From BEXUS to HEMERA: The application of lessons learned on the development and manufacturing of stratospheric payloads at S5Lab

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Abstract

In the last years the S5Lab (Sapienza Space Systems and Space Surveillance Laboratory) from Sapienza University of Rome has given to the students the opportunity to gather knowledge on stratospheric payloads by supporting the design and development of two experiments selected for the participation in the REXUS/BEXUS educational Programme, managed by three european space institutions. The insights and lessons learned gathered during the participations in the REXUS/BEXUS educational programme gave the possibility to the student to take part in the development of a third experiment in the frame of the professional research programme HEMERA and complete it successfully. STRATONAV (STRATOspheric NAVigation experiment) was a stratospheric experiment based on Software Defined Radios (SDRs) technology whose aim was the testing of the VOR (VHF Omnidirectional Range) navigation system, evaluating its performance above the standard service volume, which was launched on BEXUS 22 in October 2016. TARDIS (Tracking and Attitude Radio-based Determination In Stratosphere) was developed as a follow up of STRATONAV between 2018 and 2019. Similarly to its predecessor TARDIS was a stratospheric experiment aimed at exploiting the VOR signal, with the aid of SDRs, to perform in-flight attitude and position determination, and was launched on BEXUS 28 in October 2019. After the launch of TARDIS, a team composed both by former STRATONAV and TARDIS students was formed for the development of a third stratospheric experiment going by the name of STRAINS (Stratospheric Tracking Innovative Systems), conceived by Sapienza University of Rome and ALTEC and supported by ASI. STRAINS main objective was the proof of concept of the possibility of achieving the Time Difference of Arrival (TDOA) and the Frequency Difference of Arrival (FDOA) for navigation purposes with the aid of SDRs. The experiment was developed between 2020 and 2021 exploiting the lessons learned from the former team members of the two BEXUS campaigns and was launched on board of the Hemera H2020 stratospheric balloon in September 2021 from Esrange Space Center, Kiruna, Sweden. After a brief description of the stratospheric payloads design and manufacturing, the paper will present the major lessons learned from the previous stratospheric experiments, STRATONAV and TARDIS, and their application to the development and manufacturing of the latest launched stratospheric experiment STRAINS, as well as their educational return to the students involved in the projects.

Keywords

Stratosphere; lessons learned; Students; REXUS/BEXUS; HEMERA

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Acronyms/Abbreviations

ASI	*Italian Space Agency*
CNES	*French Aerospace Studies Center*
DLR	*German Aerospace Center*
ECTS	*European Credit Transfer and Accumulation System*
ESA	*European Space Agency*
GNSS	*Global Navigation Satellite System*
LEO	*Low Earth Orbit*
REXUS/BEXUS	*Rocket- and Balloon-borne Experiments for University Students*
ROMULUS	*Radio-Occultation Monitoring Unit for LEO and Upper Stratosphere*
S5Lab	*Sapienza Space Systems and Space Surveillance Laboratory*
SDR	*Software Defined Radio*
SNSA	*Swedish National Space Agency*
STRAINS	*Stratospheric Tracking Innovative Systems*
STRATONAV	*Stratospheric Navigation Experiment*
TARDIS	*Tracking and Attitude Radio-based Determination In Stratosphere*

1. Introduction

The Sapienza Space Systems and Space Surveillance Laboratory (S5Lab) at Sapienza University of Rome is developing a variety of stratospheric experiments with the research group's participation into international research and student programmes for stratospheric experiment launches [1], [2]. In particular, since 2016, two student experiments (STRATONAV and TARDIS) have been launched through the REXUS/BEXUS Programme, managed by SNSA, DLR and ESA, and one experiment (STRAINS, supported by the Italian Space Agency, ASI) has been launched with the HEMERA H2020 balloon launch infrastructure, coordinated by the French Space Studies Center (CNES). A third BEXUS experiment has been selected in late 2021 for a flight opportunity in the next cycle.

All the experiments share the lessons learned from the experiment design, development and operations and this heritage is generally handed over among the groups of participating students, PhDs and researchers.

The experiments share the mission idea which is always related to navigation and the wide usage of Software Defined Radio (SDR) technology for signal recording, processing and exploitation for navigational purposes.

This paper deals with the lessons learned from the development of stratospheric experiments at S5Lab. After a brief presentation of all the projects carried out for stratospheric and high altitude experimentation, the main lessons learned are in-detail described. The future perspectives and opportunity are finally presented in the conclusions.

2. Stratospheric experiments

S5Lab has developed in the last six years the following projects designed for stratospheric balloons:

- STRATONAV (Stratospheric Navigation Experiment, [3]), selected for cycle 9 of the REXUS/BEXUS Programme and flown in October 2016 from the Esrange Space Center in Kiruna, Sweden. The experiment was aimed at verifying the VHF Omnidirectional Range aeronautical navigation systems above its standard service volume for future high altitude, stratospheric and suborbital navigation;
- TARDIS (Tracking and Attitude Radio-based Determination In Stratosphere [4]), selected for cycle 12 of the same Programme and flown in October 2019 from Esrange. The payload was aimed at continuing the investigation begun by STRATONAV, by exploiting the VOR system to allow positioning and attitude determination (gondola yaw angle) via real-time Digital Signal Processing (DSP) in stratospheric flight;
- STRAINS (Stratospheric Tracking Innovative Systems [5], [6]), selected for the 2020 HEMERA balloon campaign from Esrange Space Center. The flight was then delayed of one year for the COVID-19 outbreak in Europe. The payload has been launched in September 2021 from Esrange. The experiment was aimed at verifying innovative tracking systems (based on multi-lateration or on balloon path prediction through single site angular

and Doppler measurements) for future usage on stratospheric and suborbital aviation;

A new experiment, named ROMULUS (Radio Occultation Monitoring Unit for LEO and Upper Stratosphere) has been selected for cycle 14 of the REXUS/BEXUS Programme, involving the same technologies used for navigational experiments towards Global Navigation Satellite Systems (GNSS) Radio-Occultation monitoring for weather prediction models while in high altitude flight. The experiment will be flying on the next BEXUS balloon campaign between 2022 and 2023.

All the payloads, including the STRAINS experiment for the HEMERA Programme, have been developed and carried out with an extensive involvement of University students. In particular, while STRATONAV and TARDIS were involving only students in the realization of the payloads, as per mission of the REXUS/BEXUS Programme, the mission developed for HEMERA was carried out by a core team of both researchers and students, with many former participants of the previous two BEXUS experiments.

Figure 1: STRATONAV team members involved in the 2016 BEXUS launch campaign, October 2016.

Figure 2: TARDIS team members at the 2019 BEXUS launch campaign, October 2019.

Figure 3: STRAINS team members at the 2021 HEMERA launch campaign, September 2021.

Figure 4: ROMULUS team in Rome, November 2021.

3. Main lessons learned

The main lessons learned are reported hereunder.

3.1. Software Defined Radio-based payloads

All the described experiments are based on SDR technologies for their payloads. SDRs are devices able to perform Radio-Frequency operations, including reception, recording, decoding or modulation and transmission of data through software, allowing a significantly enhanced flexibility on experimental payloads design.

The S5Lab research group involvement into SDR-related activities with STRATONAV marked the first encounter with this technology, which, in the first experiment, was only used to perform radio spectrum recordings to be analyzed at ground after experiment recovery. In the following years, TARDIS has allowed in-flight signal processing of the received signals, while STRAINS has granted the first example of SDR-based transmission in flight for its mission purposes.

The nature itself of the stratospheric missions and the tasks delegated to SDRs are already suggesting a huge evolution in the complexity of the produced codes and functionalities. While recording the spectrum is a basic function that allows to postpone the data analysis and to perform it with high-performance ground-based computers, the implementation of a transmitting chain on-board an in-flight platform needs to carefully address all the issues related to payload safety and frequency stability. The three developed missions have allowed to cope with those and to go forward with the next mission related to data acquisition for GNSS radio-occultation investigation with SDRs.

SDRs are devices that can be extremely difficult to code, develop, test and operate in the actual operational environment, especially when students are involved with leading roles in the development. The main lessons learned from these developments are to start to train the students as early as possible on basic SDR tasks, which can become part of their background before their involvement in the actual mission. In this case, this has led to the opportunity for the S5Lab researchers and students to develop a SDR course which is given at Sapienza with 1 recognized ECTS. Another lesson learned is related to the availability of similar hardware at the lab and with the objective difficulty of parts procurement in these years: differentiating the typologies of SDR to buy throughout the years has allowed, especially during the development of STRAINS, to develop code on similar (same brand or same typology) SDRs before the actual arrival of the flight SDRs in Rome. In the case of STRAINS, this has saved the team from being forced to increment the workload in the last months before flight, since the flight SDRs were tested with already made code at the arrival, instead of coding and testing after the boards arrival. Having spare models of all the SDR typologies available at the laboratory can definitely save time and allow preliminary testing of code and routines on SDR.

3.2. Interface requirements with launch system and testing facilities

The development of three experiments to be launched from the same space base has allowed to gain some sort of confidence with the launch system and its main requirements. Although the three experiments were developed in the framework of two different Programmes (REXUS/BEXUS and HEMERA), the launch system was in the end similar and the general requirements could be considered the same.

In particular, the main difference between the interfaces of STRATONAV and TARDIS (and in the future, of ROMULUS) and the ones related to STRAINS are in the power systems: BEXUS experiments are connected to an external power system through a 28.8V power line with a passthrough power socket, while HEMERA experiments have to generate the power internally and they can at most use Electric Ground Support Equipment for power generation during on-ground testing.

Despite some minor differences in the mechanical interfaces of the experiment box and external appendages, the mechanical and data interfaces were similar in both programmes and allowed to consolidate a baseline design for stratospheric experiments lifting off from the Esrange Space Center. Such experiments are based on an experiment box, whose size is limited by the maximum cross section of the thermal vacuum facility at Sapienza University of Rome, and an external appendage (e.g. a pole) fastened through a stiff system machined in aluminium. The fastening system of STRAINS was the same part used for STRATONAV with some minor fixes to adapt to the new pole design. Frangible appendages have always been chosen for all the systems, allowing not to include the risk of damaging the experiment carrier system (i.e. the gondola). Having this baseline really helped in speeding up the design and development processes especially with STRAINS, which profited from the experience of team members previously involved in the BEXUS experiments and also reused some flown parts when possible. The baseline design that has been set up through these lessons learned is now part of the laboratory heritage and it is often used with the new students (e.g. with the new BEXUS team ROMULUS), while they are allowed to change the design to fit their requirements during the development cycle of the Programme.

3.3. Number of students per team, women inclusion and recruitment practices

The number of students participating in the stratospheric missions of S5Lab changed throughout the years. With STRATONAV, a core team of six members with three support members was considered. With TARDIS, eleven students were involved in the mission, while STRAINS involved approximately 18 people in the whole development process. As visible, the rising complexity of the mission concepts allowed the involvement of more students in the projects. As far as the inclusion and gender equality are concerned, the women share of the team members increased from approximately 15% with STRATONAV to around 30% in the last two projects, namely STRAINS and the new BEXUS team ROMULUS. Although the percentage is still quite low, this reflects the number of women studying aerospace engineering at Sapienza, with an overall good result that can be improved in the next projects.

Although the “correct” number of team members is difficult to evaluate, it must be noted that recruitment of students has passed from objective difficulties in finding new people with the first stratospheric projects to a large number of students requiring participation into the laboratory teams, including stratospheric projects. This was mainly caused by the outreach programme of the first BEXUS mission and of the other projects which allowed to bring new students to the laboratory as interested in participating in similar experiences.

As of now, the recruitment practice is generally based on an internal selection process: students are often divided in teams (two teams for each of the last BEXUS participations) and a challenge is assigned to the students. The winning team gains the chance to participate in the call for proposals and, if needed, to recruit new students from the losing team. The losing team students are allowed to participate in other activities of the laboratory if they want to. This approach has allowed to select the most motivated students for the actual proposal production, to begin team building practices before the actual proposal development and to start verifying the internal hierarchy of each team well ahead the project start. The approach obviously requires a high number of volunteers (roughly two or three times the actual final number of team members) for being operative.

As far as the optimal number of team members is concerned, “usual” BEXUS teams at S5Lab have around 10 participants, which, on the authors’ vision, satisfies the high workload demand for the project yet allowing all the team members to have a decisional role on one or more aspects of the project. Additionally, the actual space in the laboratory dedicated to such activities needs to be taken into account in the process.

4. Conclusions

The Sapienza Space Systems and Space Surveillance Laboratory (S5Lab) has developed since 2015 three stratospheric experiments through the REXUS/BEXUS and HEMERA Programmes. The three experiments have flown from the Esrange Space Center in Kiruna, Sweden in 2016 (STRATONAV), 2019 (TARDIS) and 2021 (STRAINS). A fourth team named ROMULUS has been selected for the new cycle of the REXUS/BEXUS Programme in late 2021 and will fly from Kiruna at the next available opportunity offered by the supporting agencies.

The heritage in stratospheric experiments development at S5Lab has allowed to develop many lessons learned that have helped the later experiment design processes. For example, all these experiments are using SDR technologies as main payload. The complexity of the SDR tasks has increased through the years, passing from recording the spectrum on a receiving-only SDR to establish a communication link through SDRs in downlink from the balloon to remote areas in Sweden. The students’ knowledge on SDR programming has been enhanced by establishing a basic SDR course at the University, which allows to recruit interested students before the projects start.

Launching many times with the same launch infrastructure at the same launch base has allowed to build a certain heritage in the experiment design and a baseline design for all the experiments that share most part of the interfaces. The main difference between the two projects that are involved are related to the electrical interfaces and in the power system, which is external for BEXUS (through a standardized socket) and internal for HEMERA. The remaining interfaces have been generalized and, where possible, part designs have been re-used and adapted for STRAINS from previous experiments.

The recruitment of students has passed from certain difficulties in finding new team members with the first BEXUS experiment, to recruiting two teams that compete through a challenge to give birth to the actual core team of the new proposal. This has been granted through an outreach programme dedicated to the Sapienza aerospace engineering students, that are now in general more aware of such opportunities at the early stages of their academic career. As far as inclusion is concerned, women team members have increased from about 15% with the first experiment to around 30% with the later experiments. Although the percentage does not reflect an actual gender equality, this number equals the share of women students in aerospace engineering at the faculty and is demonstrating an enhanced diversity in the teams.

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