 10 mm, assuming human-in-the-loop control using only on-board instrumentation. The dynamic performance of the manipulator, however, is of little importance for its intended purpose. There is no particular emphasis on the speed with which the tasks are to be completed, and there are therefore significant advantages to operating the manipulator slowly. The resulting dynamics avoid overshoot in end-effector position, and vastly simplify the structural load models and load paths to the rover body.

B. *Rover Interfaces*

The multitude of interfaces between the rover and the manipulator were considered from the beginning of the design process. First, the mechanical interface to the rover body had to maximize stiffness and reliability while enabling practical assembly and maintenance. The rover OBC would interface with the manipulator over a Control Area Network (CAN) bus and provide control inputs in the form of joint positions and angular velocities, foregoing the need for path planning onboard embedded systems. Managing the harness of the various joints and sensors for the manipulator's full range of motion, however, would prove challenging.

The effect of manipulator movements on the rover also had to be considered. In order to avoid any chance of compromising the rover's stability, the manipulator may not significantly alter the Center of Gravity (CoG) of the rover at any position in its range. While the slow movement of the arm ruled out major problems caused by arm dynamics, the effect of static loads on the CoG had to be considered.

In addition, hardware interlocks were foreseen as a way to prevent the arm from interfering with its own structure. Placing interlock switches that brake the joint, cycle its power supply or otherwise eliminate torque when the arm is in danger of doubling back on itself is a robust way to mitigate operator error and increase system safety.

Finally, a power loss to the manipulator could present a risky scenario because the arm could fall from a highly extended position - damaging itself, the rover, or its surroundings. This risk had to be taken into account since the robot is to operate close to humans and an emergency stop is required to completely isolate the rover's batteries, rendering all power output to zero. One way to mitigate this risk would be the introduction of brakes on the lower joints.

C. *Mass and Volume*

Mass plays two key roles in manipulator design. First, weight constrains the steady-state loads on the manipulator, driving both the structural design and the minimum torque of the actuators. Second, inertial mass affects the manipulator dynamics which, given the small operational velocity of the arm, is of lesser importance.

While structural failure clearly presents a critical loading scenario, the more challenging failure mode to predict is deflection. The arm must be sufficiently stiff and lacking in backlash to ensure a steady-state end effector deflection complying with the position accuracy requirement. This steady-state arm deflection may be calculated from the aggregate deflection in the structures and backlash in the actuators, which may be mitigated to some extent with brakes.

Volumetric requirements for the manipulator are few. Confined spaces are not foreseen in the field, and as long as the manipulator does not interfere with the ground or the rover itself, there is significant flexibility in the configuration of the actuators. This allows for simple joint design and maximizes the utility of Commercial-Off-the-Shelf (COTS) components.

D. *Design for Manufacture; Assembly*

The ILR's (Institute of Aeronautics and Astronautics) in-house manufacturing capabilities had to be considered from the outset of the design phase. The project's limited budget was a major incentive for maximizing in-house production and where practical, a preference was to be given to manufacturing mechanical parts over buying them. The following manufacturing capabilities were assumed:

- Machining: 3-axis milling - .01 mm horizontal accuracy, up to 300 mm pocket depth; 2-axis turning
- Fabrication: rough sheet metal folding ; Basic tack welding of steel parts
- Additive: PLA and ABS 3D printing with 0.1 mm accuracy

Modular assembly features were considered throughout the design phase to facilitate assembly for users, optimize analysis resources by reusing robust features, and enable several manipulator configurations. Carefully designed bolted connections between manipulator structures and mechanisms would allow fast assembly and disassembly, simplify interfaces with Ground Support Equipment (GSE), and enable alterations to the manipulator's joint configuration to optimize it for specific scenarios.

III. Mechanical Design

A. Overview

The manipulator's required range of motion was determined from the archetypical tasks defined above and the system's planned position on the rover. The joints and structures were then configured as shown in Figure 1.

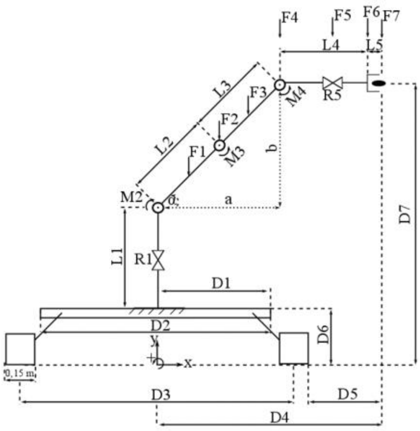

Figure 1 – Joint configuration of the BEAR manipulator

This joint configuration in turn drove the structural and mechatronic dimensioning of the manipulator. Supporting analysis included a MATLAB point mass model to verify steady-state arm deflection the dynamic performance of joint M2 and hand calculations of the stress and deflection in joint R1's shaft – a critical node in the load path. These were supported by component-level finite element analysis. Subsequent design for manufacturing and assembly yielded the design depicted in Figure 2, which is discussed in detail below.

Figure 2 – Render of the BEAR manipulator

B. Actuators and Sensors

Actuators were selected to enable the joint configuration depicted in Figure 1. With the exception of the rotary base joint, R1, all actuators had to be dimensioned for the worst-case load condition: arm horizontal and gripping the maximum payload in the end effector. To provide adequate torque for the long moment towards the arm base, joints M2 and M3 relied on stepper motors with planetary gear boxes that step the torque up by a factor of 40. R1, with no significant static torque requirement, excluded a gearbox. The two joints at the manipulator tip required less torque and greater precision for fine control of the end effector, so servomotors were selected for M4 and R5.

Besides high-level inspection instruments like the end effector webcam, the arm joints require instrumentation for their effective control. The servo motors' internal closed-loop position control meant they could be assumed to reach their demand position in negligible time, but the stepper motor joints required active position feedback. Optical encoders were added to the actuators for this purpose. The three stepper joints were also fitted with brakes to mitigate backlash and the risk posed by power cuts, as well as allowing selective denial of degrees of freedom to simplify manipulator control.

While software interlocks were envisioned to prevent the arm from interfering with the rover, hardware interlocks were added as an additional safety measure. A pair of lever switches mounted on joints M2 and M3 are triggered by a 3D-printed protrusion bolted to the top of each arm support and dimensioned to interrupt the microcontroller if the manipulator exits its design range. These switches also serve as an absolute position reference for homing the manipulator after power cycling.

The M3 gearbox-motor-brake-encoder combination, as well as its interlock switches and mounting holes for the IMU assembly are visible in Figure 3.

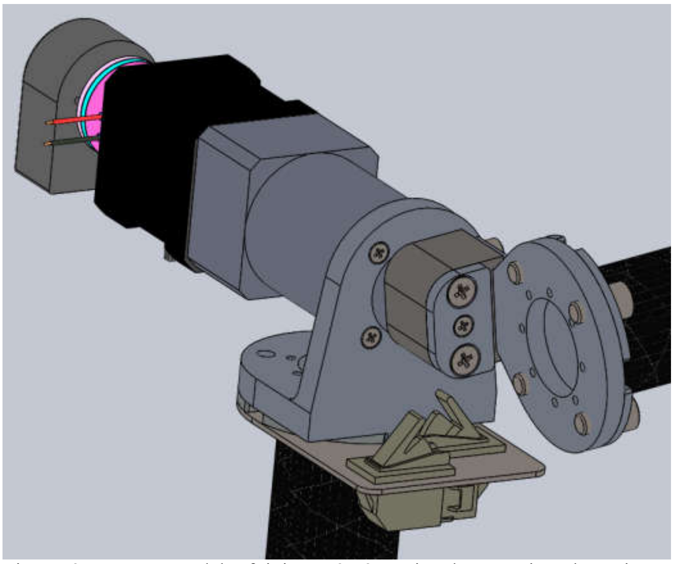

Figure 3 – CAD model of joint M3. 3D-printed protrusion that triggers interlock switches not shown.

C. Structures

Carbon Fiber-Reinforced Polymer (CFRP) was identified as an appropriate material for this application due to its high stiffness to density ratio under the arm's relatively predictable loading. COTS tubes of 1 and 1.5 mm wall thickness were selected for the arm structure, and their performance verified using the MATLAB model mentioned above. Subsequent FEA then demonstrated that the CFRP tubes would have sufficient stiffness to meet the arm deflection requirement.

The main drawback of CFRP is the difficulty in joining it to the mechanical assemblies. This was overcome by designing turned aluminum flanges that would be permanently bonded into the CFRP tubes along their inner diameter. These permanent fabrications would simplify arm assembly, as shown in Figure 3, and facilitate cabling by routing the harness through the hollow tubes.

D. *Mechanical Interfaces*

Custom mechanical assemblies were designed to manage the interfaces between the actuators, structures, sensors and arm services. Machined aluminum brackets like the one shown in Figure 3 interfaced with primary structure on the stepper motor gearboxes, whose keyway shafts protrude form the assembly and transmit torque to the arm structures. The gearbox bearings are able to handle the resulting radial loads on these cantilevered shafts, eliminating the need for external bearings to facilitate assembly and dimensional tolerancing.

Milled alignment features on the arm structure flanges mate with high-tolerance protrusions on the arm supports that interface with the actuators. This ensures angular alignment of the actuator assemblies without the need for dowel pins. In addition, these alignment features enable a modular assembly by reconfiguring the joint dimensions at 90-degree intervals. One such configuration is shown in Figure 4.

Figure 4 – Alternative manipulator configuration

IV. Control and Electronics Development

A. *Control Architecture*

The overall control architecture called for a digital communication bus between the manipulator OBC and a microcontroller handling each of the stepper nodes. A separate bus would communicate with the series of servo motors.

The manipulator OBC, receiving commands from the rover's central embedded OBC over a CAN bus, would distribute these in the form of position or velocity demand signals to the various control nodes. These control nodes, as shown in Figure 5, implement closed-loop position or velocity feedback control with dedicated hardware to drive the steppers, condition encoder signals, and handle the brake and hardware interlocks.

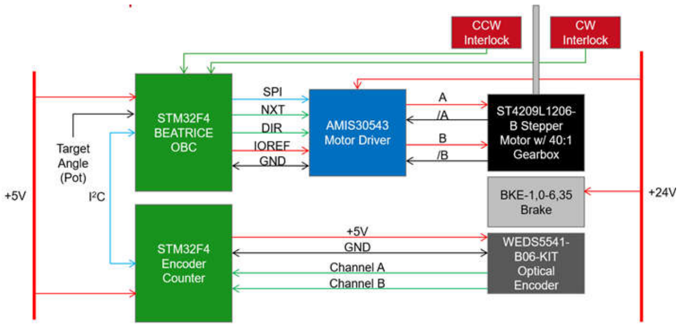

Figure 5: Schematic of control electronics for a stepper motor joint

B. *Hardware Selection*

The manipulator OBC had been predetermined as an STM32F407VGT6 chip [4]. Embedded OBCs designed by the project team use a similar microchip of the F427 family and utilization of commercially available discovery boards for the given F407 chip promised rapid prototyping. Software developed for the STM32F407 is usually easily migrated to STMF427 boards. The encoder counter board presented more difficulties. Originally, it was intended to use a basic 8-bit ATMega board with two external interrupts and I2C capability, however operating this board as an I2C slave proved to be a difficult task. Delays due in troubleshooting the ATMega chip threatened the work package's success, and so instead a second STM32F407VGT6 chip on an STM32F407 Discovery Board was used despite being overpowered for the application. This has advantages, however, in terms of reducing the required number of unique parts, workflows, and system-specific knowledge for future work on the manipulator. Furthermore, these processor might take over additional tasks in the future and complement rover's redundant design.

C. *Bread Board Verification*

A bread board verification for the first joint was set up early during the manufacturing and assembly process. Since the underlying concept for motor control is similar for all stepper motors, the set-up was representative for most joints of the robotic arm.

Given the required speed of the manipulator's movements, only a PD controller would be required, and adjusted so that the maximum joint velocity would be used up until close to the target angle. In order to achieve higher accuracy, the control loop operates in steps rather than degrees. This means that the encoder counter boards simply pass the current counter value when requested via I2C. The I2C communications are able to operate robustly even while the motor is moving and the encoder interrupts are occurring. The magnitude of the error is used to adjust the timer period determining the frequency of step pulses sent to the stepper motor. This is an inverse relationship between step count error (position) and timer period (velocity):

$$T = \frac{10000}{k_p \cdot \mid e_{(t)} \mid + k_d \cdot (\mid e_{(t)} \mid - \mid e_{(t-dt)} \mid)} \tag{1}$$

The gains and constant in the numerator were determined empirically by a test campaign after assembly of the first joint.

As the test system was only being breadboarded, some method of user input was required. The method of input, a potentiometer, was selected to replicate a future input from the R1 joint custom rotary encoder, which required use of the Analog-to-Digital Converter (ADC) onboard of the manipulator OBC. Once incorporated into the control loop, the joint was now capable of performing a start-up routine to find the limit switches and determine its absolute position, accepting a target angle, and achieving that angle with an accuracy of ±0.05°, and repeatability of $> 99\%$.

V. CURRENT STATUS

Mechanical assembly of the of the manipulator's high-torque joints is complete and ready for cabling and integration of the end effector, as shown in Figure 6. Software is now being developed, with a focus on enabling autonomous control with the Robot Operating Software package MoveIt! [1]. The software allows to autonomously create motion trajectories for the manipulator. These trajectories shall then be interpreted and executed by an embedded OBC which has real-time control over sensors and actuators. Furthermore, a custom gripper design for the manipulator is being developed.

Figure 6: Assembled BEAR Manipulator

An upcoming challenge will be the implementation of the arm's harness. Cables have to be routed in such a way that reliable data and power transmission is possible over long periods of time while not hindering the movement of the system in any way. With cabling complete, functional testing will proceed to verify the arms dynamic performance using dummy payloads, before assembling the end effector and integrating the system onto the BEAR rover.

VI. LESSONS LEARNED – STUDENT PROJECTS

The BEAR manipulator exemplifies some of the unique opportunities provided by collaborative student projects. They provide hands-on systems engineering training that replicates the communication and programmatic challenges of industrial R&D, while promoting collaboration between students of different backgrounds. But they also come with unique challenges. Besides restrictive budgets and manufacturing capabilities, student work must take place during the short semesters of study programmes, with a high rate of personnel turnover. Fostering the continuity needed to build effectively on previous work therefore requires careful management. To that end, we identify two major strategies.

First, software tools for collaboration and version control, supported by dedicated infrastructure, go a long way in decreasing communication overhead, promoting disciplined documentation, and preventing version conflicts. The required training and uptake time for tools like Git is generally justified in projects spanning multiple semesters.

Second, carefully calibrating students' academic and personal incentives for contributing to the project is critical for ensuring long-term success. Project objectives and academic requirements should be harmonized wherever possible, with a particular emphasis on allocating critical work packages to individual academic deliverables, like the master's thesis. As for personal incentives, university competitions are perhaps the most effective tool. Their strict schedules help drive the project forward, while the competitive element galvanizes the student team for a common goal.

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Proof-of-concept of the "GNSS Direct & Reflected Combination Tester" (G-DIRECT) payload from a stratospheric sounding balloon experiment over land surfaces

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Abstract—**This work summarizes the first evaluation of a stratospheric sounding balloon experiment performed towards the proof-of-concept of the new cost-effective Earth remote sensing GNSS-DIRECT payload, suitable for small satellites such as CubeSats. This payload is expected to provide accurate GNSS Radio-Occultation (GNSS-RO) observations of the atmosphere, and GNSS Reflectometry (GNSS-R) measurements of the Earth surface for very low grazing angles, when coherent scattering effects provide strong forward scattered GPS signals. Unfortunately, due to an unexpected failure in the balloon, the system only could collect data during the ascent phase, characterized by significant fluctuations of the gondola' attitude (yaw, pith, roll).**

Keywords— Sounding balloon, education, remote sensing

I. INTRODUCTION

This work has been developed at ESEIAAT - UPC BarcelonaTech, in the frame of the INSPIRE3 initiative. More details can be found in a companion paper [1]. In particular, this project corresponds to some of the activities performed within the UPC Space Program [2], allowing vocational/motivated students to participate in hands-on activities, related with aerospace and systems engineering.

The fundamental objective is two-fold: a) to foster systems engineering activities in the frame of a Final Degree Project (TFG) of an aeronautics engineering school, and b) the proof-of-concept from a stratospheric sound balloon, of a new instrument aimed at GNSS-RO (GNSS Radio-Occultation) and GNSS-R (GNSS Reflectometry) [3,4]. The experimental set-up has been developed using COTS (Commercial Off-The-Shelf) components. Among these components stand out an ARM A-53 CPU with a 1.2 GHz clock rate (Raspberry Pi 3 Model B), two GPS receivers (one for the direct signal and the other one for the refracted signal), two single-patch RHCP (Right Hand Circular Polarization) antennas, a passive thermal control, and a Kalman filter-based Inertial Measurement Unit (IMU) that provides positioning information (very important for applications such as GNSS-RO).

In agreement with the aim of INSPIRE3 project, all the design, construction and testing were carried out by the first author, as part of his end-of-degree project in aerospace engineering.

The launch campaign of the balloon took place on December 23rd, 2017. Despite the float phase was expected to be ~ 28 km, the apogee of the trajectory was ~ 12 km (ascent phase) due to an unexpected failure in the "balloon". After the flight, the experimental set-up was examined on-ground using housekeeping data, and it was determined that both hardware and software operated correctly.

This work describes the main aspects of the set-up. At present, scientific data are being calibrated using information of the trajectory, the IMU, and the antenna radiation pattern. This first launch demonstrates a correct design and construction of the set-up, and future launch campaigns are scheduled to perform a comprehensive test of the G-DIRECT payload from the float phase ~ 28 Km, with a much higher platform's stability. Section II describes the experimental set-up, Section III provides an overview of the software, Section IV shows the testing activities performed on-ground to validate the design. Finally, the launch procedure is included in Section V, and very-first preliminary results in Section VI.

II. EXPERIMENTAL SET UP

In this section, the different subsystems that form the final solution are detailed to understand their connections and operation.

A. Electronic equipment

A PCB with all the electronic equipment was designed, manufactured and tested. The main components are the following:

- A "Raspberry Pi 3 Model B" microcontroller that was selected because of its high processing data speed, great capability of storage, and the four available USB ports.

- A “BOSCH BNO055” IMU with Kalman filter, connected to the microcontroller with a UART port and FTDI converter to USB.
- A “Copernicus II” GPS receiver, operated using NMEA protocol, to collect GNSS direct signals. The device was connected with UART, using a FTDI converter to USB.
- A second “Copernicus II”, operated with TSIP protocol for scientific purposes (GNSS-RO). The device was connected to a Raspberry Pi with the native UART port (/dev/ttyS0).
- Two “Dallas DS18B20” thermometers used to record inner and outer temperatures. They were connected to the same Raspberry Pi GPIO pin, using the one-wire protocol.
- Other components: Two buttons (one for emergency reboot and shutdown the micro in a safe manner) and four LEDs to display the IMU calibration status.

B. Power

For this project, a lithium battery-based power bank has been used as it is rechargeable, does not need an additional component to control its output voltage (it provides a 5 V DC and 2 A), it is low cost and durable. The selected system was a Xiaomi, providing up to 10,000 mAh. Lithium batteries might release small gas quantities that in sea level conditions can be contained in its encapsulation material. However, under the low pressures at the expected altitudes (up to ~ 30 km), this can be a problem. Thus, the battery was tested in a vacuum chamber as described below.

C. High Altitude Balloon Module (HAB)

The module (Fig. 1) contains the electronic and communications systems. The structure must follow these requirements:

- Isolate the electronics from the extreme low stratospheric temperatures.
- Reduce the spin movement.
- The final weight of the capsule must be kept low to fulfill the legal maximum weight requirement (4 kg).

The material used to build the module is a rigid foam panel made of polyisocyanurate (PIR). It is coated on both sides with lacquered embossed aluminum. This material presents a high thermal resistance and on the other hand it is easy to manipulate. Additionally, it is covered with a thermal blanket to improve the material thermal resistance. The capsule should be sized to allocate inside all the electronics. Also, antennas have to be placed outside of the module in order to collect GPS signals, and to transimit data.

Fig 1. System inside the HAB module.

D. Communication Systems:

While the bulk of the data is saved in a micro SD card, the experimental setup has two communication systems used to transfer telemetry data. They are:

- Xbee, operating at 868 MHz of frequency with a dipole antenna and connected to connected to an Arduino Uno microcontroller via UART.
- A Iridium-based satellite communications system. Iridium is a satellite constellation form by 66 cross-linked Low Earth Orbit (780 km) satellites that can provide voice and data connections around the world. In order to communicate with these satellites and obtain the desire data an Iridium modem, a microcontroller and antenna are needed as well as contract a data line and credits. All this data from the communications systems is received in order to be able to follow the capsule. The data sent through Iridium is kept low to reduce the cost.

III. Software

The data incoming from the four instruments (IMU, NMEA GPS, TSIP GPS) and thermometers is recorded using different processes that run concurrently. The software was implemented as follows:

- Thermometers: A Python script is used to read the thermometers digital data output, from low-level functions running in kernel space.
- IMU: A Python script, based on Adafruit Python library for the BNO055 [5,6] is used. The code records the orientation angles, accelerations and calibration status.
- GPS receiver with NMEA protocol: A C code was developed to detect the USB port where the NMEA GPS is connected and then to save the data. The detection of the USB port is needed as they are assigned randomly after each system reboot.
- GPS receiver with TSIP protocol: A C code is used. Note that the TSIP protocol is more involved than

NMEA. The code was validated comparing the results obtained with a proprietary TRIMBLE application [7].

Additionally, a watchdog code programmed in C is used to monitor each of the previous applications. In case of failure, the application is restarted. Each data line includes a Unix epoch time stamp so that the data streams from the different applications can be synchronized. A bash script executed after the restart of the Raspberry Pi (using crontab) starts all the aforementioned codes.

Fig 2. System inside the vacuum chamber ready for the low-pressure test.

Fig 3. System inside the temperature test box for the temperature test.

IV. Ground testing

Before launch the system it is imperative to ensure the system will operate as expected and all their components will not suffer any damage during the flight. Keeping this in mind, different tests were performed:

- Vacuum testing. With the purpose to ensure its operation, the system was tested inside a vacuum chamber to a pressure of about 800 Pa. The system is introduced in a metallic mesh to prevent accidental damages to the chamber (Fig. 2).
- Temperature testing: The actual heat transfer from the payload to the environment includes thermal radiation, solar radiation and convection and is difficult to model and reproduce in a experimental chamber, but as a worst case scenario, the payload is introduced in a box in partial contact with dry ice at -78.5ºC (Fig. 3). The insulation system plus the heat dissipated by the electronics allow the inner temperature to be above 0º during 3 hours.

Fig 4. Image of balloon during the launch campaign.

V. Launching procedure

Before the launch, different tasks and documents should be developed and asked in order to get the suitable permissions and make a good organization and schedule for the mission. The document that is imperative to fill is a NOTAM form prepared by ENAIRE [8], the air navigation manager in Spain, certified for the provision of route, approach and aerodrome control services. Date, location, the person in charge of the mission (project manager), the different specifications of the balloon (objective, mass, helium volume…) have to be defined in this document. After that, ENAIRE gives the permission and accepts the conditions or not.

The balloon trajectory is simulated with the Cambridge University Spaceflight Landing Predictor tool [9] in order to select a launch site from which the predicted falling point is far from populated areas. The launch site is typically at about 200 km of ESEIAAT. Once the experiment is launched (Fig. 4), the Iridium telemetry system reports the balloon position periodically. This, together with a good selection of the launching site, has allowed INSPIRE3 students to recover most of the experiments. A typical image from this mission is shown in Fig. 5, while an image recorded before ground contact is shown in Fig. 6.

Fig 5. Image taken by the on-board camera at ~ 12 km altitude.

Fig 6. Image taken by the on-board camera just before landing in a low population area.

VI. VERY FIRST PRELIMINARY RESULTS

This section is focused to show the results extracted from the thermometers results, IMU, GPS module with NMEA protocol, and GPS module with TSIP protocol.

- Trajectory. The recorded trajectory is shown in Figs. 7 and 8. As aforementioned, due to a balloon failure, the maximum altitude reached was ~ 12 km.
- Temperatures. The payload and the external temperatures are shown in Fig. 9. While the system performed correctly, an additional heating system might be needed. The next mission will include electrical heaters.
- IMU. The "BNO055" data was recorded correctly (Fig. 10) but the system lost its calibration, so we cannot be confident on the heading measurements. Future missions will include either a redundant IMU or a sun tracker system.
- A first evaluation of the Signal-to-Noise Ratio (SNR) as collected by the limb-looking antenna (Fig. 11) shows significant fluctuations, that could be attributed to the random movement of the gondola (Fig. 10) during the ascent phase flight. On-going activities include the correction of the antenna pattern using available information from the IMU.

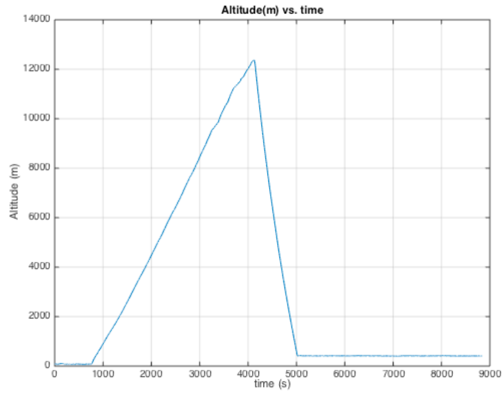

Fig 7. Altitude of the balloon as a function of the time during the experiment.

Fig 8. Trajectory followed by the balloon during the flight.

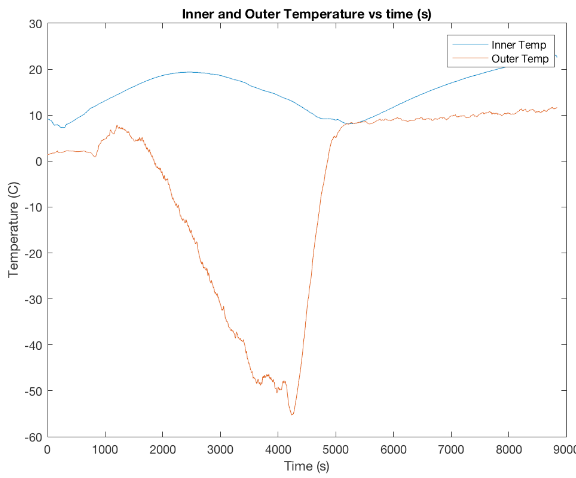

Fig 9. Evolution of the inner and outer temperatures of the payload box.

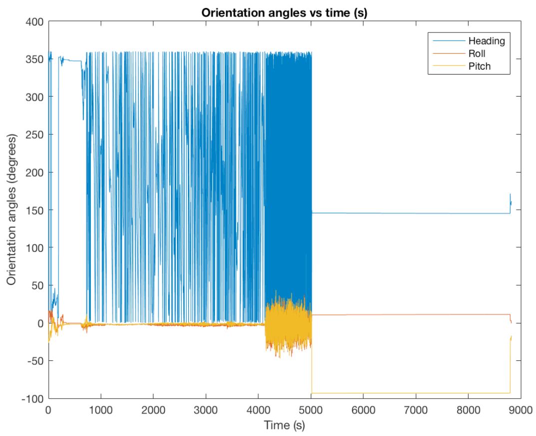

Fig 10. Evolution of orientation angles as a function of time.

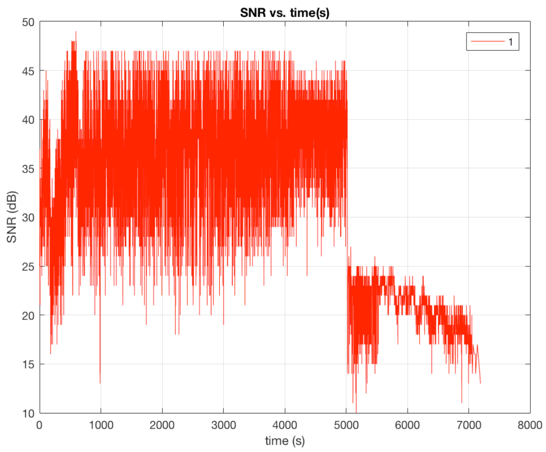

Fig 11. SNR evolution vs time for a given satellite in view (PRN 1).

VII. Conclusions and Future Actions

The design, assembly, testing, launch and successfully recover of the "GNSS Direct & Reflected Combination Tester" in a short period of time (one semester) was a challenge. The proposed system operates reliably and the data from all the documents has been recorded without problems, despite the unexpected failure of the balloon. The current emphasis is in the post-processing of the results, as well as the preparation of the next launch.

Acknowledgment

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Spacepaprika – a workshop based educational program that raised the question of space education in Hungary

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***Abstract*— The paper aims to show that the project based learning (PBL) is a valid alternative in space education besides the university's accredited academic degrees. It's even more valid in Hungary where there are no dedicated space studies in engineering nor in space science yet. We performed a questionnaire-based study inquiring participants in the age group of 16-35 years regarding their interest in space studies and analyzed the data by applying statistical methods. The results are discussed in the view of the Hungarian higher education system.**

Keywords—education, space studies, project based learning

I. Introduction

The yearly educational event 'Űrakadémia' held by the Hungarian Astronautical Society (MANT) and Space Generation Advisory Council (SGAC) is an excellent demonstration of the idea of project based learning. This event focuses on broadening the knowledge of the participants who created a strong, actively cooperating network of young professionals and university students with their project tasks living towards.

One of these tasks is called 'Spacepaprika' and targets the need to solve some of the healthcare problems occur during manned interplanetary space missions. According to our present knowledge astronauts who have been in space for more than 6 months have significantly higher risk of type 2 diabetes [1] and since the medicines decay more rapidly in the harsh space environment [2] it is essential to produce some of those on-board. One way to make medicine substance is to grow plants that can be used also for food supplement. Paprika contains significant amount of vitamin C and capsaicin, which can contribute to lowering the risk of type 2 diabetes [3]. The details of this plant growing project was elaborated by young people between the age of 18 to 35 in small groups. Despite having rather different background in science the participants were really interested in space studies and enjoyed being involved more deeply.

The experiences acquired during these events gave the idea to write a study that aims to find the answer to the questions about the actual interests and needs of space education as postgraduate and undergraduate studies. Our study is based on a questionnaire targeting different age groups from 16 to 35 years, containing questions about the different accredited - BSc, MSc and PhD - and other degrees or trainings like PBL.

II. Methods

A. *Participants*

Altogether, 172 Hungarian subjects participated in our study. 12 participants were removed from the sample since their self-reported interest for space education was lower than 3 on a Likert scale from 1 (not interested at all) to 5 (very interested). Our target group stands of adolescents from 16 years and young adults up to the age of 35. We have chosen this age group because in this period of life it is likely that participants will start new studies[4]. Mean age was 26.59 (SD = 5.26). 6.3% of the participants were high school students, 42,5% university students (BSc/BA or MSc/MA), 6.9% PhD students, 43.1% were employed or self-employed, 0.6% participates a Specialization training programme currently and 0.6% were job seekers. Data were collected by convenience sampling.

B. *Questionnaire*

The questionnaire consisted two separated sections: after filling out the first, participants had the opportunity to decide whether they want to continue with the second part. The first part (besides demographic data reported above) consisted questions about how important participants find different aspects of a potential future space education.

TABLE 1. QUESTIONS RELATED TO ACCREDITED EDUCATIONS BASED ON THE INTRODUCTION.

Benefits of accredited education
1.1 The training should be part of the Hungarian education system (BSc, MSc).
1.2 The training should be accredited.
1.3 The training should provide access to another Hungarian training course.
1.4 The training should provide opportunity for a foreign or international Bologna Process (MSc, PhD) training.
1.5 It should be a general, multi-area training.
1.6 It should provide uniformed and identical training for each student. (Not including optional subjects)
1.10 It is not necessary to have a maximum number of students in a lecture or practice - as a good instructor will probably hold a good lecture - so more people can access the lesson.*
1.19 Lexical knowledge is important because it bases the understanding of the problem.
1.21 Preference for individual and non-group practical problem solving.
1.23 Grade-based assessment.

TABLE 2. QUESTIONS RELATED TO PBL BASED ON THE INTRODUCTION.

Benefits of PBL
1.7 The training should provide up-to-date training.
1.8 The thematic should follow the market demands.
1.9 Targeted, detailed training.
1.11 Market participants and possible employers should be involved in the education.
1.12 Participation in projects that meet real problem solving and market needs.
1.13 The educational institution also engages in labor mediation.
1.14 An experienced helper (mentor) should be available if needed.
11.15 Leading the students to solve a problem instead of telling them how to solve it.
1.16 Smaller number of students facilitates more individualized training both in the interest of professional specialization and in the pace of progress.
1.17 In practice, instead of a tutor, there should be more experienced assistants (mentors).
1.18 The curriculum should mainly unfold and solve realistic problems with active participation.
1.20 The training should be intensive so that the knowledge is transferred as soon as possible.
1.22 Involving foreign trainers into the training.
1.24 Transpose the contents of the theoretical lectures into the curriculum of practical lessons.

All of the questions were Likert scales from 1 to 7 where 1 indicates 'not important at all' and 7 indicates 'extremely important'. Originally, we had 10 questions about the advantages of accredited education, but when running reliability analysis, we excluded one of the questions which did not seem to fit into the questionnaire (marked with * in Table 1; item-total correlation = 0.085). With the remaining nine questions, Cronbach's Alpha was 0,694, indicating an acceptable reliability. We had 14 questions about the benefits of the PBL. This scale was also reliable ($\alpha = 0.771$).

The second part of the questionnaire consisted of checkbox type questions. The participants were asked to read a summary of education systems and methods before answering these questions. The advantages and disadvantages of every mentioned educational system and form were highlighted as a list. The text comprehension by the filler was verified by two questions and those participants who did not give a correct answer to both were excluded from further analysis.

III. RESULTS

A. On the benefits of accredited education and PBL

Participants' mean score on the 'Benefits of accredited education' (see Table 1) was 5,09 (SD = 0,83) while on the 'Benefits of PBL' (see Table 1) 5,80 (SD = 0,62). Since neither the 'Benefits of accredited education' scale nor the 'Benefits of PBL' scale were normally distributed (Skewness = -0.570 and -0.976, Kurtosis 1.185 and 2.356, Shapiro-Wilk's test p value = 0.009 and <0.001, respectively), we performed a Wilcoxon's signed ranks test. It revealed that people preferred the benefits of the PBL (Mdn = 5.86) to the benefits of accredited education (Mdn = 5.22), T = 11355.0, $p < 0,001$, r = 0,055.

We could not show any differences among people on different level of education (high school student, university student, PhD student, employed, job seeker or other) in how they see the benefits of accredited education ($H(5) = 9.058$, $p = 0.107$) or PBL ($H(5) = 1.817$, $p = 0,874$).

It seems, age is also unrelated to these preferences, neither the 'Benefits of accredited education' ($r_s = -0,120$, $p = 0.118$) nor the 'Benefits of PBL' ($r_s = -0,006$, $p = 0.941$) showed significant correlation with age. We also tested the effect of interest in space education. It seems, it has no effect either, neither on the 'Benefits of accredited education' ($H(2) = 2.782$ $p = 0.249$), nor on 'Benefits of PBL' ($H(2) = 2.369$ ($p = 0.306$).

TABLE 3. 'WHAT KIND OF TRAINING WOULD YOU CHOOSE IN SPACE EDUCATION AS A FURTHER TRAINING FOR YOUR EXISTING STUDIES?'

	No	*Yes*
PBL	21	38
BSc	16	5
BSc - specialization	39	20
MSc	24	35
PhD	39	20
Specialization training programme	28	31

TABLE 4. 'WHAT KIND OF TRAINING WOULD YOU CHOOSE FOR SPACE EDUCATION IF YOU HAVE NOT STARTED YOUR UNIVERSITY STUDIES YET?'

	No	*Yes*
PBL	33	26

BSc	38	21
BSc - specialization	23	36
MSc	26	33
PhD	46	13
Specialization training programme	47	12

B. The second part of the questionnaire

116 participants decided after the first part, that they continue filling the second part as well. We included only those participants into these analyses who answered both of the verification questions correctly, thus, we had 59 participants. In order to get a clearer insight to which type of education (namely, PBL, BSc, BSc specialization, MSc, PhD and Specialization training program) people prefer, we performed Chi squared analyses to compare how many of our subjects would choose each type. Participants' preferences are shown in Table 3 and 4.

B.1 'What kind of training would you choose in space education as a further training for your existing studies?'

Chi squared test has shown that there are significantly less people who would choose space education as BSc than who would not choose ($\chi2(1) = 25.780$ $p < 0.001$). The same results occurred for BSc specialization ($\chi2(1) = 6.119$ $p = 0.013$) and PhD ($\chi2(1) = 6.119$ $p = 0.013$). It seems there is no significant preference about space education as MSc studies ($\chi2(1) = 2.051$ $p = 0.152$) or specification training program ($\chi2(1) = 0.153$ $p = 0.696$). However, there were significantly more people who would choose PBL as their space education than who would not ($\chi2(1) = 4.898$ $p = 0.027$).

B.2 'What kind of training would you choose for space education if you have not started your university studies yet?'

For the questions where we have asked what educational system participants would prefer if they had not started their higher education yet we have found the following results. Significantly less participants have chosen BSc for a possible space education form compared to those who would prefer it ($\chi2(1) = 4.898$ $p = 0.027$). There were no significant result regarding the BSc specialization ($\chi2(1) = 0.831$ $p = 0.091$) the MSc ($\chi2(1) = 4.898$ $p = 0.362$) or the PBL ($\chi2(1) = 0.831$ $p = 0.362$). However, it seems more people prefer not to choose PhD or specification training program ($\chi2(1) = 4.898$ $p = 0.027$) than who do.

IV. DISCUSSION

Hungarian higher education system and the implement of the Bologna process

The national higher education system in Hungary is part of the Bologna Process, thus, applies the three cycle system (bachelor/master/doctorate) aiming to achieve increased compatibility between education systems and enables easier mobility for students and job seekers within Europe. Despite Aerospace engineer and Aerospace sciences are common studies at universities in the Bologna Process, the Hungarian system lacks these special, space related study opportunities.

These foreign implements could be practicable to be the base to create a space education in the form of an accredited system in Hungary. But before that, about the implement of the Hungarian Bologna process and the ongoing education the following can be established. The features of these type of educations are instructor-centered presentation, linear and rational curriculum, from part to whole syllabus and the teaching and learning are raw knowledge transfers. Its advantages are that it's an accredited education and part of the Bologna Process. It's accepted as a possibility of further education even abroad. The possibility to participate in them as a state-supported scholarship holder makes it also more attractive. Roughly the disadvantages can be summarized in the following: overly theoretical education and the introduction of new technology and subject to the framework is problematic; practical training is almost missing from these education. The opportunity to do professional practice is very limited. Such an option is the co-operative training where a student can be outsourced to an industrial or research partner for a semester to solve a task and write a thesis. The number of participating students is very few and it's not obligatory. Furthermore, it is inflexible and not innovative. The institution's financing model in most places results a situation similar to mass production where student-centeredness is often an unknown concept; the questions remain in the students. In the case of PhD training, it is already a research job where the students acquire - or develop - knowledge on a project basis, but less mentored.

The Project Based Learning is a new form of education in Hungary. There is only a few firm who implemented it into programmer training. Interest in PBL came up in higher education to reflect the criticism raised by the labor market that the students whose just got their degree does not capable to proper work in alone nor in group cause they don't have sufficient knowledge and especially problem-solving skills[5-6]. Today, beside Hungary, PBL has become a widespread teaching method in disciplines where students must learn to apply knowledge not just acquire it, and be able to transpose the learned into reality. PBL derives from the theory that learning is a process in which knowledge is formed. Learning is derived from the learner's activities, the role of the instructions only play in order to substantiate the problem exploration and to inspire constructivism. There are three basic pillars of methodology [5].

- Learning is a constructive process. Learning becomes the most successful when raw information is met with a real situation that has already been realized in practice. This learning type is able to create the most intrinsic motivation for students. The learning process needs to be accompanied by a strong mentoring program that only needs to provide the framework and baseline The instructions should only serve as a help to find the solution rather than solving the problem itself.

- Metacognition that is, in this case knowing the knowledge and learning the learning processes. The student must know what she or he can and should be able to use in problem solving. The student need to know how high her or his knowledge is and how to expand it. How they can integrate their newly acquired knowledge into the overall picture that is already formed in them and determine how difficult the problem is. For an unknown topic, a strategy should be drawn up on how to abolish it. In the development of metacognition, direct contact between the mentor and the student is as essential as the expectation of solving the problem beyond her or his knowledge.
- Social and cultural impacts play a major role in learning, especially in promoting teamwork, and teamwork provides a competitive environment that plays an important role in maintaining morale. In the case of small group work, the exposure of students to an alternative perspective is indeed a challenge to understanding the fundamentals, thus getting closer to the depth of the problem.

Calling for quality and relevant project tasks is a prerequisite for PBL education. There are serious expectations for the industry or research partners to make the PBL successful. Because of the mentoring program of the education, the mass production method is excluded, so the cost of training is expected to be higher. Successful PBL training contracts with partners to solve the partners' problem by a student and that is also a matter of financial attractiveness. The student's screening and preparation for the job is also the responsibility of the training provider institution, including employment and HR services.

Preferences expressed in the survey and further motivations

Taken together, our study has shown that there is an interest in space education in our target group, regardless of the age or the current level of education. Its plausible cause is the long-time lack of the space studies in Hungary. PBL education could be a suitable alternative. On the one hand, based on the first part of the questionnaire, the benefits of the PBL are more preferred than the accredited education types, although the difference is quite small. On the other hand, based on the second part of the questionnaire, PBL was the only form of education that attracted a majority when asking explicit questions like the 'What kind of training would you choose in space education as a further training for your existing studies?'.

Both the accredited and non-accredited trainings reached a high score, thus, the benefits of both seem to be important for potential future applicants; however, the benefits of the accredited trainings seems to be the accreditation itself. On this ground our study can be generalised to the Hungarian higher education system in general (since there was no difference in preferences based on how much participants were interested in space education. The main benefit of the accredited education is the state-approveness both on the national and international level. On the other hand PBL training could not be accredited caused by the features of the Hungarian educational system.

We could not show any differences between people on different level of education (from high school to employment) which is somewhat counterintuitive. Since for those who already finished their studies, or who are job seekers, or want to switch their professions (otherwise the space related topics could reach higher level of interest among people), PBL would be plausibly a good opportunity. Instead of accreditation they seek for professional challenges and experience, meanwhile they don't have the opportunity to study in a state-scholarship programme - or at least in the Hungarian education system. However, according to our data the PBL is an attractive option for anyone regardless of their current education level. On the other hand it is important to note that insufficient sample size is a possible reason for our insignificant results in that question. Thus, further studies are necessary.

Based on the survey there is need for space education primarily in the form of PBL, but there is also a claim for MSc and specialization training programme. Nevertheless, BSc would not be chosen even if the question is 'What kind of training would you choose for space education if you have not started your university studies yet?'; which confirms the insignificant results described above with regard to those at different levels of education. The reason could be that BSc is a very basic training where the main subjects are shared among different specializations in the Hungarian implementation.

Further research is necessary on the employment recruitment capability of Hungarian space industry and research facilities. Based on that, a market research has to be done to explore the optimal way to create PBL education on the field. This process has already started with consultations with possible partners and a roundtable discussion was held.

V. Conclusions

It was clearly shown that there is an explicit interest in space education in our target group, regardless of the age or the current level of education. The listed benefits of both the accredited and the PBL trainings were indicated as important, however, it must be noted that the most valuable benefit of the accredited system was the accreditation itself. The PBL system that provides professional challenges and experiences is an attractive opportunity for those who already finished their basic academic studies but not exclusively for them. Our study has triggered a lively interest towards the facilitation of space education in Hungary and we are planning to organize further research on the employment recruitment capability and the optimal way to create PBL education in this field.

ACKNOWLEDGMENT

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A strategy to support new careers in space sector

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***Abstract*—The space sector is facing the global problem of the lack of new space experts. In countries where aerospace engineering as curriculum does not exist, this problem is even harder since regular university programs do not offer a global overview about the possibilities in the space sector. In Hungary, the Space Generation Advisory Council with the Hungarian Astronautical Society is working on this issue providing several opportunities for university students and young professionals and helping them in career orientation towards space related areas and other STEM fields. Our activities combine different methods and approaches of knowledge sharing for inspiring the next generation. We have a special focus on university students by offering them out-of-class activities. In this paper, the strategy of this process with special events and opportunities will be described based on four years of experience.**

Keywords— spacegeneration;education; STEM; outreach activities

I. Introduction

Although there is no aerospace engineering faculty in the country, many young people interested in space have made a great impact already on the Hungarian space activities. To support the growing number of employees in the national and international space sector, the Hungarian members of UN-established Space Generation Advisory Council (SGAC) in collaboration with the Hungarian Astronautical Society (MANT) organizes several events during the year for university students and young professionals between age of 18 and 35 years to expand their knowledge of international space policy issues and space research, build relationships and think creatively about the future [1]. The young Hungarians can participate on the Space Academy Club in every second month, which is a two-hour-long open workshop with two lectures with the up and coming space topics held in different universities in Budapest. During the summer the four-day-long Hungarian Space Academy is another unique possibility for the enthusiastic students and professionals, where they can work together on a space related project and learn about space in tutorial lectures given by Hungarian professionals from national industry and academy.

The aim of these programs is to share knowledge, inspire and orient the young generation towards space related careers, in addition, to develop and maintain a dynamic forum for the young generation in our country, where they can study and connect.

II. Organizations

A. Space Generation Advisory Council

The *Space Generation Advisory Council* (SGAC) is a global non-governmental organization and network, which aims to represent university students and young space professionals to the United Nations, space agencies, industry and academia. SGAC was established as a recommendation from the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III) held in Vienna in 1999. SGAC has Permanent Observer Status in the UN Committee on the Peaceful Uses of Outer Space (UN COPUOS) and is regularly present at its annual meeting and its two subcommittee meetings. These presentations cover the outcomes of SGAC's annual conferences and projects throughout the year. This includes the reporting the recommendations and outcomes gathered at the annual Space Generation Congress (SGC) and the annual Space Generation Fusion Forum (SGFF), bringing together top young minds from around world to focus on.

SGAC is headed by the Executive Council, with two elected co-chairs and 12 elected regional coordinators, two per UN region. The Executive Council is supported by an appointed Executive Office, which is made up of a treasurer, executive officer, two co-secretaries and other members. SGAC representatives in the UN countries are named as National Point of Contacts. They have various duties including promoting the global activities of SGAC in the country, coordinating the SGAC activities in the country and organizing different events. In the Space Generation Network with 13000 volunteers, the members can participate in the work of the 8 Project Groups and on different SGAC events, in addition they are able to apply to scholarships and competitions.

B. Hungarian Astronautical Society

In the last 4 years, the *SGAC Hungary* activities were carried out with collaboration and active help of the members of the *Hungarian Astronautical Society*. This is the oldest Hungarian non-profit space association, founded in 1956. This society gathers Hungarian space researchers, users of space technology and everyone who is interested in the interdisciplinary and state-of-the-art uses and research of outer space. The aim of the association is to raise public awareness about space exploration and uses. It also provides opportunity for space enthusiasts to meet, exchange ideas and work together.

MANT, through its members from various fields of science, organizes conferences, youth forums, summer space camps, issues periodicals, releases media material and holds lectures about space research and connected scientific fields [2]. The association is a voting member of the International Astronautical Federation (IAF) since 1959. Members of this society participated in the UNISPACE III conference when SGAC was established. Memorandum of Understanding between MANT and SGAC was signed on Sep 30 2014 during the International Astronautical Congress in Toronto, Canada.

Fig. 1. Participants of the MANT Space Academy 2015, a four-day-long event organized by the MANT and SGAC for university students and young professionals interested in space research.

III. Methods of Knowledge Management

Our aim is to collect and share information about the opportunities and the latest results of the Hungarian space sector in order to help millenials starting space related careers. The knowledge sharing system is based on two pillars, the personal and the online communication. One way of the information transfer is the regular meetings and events, which enable the interested students and young professionals to expand their knowledge and professional network. We believe that the most effective way of involve young minds in this sector is introducing them to the representatives of the space community from various areas who can share their experiences and advices with the audience and also assist them in job research.

A. Events

Since 2014 we are facilitating and managing space education and life-long learning in Hungary. Several space related events are held allowing participants to obtain relevant insights and ideas appropriate to their fields.

The *Space Academy Club* is a two-hour-long open and free workshop with two lectures followed by a free talk, which is organized in every second month during the academy year in different locations in Budapest. The two lectures are usually chosen from the most relevant and up and coming space topics covering wide range of space research, which are sometimes presented in front of the public for the first time. The typical number of participants is between 30 and 70 people.

Selected topics from the past:

- European Space Agency's Earth Observation programmes
- Roundtable discussion with talented young professionals from the Hungarian space sector
- SMOG-1 picosatellite developed at the Budapest University of Technology and Economics
- The past and the future of Solar System research in Wigner Research Centre for Physics of the Hungarian Academy of Sciences
- Using new generation cognitive behavioral training in space exploration
- Landing site choice, deep drilling and water production - engineering work for Mars rovers
- Rocket for the ARDERA (Amateur Rocket Development Adventure) project
- 85^{th} birthday of the Hungarian space researcher Iván Almár, who is one of the pioneers of the Hungarian space sector
- How to present your scientific work in 30 seconds? A communication training for students and young professionals
- From books to the space: achievements of the Space Research Group of the Budapest University of Technology and Economics
- Opportunities in the space sector – Introduction of the Space Generation Advisory Council
- Opportunities and limits of the GNSS systems
- Possibilities and limits of interstellar travel
- How satellites contributes to estimate the factors of the climate change?

In August, the four-day-long *Hungarian Space Academy* provides a unique possibility for the enthusiastic Hungarian students and professionals, where they can work together on a space related project and learn about space in tutorial lectures given by Hungarian professionals from national industry and academy [4]. The event is supported by the Hungarian Ministry of National Development as well as different Hungarian space-oriented companies.

Since Hungary joined the European Space Agency (ESA) as a full member in November 2015, our main topic covered policy aspects. At the first Space Academy in 2015, we asked the 28 participants with different background and professions (e.g., liberal arts, biophysics, astrophysics, engineering) to choose between different optional programs of the ESA. The aim of this event was to give an overview about the national space activities and the participants prepared an important recommendation for the Hungarian Space Research Council with their opinion about the optional programs with the greatest potential in order to take advantage of the ESA membership during the next years and decades.

In 2016, we focused on the International Space Station. The 25 participants met with space experts form the country who already have ISS related project. The lessons learned helped the members of the working groups to design a biological experiment and create a detailed proposal. This was the summer where the “SpacePaprika” project has been born. As the continuation of this project, the SpacePaprika Workshop was held in February of 2017 in Budapest.

In 2017, we discussed the potential use of cubesats in Moon missions. During the program the participants listened lectures about the main Hungarian space research projects, funding opportunities and a presentation about SGAC. They also designed an CubeSat experiment with a conceptional proposal and explicated what are the benefits for Hungary of this projects.

The 2018 event is scheduled for Aug 2-8 and our main discussion topic will be the space education.

We are active to organize European SGAC related meetings in Hungary. On the one or two day long regional workshops, like the European Space Generation Workshop or the European Student Forum organized by SGAC, delegates can discuss the most significant topics in space activities, like how the transition from university into a career could be facilitated in the European region. The participants usually work in working groups during the workshops and make recommendations, helping to shape and providing insight into the future activities of the European space sector. The results are presented at high-level scientific conferences and submitted to different European stakeholders. Furthermore, the reports of the workshops are included in the annual report of SGAC and submitted to the UN COPUOS.

The *Space Academy Free Talk* is an informal meeting with a talented and successful Hungarian space expert. The first Free Talk was held on the 14th of July with a remote sensing expert form the German Aerospace Center (DLR).

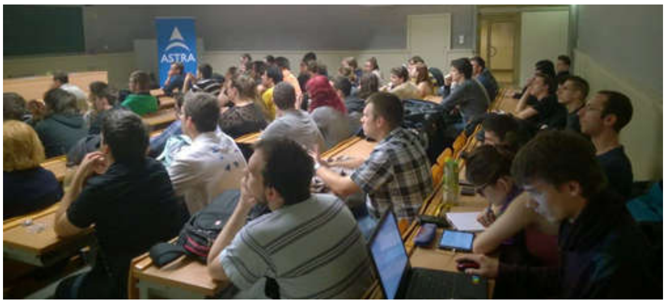

Fig. 2. Audience of the bimonthly event, the Space Academy Club held in the Eötvös Loránd University in 2015. The event is held in Budapest for university student and young professionals between age of 18 and 35.

Yuri’s Night parties and events are held around the world every April in commemoration of Yuri Gagarin becoming the first human to venture into space on April 12, 1961, and the inaugural launch of the first Space Shuttle on April 12, 1981. Yuri’s Night events combine space-themed partying with education and outreach. Hungary joined to this global celebration series three years ago and within this program we spend a night in Budapest with a special guest and young people interested in space activities.

B. Multimedia techniques

The second pillar of our knowledge sharing method is the use of several online tools and platforms. As Generation Y grew up together with the information technology we try to reach the target audience on different online channels and attract their attention to the events where they can meet real space researchers and job opportunities.

We use multiple ways of communication like Facebook, emails, website, and event landing pages. On our Facebook page [3], we share space related regional and international events, job, internship and scholarship offers of the space agencies and space related companies in Hungary and abroad, as well as interesting space news, especially the achievements of the national space sector to raise awareness that our country has ongoing space activity and research. The participants of our events can also use Facebook groups as communication channel. Based on our experiences, this is the most effective

Fig. 3. Participants of the first E-SGW in 2016

way of reaching the members of Generation Y. According to our statistics the most popular posts are the videos, the links and the photos. For sharing space images and advertise the events we also use Pinterest. Those who are interested in our activities, can subscribe to our mailing list. For the modern look and the appropriate marketing, we are using the MailChimp™ mailing system [5], which allows us to send out well-designed mass mails with content organized by the AIDA method (Attention, Interest, Decision, Action), and to follow the status of the email (opened, read, clicked, etc).

IV. Conclusion

Space offers several possibilities for those, who would like to work in the space sector. Using the modern, multimedia-based techniques, information and events can be spread among the interested students and young professionals. Besides, the professional events provide opportunity for receiving first-hand information and knowledge sharing.

At the special space related events organized during the last 4 years, a group of enthusiastic Hungarian students and young professionals was formed, with members who are willing to contribute and take care of the future of the Hungarian and European space activity.

In the future, MANT and SGAC Hungary would like to continue the support of the Hungarian and the European space sector with the education of next generation of space experts by organizing events like the Space Academy and the Space Academy Club (workshops with lectures during the academy year) and maintain continuous online communication. Our goal is to help interested young people to find the relevant information, getting knowledge about the different space related opportunities and building new relationships and network to find the most suitable profession and jobs in the space sector.

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Scientific dissemination through an astronomer's eyes

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***Abstract*—The space exploration and astronomy is the most spectacular discipline from all, however not many of us can talk simply about our research field despite of the huge interest from the public. This part of the science still can amaze and make the common people think and because of this we have the obligation to speak about it clearly. Unfortunately as I see this is one of the biggest defect in the hungarian education.**

I would like to provide an insight to the most popular topic about space and astronomy, and tell about how can we present our complex but fascinating results with the feeling of a cool science fiction.

There are many great initiative in the world and many admirable plans to make this easier, but I feel that the world needs so much more. I would like to introduce some of my ideas to magnify and enlighten the importance of astronomy and space exploration for example by the organization of the scientific dissemination in a much more associated and interdisciplinary way than it is now but taking care of the integration of the things which work well.

Keywords—dissemination; astronomy; techniques

I. Introduction of my experinces

I had the luck to give lectures almost at every observatory in my country in the last ten years about astronomy and space exploration and I would like to share my experiences on that field.

I started at Szeged Observatory in my hometown as a student of the University of Szeged (SZTE). All we had (and all we still has) there was a projector and one or two functional telescopes. That's where we have to rely on our creativity to figure out how to demonstrate with minimal equipments.

After that I get a chance to work at Pannon Observatory which is a dedicated demonstration center for astronomy and space exploration. Due to its almost ideal location, five or six working telescopes, the planetarium system, the 3D movie theater and the exhibition on 400 square meters it is a remarkable place, where almost the only problem is the vast number of possibilities.

Last year I've started working at the Konkoly Observatory as a junior research fellow and support astronomer. The latter title is the personnel for the Observatory at Piszkéstető, where we can find the biggest telescopes of Hungary. It is usually a scientific observatory station but sometimes it is open for group of curious visitors... in daytime. So there the astronomer can rely only his or her knowledge and can show the telescopes which is not so interesting as if we can look into one of them.

Now I've been contributing in the last months to the preparation (such as social media activities, creative ideas, event organization, etc.) of the Observatory complex at Svábhegy in Budapest. Hopefully in the near future will open their gates for the public and then I'm going to participate in the actual lectures as presenter.

I think these experiences gave me such an insight that help me painting a trustworthy picture about the space related scientific dissemination in my central european country. Although I mentioned only observatories in my career where the focus is usually on the astronomy, however as my best knowledge we have not any permanent dedicated space related exhibition in the Hungary so the task of speaking about space activities has been left to the observatories, which is one of my main point.

II. Emerging problems

Since the technology evolved in the last decades in a gear what we've never experienced the common people have got farther and farther away from the science and the unreliable media sources takes away more and more credit from the scientist and nowadays it is a really hard task to distinguish the fiction from reality. These reasons put a heavier duty to us to make the unbelievable results palpable and make the unimaginable but reachable goals realistic.

Basically the funding of the researches and developments approaches the needs in those countries where some kind of healthy public outreach works, which is a little bit hard question in the case of space activities, but until the sources of these are mainly from public funds we need to reach out and show the results and benefits of our work.

After we recognize the need of these kind of activities then we can talk about the implementation. The quality of a scientific presentation depends on two parts, on the physical tools and the recency of these tools (and here tools mean everything from the advertising techniques to the actual presentaion equipments) which we use and the number and the presenation skills of the performers. Thereafter this quality can convince the public opinion one way or another about the necessity to investigate a discipline and ultimately the public opinion can attracts the attention of supporters at decision-making.

III. CASE STUDIES

1) *The rising of Szeged Observatory*

As it was mentioned in the introduction at Szeged Observatory we have only a lecture room officially with 40 seats and some images on the wall, a projector and one or two telescopes, still we've been producing a solid growth in attendance since 2015 (unfortunately there is not any detailed statistics for the time before that, see Fig. 1.), but the average number of visitors per year could be around constant 1000 people in the previous years. This progression is in good agreement with the launching of the observatory's facebook page back in 2014 which shows us very well that using properly and regularly the social media could be an effective help to raise awareness for your cause.

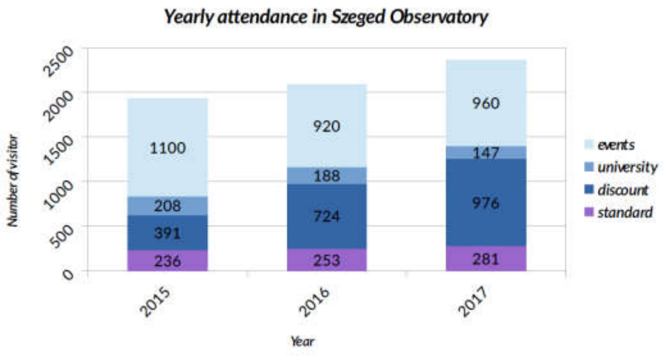

Fig. 1. Annual number of visitors at Szeged Observatory. Events' number means the guests on our greater one night shows, University, Discount and Standard mean the number of guests from SZTE, from other educational or social institute and from anywhere else respectively on the regular friday nights.

2) *Gateway to Space Exhibition at Budapest*

In 2016 and 2017 this international exhibition visited Hungary for two short period. There was a great visitor number in each period on the one hand due to its unique collection but on the other hand thanks to the lack of anything nearly similar things in our country. However it was clearly a huge success as an exhibition but the low number of expert staff made it a little impersonal.

3) *A remarkable example - Griffith Observatory*

I participated in a summer school in California in the summer of 2014, and I was lucky to visit Los Angeles where we can find this historical observatory. It has the perfect ratio of interactive and passive exhibition elements, the museum guides are very interesting and the leader is extremely prepared both in professional and communicational ways. It can satisfy the needs from simple interest to the technical details.

4) *3 years at Pannon Observatory*

I've worked for three years at Pannon Observatory as performer where I could meet very numerous people. The place celebrates its 5th anniversary this year and more than 100 000 guests visited it during these years. The equipments are the best in the country but here we face the same staff shortage problem again.

The Pannon Observatory has exhibition halls about both astronomy and space exploration. During these years I heard many times the following topical questions:

- "Are there any alien life forms?"
- "Have you seen any UFO or flying saucer?"
- "Is it true that the USA faked the Moonlanding?"
- "Why didn't we go back to the Moon?"
- "When do we can reach the Mars?"
- "Is it true that the Sun will explode some day?"
- "Do the black holes suck in everything?"
- "Can we predict our future based on the stars?"
- "Is there such thing like hungarian space industry?"

And this list could go on. But the important message is clear here that the popular cultular things stand in the center of the people's interest.

IV. POSSIBLE SOLUTIONS

A. *Equipments, tools, and their interactivity*

The vast unreliable information of nowadays raises the necessity of the places where we can hear about the results from reliable sources, from scientists and professionals. However in the 21st century the people prefers more and more the audio-visual and interactive learning methods. So we have to adapt the new equipments and we have to do it fast, because these changes rapidly (we can think here for instance augmented and virtual reality technology, any smartphone application), and we have to change with them to be up to date as our work.

B. *Manpower and presentation skills*

On the other hand we can not just rely on the technology. The people need somebody who answer, they need some personal experience and contact. As we can see these tasks need many workhour, a lot more than a researcher or engineer has. However we need to see that there is a lot of work which especially not the professionals' field (like marketing, or legal questions, graphic designing in some case), and one can't be good in anything. Moreover if we count the experts in any space related topic we can clearly see that they can't be enough for all the needs. So here the obvious solution is to connect the scientists and engineers with each other and outer experts (in media, law, etc.).

V. SUMMARY

We should create networks where we can share the tasks and responsibles based on the participants best qualities instead of that these few experts separate themselves into little competitive groups in which everybody trying to do something that he or she can't or doesn't understand well. Beside this we should try to speed up the process of using nowadays technical solutions and maybe try to foresee the near future trends and adapt to them.

ACKNOWLEDGMENT *(Heading 5)*

Thanks to Szeged Observatory, Pannon Csillagda and Konkoly Observatory for the opportunity to do what I love and to show people how interesting science in which I can work. Thanks to SZTE for the chance to visit California, and thanks to Space Generation Advisory Council for acception of my application to European Space Generation Workshop (three times) where I could collect ideas and motivation for how to do my work. I also want to say thank to the organizers for the extra preparation time.

VIPER – Student research on extraterrestrial ice penetration technology

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***Abstract*—Recent analysis of scientific data from Cassini and earth-based observations gave evidence for a global ocean under a surrounding solid ice shell on Saturn's moon Enceladus. Images of Enceladus' South Pole showed several fissures in the ice shell with plumes constantly exhausting frozen water particles, building up the E-Ring, one of the outer rings of Saturn. In this southern region of Enceladus, the ice shell is considered to be as thin as 2 km, about an order of magnitude thinner than on the rest of the moon. Under the ice shell, there is a global ocean consisting of liquid water. Scientists are discussing different approaches the possibilities of taking samples of water, i.e. by melting through the ice using a melting probe. FH Aachen UAS developed a prototype of maneuverable melting probe which can navigate through the ice that has already been tested successfully in a terrestrial environment. This means no atmosphere and or ambient pressure, low ice temperatures of around 100 to 150K (near the South Pole) and a very low gravity of 0,114 m/s^2 or 1100 µg. Two of these influencing measures are about to be investigated at FH Aachen UAS in 2017, low ice temperature and low ambient pressure below the triple point of water. Low gravity cannot be easily simulated inside a large experiment chamber, though. Numerical simulations of the melting process at RWTH Aachen however are showing a gravity dependence of melting behavior. Considering this aspect, VIPER provides a link between large-scale experimental simulations at FH Aachen UAS and numerical simulations at RWTH Aachen. To analyze the melting process, about 90 seconds of experiment time in reduced gravity and low ambient pressure is provided by the REXUS rocket. In this time frame, the melting speed and contact force between ice and probes are measured, as well as heating power and a two-dimensional array of ice temperatures. Additionally, visual and infrared cameras are used to observe the melting process.**

Keywords—student project; phase change; icy moon; sounding rocket; ice drilling; melting probe

I. INTRODUCTION

The Vaporizing Ice Penetration Experiment on a Rocket (VIPER) is a REXUS-Experiment to collect scientific data while melting probes penetrate samples of water ice in low temperature, low gravity and low ambient pressure on a sounding rocket. It is managed and realized as a student project at FH Aachen University of Applied Sciences (FH Aachen UAS). In total, around 15 students from FH Aachen UAS and RWTH Aachen University are working voluntarily at VIPER since November 2016.

VIPER is funded by FH Aachen UAS and by the REXUS/BEXUS programme. Additional travel budget is provided by the Hans Hermann Voss Foundation.

A. Student Projects at FH Aachen UAS

In many courses at FH Aachen UAS, students are encouraged to establish student projects on a voluntary basis. These are usually related to the student's field of study, but not part of the official curriculum. Based on their own ideas, students can submit project proposals to a panel of professors in a competitive manner once a year. The best proposals qualify for monetary funding including material purchase and travel expenses. Also non-monetary support will be provided in the form of working space, possibility of using laboratories and test facilities at the university and support by a supervising professor. Projects are not limited to university funding, but may also apply for external support.

The student projects are managed and conducted totally by the students themselves. The aim of the university is to set up an environment, where students can apply their theoretically acquired skills to real problems in an interdisciplinary way. Students learn to estimate their skills and personal strengths realistically and to take responsibility for the budget and a team.

All student work is conducted on a purely voluntary basis and carried by the team's motivation to reach a common goal.

As in 2018, there are more than 25 projects currently running. Examples from different faculties are short-movie productions, new city planning approaches, a formula student racing team, development and testing of unconventional aircraft designs or design of planetary exploration equipment.

B. Background & Scientific Objectives

The presence of subglacial liquid water on the icy moons of our Solar System [1] implies the possibility of environmental conditions suitable for life. Especially Enceladus, the cryo-volcanically active moon of Saturn, seems to be a promising candidate and there is some hope in the scientific community that an Enceladus exploration mission might unravel the existence of extra-terrestrial life. Next generation mission concepts consider orbiting and sample-returning of plume material [2, 3]. If these further strengthen any evidence for life, a mission that samples and analyses the subglacial liquid directly would be the natural next step [3, 4]. In order to access the extra-terrestrial subglacial water reservoirs, a thick ice layer must be penetrated.

A very promising approach for this challenging task is to use a thermal melting probe [4]. Melting probes enforce ice penetration by heating, such that the ice in the vicinity of the probe melts. In combination with an applied force, e.g. given by the probe's weight, motion through the ice is possible. The amount of necessary power to heat the probe roughly scales with the cross-sectional area of the melting channel. Therefore, a melting probe typically looks like an elongated cylinder with a heated melting head. In comparison to other ice penetration technologies, e.g. hot water or mechanical ice drilling, its design is smaller, lighter, and comprises less complex mechanical devices.

Melting probes are not a novel technology as they have been already successfully applied for terrestrial research in the 1960's [5, 6]. Although the basic concept remained the same, over the recent years more advanced designs have been reported and tested [7, 8, 9, 10]. More complex technical designs have also necessitated the development of advanced mathematical models [11, 12, 13, 14].

For the majority of potential target environments for extra-terrestrial melting probes, the ambient pressure is below 6.1 mbar, which is approximately the triple point of water. Hence, the ice will sublimate during the initial phase of ice penetration. The produced vapour will eventually refreeze at the probe's hull or at other critical locations. Under certain circumstances, this can cause stall of the probe.

No melting probe has yet been used in an extra-terrestrial environment, in which low temperatures, a low environmental pressure as well as a small gravity is present. Towards an extra-terrestrial melting probe mission, a lot of testing and modelling effort is required. Two of these extreme conditions can be tested on the ground in a thermal-vacuum chamber, as it has been done in [15]. However, the combination of all three environmental conditions has not been studied so far. From experiments, it is known that both, a low pressure and a low temperature have a dramatic impact on the melting velocity of a melting probe. In order to better understand the role of gravity regarding ice penetration by melting probe technology, we developed VIPER.

C. The REXUS/BEXUS programme

Based on a bilateral agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB), REXUS/BEXUS (Rocket resp. Balloon Experiments for University Students) allows students to have their scientific experiments or technology demonstration to be launched on a sounding rocket or a high-altitude balloon from Esrange Space Center in Sweden. Each year, student payloads for two rockets and two balloons are selected. Usually around half of the available space is given to experiments from Germany, while the other half is open to experiments from all member states of the European Space Agency (ESA).

Successful applicants are granted a limited sponsoring for material and travel expenses and workshops introducing standards and working methods for space application.

FH Aachen already participated in the REXUS programme twice to qualify a vibration isolation mechanism for sounding rocket experiments (VIBRADAMP and ADIOS) [16] and in-flight modal analysis of the rocket structure [17].

D. VIPER: Experiment Overview

Utilizing the reduced-gravity phase in flight, VIPER is going to simulate penetration of an icy moon with low gravity and nearly no atmosphere. To do so, it carries three separated ice samples and three independently deployable heated melting probes. The melting probes are securely locked during launch and descent of the rocket to prevent damage to the experiment or the rocket itself during high-load flight phases. While approaching the reduced gravity phase of the flight, the melting probes become unlocked and three springs (one per probe) are pushing them into the ice samples.

Measured data while proceeding through the ice include penetration depth, differential pressure inside the experiment container relative to the rocket's ambient pressure and a temperature field with high spatial resolution for each of the ice samples. Additionally, two cameras (one for visible light and one for infrared footage) are documenting the experiment.

The VIPER experiment is located inside a standard REXUS rocket-module with a length of 300 mm and a diameter of 356 mm. Experiment space is divided into two zones, the wet zone and the dry zone. The dry zone is connected to the rest of the rocket's interior. It contains most of the electronics components, such as the experiment's communication and control systems. Furthermore, it contains data processing and storage components and a power management system including additional batteries. Water (i.e. ice or vapour respectively) is only allowed inside the wet zone. Here, the ice samples are located as well as melting probes, locking mechanism, cameras and most of the sensors. While penetrating the ice, sublimation produces a steady vapour mass flow, which can leave the wet zone through four venting holes connected symmetrically to the outer rocket structure by tubes. This guarantees to keep the experiment's inner pressure below the triple point of water, which is necessary to simulate the conditions on an icy moon.

The experiment data and camera footage will be stored locally on redundant flash storage. Additionally, most of the data and camera footage will be transferred to the ground station via a downlink.

II. Space Education

A. Provided Infrastructure at FH Aachen

FH Aachen UAS offers Bachelor's and Master's degree courses in aerospace engineering at a dedicated faculty. Multiple laboratories for automotive and aerospace research provide useful tools to design, manufacture, qualify and test space equipment. Talking about space application, these include a manufacturing workshop, rapid prototyping facility, electronics lab, thermal imaging systems, vacuum chambers in different sizes, thermal simulation chambers and vibration simulation facilities. During the development of VIPER, some of these tools were heavily utilized (see chapter IV).

VIPER was provided their own office and dedicated working space in the laboratory, which are in their own responsibility.

B. Experiencing research facilities and the science community

In the eyes of many students, getting access to laboratories and research facilities symbolizes the next-higher step between theoretical studies and real research and engineering work. Closing this gap is seen essential not only to sharpen the student's sense of responsibility, but the feeling of appreciation is also valuable in motivating them to graduate successfully in a demanding course like aerospace or electrical engineering. In addition, the practical aspect of designing and manufacturing parts is a very useful extension to deepen and apply the theoretical background from the lectures. Students learn that the best theoretical option is not always the best regarding costs, practicability or availability of different components.

Visiting and working at facilities and laboratories of ESA and DLR gives the students a way better idea of what designing and manufacturing a rocket experiments and space hardware in general is about than any lecture at university or short excursions can do. Apart from that, the REXUS programme offers the possibility to work together with highly experienced space engineers and scientists. Also among the teams themselves, an informal network between the participants all across Europe formed after experiencing similar problems since being selected to participate.

In the opposite direction, students used VIPER in schools, to get pupils interested in space related technology and STEM in general. The team presented its experiment and the REXUS/BEXUS programme at schools in Aachen and Berlin, to give an insight into high altitude and space research while still at school.

C. A critical view on professional standards in student projects

Nowadays, space industry is predominantly working according to common standards by the European Cooperation for Space Standardization (ECSS). For companies, ECSS standards are providing a frame for quality management, as well as project management methods. Trying to transfer them as a whole to small student projects like VIPER will probably lead to perfect documentation on one hand, but frustrated students and no hardware at all on the other hand. This can even be extended to university research projects. ECSS standards should not be put aside as useless or even obstructive, though. Interpreted as guidelines how it should be done, they became apparent to be a useful tool in the VIPER project.

Taking project management as an example, it was a demanding challenge to find the best balance between following accurately elaborated work packages and letting people follow their own idea of what to do next. Mostly, the second is more productive at first, since working becomes more dynamic and flexible. But especially when this work is affecting interfaces, problem arise on a regular basis. Students learn to understand there is more than one side of the coin, e.g. defining an interface two weeks later may be easier for one person, but detains another person depending on that interface from effectively proceed with his working package. Generating a level understanding for management decisions can be essential for students, whose eventual jobs will be in a highly managed environment, such as the space industry.

A similar approach may be useful for actual engineering, e.g. in electronics and PCB-design: Standards may define a minimum distance between conducting lines for a certain current. Taking this as a general design rule is totally reasonable and advisable. But if in a later design iteration changes are necessary and one has to decide between a strikingly increase in either budget, effort or complexity on one side and a slight undercut of the minimum distance on the other side, the second solution may be worth consideration.

Some common practice from industry can give real advantages to small space engineering projects, though. Best example may be well-conceived requirements for all aspects of the application or experiment, as well as a sound risk analysis. Both makes students think about their project in every detail. In contrast to working with just a rough picture in mind, this method ensures that all team members are working towards a common goal with a precise sense of how this goal looks like. Students will learn, that in this way, a solid base of requirements helps preventing miscommunication inside the team.

Reviews (conducted by an external or internal review board likewise) on a regular basis became apparent to be a powerful tool not only to report progress, but also making the team aware of weaknesses in their current design. Additionally, students get used to confidently present their work in front of a critical group of experts, which may become useful later on in presenting research on scientific conferences.

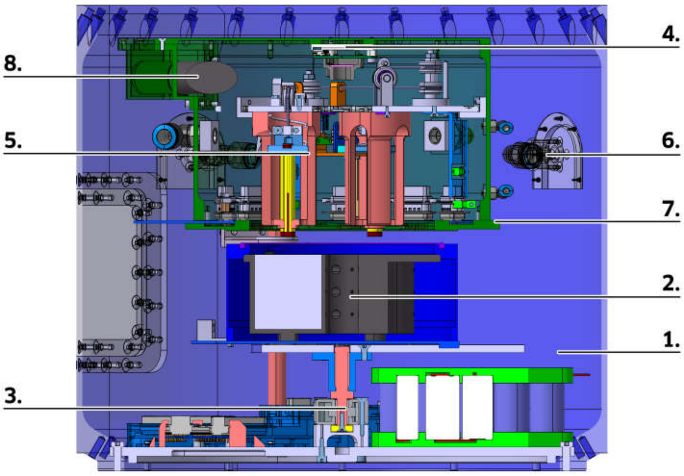

Fig. 1: VIPER experiment design

III. Experiment Design

The VIPER experiment design was developed primarily to fulfil the given scientific requirements. In addition, since the experiment shall fly on a rocket, there where requirements given by the launch provider. Most prominent to mention is that water contamination of any other inner part of the rocket than our own module has to be avoided in a reliable way. Components labelled in Fig. 1 are described in the following. Including the rocket module (1.), the total mass of the experiment is 13.7 kg.

A. Mechanical Design

The Ice Sample Container Assembly (ISCA, 2.) represents the center of the whole experiment. It assembles three cylindrical, triangular arranged containers, which store solid water ice samples. In each ice sample, nine PT100 temperature sensors are integrated to measure a three-dimensional temperature field while the melting probe penetrates the ice. The ISCA is inserted shortly before launch and lifted by a combination of a self-locking worm gear and lead screw (3.) until locking up against the Cupola.

The Cupola (7.) is the sealing counterpart on top of the ISCA. It is located and fixed in the upper section of the rocket module and contains the Heat Probe Pushing Mechanism (HPPM, 5.), cameras (one optical and one IR camera, 4.) as well as a venting system (6.) which is connected to the rocket's hull. Two feedthrough PCBs on top of the bottom side of the Cupola provide electrical connection with D-SUB connectors from the outside to the inside. Because water (or vapour) can leave the Cupola only through venting tubes, there is no way for it leaking into the rest of the rocket module.

One HPPM is placed above each ice sample. Two springs with spring rate R=388 N/m (max. 32N) and one with R=867 N/m (max. 78N) push the melting probes simultaneously against the ice samples during the experiment. The melting probes are relieved by a self-locking linear spindle drive, powered by a brushless direct current (BLDC) motor (8.), providing a maximum melting distance of 45mm. The force of the linear drive to relieve or to retract the melting probes is transmitted by a highly flexible stainless-steel wire. A special arrangement of guide pulleys ensures an optimal use of space. The spindle drive provides a maximum force of 189 N, while the maximum force of the three springs equals 142 N in the fully retracted state. At the carrier of the spindle drive, a set of tension springs is used to keep the steel cables tensioned. The melting probes contain heating cartridges inside a copper shell. Two of them are powered with 70W and one with 35W. Except for the tip, the copper shell is additionally covered with PTFE insulation. Using an optical encoder for each probe, the melting distance, speed and contact force may be derived.

B. Electronic Design

The electronic system divides into three major subsystems: data acquisition from the cameras and other sensors, actuator (motor and melting probe control) and power management.

On the mainboard, a STM32 microcontroller is located along with two redundant flash chips for sensor data storage, and all sensors are connected to the mainboard.

The two cameras, a white/black-CMOS camera from iDS and a Flir Lepton III LWIR-camera, are connected via USB, SPI and I2C to a Raspberry Pi Compute Module 3 mounted on a custom board. This appeared to be necessary for size reasons and because the USB-Hub normally used on Raspberry Pis is not capable of the data rate generated by the camera.

Power management: A custom powerboard converts 28V/1A supplied by the service module to 5V and 3.3V and distributes the power to all electronic components except the melting probes, which are supplied by our own battery through custom 24V boost converters. To supply three melting probes with in total 175W, different battery types were evaluated. Where the best trade-off appeared to be using a pack made of 9 cells COTS high-power-type NiMH from Panasonic [BK300SCP]. Battery packs were qualified by ourself for usage at high currents and in vacuum. Since batteries provide a voltage of between 8V and 12V during discharge, but the heating cartridges require a voltage of 24V, boost converter are required. Thermal tests inside the vacuum chamber showed, that overheating issues may occur with the first boost converter revision using normal FR4-PCBs. Therefore, boost converters were optimized to have a single side layout to be used on an Insulated Metal Substrate PCB to ensure sufficient cooling.

In total, eleven printed circuit boards were designed, some of which are noticeable. Two PCBs only have connectors and wires mounted and are designated to provide a proper sealed feedthrough for connections into the wet part of the experiment. Four PCBs (mainboard, powerboard, pi-board and the boost-converter) are quite complex. We nearly exclusively used SMT components on our board because they are small, less fragile to vibrations and faster and easier to assemble. To keep the design process simple, it was aimed for double-sided PCBs with a single assembly side, although this last was not possible for mainboard and powerboard. All huge components are fixed by screws or are glued onto the boards.

C. *Software Design*

For REXUS experiments there are basically three software-parts to consider. First, all generated data shall be recorded, processed and filtered. Also the experiment has to be controlled, in our case melting probes are released and later retracted by a BLDC motor, the probes are switched and sensors and are turned on. These actions have hard real-time requirements and therefore, software runs on a microcontroller without operating system.

Second: The (so-called) groundstation receives data during flight, processes, filters and displays it to the groundstation operator. It has to display experiment data clearly and has to provide protection against accidental misuse. Furthermore, commands may be sent from groundstation to experiment module to enable a test mode for cold tests.

Third part is the communication between groundstation and experiment module, which is also used inside the experiment to communicate between the two processors. The REXUS rocket provides a serial connection of 34800 baud, bidirectionally transmitted via cables on ground, respectively only from rocket to ground using a wireless connection after launch. Since connections might be interfered, resulting in data loss or bit flips, an error detection was implemented. The code for the communication is generated by a self-written code-generator and shared between all platforms to minimize the possibility of errors and to provide the maximum test-coverage.

For all software parts, C++ was chosen as programming language. C++ as a compiled language has the advantage of showing errors during compilation and earlier than any interpreted language, very important for maximum reliability. Where possible, already existing and tested frameworks were used. Code for the groundstation is written with Qt. The microcontroller is programmed using the xpcc framework [http://xpcc.io/] that provides cooperative multi-tasking and many drivers for sensors and actuators used in our experiments. Additionally, we wrote some drivers that did not exist before and upstreamed them to the framework.

D. *Thermal Design*

VIPER consists of a purely passive thermal control system involving proper materials, phase change materials and insulation.

The timespan between ISCA insertion and rocket launch is in the order of 50 minutes or even larger. In order to meet the requirement of ice sample temperatures smaller than -30 °C before the ice penetration starts, the ISCA is filled with self-produced dry ice snow. The resulting low temperatures induce condensation while the rocket is on the ground. The ISCA is therefore utilized with water-absorbing material on its circumference.

The three melting probes, on the other hand, induce high thermal loads at a short timespan to the HPPM assembly. We therefore use custom 100 W heating cartridges of 50 mm length with an inhomogeneous power distribution (99 % of the total power is located at the first 20 mm near the tip). It should be noted that we operate the three heating cartridges at 70 W, 70 W and 35 W, respectively. Both, numerical thermal analyses as well as validation experiments revealed that using these heating cartridges reduces the maximum temperature of the whole assembly drastically to an acceptable value of approximately 55 °C.

Additional numerical analyses have been conducted in order to calculate the minimum and maximum temperatures at critical locations including the thermal loads due to rocket launch, e.g. at the bulkhead where the boost converters are located. The results show that the temperature-critical parts of VIPER will sustain all expected thermal loads during launch and operation.

IV. Engineering Approaches, Sticking points and lessons learned

A well-known engineering principle for applications appearing outstanding complex is the KISS approach ("Keep is simple and stupid"). Slightly modified to "Keep it safe and simple", KISS turned out to be extremely valuable for a project like VIPER with its limited budget, workforce and experience, while handling strict requirements concerning space, weight, autonomy, and thermal management.

For structural design, students used the university's CAD tool (CATIA V5-6R2012) to generate a detailed three-dimensional model of the whole experiment. With respect to the very limited space available inside the rocket, CAD proved useful for defining hardware interfaces, checking accessibility and estimating masses. Initially, it was planned to make use of rapid prototyping technology to manufacture sensor mounts casings and similar components which are not exposed to high mechanical or thermal loads. While we did not experience issues deploying 3D-printed parts into vacuum, the final experiment design nevertheless contained only a few minor components manufactured this way. Though manufacturing effort and costs were extremely low compared to traditional milling lathing from aluminium pre-product, but this advantage was totally drained by manual postprocessing to achieve required tolerances and geometries. This was true especially for more complicated components, such as electronics casings. Several components, for which additive manufacturing seemed beneficial at first were later on redesigned and manufactured again using classic technologies.

To conduct thermal analyses on specific items, detailed CAD-models were simplified again to reduce computational effort in ANSYS Workbench to a reasonable level. After applying correct boundary conditions, thermal simulations were confirmed by experimental pre-tests with adequate accuracy.

Essential for lowering the cost and design effort is the usage of commercial off-the-shelf (COTS) components, especially talking about electronics design. Still, a certain mental flexibility should be maintained when changes in requirements arise. Sticking to a COTS solution too vigorously may lead to a huge increase in effort or insufficient system performance. In example for VIPER, using COTS subassemblies in the electronics subsystem was constrained by requirements especially for size, weight and precision. Most of the power electronics and communication setup had to be developed on custom printed circuit boards (PCBs). Identifying the point when to switch to a custom solution is vital for taking advantages from COTS components, it requires some engineering experience, though.

While designing the experiment, a strongly interdisciplinary working attitude of all team members seems very advantageous to solve problems. One great example from the VIPER design process is the electrical feed-through of nearly 200 lines connecting sensors, melting probes and motors in the wet zone with electronics in the dry zone. This feed through had to be vacuum and vapour sealed, but there was also only very small installation space on a curved surface available. For COTS components this emerged to be a serious problem, which had to be solved. Finally, only the idea of using a PCB as lower ISCA cover and cable feed through in one part made it possible to have the required amount of sensors installed in the wet zone. Sensors and power lines are soldered to the PCB, which then is glued below the ISCA in a second step. Following this, standardized D-Sub High Density Connectors provide a pluggable interface to electronic parts in the dry zone.

V. Conclusion

Student projects provide an opportunity to educate students beyond their courses' curricula and to help them gaining work experience before graduation. In case of the VIPER team, 15 students designed a full rocket experiment to be launched on the REXUS 23 sounding rocket. VIPER is going to contribute to research related to the exploration of icy moons by investigating the melting performance of melting probes in low pressure and low gravity regimes. The data will be compared to similar experiments on Earth. The results will help to develop and validate computational models for melting probes in extraterrestrial environments.

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The improvement of science learning through astronomy

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***Abstract*— With the experience of almost three years teaching Astronomy in the public schools of Manaus, Brazil, the volunteers of the social project called Projeto Cosmos analysed the enthusiasm and commitment of the students on astronomy and astronautics lectures and workshops promoted by the project.**

In contrast to this observation, teachers reported that their students' performance in subjects such as mathematics, chemistry and physics was insufficient and most of them did not even like the subjects.

At that time, the volunteers began to develop activities and didactics that explored more natural sciences and mathematics in the context of astronomy. The first planned activity was to teach ratio and proportion by playing with the size scales of the planets of the Solar System and the distances among them. The second activity was as exploration of chemical elements through the origin of the universe, the birth of stars and planets. And the final one was through rocket building workshops, exploring concepts of kinematic physics, dynamics, hydrodynamics and hydraulics.

We then verified how receptive the students were to the concepts when they were covered from an astronomy perspective. In addition to qualitatively measuring students' enjoyment of participating in activities, even if they were based on subjects considered uninteresting, we quantitatively measured how the new approach and methodology has helped students to learn topics in natural sciences and mathematics and how they increased their performance in the subjects.

Keywords— Astronomy; education; natural sciences; mathematics

I. Introduction

Since 1998, the Brazilian Olympiad of Astronomy and Astronautics (OBA) has been held for primary and secondary schools. Even though many schools still do not participate, students who have this privilege earn a great opportunity to improve their knowledge in astronomy.

Taking into account our own difficulties in having a good performance in the Olympiad, in a self-analysis from the beginning of our school career until high school, we knew very little about this science. We then decided in 2015 to create a social project that, in addition to disseminating astronomy and related subjects, it also could help students with preparatory classes to the OBA.

Given the importance of this task and the gap in Brazilian education over astronomy, Projeto Cosmos joins other non-formal education initiatives in order to bring this Science to as many schools as possible.

II. Justification

The teaching of science in Brazilian schools generally follow the same model. The students spend the year studying and deepening in several subjects separately so that at the end of their high school, they would have a body of knowledge big enough so they can deal with everyday issues and exercise their role as citizens. [1] But it is no novelty that this teaching model contains several failures: the students are overwhelmed with isolated subjects, many of them cannot relate what they learn in each discipline with one another because they are guided in a single, restricted and limited direction in the classroom.

In the educational curriculum defined by the Education Ministry [2], astronomy does not come as a discipline, but rather diluted in other subjects such as geography and physics.

However, teachers often do not learn astronomy content during their educational background and prefer not to teach this science. When it is done, it is usually based on textbooks riddled which conceptual errors and outdated information.

The works of [3,4] has studied conceptual and misinterpretation errors about astronomy in geography textbooks of elementary education, where it is possible to find distorted representations of the solar system and even incomplete explanations of the moon phases.

Thus, both the deficiency in teachers' educational background and the lack of revision of textbooks imply a poor education level on elementary astronomic phenomena for Brazilian young population.

But teaching astronomy is a powerful tool for science education, for its multidisciplinarity, the ability to arouse fascination and curiosity in the individual, for its accessibility and easy popularization, among other justifications [5].

III. CURRENT SITUATION OF BRAZILIAN EDUCATION

Due to the exaggerated specialization of the disciplines, this has created a distance between what they study in the classroom and their daily lives. The students are unable to relate what they learn in school to the outside world, and this happens even within universities where teachers are formed with little contact with other areas of knowledge beyond their own as related. [6]

These problems have been observed since the 1960s in Europe [7] and in response to this exaggerated specialization of knowledge, a new pedagogical positioning has been presented: interdisciplinarity. This proposal brings contextualization along with knowledge, so that content is taught without limiting to a certain subject but involving several areas of knowledge and then presenting students a more complete and less fragmented view of the object of study.

The interdisciplinarity proposal is already widely discussed in several universities in Brazil, both in approaches and problems related to their application. One of the main difficulties is the teachers' formation, which is directed solely to their area and now they feel insecure to deal with the new task. [1] The distance in language, perspective and methods between disciplines presents a challenge for many teachers. According to Santomé [8], the interdisciplinary practiced in the school require from teachers a different posture.

IV. METHODOLOGICAL PLURALISM

Reference [9] says that scientific education has the role of developing critical and logical thinking. It also develops the ability to solve problems and take solutions based on data and information. Thus, the Science teaching contributes to formation of citizens [10]. Its purpose is not necessarily to train scientists, but individuals with the ability to question, interfere and modify the reality in which they live [9,11].

The work of [11] also discusses the challenge of arousing students' interest in basic education through scientific knowledge, since concepts related to chemistry, physics and biology are seen as unattractive to students and hard to understand. The reasons would be the way the contents are approached [12] and the method used by the teacher during the exhibition of the classroom [13].

To overcome this challenge, it is important that concepts worked in the classroom approach the daily lives of the students, making the science dialogue with situations experienced by them [11]. Besides to using different methodologies and teaching tools such as experiments [14,15], ludic activities [16,17,18], audiovisual resources [19], among others.

An interesting approach is to use several methodological resources in the same class to provide meaningful learning. This technique is called methodological pluralism, based on the fact each student has his/her own rhythm of learning and different motivations, so that a single didactic style serves only a few students, and the solution would be to use varied strategies. [20] A pluralistic proposal involves Reading, research, questioning, discussion and debates, using videos, texts, models, experiments, simulations and observations [21].

Analyzing the level of students' satisfaction with the different educational resources addressed in the Extension Course of Astronomy proposed in [22], it's noticed that the two most evaluated were practical activities, such as workshops and model construction, and the videos shown during the classes. Overall, students were very pleased with the various methodologies proposed in the course and described as essential for a better understanding of knowledge.

V. MULTIDISCIPLINARITY OF ASTRONOMY

Teachers aiming to approach the interdisciplinarity with high school students in a public school in Sao Paulo, chose to talk about the Sun [23] and with that, were able to approach several topics such as: estimation of solar diameter, the importance of the Sun for life, nuclear reactions and the production of energy inside the stars, spectroscopy and the chemical components of a star and etc. In addition to all these topics involving the natural sciences and mathematics, the topics were addressed with lectures, videos and discussions about the subject, as well as practical activities such as build a home-made spectroscope using low cost materials.

From students' comments it was possible to verify that the activity was motivating for the learning of modern concepts of science. In addition, students' enthusiasm and involvement with the activity, observations, discussions and experiments were evident, providing enriching moments in the learning process, which is rarely seen in classrooms. These moments finally reflected in the good results of experiments.

Faced with the challenge of applying interdisciplinary practices in schools, Projeto Cosmos' volunteers have been doing various activities in schools of Manaus involving mathematics, physics and chemistry always in the context of astronomy. At first the content was elaborated trying to explain in a dynamic and simple way, respecting the students' study level. But because astronomy is a multidisciplinary subject, it is inevitable to approach the contents covering various areas of knowledge, besides being unfeasible to present contents involving only some specific discipline such as physics or mathematics.

Simple topics like The Solar System allow the volunteers of Projeto Cosmos several possibilities to elaborate the activities and workshops. It is possible to explain the real scale of the solar system, the planets and they distances thus teaching mathematical notions of reason and proportion in a way that arouses interest and joy for the class, something unusual in math classes. It is possible to explore the origin of our solar system and explain topics such as the thermonuclear fusion of a star, the production of heavier chemical elements and what it reflects in the solar system today, exploring physics and chemistry together.

When the volunteers brought the low-cost material rocket-building activity, it has been possible to approach various concepts of astronautics, such as the engineering behind the rock structure. It has been discussed topics such as aerodynamics, Newtonian dynamics, kinematics and energy concept. All these subjects are studied in the classroom separately, but none of them with as much enthusiasm and dedication as was accomplished in the activity.

VI. Methodology

The Projeto Cosmos' lessons were set up to use various didactic strategies: subject explanation, audiovisual resources, experiments, workshops and challenge questions. The project's volunteer act as advisor, guiding the students and instigating them to think scientifically about issues close to their daily lives.

Specifically, to further explore the multidisciplinarity of astronomy, we have developed three lectures, each with the aim of reinforcing concepts of a specific subject: mathematics, chemistry and physics.

All lectures were held in different high school groups of the same public school in Manaus. 55 students participated of the lesson about Astronomical Numbers. 69 students participated of the lesson about chemistry of the stars. And 36 students participated of the lesson about rocket physics.

It is important to point out that all the videos used in the lectures were available on the Youtube website and the workshops were based on suggestions proposed by Nogueira & Batista [24] and Nogueira & Pessoa [25].

We apply individual questionnaires at the beginning and end of activities. The initial research contained questions about how well students appreciate math, chemistry, and physics. Also if they had ever had contact with astronomy before in their school, if they had already imagined themselves to be a scientist in the future and we asked how often they had the opportunity to participate in scientific experiments in science disciplines.

The final research evaluated how much the student liked to participate in the project activity, and also contained discursive questions, asking what he had learned interesting, what he liked most in class and asking him to leave some criticism, suggestion or praise for the project. In the specific lectures of chemistry and physics was also asked about how much the activities covered were useful in relation to the content for the respective discipline.

Thus, in addition to understand the relationship of students with science subjects and their contact with astronomy, we also seek to validate the teaching methodology applied in the lectures of Projeto Cosmos, verifying which pedagogic resources were most accepted and which satisfaction index and enjoyment of the students in relation to the activities we proposed.

A. *Astronomy and mathematics*

"Astronomical Numbers" explores the sizes and astronomical distances in scale and in this way, it is possible to reinforce mathematical notions of reason and proportion.

We often read large numbers about the size of stars or distance between planets, but we have difficulty imagining such measures. By comparing them with distances and sizes closer to our daily lives using scales, we can have a real sense of how big these numbers are and then improve our view of the outer space. Most images available in books about the solar system are not in scale. Adjustments are made so objects can fit into a small image. Without an additional explanation, students' view of planets size and distance becomes erroneous.

In this class, we proposed two workshops: one reproducing the size of the planets of the solar system in scale and another reproducing the distances between the planets. In the first activity we drawn the design of the circumferences on a paper, and the students used tin foil and old newspaper to recreate the planets in a three-dimensional plane. The second workshop measured distance in inches from one planet to another, and they were positioning each planet's name on a long paper tape.

Also, in the same class we added two short related videos showing in scale the size of the planets of the Solar System and the relative size of several stars and also galaxies.

Finally, we proposed a challenge question that explored the spatial vision of these astronomical objects by asking the students to compare it with everyday objects.

B. *Astronomy and chemistry*

"The Chemical Elements and the Stars" explores the birth and evolution of stars and how to identify its chemical elements by analyzing its light spectrum. In this way, we can reinforce the concept of atoms, thermonuclear fusion, light as electromagnetic wave and spectroscopy.

In this lesson, between the parts of explanation that contained a lot of images and gifs, we inserted three videos. First was about stellar evolution, the other compared size of stars and the last one was about thermonuclear fusion whose title was "Rockstar and the origin of the metal", a very interactive animation produced by a group of dissemination of Astronomy of University of Sao Paulo (USP) [26].

In addition, we introduced an experiment to show how different chemical elements produced flames of different colors. And finally, a challenge for students to analyze a spectrum of a fictitious star and infer the chemical elements present in it.

C. *Astronomy and physics*

"Rocket Physics" covers several concepts of astronautics, such as the engineering behind the rocket structure, as well as concepts such as aerodynamics, Newtonian dynamics, kinematics, and energy concepts. In addition, we commented a bit on the current outlook and future goals of the aerospace industry.

In this lesson we included, among explanations of the topic, four short related videos. The first was an animation of the Minute physics channel that explained about gravity. The second an animation about how rockets put a satellite into orbit. The third, a video with edited parts of the SpaceX Falcon Heavy’s launch. And finally, an animated video about the challenging plan to get a person to Mars.

As a practical activity, we did a plastic bottle rocket construction workshop and the launch was done with water and compressed air.

VII. Results

As for the general evaluation of the students on how much they liked the subjects of math and sciences on a scale of 0 to 5, being 0 for really do not like and 5 for quite like, we obtained averages of 3.93 for the discipline of mathematics, 3.46 for the discipline of chemistry and 3.75 for physics.

The result of the final research on how much they liked the project activities on a scale of 0 to 5, for the students who participated in the lecture of "Astronomical numbers" the average of evaluation was 4.91. The average rating of those who participated in the "Chemical Elements of the Stars" was 4.79. And the average satisfaction of those who participated in the "Physics of the Rockets" was 4.77. These data are very motivating because they demonstrate a very high degree of teaching didactics’ approval. It also indicates the potential of using astronomy along those disciplines in order to increase student’s interest.

Asked if they had ever heard about Astronomy in the school environment, impressive 80% of the students said no. This data reflects how much this science is left in the background in Brazilian education.

In response to the question “have you ever imagined being a scientist in the future?” 50.4% said no, 35.3% yes and 14% responded that in childhood yes. As for the question about how often they performed scientific experiments at school, most answered that they rarely or never did.

Regarding the essay questions about what they liked most in class and what interesting things did they learn, we received some very interesting answers. In the lecture about the chemical elements of the stars, which we considered as the hardest of all three conceptually, in the question about what they liked most, 27% of the students talked about how good explanation was, which shows that we succeeded in explaining complex subjects in a simple way. 15% of the students said they liked absolutely everything. And the third answer that most appeared was in relation to the videos. The rest of the answers talked about specific topics covered in the class. In particular, students really liked the video "Rockstar and the origin of the metal", an animation that contained a funny character learning more about the chemical elements. With this we see that it is not enough just to add videos that complement the explanation, it is important that the language of the video is didactic and the video is attractive to young people.

Another interesting result was in "rocket physics" class, which many students commented the video about the launch of the Falcon Heavy as the thing they liked most in class. 31% of the students also mentioned the didactics of explanation as what they liked most. The other responses commented with equal enthusiasm for videos and the rocket building workshop.

In the question about what they thought most interesting in class, it was possible to realize that students had never studied most of the topics of astronomy that were approached in the lectures. The student’s facial expressions were often of surprise and admiration.

Finally, in the section open to criticism, suggestions and praise, many students wrote asking for Projeto Cosmos to come back to school, thanked us for the lesson and praised the volunteers' didactics. The result and feedback from the students was very helpful and we were able to validate our new teaching methodology.

VIII. Conclusion

Faced with the educational problems in schools and the need to change the approach of disciplines, the teaching of astronomy is a great opportunity still unexplored by teachers and schools. The greatest difficulty is the lack of preparation and knowledge of teachers, which makes it difficult to approach the subject in schools and reflects the importance of initiatives such as Projeto Cosmos.

With all the activities already carried out by Projeto Cosmos and other initiatives, it became evident how astronomy is a powerful teaching tool because it has the ability to relate several disciplines, as well as to create an environment in the classroom that arouses interest and fascination of students.

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ESEO-TRITEL experiment to measure the cosmic radiation

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***Abstract*— The development of the European Student Earth Orbiter (ESEO) was announced by the European Space Agency Education Office for students interested in the space exploration. The ESEO-TRITEL Team is joined to this international cooperation supported by the Centre for Energy Research, Hungarian Academy of Sciences. The development of the TriTel 3D silicon detector telescope began in the Centre for Energy Research several years ago in order to determine the average radiation quality factor of the space radiation field for dosimetric purposes. In the year 2011 it was operated onboard the European Columbus module of the International Space Station (ISS) and was installed in the Russian segment of the ISS as well. The ESEO version of TriTel will fly higher than the ISS version, at an altitude of 500-600 km. At this altitude the Earth's geomagnetic field is much lower and the spectrum of the radiation field is also different. In the ESEO-TriTel experiment the anisotropies in the radiation field, the effects of the Earth shadow and the South Atlantic Anomaly (SAA) will be analyzed and the results will be compared with the fluxes calculated with the standard AP-8 and AE-8 trapped proton and electron models. In the near future the frequency of manned space flights will probably increase, we can think of the continuous human presence in the near-Earth region (low Earth orbits) or the proposed human Mars expedition. That is why the cosmic radiation field is interesting not only in the near-Earth region but at higher altitudes or in the interplanetary field as well. The present paper addresses the brief overview of the ESEO-TRITEL payload and its development status in the frame of the ESEO project.**

Keywords*— *ESEO, TriTel, space dosimetry, radiation, silicon detectors

I. INTRODUCTION

The development of the European Student Earth Orbiter (ESEO) was announced in the year of 2008 by the European Space Agency for students interested in space activities. It is stated in the ESEO mission objectives: “measure the ionizing radiation environment in orbit”. The ESEO-TRITEL payload will fulfil this objective during the mission of the satellite. The MTA Centre for Energy Research (MTA EK) is responsible to support, coordinate and provide professional background for the ESEO-TRITEL student team, which is responsible for the ESEO-TRITEL payload development activities.

After one year of pause in year 2013 the ESEO project was restarted with a new organizer company (SITAEL) and with new satellite design, requirements and constraints. The main goal of the present development is to fit the ESEO-TRITEL design to the currently valid ESEO requirements, build up the ESEO-TRITEL PFM (Proto-Flight Model) and make it through the ESEO verification process to provide a flight proven ESEO-TRITEL payload for the ESEO mission. TRITEL is an already existing space qualified cosmic radiation instrument. The engineering approach focuses on the modification of the original design to enable its operation as a payload on board the ESEO satellite. The changes in the design affected mostly the mechanical, the electrical, the thermal and the data interfaces.

II. SPACE DOSIMETRY AND COSMIC RAY RESEARCH STUDIES

Looking into the near future, the research of the cosmic rays in general and mainly from the dosimetric point of view becomes more and more important, as a continuous increase in human presence is in progress in the Near-Earth region (e.g. International Space Station expeditions, future lunar or Mars-missions, supersonic airliners, commercial suborbital flights etc.).

The first experiment involving cosmic rays was performed on a balloon by Victor Hess in 1912. Hess discovered that up to about 700 m the ionization rate decreased but then increased with altitude showing an outer space origin for ionization [1]. In the first half of the 20th century the first scientific balloon experiments has been performed to study the upper stratosphere for longer time scales up to months [2]. This was the beginning of a detailed study of the incoming cosmic rays as well.

Generally the incoming primary cosmic rays (the Galactic Cosmic Rays originating from the Universe and the Solar Cosmic Rays originating from the Sun) interact with the Earth’s magnetosphere and the atmosphere providing a complex radiation environment [3]. The spectra of the galactic cosmic rays are well known for the different type of charged components. With about 85% contribution, the most important components are the protons (12% α-particles, 1% heavier ions and 2% electrons in the relativistic energy range 1 to 10 GeV) with a maximum detected flux peak at around 1 GeV and a quick decrease below and above this energy [3]. In case of solar maximum conditions the decrease in the galactic cosmic rays flux is well studied using several satellite data (such as Pioneer and Voyager deep space missions) showing one order of magnitude decrease [4] mainly in the energy range below 1 GeV [5]. Based on earlier studies, below 10 MeV there is a significant increase in the flux of the protons due to the solar component [6].

The magnetic field of the Earth significantly influences the radiation environment through the geomagnetic shielding effect of the magnetosphere. The penetrating ability of the charged particles into the geomagnetic field is determined by the magnetic cut-off rigidity [7]. For each point and each direction of incidence there exists a threshold value of magnetic rigidity, called the geomagnetic cut-off. Below this cut-off value no charged particle can penetrate from the given direction [8]. During geomagnetic activity events the cut-off rigidities may decrease significantly with several orders of magnitude providing a much higher charged particle flux at lower energies in the atmosphere. In case of protons it has been shown that the cut-off rigidities can decrease even to 0.001 MV [9].

One of the many risks of long-duration space flights (e.g. International Space Station expeditions, future lunar or Mars-missions, etc.) is the excessive exposure to cosmic radiation. The dose equivalent in orbit may be two orders of magnitude higher than that under the shield of Earth's atmosphere. Due to significant spatial and temporal changes in the cosmic radiation field, radiation measurements with advanced dosimetric instruments on board space vehicles and satellites are extremely important. Since dose equivalent, which characterizes the stochastic biological effects of the radiation, was defined in terms of a LET (Linear Energy Transfer)-dependent quality factor, determining the LET spectrum and the quality factor of cosmic radiation is necessary.

III. TRITEL SPACE DOSIMETRY TELESCOPE

In order to study the cosmic radiation field in orbit for dosimetric purposes, the development of a three dimensional silicon detector telescope (TRITEL) with almost uniform sensitivity got underway in the former KFKI Atomic Energy Research Institute (AEKI) in the last decade (now MTA Centre for Energy Research). The instrument comprising three mutually orthogonal, fully depleted PIPS (Passivated Implanted Planar Silicon) detector pairs is designed to measure the energy deposit of charged particles (see Fig. 1).

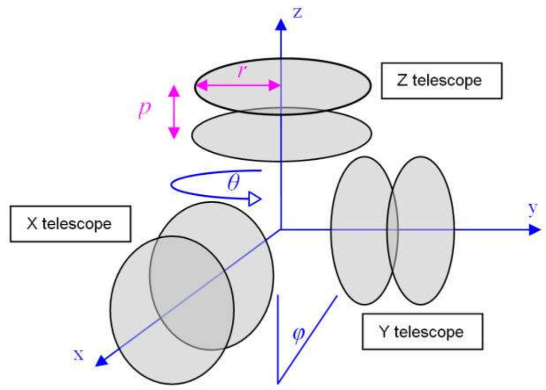

Fig. 1. The TRITEL telescope geometry

The detectors are connected as AND gate in coincidence in pairs forming the three orthogonal axes of the instrument. By evaluating the deposited energy spectra recorded by TRITEL the absorbed dose, the LET spectra in three directions, the quality factor and the dose equivalent can be determined. Since we are interested in the equivalent dose in tissue, the LET spectra in silicon will be converted to LET spectra in human tissue [10].

Although the instrument cannot determine the arrival direction of the individual particles, due to the three-axis arrangement an assessment of the angular asymmetry of the radiation might be possible [11]. The effective surface of each detector is 220 mm^2 with a nominal thickness of 300 µm. The most important geometrical parameters of the TRITEL telescope are summarized in Table 1.

TABLE I. GEOMETRICAL PARAMETERS OF THE TRITEL TELESCOPES

Parameter	Value
Radius of the detectors (r)	8.4 mm
Effective surface of the detectors (A)	220 mm^2
The gap between the detectors in one telescope axis (p)	8.9 mm
Ratio of the separation between the detectors and the radius (q = p/r)	1.06
Geometric factor, G (for one telescope axis in 4π)	5.1 cm^{2}sr
Maximum angle of incidence (for one detector pair)	62.1°
Minimum path length in the detector (depletion layer thickness, w)	300 µm
Average path length in the detector (for an isotropic field)	361 µm
Maximum path length in the detector (for maximum angle of incidence)	641 µm
Ratio of the maximum and minimum path lengths	2.14

IV. ESEO-TRITEL PAYLOAD DESIGN

A. General

The main design goal in the frame of the ESEO mission is to design, develop, manufacture and verify through intensive test campaign a new, satellite version of the TRITEL three dimensional dosimetric telescope.

B. Measurement Details

After comparing the expected maximum proton and electron count rates for the ESEO mission can be concluded that the most significant trapped component will be the trapped electrons with at least two orders of magnitude higher count rates at the altitude of the ESEO satellite. The regions where trapped electrons will be detected are much more extended than that of the protons.

ESEO-TRITEL will measure the energy deposit of charged particles. Hence the absorbed dose and (from the coincidence spectra) the LET spectrum of the particles can be determined. At count rates higher than 50000/s, the dead time of the system exceeds 10% and the dead time correction algorithms might become unreliable [12]. The thickness of the aluminium shielding in front of the detector was chosen such that the expected maximum count rates are below this value. Due to the spectrum of the trapped electrons, the number of counts does not decrease significantly above 1.2 mm of shielding thickness.

Our calculations were performed for the worst possible cases, i.e. passing through the SAA or the Polar Regions, where the trapped flux is the dominant component. Outside these regions the trapped flux can be neglected; in this case the dominant component will be the non-trapped particles flux which was calculated by CREME96 [13]. According to the calculations the maximum electron and proton fluxes are at least three orders of magnitude lower during normal geomagnetic conditions than the maximum fluxes in the Polar Regions and in the SAA. If we further increase the thickness of the shielding in front of the telescopes the measurements might become unreliable due to the poor statistics.

The choice of having an aluminium shielding thickness of 1.2 mm has one more important advantage: this thickness is equivalent to the effective thickness of a typical space suit, which means that the spectrum of the cosmic radiation will be very similar to that inside a space suit, hence it will be possible to estimate the dose the astronauts would get during different periods in the orbit of ESEO.

If the count rates will be much higher than expected according to our conservative model (e.g. in case of large geomagnetic storms), the measured count rates will saturate, i.e. for these periods only a lower limit of the flux and dose will be determined.

C. Payload Specific Design Details

According to the current ESEO design TRITEL will be located at the bottom panel of the satellite, looking into fixed, nadir direction. Fig. 2 shows the internal view of the ESEO-TRITEL payload. The detector part of the payload will be located outside the wall of the spacecraft, thus, besides the foreseen 1.2 mm aluminium wall thickness of TRITEL no additional shielding will be in front of the detectors [14]. Based on the study of the expected radiation environment the shielding in front of the detectors were chosen such that the expected maximum count rates are below the 50,000/s value, which corresponds to the 10% system dead time level. Additionally it is equivalent with the effective thickness of a typical space suit given the possibility of dose assumption for astronauts in case of similar orbital parameters.

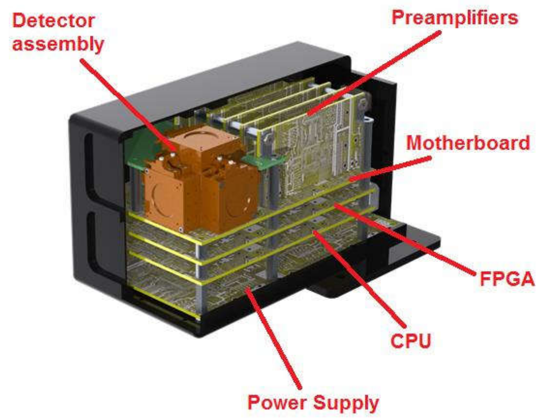

Fig. 2. The ESEO-TRITEL mechanical design (CPU: Central Processing Unit, FPGA: Field Programmatic Gat Array)

The main technical parameters of the ESEO-TRITEL payload are summarised in the Table 2.

TABLE II. THE TECHNICAL PARAMETERS OF THE ESEO-TRITEL PAYLOAD

Parameter	Value
Mass	956 g
Dimensions	155 mm [L] x 107 mm [W] x 83 mm [H]
Power consumption	2.8 W
Input voltage range	15.5 – 34.0 V
Operational temperature range	-40 - +30°C*
* Corresponds to the temperature of the detectors itself, the other electrical components are operational up to 85°C.	

Detailed mechanical and thermal simulations were performed in order to verify at CDR (Critical Design Review) level the mechanical design of the ESEO-TRITEL payload according to the ECSS (European Cooperation for Space Standardization) standards.

Based on the design development ESA and SITAEL provided the authorization to manufacture the payload PFM and start the acceptance verification test campaign, which contained the following, major tests: functional tests, calibration activities, specific manufacturing related inspections, vibration tests, thermal-vacuum (T-VAC) tests, EMC (Electromagnetic Compatibility) tests. The ESEO-TRITEL Team was responsible to carry out the extensive test program in the light of the ECSS standards. Most of the tests were provided in the internal facilities of the MTA EK, only some specific calibration activities, the vibration and EMC tests were made in outer locations. For details see Fig. 3-6.

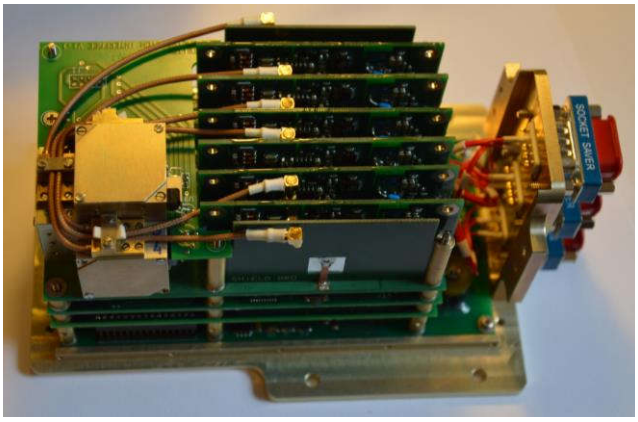

Fig. 3. ESEO-TRITEL PFM during assembly and integration

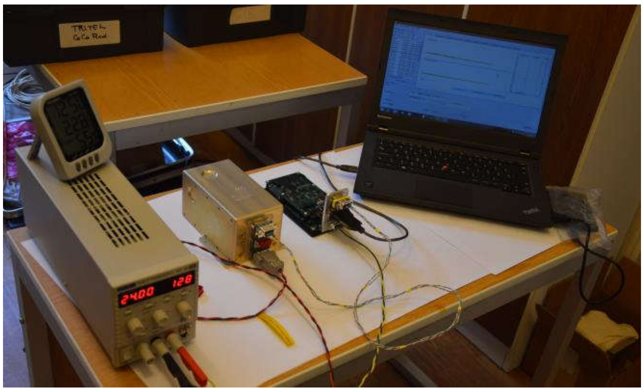

Fig. 4. ESEO-TRITEL PFM functional testing at MTA EK

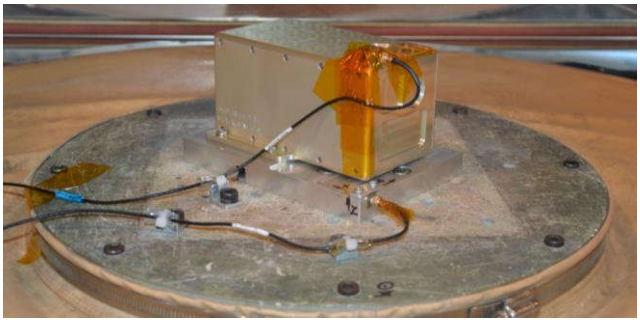

Fig. 5. ESEO-TRITEL PFM on the shaker at the vibration facility

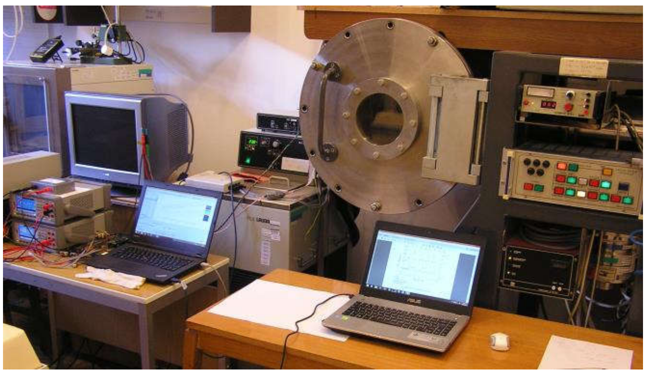

Fig. 6. ESEO-TRITEL PFM T-VAC testing in progress

At the end of the test campaign ESA and SITAEL organized at MTA EK the payload PFM Delivery Review Board in which the test results were accepted by all parties and the ESEO-TRITEL PFM was nominated as ready for satellite level final integration.

V. Educational Summary

MTA EK has been supported almost 10 years long the ESEO-TRITEL student team. During the overall project duration 16 university students have been participated directly in the activities of the student team. More than the half of the students participated on ESEO related educational courses or on scientific/technical conferences supported by MTA EK. Several thesis works have been prepared in the frame of the project. Currently the ESEO-TRITEL Team has 7 participant students from the Budapest University of Technology and Economics. The project has been provided real hands-on experience for the university students in the field of space research and space technologies.

VI. Summary

The ESEO-TRITEL 3-dimensional silicon detector telescope will be operated on board the ESEO student-made satellite at the end of 2018 to carry out measurements about the cosmic radiation field mainly from dosimetric point of view.

The main mission objectives (and requirements) have been identified in all details according to the expected ESEO orbital parameters. The final mechanical design has been provided with detailed mechanical and thermal simulation results in order to demonstrate the feasibility of the payload design. The payload PFM has been manufactured and inspected by ESA and SITAEL experts. The acceptance test procedures have been accepted and thus the test campaign was started accordingly.

The development stage of ESEO-TRITEL at the moment is in the final stage since ESA and SITAEL accepted the ESEO-TRITEL payload PFM for delivery and final satellite level integration. All acceptance verification tests have been carried out on the payload PFM without major issues, thus the instrument is ready for operation onboard the ESEO satellite.

VII. ACKNOWLEDGEMENTS

The authors acknowledge the services provided by the organisers of the ESEO project, especially the European Space Agency Educational Office, SITAEL, and the experts of the organisations who supported the student teams throughout the project.

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Ground segment solutions for the ESA ESEO educational mission

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***Abstract*—Since 2003, the Microsatellite and Space Microsystems Laboratory at the University of Bologna (UniBo) has extended his research activities to the design of a Ground Segment (GS) for small satellites low Earth mission (LEO). In the framework of the European Student Earth Orbiter (ESEO), an ESA Education Office project for the development of a micro-satellite mission, to be launched in LEO, with SITAEL S.p.A. as the industrial system prime contractor, the first-generation ground system has been upgraded to support the ESEO microsatellite operations. UniBo is in charge for the design and development of the mission control center; the implementation of the primary ground station for TeleMetry and TeleCommand (TMTC) operations in Ultra-High Frequency band and of the secondary one for the downlink of payloads data in S-band. The GS follows the software-defined radio (SDR) paradigm, which allows fast and economical reconfiguration capabilities. Thanks to its versatility and ease of operations, the GS is a valuable tool for offering extensive hands-on experience to students.**

Keywords: Ground segment, Software defined radio, Small satellites, ESEO

I. INTRODUCTION

Starting from the 2003, the research activities of the Microsatellite and Space Microsystems Laboratory at the University of Bologna (UniBo) has concerned with the design of a Ground Segment (GS) for small satellites low Earth mission (LEO). The first step in this field was the ALMA Sat-1 (ALma MAter Satellite) project [1]. It was entirely designed, manufactured and assembled in the Microsatellites and Space Microsystems Laboratory. ALMASat-1 represented a great effort from and educational view-point, and its development paved the way to the subsequent space-related activities.

An upgrade to the first generation of ground segment is due to the active role of UniBo inside the European Student Earth Orbiter (ESEO) [2]; an ESA Educational Office project for the development of a micro-satellite, to be launched in LEO, with SITAEL S.p.A. as the Industrial System Prime Contractor. The design and development of the mission control center, the implementation of the primary ground station for TeleMetry and TeleCommand (TMTC) operations and of the secondary one for the downlink of payloads data are fundamental tasks to achieve for the University of Bologna.

The Primary TMTC GS operates in Ultra-High Frequency (UHF) band for uplink and downlink. It makes use of two Yagi antennas: one, in the amateur band (430-440 MHz), for performing TMTC radio communication with the ESEO satellite and another, operating in the commercial UHF band (400 MHz), for future applications. With respect to the first-GS implementation, the current one is now following the Software-Defined Radio (SDR) paradigm, which allows fast and economical reconfiguration of the ground station thanks to the wide frequency band of radio frequency front-end and since the signal is digitally processed at software level [3].

The Secondary Science Data GS operates in S-band, thanks to a parabolic dish antenna with a septum dish feed.

A dedicated control room is also available, furnished with technical equipment to support the mission monitoring and control related activities: in this respect, the design of a spacecraft monitoring and control (M&C) system is essential to efficiently perform the operations. To this end, an intuitive and easy-to-use graphical user interface was developed which helps the spacecraft operator to handle TMTC data. It has a threefold purpose: a) the selection of the desired commands b) the visualization of the satellite telemetry data and c) the connection to a database for storing the downlinked data and retrieving the various commands and satellite parameters.

Even if developed within ESEO program, the ground segment is being designed to operate a wider range of small and micro satellite LEO missions with minor modifications.

Finally, it is important to underline that our university is also involved in the ESEO project as provider of the GPS Navigation Payload.

II. BACKGROUND

The activities of the Microsatellite and Space Microsystems Laboratory started with the ALMASat-1 project (Fig. 1), a microsatellite launched in February 2012 on board the VEGA maiden flight, with the purpose of validating the platform technology and the on-board micro-propulsion system.

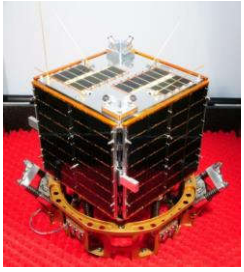

Fig. 1. ALMASat-1 installed on the release system [1]

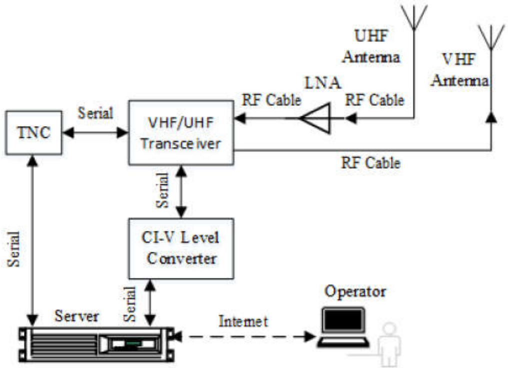

Fig. 2. ALMASat-1 ground station configuration [2]

The design and development of an amateur radio ground station for small LEO satellites was necessary to support ALMASat-1 operations and it represented a fundamental heritage for ESEO mission. The Radio Frequency (RF) communications of the mission were established on Very High Frequency (VHF) uplink (2x9 elements Yagi antenna) and Ultra High Frequency (UHF) downlink (2x19 elements UHF Yagi antenna). The RF system was based on commercial analogic radio, Low Noise Amplifier (LNA) and terminal node controller compliant with the International Amateur Radio Union (IARU) guidelines and with the AX.25 standard protocol (Fig. 2).

III. ALMA MATER GROUND STATION

From 2003, considering the UniBo role inside the ESEO project and the idea to support a wider range of small and micro satellite LEO missions, the ground station (located in Forlì) has experienced a series of improvements in terms of hardware and software.

The current configuration provides therefore coverage service for two different bands: UHF-band and S-band. Necessary for TMTC operations of the ESEO spacecraft, the former band is implemented by a 2x19 elements Yagi antenna (430-440 MHz) with a gain of 16 dBi. The latter band for (backup) downlink of payloads data, is performed by a 3m parabolic dish antenna (up to 11 GHz) with a gain of 35.4 dBi. An additional antenna for a specific commercial ultra-high frequency band (401-402 MHz) is installed for supporting an In-Orbit Validation mission with a private company and following the idea of a flexible ground station. It is formed by an array of two 2x20 elements Yagi antennas mounted vertically each one having 17.4 dBi gain. The use of a coupled antenna configuration instead of a single one, for reaching the target of 20 dBi, allowed a more compact design, avoiding at the same time potential interference with the closely located S-band antenna.

Due to the wide frequency band of RF front-end and since the signal is digitally processed at software level, the SDR-based communication system allows fast and economical reconfiguration of the ground station. Without a doubt, this is the most important upgrade respect to the first generation of ground system.

Moreover, a dedicated control room (Fig. 3) is also available, furnished with technical equipment to support the mission monitoring and control related activities: in this respect, the design of a spacecraft monitoring and control (M&C) system is essential to efficiently perform the operations.

A. *UHF-Band Segment*

As shown in Fig. 4, thanks to a High-Power Switch (FMSW2038, Fairview Microwave), the radio-amateur band antenna can be used in Transmission (TX) or Receiving (RX) mode. In the former case, a 50W High Power Amplifier (ZHL-50W-52, MiniCircuits) is coupled with a Band Pass Filter (3B110-415/T130-O/O, K&L Microwave) in order to avoid transmission of unwanted harmonics generated by the HPA. In RX mode, a BPF (4B110-435/U20-O/O, K&L Microwave) followed by a Low Noise Amplifier (FMAM63003, Fairview Microwave) is placed right after the antenna. In this case, the saturation of the LNA is avoided by the selected filter. The commercial band antenna works only in RX mode, and the implementation of a second switch (SR18-SMA2, Fairview Microwave) is necessary since both UHF-band are handled through the same SDR (USRP N210 + SBX daughterboard, Ettus Research). In this case, the LNA is the same model of the previous one while the BPF (6B110-401.5/U20-O/O, K&L Microwave) is also selected to avoid the transmission of power from the radio-amateur band antenna to the commercial one.

These two bands are mounted on a single rotor (Alfaspid, from RF Hamdesign) and they are driven by the same controller thanks to the satellite tracking software GPredict. The selected rotator can provide a tracking speed up to 6 deg/sec for azimuth and 4.5 deg/sec for elevation, with an angular accuracy of ± 1 deg (autotracking + pointing error).

B. *S-Band Segment*

The S-band segment works in RX mode only (Fig. 5). The signal received by the antenna is first filtered (7FV40-2250/U100-O/O, K&L Microwave), amplified (KNU LNA 222 AH, KHUNE electronic), and lastly processed by the SDR. In the next future, the uplink segment will be implemented as well.

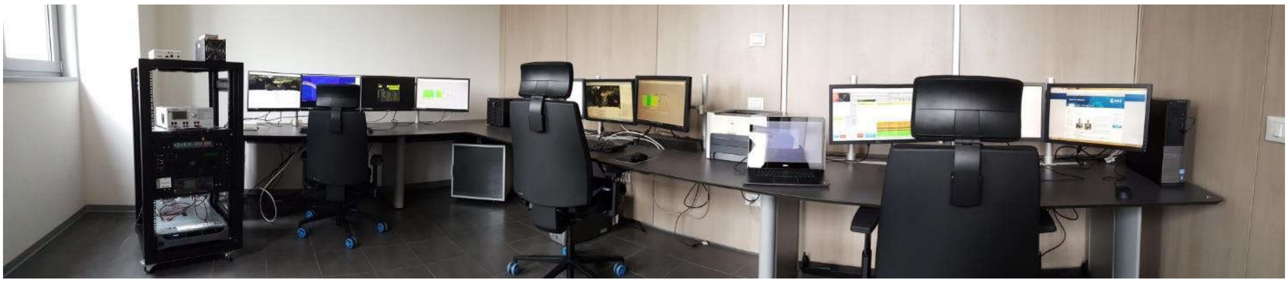

Fig. 3. Mission Control Room

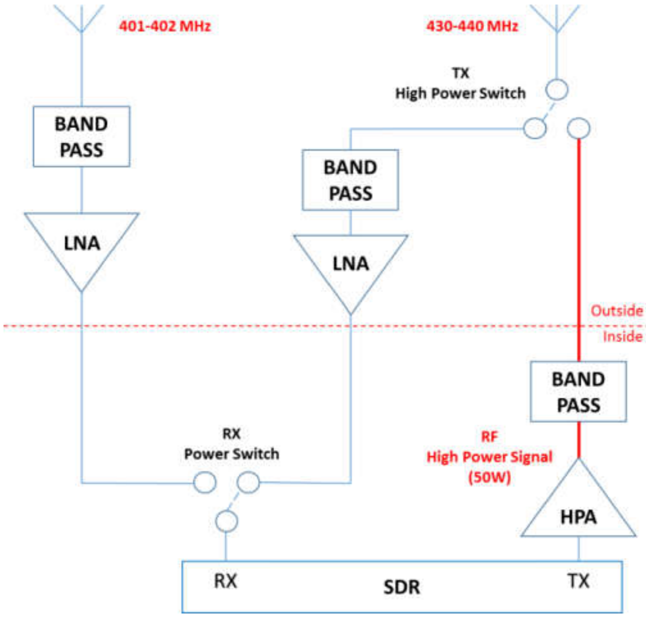

Fig. 4. UHF-Band Segment

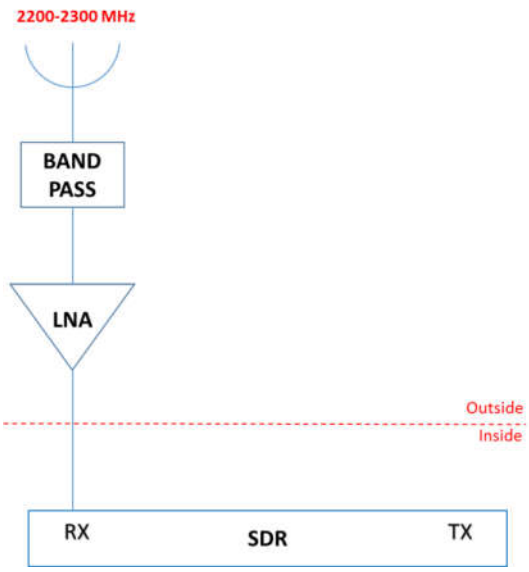

Fig. 5. S-Band Segment

IV. SDR IMPLEMENTATION

The ALMA MATER Ground Station enhances its capabilities by introducing a software-defined radio. Using different modulation scheme, communication protocol and frequency, the SDR allows to reconfigure the ground station in a fast and cheap way. Moreover, the implementation of an SDR environment is beneficial also for educational purpose, as, engineering student can apply their knowledge in communication theory to practical applications developing digital communication algorithms on a computer.

The signal acquisition/transmission, the signal demodulation/modulation and the frame detection in a SDR environment represents a fundamental progress with respect to the first-generation ground system. The implemented SDR system includes the Universal Software Radio Peripheral (USRP) platform by Ettus research, model N210 (Fig. 6), hosting the FPGA and ADC/DAC, the wide bandwidth transceiver named SBX daughterboard (Fig. 6) and the host PC running a dedicated software.

The SBX daughterboard provides up to 100 mW (20 dBm) of output power, a typical noise figure of 5 dB and 40 MHz of bandwidth. The low power transmitted justifies the necessity of amplify the signal by the HPA.

Based on LabVIEW, the software for the SDR is developed as part of the GS update activities for the ESEO project. It is built through five parallel loops performing the GFSK modulation, Reed-Solomon channel coding, AX.25 packet encoding, signal analysis, display and recording. The SDR software is connected to Orbitron satellite tracking software [4] through a Dynamic Data Exchange (DDE) for automated Doppler frequency shift compensation. In detail [5]:

- Signal acquisition and display (Fig. 7);
- Signal IQ data recording;
- Signal demodulation and User Datagram Protocol (UDP) connection;
- UDP connection and signal modulation and trasmission;
- DDE connection.

Through the signal acquisition and display loop, the operator can visualize in a simple GUI all the necessary information about the signal (RX Time Domain Plot, Baseband

Power Spectrum and Waterfall) and USRP parameters (Fig. 8). Five parameters are necessary to configure the SDR [5]:

- *Device name*: is the IP address of the USRP device;

Fig. 6. USRP N210 and SBX daughterboard by Ettus Research (source: https://www.ettus.com/product/details/UN210-KIT)

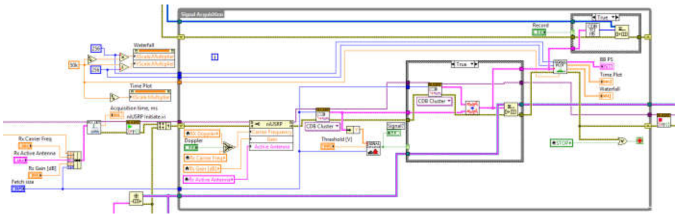

Fig. 7. LabVIEW Block Diagram of the Signal Acquisition loop of the SDR Software [5]

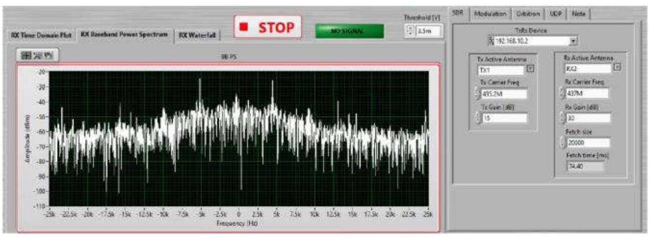

Fig. 8. SDR Software GUI [5]

- *Antenna*: is the selected antenna port. In particular it is possible to select TX1 (transmission) and RX1 (reception in half-duplex) or RX2 (reception in full-duplex);
- *Carrier frequency*: it represents the TX/RX carrier frequency of interest;
- *Gain*: is the amplification of the signal before the digitalization;
- *Fetch size*: specifies how many samples are required at each iteration.

V. Spacecraft Monitoring and Control System

Performing the operations in an efficient way is a mandatory task for a spacecraft M&C system. A spacecraft operator has to handle TMTC data through an intuitive and easy-to-use graphical user interface in order to perform:

- The selection of the desired commands;
- The visualization of the satellite telemetry data;
- The connection to a database for storing the downlinked data and retrieving the various commands and satellite parameters.

Implemented in LabVIEW, the software consists of three views [5]:

- The main display (Fig. 9), that allows the operator to select the commands from the TC list box filtering by equipment/payload and type and enable the time tagged options. It is possible to send the command to the spacecraft directly or it can be queued into the TC stack. From the TC stack, the command can be sequentially sent to the spacecraft or deleted;
- The TM data display (Fig. 10), in which each parameter value is expressed in engineering units and visualised by a specific indicator (numeric display, slides, lights), easily identified by selecting the desired equipment/payload tab. An indicator above the name of each subsystem highlights if there is an error and an automatic warning e-mail informs the engineers about possible issues;
- The TC set display (Fig. 11) are grouped by equipment and payload (one for each tab).

A summary of the functionalities implemented in LabVIEW are reported in Fig. 12 and Fig. 13. The former is related to the uplink chain while, the latter, to the downlink one. In these flowcharts, it is easy to distinguish the tasks performed by each application and device.

VI. Educational Activities

ESEO project is a unique opportunity for students; they can test themselves on something of concrete in order to become well-qualified space-engineers. Following this philosophy, the University of Bologna, in particular the Microsatellite and Space Microsystems Laboratory, is offering a series of internship and final project activities.

During the design and implementation phase of the Ground Segment, students have had the opportunity to develop hands-on experience on hardware and software, according to their skills. Some of the activities performed were the production of waterproof housing for outdoor RF components, the testing of the receiving chain, and its validation through real satellite tracking.

VII. Conclusions

The success of a space mission also depends on an effective ground segment: a combination of components dedicated to the main functions/operations at ground level necessary to establish a reliable communication path for the mission.

In this paper, we gave a perspective over the past and present activities of the Microsatellite and Space Microsystems Laboratory at the University of Bologna towards the design of a ground segment able to support small satellite platforms in LEO.

The implementation of different types of antennas (UHF Yagi antenna, S-band antenna) and related RF-chains hardware, jointly with the adoption of SDR based transceivers, allows this facility to be easily reconfigured for various mission requirements in terms of frequency, data formats and rates, coding scheme and modulation. The S/C M&C application, which has been tailored for ESEO mission, offers several generic functionalities that can be re-used for other missions.

Finally, the choices at software-level as well as the use of SDR-technology are compliant with the ESEO project philosophy to prepare a well-qualified space-engineering workforce for Europe.

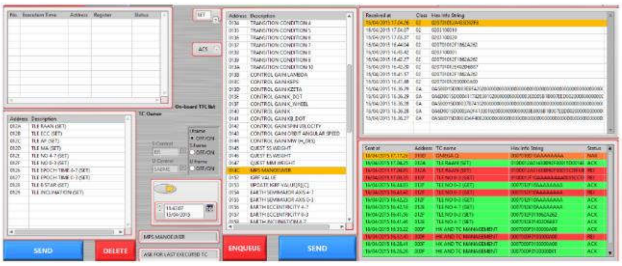

Fig. 9. Spacecraft Monitoring and Control GUI [5]

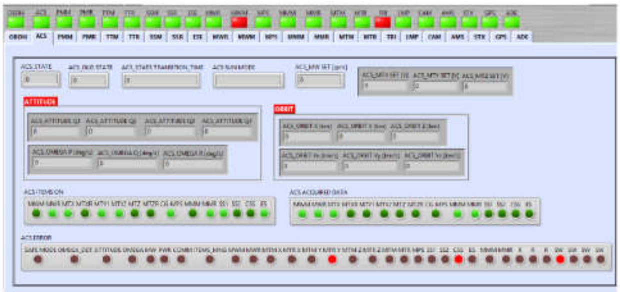

Fig. 10. AOCS Telemetry Display [5]

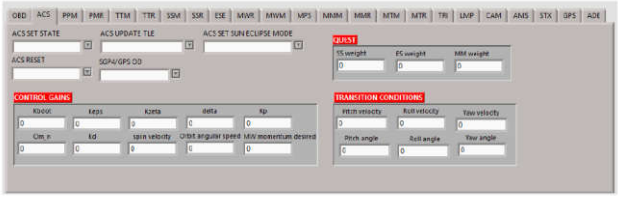

Fig. 11. AOCS Telecommands Display [5]

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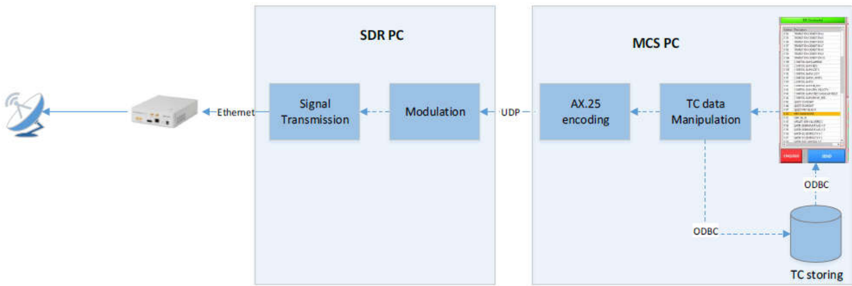

Fig. 12. Uplink Chain Flowchart [5]

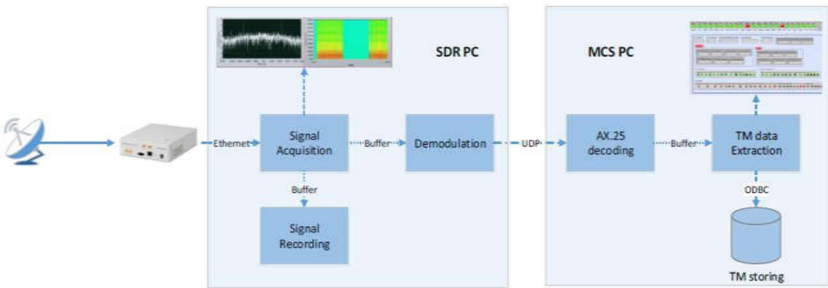

Fig. 13. Downlink Chain Flowchart [5]

The educational programmes with involvement of DLR´S Mobile Rocket Base

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***Abstract*—Mobile Rocket Base (MORABA), a department of German Aerospace Center's Space Operations and Astronaut Training provides the national and international scientific community with opportunities to prepare and implement rocket- and balloon-borne experiments. The fields of research include aeronomy, astronomy, geophysics, material science and hypersonic research. Further, MORABA supports educational programs for scientific experimentation as well as engineering disciplines. This paper presents MORABA's involvement in the educational programs "STudentische Experimental-RaketeN", or STERN shortly, and REXUS / BEXUS. On one side, STERN supports students from aerospace universities across Germany to design, build, test and launch their self-developed rockets. On the other side, the REXUS/BEXUS programme allows European students to carry out scientific and technological experiments on research rockets and balloons. We discuss the different technical views and outputs of the MORABA activities within these programmes. In conclusion, the range of different topics makes the programmes very effective and enhances various skills of the participating students, partners including MORABA.**

Keywords— STERN, REXUS, BEXUS, sounding, balloon

I. INTRODUCTION

It is strategically as well as economically important for Europe to secure its access to space through launch vehicles or scientific payloads of its own. To make sure that Europe will continue playing a crucial part in the development of e.g. new launcher systems and to prevent any loss of development competence, students and young professionals have to be trained and educated [5]. Especially in Europe, we are missing hands on space education [5]. The goal of space related educational programs is to increase awareness to the needs which the space sector faces now and in the future [5]. MORABA is taking a prominent role in the effort to inspire interest in science, technology, engineering and mathematics through its unique mission, workforce, facilities, research, and innovations. The paper gives an overview about MORABA and its actives inside the educational programs with MORABA participating.

II. MOBILE ROCKET BASE (MORABA)

The Mobile Rocket Base (MORABA) was founded in 1966 as part of the Max Planck Society (Arbeitsgruppe für Weltraumforschung) under the initiative of Professor Dr. Reimar Lüst, at that time founding director of the Max Planck Institute for Extra-terrestrial Physics. MORABA was later, in 1967, integrated into DLR and is based in Oberpfaffenhofen, Germany.

MORABA's main task is to support the national and international research community in the preparation and execution of sounding rocket- and balloon-borne experiments. These cover a variety of scientific fields, such as atmospheric physics, astronomy, microgravity and linear acceleration experiments, hypersonic research, technology testing and of course education. By providing and operating mobile infrastructure (TT&C, RADAR and rocket launchers), it is possible to perform complex scientific missions at almost any location that might be required by the experiment. Most frequently, launches are conducted from Esrange Space Center (Sweden), Andøya Space Center (ASC) and Spitzbergen (Norway), Natal and Alcântara (Brazil), but remote locations like Antarctica or Woomera (Australia) have also been used. Minimal infrastructure is required to establish a launch site at other desired locations.

The development of new launch vehicle systems to meet the scientific requirements of the various missions constitutes a key capability of MORABA. Military surplus propulsion units are converted for the use as sounding rockets and commercially available systems are acquired as necessary. The cost-effective combination of these motors to make up the desired launch vehicle as well as development of rocket subsystems like fin, motor adapter are key competences of MORABA. A long standing collaboration with our partners in Brazil (DCTA/IAE) offers a unique ability to directly tailor the design of new rocket motor systems for research purposes in a collaborative approach with the rocket motor manufacturer.

A further objective of MORABA is the development, fabrication and testing of commercially unavailable mechanical and electronical components and systems for sounding rockets and balloons as well as for short duration satellite missions.

MORABA is one of a few institutions worldwide which offers the science community all necessary infrastructure and expertise to perform sounding rocket based missions. The mobile infrastructure of MORABA meets highest international standards and enables even very demanding scientific missions. MORABA is ISO 9001 and OHSAS 18001 certified for "Preparation and Conduct of Sounding Rocket Missions for various Scientific Applications" by TÜV Süd. Primary customers of MORABA's expertise and facilities are universities and research institutions, DLR institutes, as well as national and international organizations and industry. The majority of the projects with MORABA participation are programmatically funded by the German Federal Ministry of Economics and Technology (BMWi), the DLR Space Administration and ESA.

III. SPACE EDUCATION

The aim of the space educational programs are to help young Europeans to gain and maintain an interest in science and technology, with the long-term objectives of contributing towards the creation of a knowledge-based society and ensuring the existence of a qualified workforce that will ensure Europe's continued leadership in space activities [4].

Nowadays, worldwide it exist numerous educational space programs. MORABA participates into two educational hands-on projects:

- REXUS BEXUS program
- STERN program

A. REXUS BEXUS

Each year the German-Swedish program "REXUS BEXUS" (Rocket/Balloon Experiments for University Students) supports up to 20 student teams from across Europe to participate in a hands-on educational program allowing them to fly their research or technology demonstrating experiment on one of two sounding rockets or two stratospheric balloons. An important feature of the program is that the students experience a full project life-cycle which is typically not a part of their university education and which helps to prepare them for further scientific work. They have to plan, organize, and control their project in order to develop and build up an experiment but must also work on the scientific aspects. The program logo is shown in Fig. 1.

Fig. 1: REXUS BEXUS logo

The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA). EuroLaunch, a cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. REXUS and BEXUS are launched from SSC, Esrange Space Center in northern Sweden. The REXUS BEXUS program has been carried out in its current format since over 10 years. In that time, it has developed significantly, building upon strengths to provide a richer experience and increasing the educational, scientific, and promotional outputs [6].

BEXUS experiments are lifted by a balloon with a volume of 12 000 m^3 to an altitude of 25-30 km, depending on total experiment mass. The total mass may be more than 300 kg and the flight train length more than 100 m. A typical BEXUS flight configuration consists of a balloon of the Zodiac 12 SF type which is filled with Helium. Payloads are assembled on a medium-sized gondola (1.16 m x 1.16 m x 0.84 m). The flight duration is 2-5 hours. The BEXUS payload is modularized to provide simple interfaces, good flexibility and independence between experiments. Mobile Rocket Base is partly responsible for the campaign management and operations of the launch vehicles. Furthermore, MORABA provide technical support to the student teams throughout the project.

REXUS experiments are launched on an unguided, aerodynamic-stabilized rocket powered by an Improved Orion motor with solid propellant. It is capable of taking maximum 108 kg of payload to an altitude of between 75 km and 85 km. The REXUS payload is modularized to provide simple interfaces, good flexibility and independence between experiment modules. Up to five experiment modules with a 14 inch diameter and maximum payload length of 6257 mm can be accommodated. The vehicle consists of an Improved Orion motor, a motor adapter, a recovery system, a service system, the experiment modules, a nosecone adapter ring, sometimes a nosecone experiment and either an ejectable or non ejectable ogive nosecone. The REXUS rocket systems are mainly provided by MORABA and shown in Fig. 2.

1. Tailcan and Fins

Three fins on the REXUS rocket provide stability during flight and allow the rocket to maintain its longitudinal axis'

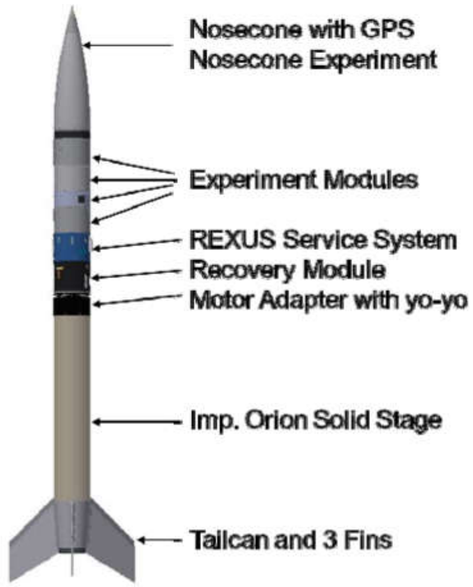

Fig. 2: REXUS rocket

orientation and intended flight path. The fins are mounted at the tailcan which is attached to the motor. Fitting fins on a rocket serves to provide lifting surfaces at the aft end of the motor and thereby position the Centre of Pressure aft of the Centre of Gravity. Moreover, the finset has a setting to spin the rocket at a defined rate as a function of flight velocity. The spin of the rocket reduces its impact dispersion. Also a retractable launch lug is mounted on the tailcan which facilitates attachment of the rocket vehicle to the launcher rail.

2. Motor Adapter incl. yo-yo Despin

The main objective of the motor adapter is unidirectional separation of the payload and the motor. The motor separation can be divided in two events.

a) Opening and jettisoning of the manacle ring

b) Motor separation by plungers

A further objective of the motor adapter is to end the spinning motion about the longitudinal axis prior to separation of the payload. A de-spin system (the yo-yo) is used to de-spin from approximately 3 Hz to a maximum residual spin rate of +/- 0.08 Hz (+/-30°/s). The yoyo consists of two cables with masses at the ends. The cables are wrapped around the motor adapter and the two masses are placed diametrically opposite to each other. When the masses are released, the spin of the rocket flings them away from the spin axis and the cables are unwound. This transfers angular momentum from the rocket to the masses and thus reduces the spin of the rocket to the desired value.

3. Recovery Module

The recovery system is capable of landing payloads with the designated payload mass from approximately 100 km apogee. The system is designed to decelerate from 150 m/s sink velocity to 8 m/s impact velocity. It is a two stage parachute system. The drogue chute has a diameter of 1,36 m and the main chute of 6,90 m. The recovery module is positioned in the back end of the payload and contains a drogue chute, which deploys the main chute. It also contains a heat shield, which protects the parachutes during the high speed part of the re-entry. Barometric switches initiate the pyrotechnic sequence for ejecting the heat shield and releasing the parachutes at a present altitude and subsonic speed.

4. REXUS Service Module

The objectives of the Service Module are to establish the communication between the ground and the experiments, and to control the experiments. Furthermore it records significant flight performance parameters, like position, acceleration, speed, rates and attitude. Additionally, the Service Module has the capability to supply energy to the experiments.

The Service Module consists of two sections. The first one contains the electronic part of the Service Module (E-Box), while the other devices such as RF-parts, GPS, sensors and batteries are mounted on the bulkhead of this module.

5. Nosecone

The REXUS rocket has two different kinds of nosecone – ejectable or non ejectable. The use depends on the request of the experiment. If an experiment team needs to be placed under the nosecone and requires to eject something, an ejectable nosecone is provided. Both nosecone types are 14 inch in diameter, 4:1 ogive nosecones. The nosecone separation process is the similar to the motor separation by manacle ring and plungers. Inside each nosecone is a GPS tip antenna.

The MORABA support within the REXUS program, which is offered to the international student community, includes in cooperation with all partners the following services:

- General management and planning of the REXUS project
- Issue of the REXUS user manual and support for the other guidelines
- Organization of the Training week at DLR Oberpfaffenhofen every second year
- Review of selection proposals and selection workshop participation
- Provision of subsystems necessary for a REXUS rocket mission (see description above).
- Integration of participating experiment modules into the flight configured payload and pre-flight testing of the payload (TM, TC, flight simulation test, dynamic balancing, vibration tests and determination of physical properties).
- Transport of modules and required equipment from the integration facility to Esrange.
- Organization and planning of the launch campaign incl. issuing the flight requirements plan
- Payload assembly and testing at the range.
- Launch and recovery.
- Data acquisition with provisions of real-time, quick-look and replay data from the modules and the payload subsystems (e.g. g-levels).
- Disassembly of payload and return of experiments.
- Post flight report.

B. STERN

The program "STudentische Experimental-RaketeN", designated STERN, allows students from aerospace universities across Germany to design, build, test and launch their self-developed rockets. On behalf of the German Federal Ministry of Economics and Energy (BMWi), the DLR Space Administration conducts the German Space Program. In the frame of the national space program, STERN was initiated and launched in April 2012 [5]. The program logo is shown in Fig. 3.

The goal of the STERN program is to increase awareness to the need of the space transportation sector regarding both the technical sector and the human resources. Thus, the main objectives of the program are threefold, namely [5]:

- Inspire student interest in space transportation subjects through hands-on activities during development of their own sounding rocket,
- Entice universities with financial support to supervise and support student projects,
- Increase course work and lecture activities in fields such as launch systems, propulsion systems or similar which address space transportation issues.

Fig. 3: STERN logo

The focus of the STERN program is the development of the complete vehicle with main focus on the propulsion system within three years. Therefore a payload is not mandatory and not part of the program. According to the program announcement [5], the sounding rocket has to suffice a specific set of requirements, namely:

- Minimum velocity of Mach 1,
- Mandatory recovery system,
- Functioning telemetry system to transmit key parameters including at least – but not limited to – acceleration, velocity, altitude and position of the rocket.

Besides these basic requirements, one key characteristic of STERN is that the university teams have the freedom to design their sounding rockets as they see fit. There is no principal upper limit on the flight altitude or restrictions in the choice of propulsion concept (solid fuel, liquid fuel, hot water or hybrid), although there can be restrictions by the launch range. A commercially available solid propulsion motor can be used as well as own developments such as, for instance, solid, liquid, hybrid or hot water propulsion.

Eight teams were selected by DLR Space Administration to participate in the STERN I program with a project start in April 2012. The first STERN cycle is coming to a close at the middle of 2018. Five student teams launched a total of eight rockets in Kiruna, Sweden, during three separate campaigns. A second funding period (STERN II) started in June 2017 currently planned with three university student teams.

Fig. 4 depicts a summary of the participating STERN I universities, their sounding rockets and some system properties. There are seven single-stage rockets all based on hybrid propulsion systems. TU Dresden developed a liquid, single-stage propulsion system based on an ethanol-LOx mixture. The hybrids used either nitrous oxide or oxygen as oxidizers. Their solid fuels ranged from PE, HTPB to paraffin. TU Berlin developed a two-stage rocket. The first stage is based on hot-water propulsion, while the second stage burned a commercially available solid rocket motor. U Stuttgart built HEROS, the longest rocket measuring about 7.5 m. SHARK by TU Berlin was the shortest rocket just shy of 3 m.

As in any development program, the students have to pass several reviews in which they have to present and defend their rocket design in front of an expert panel. This practically oriented study should prepare the students for possible later work in industry. The DLR Mobile Rocket Base and the DLR Institute of Space Propulsion as well as the DLR Space Administration accompany the students during the reviews and until launch. Hereby the Space Propulsion Institute supports with its research and testing experience of rocket engines and

University	UAS Augsburg	TU Berlin	TU Brunswick	UAS Bremen	U Bremen	TU Dresden	TU Munich	U Stuttgart
Engine	1-stage: Hybrid (PE + N_2O)	2-stage: 1. Hot water, 2. Solid (Al + APCP)	1-stage: Hybrid (HTPB + N_2O)	initial 1-stage: Hot Water 2-stage: Hybrid (PE+N_2O)	1-stage: Liquid (Paraffin + LOx)	1-stage: Liquid (Ethanol + LOx)	1-stage: Hybrid (HTPB + LOx)	1-stage: Hybrid (Paraffin + N_2O)
Thrust (nominal)	1.000 N	2.000 N	1.250 N	2.350 N	1.800 N	500 N	10.000 N	10.000 N
Mass at lift off	23,4 kg	23 kg	24,1 kg	75 kg	80 kg	≤ 25 kg	150 kg	172 kg (3) - 176 kg (1)
Burning time	10 sec	6,9 sec	10 sec	16 sec	30 sec	20 sec	15 sec	25 sec
Max. acceleration	9 g	14 g	3,65 g	2,3 g	5,7 g	2,5 g	6 g	7 g

U = University, TU = Technical University, UAS = University of Applied Science

Fig. 4: STERN rocket family

MORABA with its experience in sounding rocket operations and mission and system design.

Likewise, the reviews as well as special workshops offer a platform for the exchange of technical information. In the project there are two kinds of workshops. The first one called STERNStunden, which is organized every two years, is conducted in Oberpfaffenhofen. This workshop focuses on the rocket vehicle system and all subsystems except the engine. The DLR Institute of Space Propulsion organizes every year the second kind of workshop, which is dedicated to propulsion relevant topics. Beside lectures, the major part consists of exercises, where the students have the opportunity to strengthen their practical capabilities.

The DLR Mobile Rocket Base and the DLR Institute of Space Propulsion are also responsible for the coordination and organization of the program, which means releasing the STERN user manuals and guidelines, creating templates, organization of a teamsite etc. Moreover, DLR MORABA is in charge of the social media outreach program of STERN.

During the launch campaign, the responsibility for each mission resided with the STERN teams. MORABA coordinated and managed the mission activities at the launch site. [2], [3]

IV. Conclusion

The demanding aspect of all space educational programs is that it requires knowledge in a large variety of engineering topics as well as operational processes. This range of different topics makes the REXUS BEXUS as well as the STERN program very appealing and enhances various skills of the participating students and partners. The challenging and extensive tasks of preparing and conducting an experiment or a launch campaign are excellent opportunities to gain hands-on experience for the students. However, the profit from such a project is not limited to the students. Also the space industry or DLR as a non-profit research organization derives benefits.

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Optical Characterisation of the ESEO Optical Payload

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Abstract—**Rarely have educational technology demonstration missions flown with calibrated optical instruments. As an effort to improve the situation, this paper presents the process and lessons learned during the pre-delivery optical characterisation of the dual-camera payload for the European Student Earth Orbiter (ESEO). In terms of optical characterisation, the following measurements were performed on the proto-flight models of the ESEO cameras: focusing, point spread function, sensor linearity, thermal noise and spectral responsivity. The primary goal of the ESEO project is to increase the competitiveness of European space technology through hands-on education. Along with the technical processes, the educational impact in Estonia is also presented.**

Keywords—ESEO; camera; imaging; calibration

I. Introduction

The primary objective of the European Student Earth Orbiter (ESEO) is to measure the radiation levels in LEO. The ESEO technical objectives are to test an experimental S-band communication system, a GPS receiver, an attitude and orbit determination and control software, and a deorbiting payload at about 520 km altitude. Additionally, ESEO hosts an optical payload to take photos of the Earth in the visible spectrum for educational outreach [1]. However, the optical payload could also be used for quantitative measurements, for example monitoring plankton blooms, vegetation, or changes in the polar ice caps.

Cameras on small educational missions often serve educational outreach purposes for which radiometric accuracy is not critical. Small cameras with radiometric calibration have flown for example on the BRITE [2] constellation to monitor stellar variability, on SwissCube [3] to observe the airglow phenomena, and OPAL [4] to map thermospheric temperature variability over the thermospheric gap.

The ESEO optical payload consists of two visible spectrum cameras, shown in figure 1. The primary camera is based on ESTCube-1 experience [5,6,7], and is used as a wide-angle framing camera. The secondary camera is an experimental telescopic camera for imaging with improved ground resolution.

The primary camera has a 4.4 mm telecentric lens, VGA CMOS RGB colour sensor and an IR cut-off filter. With a field of view of 46 x 35°, from a 500 km orbit the ground resolution of the primary camera is around 635 m per Bayer pattern pixel [5].

The secondary camera has a Zeiss C Sonnar T* 1.5/50 lens, a 2592 x 1944 pixel CMOS RGB colour sensor [8] and an IR cut-off filter. For the secondary camera, the field of view of 6.63 x 5° from an altitude of 500 km yields a ground resolution of about 22 m per Bayer pattern pixel. Both cameras have fixed focus at infinity and are equipped with efficient baffles.

The aim of the ESEO project is to involve students from universities all over Europe, and provide hands-on experience in the development of a spacecraft for ESA. As a joint project between Tartu Observatory and University of Tartu, the ESEO optical payload was developed by a small team of students over the course of about 3 years. The cameras have passed unit-level electrical, functional, vibration and shock, thermo-vacuum and EMC testing [9].

In the scope of this paper, the procedures for the optical characterisation of the cameras, as well as the lessons learned in the process are discussed. In section IV, the educational impact of the development of the ESEO optical payload is presented.

II. Optical Characterisation

Before the final assembly and optical characterisation, the cameras were focused to infinity. Once focused, the focusing mechanisms of both cameras were fixed with a small amount of epoxy on the threads. The aim was to ensure that the vibrations and shocks encountered during transportation and launch would not de-focus the cameras. This made further adjustments impossible. Therefore, the configuration of optimal focus was estimated and verified with multiple methods before applying epoxy on the adjustment screws.

Fig. 1. The primary camera (left), and the secondary camera (right) of the ESEO optical payload.

Fig. 2. Test setup for the artificial point light source used for focusing the ESEO secondary camera.

During the optical characterisation of the cameras, the following measurements were performed on the assembled flight models: dark current / thermal noise, linearity and spectral response.

A. Camera focusing

With a hyperfocal distance of less than 2 m, it was possible to focus the primary camera using a test target hung on a wall. A binary line pattern target at a distance of 4 m was imaged while adjusting the distance of the lens from the image sensor until the optimal sharpness of the pattern edges in all three colour channels was obtained. The result was verified by imaging trees through a lab window.

The secondary camera, however, was more difficult to focus in the optics lab due to its hyperfocal distance of around 190 m. At first, coarse focusing was performed, by adjusting the focusing flange while imaging scenery through a lab window. The optimal position of the focusing flange was marked as zero, and taken as the reference point for further tests. In order to obtain comparable measurements during all the tests, a torque-limited screwdriver was used to always fasten all the focusing flange screws with a constant torque of 0.28 Nm.

An artificial point light source was constructed using an LED, a condenser lens, a 50 µm pinhole and an 80 mm aperture ED refractor telescope. The setup is shown in figure 2. The refractor telescope was focused to infinity at each used wavelength, using a small infinity focused refractor as a reference. Blue (470 nm), green (525 nm) and red (625 nm) LEDs with pre-characterised emission spectra were used as a semi-monochromatic light source. A symmetric range of focusing flange positions around the reference point was scanned while taking images of the point light. On each of the image sensor channels (R, G, B), the Full Width at Half Maximum (FWHM) of the response image was measured for the three LEDs. For verification, a symmetric range around the optimal point of focus was scanned while imaging a cell tower at 27 km through a window.

As a result of scanning the focusing flange positions of the secondary camera while imaging the artificial point light, V-curves were obtained for each channel of the image sensor. While the optimum of the blue and green V-curves overlapped, the optimal point of focus for the red channel was further away. As a compromise, a focuser position between the blue and red optimums was selected. The verification images confirmed the optimal point of focus. While the blue and green channels had a similar sharpness, the red channel looked more smeared due to longitudinal chromatic aberration.

B. Point Spread Function (PSF)

To aid in the selection of the lens for the secondary camera, the PSF of all the candidate lenses was measured. The quality of the lenses showed significant variation. Out of three samples, the lens with the least distortions was integrated into the secondary camera PFM. On the selected lens, PSF measurements were performed before and after replacing its iris with an aperture diaphragm. The measurements were conducted by the commercial service provider Difrotec, following their original methodology, using their

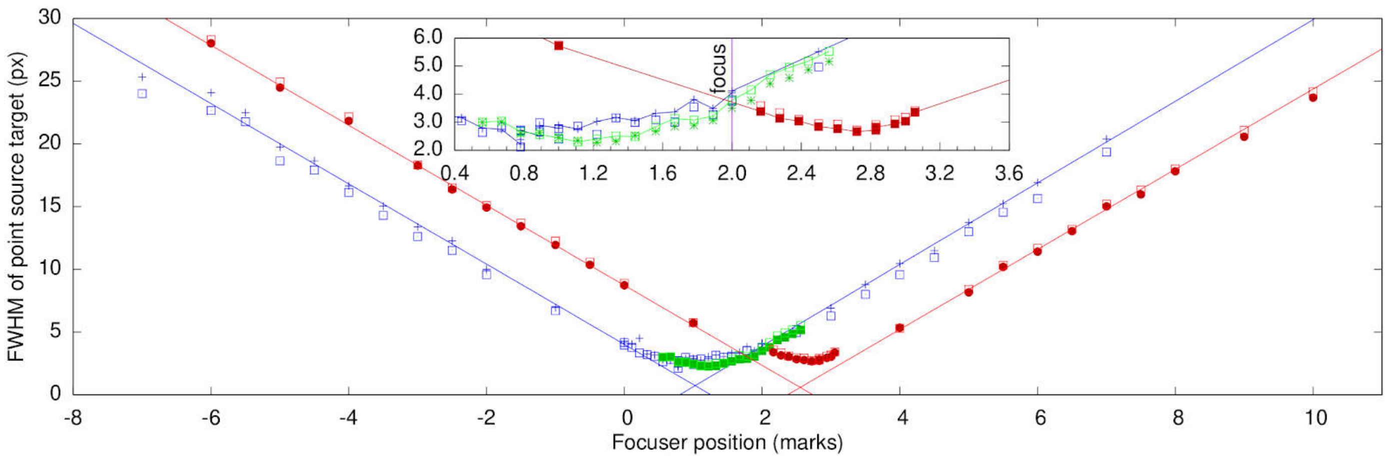

Fig. 3. Results of the ESEO secondary camera focusing test with artificial point light. Blue, red, and green symbols represent measurements carried out using LED light sources with corresponding colours. Filled and open symbols note FWHM along pixel rows and columns, respectively. The inset shows a magnification of the V-curve intersection region with the selected focuser position marked.

interferometer D7 that provides an accuracy of 0.6 nm [10].

C. *Thermal noise*

Both cameras were placed in a climatic chamber, with the optics capped and all of the chamber windows covered. Measurements were performed at temperatures from -20 to +40 *C with a 10 *C step and 1 h dwell time.

In orbit, the cameras would be typically used with the sensor colour channel gains close to 1 and an exposure time ranging from 0.2 to 4 ms. At each temperature, dark frames were acquired at gain settings 1, 2, 4, 8, 12, 15.75 (all channels) and exposures 0.1, 1, 10, 100, 1000 ms. 16 images were taken for each combination. In addition to dark frames the same amount of bias frames was taken with an exposure of 12.5 µs. Although in orbit a gain of 1 would be preferred to minimise thermal noise, other gain values could be used to partially compensate for the degradation of optics and filters.

D. *Linearity*

In order to measure the linearity of the image sensors at different gains, the cameras were mounted in front of an integrating sphere and images were taken with different gain and exposure combinations. Following the test, 10 dark frames were acquired for each gain setting.

The linearity of the primary camera was measured for gains 1, 2, 4, 8 at exposures 83 µs to 12.5 ms. The linearity of the secondary camera was measured for gains 1, 2, 4, 8, 12, 15.75 at exposures 17 µs to 20 ms. Images were not taken at gain and exposure combinations that would have resulted in under- or over-exposure.

E. *Spectral responsivity*

The relative spectral responsivity of both cameras was measured with a monochromator in the range of 350-1000 nm. Following the measurements, dark frames were taken and reference measurements obtained using a calibrated sensor.

III. DISCUSSIONS

A. *Focussing issues*

The design of the primary camera incorporated some enhancements based on the ESTCube-1 experience that made focusing easier: in addition to having marks on the camera body, a collar with a scale was attached to the lens.

On the secondary camera, the image sensor was mounted on sliding contacts and had to be pressed against the focusing flange with four screws. Despite also having a scale on the focusing flange, this made focusing the camera difficult. All four screws had to be tightened with equal torque after every adjustment to obtain repetitive sharpness measurements and in order not to tilt the sensor. The issues could have been avoided with a camera design that enables focusing by moving the lenses instead of the sensor. Additionally, the sliding connectors could be replaced with a flexible cable or rigid-flex PCB.

B. *Component quality*

The measured characteristics of the components used in the cameras showed significant deviation from the manufacturer specifications. For example, we received a low-pass filter with a measured cut-off wavelength of 750 nm instead of the specified 700 nm.

Due to the lack of comparable contrast measurements throughout the camera development as well as due to the inconsistent quality of the COTS lenses, we overestimated the image quality with the aperture wide open. Late in the development, modifications had to be made to add the aperture diaphragm back into the camera design.

We underestimated the chromatic aberration of the secondary camera lenses, especially at red. While the lenses would be acceptable for imaging with a narrow bandwidth, imaging the whole visible range results in a remarkable loss of contrast.

C. *Testing issues*

Most often, test setup consumes more time than performing the measurements. It took several days to align all the components of the artificial point light setup. The abrupt misalignment of the test setup caused another day of delay. By constructing a dedicated imaging target that is focused into infinity, the setup time can be reduced significantly.

Due to simplifications in the electronics design of the cameras, image transfer from the cameras to PC was limited to the speed of USB1.1. The duration of the optical test campaign would have reduced several fold if the cameras had supported USB2.0 interfaces.

IV. EDUCATIONAL IMPACT

The ESEO project is overseen by the ESA Educational Office and SITAEL S.p.A. The ESEO optical payload was developed in cooperation between the University of Tartu and Tartu Observatory [11]. The optical payload team consisted of 3-4 core members: one PhD student, two master students and a volunteer who was not a student at that time. While all of the core members had ESTCube-1 heritage, only one of them had prior experience with optics (development of the ESTCube-1 tether imaging system).

The project management, development and testing was performed by students with access to the Tartu Observatory (TO) facilities under the supervision of experts from the TO astronomy, remote sensing and space technology departments. In total, the participation was as follows: 13 students from 5 universities, two non-student volunteers and 4 supervisors. The project has been a valuable experience on how to publish research results, and has resulted in three conference proceedings with 21 co-authors in total. The fourth conference proceeding is currently being prepared, and a journal paper is planned on the in-orbit results.

Limited resources power innovation. Throughout the development of the cameras, the team often had to improvise in order to quickly react to surprises. The solutions had to be cost-effective and cause little to no delays in the project timeline.

With the participation in the ESEO project, the team of students gained invaluable experience in communication with ESA, as well as in preparing documentation following ECSS standards. This has provided momentum for the next cooperation projects within ESA.

V. Conclusion

The flight model of the dual-camera optical payload for ESEO has passed the acceptance tests and is ready for delivery. Basic optical characterisation of both cameras has been performed, in order to enable quantitative measurements based on the camera images. The ESEO satellite is planned to be launched in 2019.

Based on the design of the ESEO secondary camera, two similar cameras will be integrated on board the 3U CubeSat ESTCube-2 with a planned launch in 2020.

The ESEO cameras were developed and characterised by a small team of students. The educational impact is described in section IV.

Educational programmes similar to ESEO are important for training engineers with little experience and accelerate their future careers in space technology. Although educational programmes are difficult to manage, they facilitate hands-on learning that cannot be substituted with lectures. With the reduction in the development and launch costs of nanosatellites, more universities are able to afford their own educational missions. Therefore, the ESA educational missions could be more ambitious. Especially since it is ambition that inspires students to participate.

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