STRATHSAT-R: DEPLOYING INFLATABLE STRUCTURES FROM CUBESATS IN MILLI GRAVITY

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ABSTRACT

The StrathSat-R experiment is a student-led sounding rocket experiment to test novel inflatable structures in space conditions. This experiment is the first step in what will be the first Scottish university satellite program. A multidisciplinary team of over 25 undergraduate and graduate students was formed to design, build and test the experiment between June 2011 and the REXUS13 (Rocket-borne Experiments for University Students) launch in early May 2013. The student team is part of StrathSEDS, a subdivision of UKSEDS (UK Students for the Exploration and Development of Space) and led by a core team of six students. The experiment aims to test novel inflatable space technology in milli-gravity and micro-pressure conditions. It consists of three distinct sections, the ejection housing on the rocket and two ejectable modules that are based on a CubeSat architecture measuring 10x11x13 cm^3. Shortly before reaching apogee, the two satellites are ejected from the rocket and will deploy their individual inflating structure during free flight. After landing, the ejectable modules will be recovered by using a GPS (Global Positioning System) beacon and an RF (Radio Frequency) beacon. The two modules carry two different structures resulting in distinct mission objectives. The aim of FRODO (Foldable Reflective system for Omnialtitude De-Orbiting) is to deploy a large, conical reflective sail from a small volume (4x10x10 cm3). This is the first step in the technology development of a passive de-orbiting system for high altitude spacecraft which will in the future utilise solar radiation pressure, the J2 effect and aerodynamic drag. The objective in the REXUS experiment is to test the inflation space conditions, to validate the shuttlecock attitude dynamics and to assess the structural behaviour of the device during re-entry. The aim of SAM (Self-inflating Adaptive Membrane) is to serve as a technology demonstrator for the residual air deployment method with a bio-inspired cell design approach. The unique architecture of the membrane sub-structure opens the possibility of changing the shape of the membrane to be adapted to various space mission stages or environmental conditions. Proving this concept in micro-gravity conditions will open the door for future space structures serving multiple purposes. On the 9th of May 2013, the StrathSat-R experiment was launched onboard the sounding rocket REXUS 13 but failed to be ejected due to a procedure error.

1 INTRODUCTION

The purpose of StrathSat-R was to deploy two cubesat like structures with inflatable payloads that act as technology demonstrators for two concepts.

The first of these concepts is an SRP (Solar Radiation Pressure) augmented de-orbiting system that has developed through research undertaken by the University of Strathclyde's Advanced Space Concepts Laboratory. This was an ERC (European Research Council) funded project which investigated highly non-Keplerian orbital dynamics and applications. The de-orbiting concept utilises solar radiation pressure and the J2 perturbation to passively increase the eccentricity of an initially circular orbit until the perigee is affected by drag and the spacecraft de-orbits. This technique is particularly effective in MEO (Medium Earth Orbit) but can be applied to even higher altitudes. After the deployment of the reflective sail the de-orbiting manoeuvre takes place completely passively. This research could open up new high altitude orbital regimes for future pico- and nano-satellite missions. A conical (or pyramidal as developed here) structure is needed to exploit the shuttlecock-effect which passively maintains the spacecraft in a sun-pointing position.

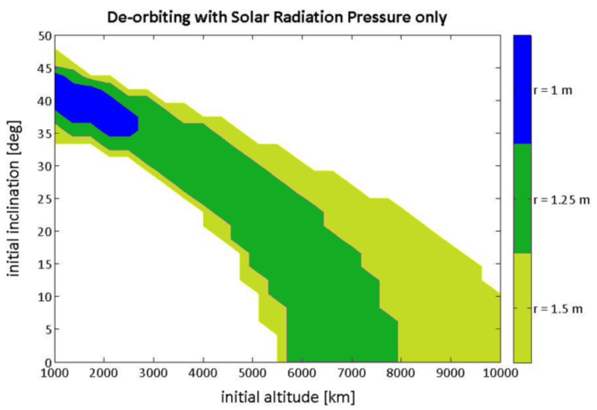

Figure 1: Regions in which a 1U CubeSat (1.3 kg) can be deorbited using solar radiation pressure only from an initially circular orbit using a reflective cone of given maximum cross-sectional radius (r)

The results of this research for orbits in the lower MEO regime [1] are shown in Fig. 1. It can be seen that a 1U CubeSat with a deployable reflective cone of around 1.2m radius can de-orbit from high altitude circular orbits with a range of different semi-major axes and inclinations. One aim of this REXUS experiment was to show that such a device could be manufactured and implemented at a low cost and by students. This will hopefully pave the way for a follow up satellite mission to demonstrate the principle in orbit.

The second concept is an inflatable membrane with the capability to change its shape in orbit. This concept is driven by the constraints that are placed on space vehicle size due to launch vehicles dimensions. These constraints make the use of deployable structures necessary with their low stowage and high in-orbit volume. For the success of future space missions involving large space structures, the development of new deployable structures and the improvement of current designs are of great importance. Applications can be easily envisioned through truss structures, masts, crew quarters, transport tunnels, large solar arrays, solar concentrators, solar sails, balloons or antennas. [2] Various research has been undertaken in the development of ultra-lightweight deployable structures from which it has been crystallised that the use of inflatable structures is a very promising approach for the middle to long-term development of space structures. [3] Over the last 50 years, research has been conducted at various institutions all over the world in the field of inflatable structures; new membrane materials have been discovered that can withstand the space environment, advanced simulation tools were developed that capture the highly non-linear behaviour of the inflation process and rigidisation techniques have been investigated making the structure non-reliant on the inflation gas after deployment.[4]

Developed for this experiment was a cellular element structure, which has an advantage over traditional single element structures as it can exhibit both stiff and flexible properties. This effect is produced by the rigidity of the pillows combined with the flexible seam lines resulting in the ability to hold the structure in a fixed position and to reconfigure the structure. The second goal of this endeavour was to develop a structure that could be used to adapt itself to various environmental or mission conditions. For example, the structure could serve as a substructure for a solar concentrator and adjust its focal point autonomously by changing the curvature of the entire surface. By achieving an adaptable structure the number of possible applications becomes almost limitless. [5]

2 MISSION OUTLINE

The StrathSat-R experiment consists of three distinct sections; two ejectable modules and one data storage with ejector assembly that stays on the rocket and expels the experiments. The first ejectable module (FRODO) deploys an inflatable reflective sail, which represents the first step of development for a CubeSat de-orbiting device which utilises solar radiation pressure. The second ejectable module (SAM) deploys an inflatable membrane which will transfigure in flight, as a step towards a smart structure which adapts its shape to various environmental conditions. These two modules are ejected from the rocket after de-spin near to apogee, which was 83km for REXUS 13. After which the structures should have inflated passively using residual air inflation. The inflation is filmed initially by both the cameras on-board the rocket and those on the modules. During the whole flight images of the structure were to be taken and stored on SD cards in the ejectable modules. Once the modules reached an altitude of around 5 km the timeline was to trigger an event which was the release signal for the parachutes on both modules. This signal shall also activate the tracking system with GPS positions relayed through a modulated signal from a VHF (Very High Frequency) antenna, which would also act as an RF beacon for tracking by the recovery helicopter. At this stage data should be recovered from SD cards on all three sections of the experiment, which shall be post-processed to recover the images.

2.1 Mission Objectives

Ejectable Module 1: Foldable Reflective system for Omnialtitude De-Orbiting (FRODO)

1) Test deployment of the device in milli-gravity and near-vacuum conditions. (primary objective)

2) Test the passive attitude control. (secondary objective)

3) Observe the structural integrity of the device during the re-entry when ambient pressure rises. (secondary objective)

Ejectable Module 2: Self-inflating Adaptive Membrane (SAM):

4) Observe deployment behaviour of the full size membrane from the module in a space environment (primary objective)

5) Alter shape of the membrane autonomously without the influence of perturbing gravitational forces. (secondary objective)

3 DESIGN

3.1 Mechanical

The mechanical design of StrathSat-R is based around the three main subsystems; the SHIRE (Storage Housing In Rocket for Experiment), SAM and FRODO that can be seen in Fig. 2. The SHIRE provides the structural support and necessary elements for retention during launch and jettison of SAM & FRODO in space. The structure is largely machined from Aluminium 6082-T6, with electronic components, PCBs (Printed Circuit Boards), steel machine elements, Perspex covers and Polyimide camera windows forming the rest of the assembly.

The loads experienced during launch are transferred to the experiment module skin via the D-Brackets and hatch reinforcement blocks. Upon ejection of SAM and FRODO, the experiment is exposed to the environment. Therefore Perspex snow covers are incorporated to prevent excessive ingress of debris during the landing phase.

The ejectable modules are segmented into three regions; one housing the subsystem electronics, one housing the deployable experiments and a third housing a parachute required for safe descent and landing. A loosely fitting lid panel is incorporated in order to enclose the deployable payload during launch, but is free to jettison upon ejection of the modules. It is held in place during launch by the compressive action between the hatch assembly and the spring platform.

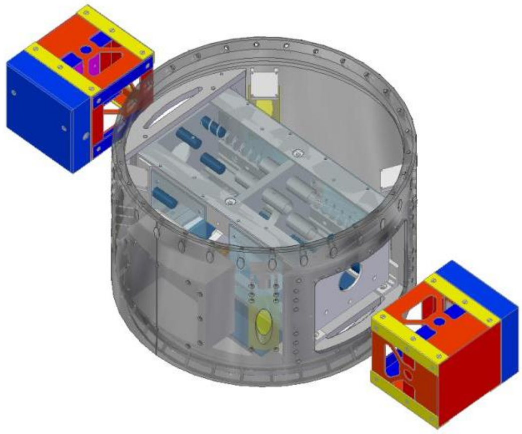

Figure 2: Isometric view of experiment after ejection (hatches not displayed)

Mounting of the electronics within the ejectable modules is achieved by strapping two SAFT batteries securely against the plate that separates the payloads from the electronics enclosure. The PCBs fill the remainder of the space in the electronics enclosure, where they are spaced using anti-vibration spacers.

3.1.1 Retention and Ejection System

As described previously, the SHIRE remains in the rocket module throughout flight and housing both experiments and provides the ejection platform. The team leaned their design on the proven REXUS11 RAIN ejection system to use a module for ejection rather than the nose cone position on the rocket. This design has the advantage that it can deploy the two cubesats simultaneously and symmetrically from the rocket. The retention mechanism employed previously for this type of ejection was to make use of a groove that was cut in the full circumference of the outer skin of the rocket, in this groove a retention cable is ran which holds the hatches in place. Pyro cutters are then used to severe the cable and the devices are ejected. During the design phase, Eurolaunch expressed concerns about the structural effect that cutting the groove in the rocket had. Based on this, the StrathSat-R team, with input from Eurolaunch, developed a new method of retaining and ejecting the cubesats from the rocket.

The route for the cable is shown in Fig. 3 the main change is the removal of the groove. Instead the single cable is entirely within the rocket and is routed through the hatch blocks and secured at both the tensioner and the rocket wall. The cable runs through two pyro cutters, the reason being that if one fails the cubes will still be ejected. The cable has a stopper connected to it within each of the hatch blocks, the purpose of this is to ensure that all of the cable is removed from the rocket upon ejection as it is pulled out with the hatches.

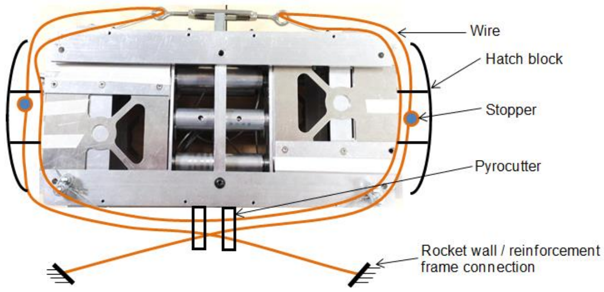

Figure 3: Retention Cable Route Highlighting Tensioner Position and Stoppers

In order to develop this system, constant feedback was required from Eurolaunch at every stage as well as thorough testing. A problem identified through vibration testing was a slip that occurred between the hatch and the hole in the rocket skin. The solution to this was to cut a lip on the inner surface of the skin where it met with the hatch. This resulted in the hatch being inset in relation to the skin of the rocket and so slip could not occur. Fig. 4 shows the slip that occurred prior to the correcting measures were taken.

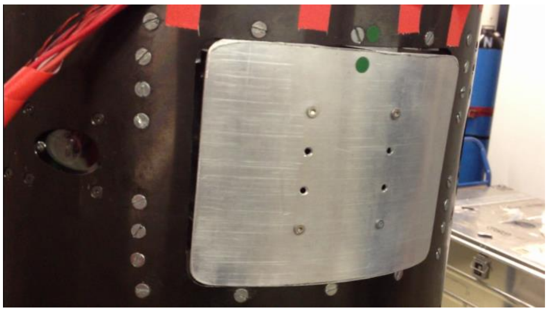

Figure 4: Hatch Slip after Vibration Testing

The retention system uses two TRW pyro cutters as they were to be operated by Eurolaunch from the RXSM (REXUS Service Module) and therefore had to adhere to the interface and component requirements set by them. The force for ejection is provided by eight springs (four for each payload) which are compressed by the retention system and are arranged to provide an even force to the base of each cubesat.

3.2 Payloads

3.2.1 FRODO

FRODO's payload consists of a self-inflating pyramidal structure that deploys from the module using residual air inflation in partial vacuum conditions once the module is ejected from the rocket (Fig. 5).

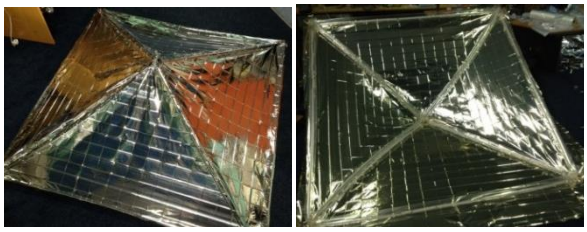

Figure 5: Manufactured FRODO Payload

Residual air inflation occurs when small pockets of air are allowed to grow in volume due to the lack of external pressure.

The inflatable structure is a square-based pyramidal sail of base length 1.772 m and height 0.512 m, see Fig. 5. A pyramid of this side length has a reflective surface area of 3.628 m^2, which is equivalent in performance to a cone of radius 1m, shown in blue in Fig. 1. This is the smallest structure which can de-orbit a 1.3 kg CubeSat effectively at altitudes just below 3000 km.

The pyramid is comprised of eight separate and independent booms along the edges of the structure, and a reflective sail on the triangular faces of the pyramid. The square-based pyramid introduces redundancy in the base booms, where one can be deflated and the structure maintains its general shape. A partial or total deflation by a leak of one of the oblique booms may introduce deformations in the shape of the structure, but it is still an improvement from having all the booms interconnected, which could result in total failure if a leak occurred.

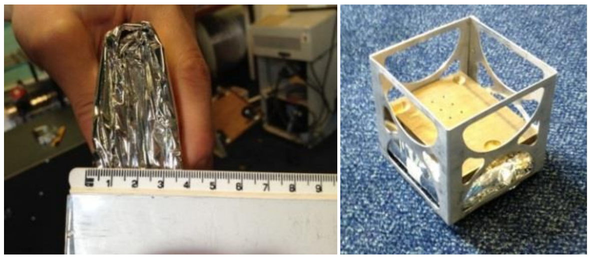

Figure 6: Packaged FRODO Payload

FRODO is a passively deployed structure, with no actuators in its design. The structure is deployed and its shape maintained by the inflated booms. The structure can therefore be packed very efficently, Fig. 6 shows the packed FRODO payload in the CubeSat prototype.

3.2.2 SAM

SAM [6] consists of an array of 18 inflatable circular cells in two rows. The diameter of the spherical elements is chosen to be 14.5 cm to fit the storage box of 10 cm by 10 cm in the central sphere. The spheres are manufactured from 12micron thick, reflectively aluminized, Polyethylene Terephthalate (PET) which is sealed with adhesive on the cell's circumference. Fig. 7 shows a screen shot from an LS-DYNA simulation of the inflated 36 spheres of SAM.

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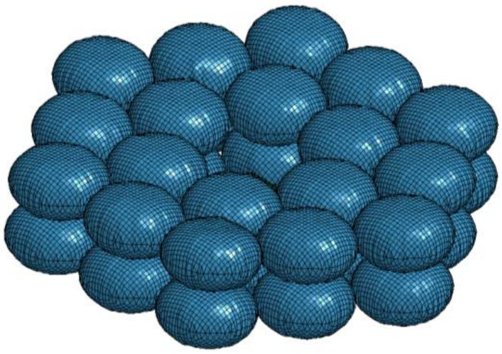

Figure 7: SAM with deployed structure (module to be placed in centre)

The experiment has two main stages, the deployment phase and the adaptive phase. After ejection from the rocket has been achieved, deployment begins as the inflatable structure is exposed to the atmosphere. The deployable structure of SAM is deployed by using the expansion of trapped air in the spheres when subjected to vacuum (space) conditions

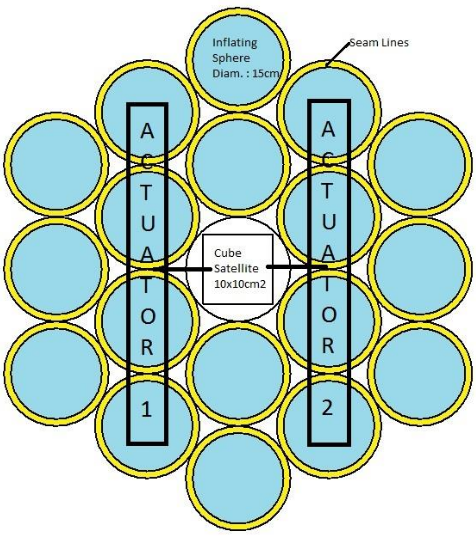

Figure 8: Top view on SAM with actuator placement

In order to make SAM change it's shape, four cells to the left and to the right of the cube are joined to form a larger actuator cell. These cells are connected to a pump in the cube via tubes. In the adaptive phase pump from the bottom array is getting pumped into the top array to deform the structure.

3.3 Electronic

The system architecture is based around three core modules which are replicated for each section in the experiment. The modules within the system are broken into; power, data handling and tracking. Each subsystem is located on its own PCB in keeping with the modular design process as well as providing EMI isolation, a necessity when using high speed digital logic and RF circuitry within the same design.

The power PCBs are identical for each of the ejectables and consist of a battery charging circuit and connectors to SHIRE and other PCBs within the module, each cable is twisted to ensure further reduction in EMI. The SHIRE module's power board consists of power filtering to meet EMC conductivity requirements and high quality switching regulators to regulate the sounding rocket's 28 V supply to appropriate power rails. The tracking PCB is identical in both the ejectable units and consists of local power conditioning, GPS, Globalstar and RF beacon circuitry. Tracking is not needed in the main unit, SHIRE, as that will remain part of the recovered rocket. The data handling PCB contains a microcontroller, FPGA and I/O support circuitry. The data handling PCB is adaptable to the variety of sensors that had originally been specified for the design but were later dropped due to reduction in scope to ensure the success of the design. During manufacture only those components needed for each module will be populated which lowers PCB design and manufacture cost.

3.4 Embedded Software

The software was developed using the MBed NXP LPC 1768 Microcontroller Unit (MCU). It utilises an ARM Cortex M3 and is a robust and flexible development unit for use in each module.

The entire development board is included on the surface of the flight computer PCB using headers. This approach was chosen to allow a modular approach to be taken to developing embedded software for subsystems, to allow flexibility, and lower design complexity.

There are not enough inputs and outputs provided on the development platform to support the intended applications alone, therefore an 8-channel I^2C multiplexer, and a 16-bit SPI multiplexer has been used. The I^2C multiplexer allows a single I^2C interface to communicate with 8 different I^2C devices. The SPI multiplexer serves to increase the number of digital I/O pins.

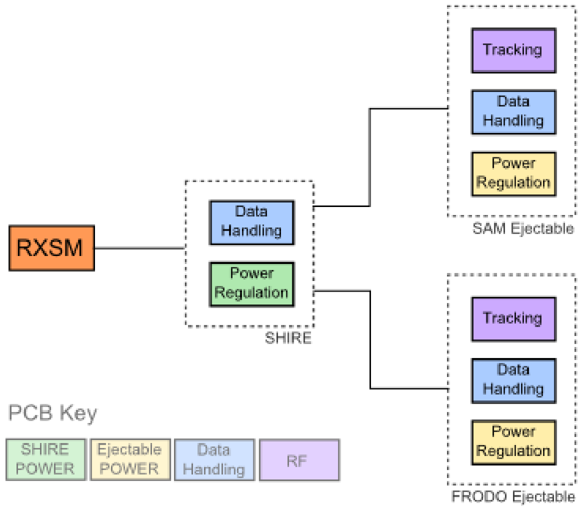

Figure 9: Electronic System Architecture

A basic block diagram of the electronics is shown in Fig. 9, this details the link between the three systems built by StrathSat-R and the interface to the RXSM. This diagram displays the modular nature of the design as it can be noted that the ejectables are identical and the data handling is replicated across all three systems.

3.5 Data Handling

The original design for StrathSat-R envisaged a system that would utilise two cameras per module and four on SHIRE. As the project developed the implementation of the cameras selected fell behind and with further pressure on ensuring a minimum level of functionality to ensure launch, the decision was taken to remove the cameras being developed and replace them with a COTS version. The selected replacement was the HackHD as it features a wide angle lens, includes all software and hardware on a single board, wrote to a micro SD card onboard and required a simple push button to activate. Also of benefit is an output line is used to activate an LED, this line was used to confirm the status of the camera as it had two modes, recording and stand by. In order to ensure successful storage of the footage to the SD card it is required that the camera is switched off and the command line and given time to save the data. If this is not allowed to happen then the data can be lost or prove difficult to recover. For this reason the cameras are switched off before impact to ground on both the SHIRE and on the two modules. The cameras on SHIRE are also cycled during descent to ensure at least the critical section of footage, the modules ejection, has been saved.

3.6 Experiment Timeline

The flight computer has to interface with the service module, of the sounding rocket, which will provide signals to notify the experiment of lift-off (LO) and start of experiment (SOE). At T-600s before launch the experiment was powered on and entered its timeline mode. The SOE signal was sent at T-115s and was used to synchronise all timelines. At T-20s prior to the LO signal the SHIRE cameras were activated. This was to take footage of the ascent of the rocket as well as the ejection of SAM and FRODO. If no LO was given after this then after 40s the system would enter a standby mode that turned the cameras off and awaited LO, this was to save memory on the SD cards. When LO is given the timeline has entered its full flight mode.Once the experiments are ejected, at T+140s, they will use their own internal timelines, with SAM aiming to perform shape changing manoeuvres for approximately one minute before switching the cameras off while FRODO's cameras are left on till after the parachute's deployment. At T+965s the microcontroller will trigger the pyro cutter to release the parachute and also switch from the data board to the RF board. The GPS data will also be modulated to a carry and transmitted via the VHF antenna that will be exposed once the parachute is unfurled.

3.7 Tracking & Recovery

The tracking and recovery stage of the mission is triggered by the timeline, which activates a pyrocutter. This severs a tensile retention wire, releasing the parachute enclosure lid. A spring and spring loaded RF beacon will then assist in removing the lid, allowing the parachute, which is fastened to the four corner screws, to unfurl. As simple method has been employed to actuate the RF beacon, this is to attach a bi-stable material (in this case a small section of measuring tape) to the beacon. When the retaining force provided by the lid is removed the beacon will experience a restoring moment due to the tape measure and then rotate into a vertical position in order to achieve an optimal gain pattern. After the parachute is deployed, the GPS receiver and RF beacon activate and continue to relay GPS coordinates to the team continuously until recovery. Fig. 10 shows the layout of the devices that have been described here.

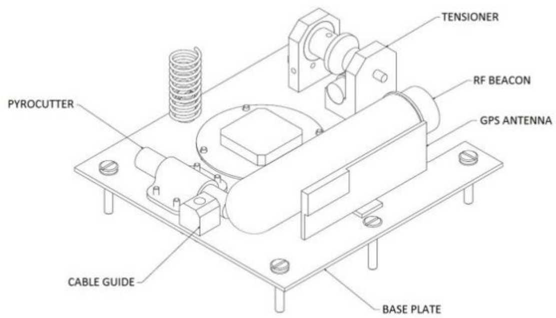

Figure 10: Drawing of the devices stored inside the parachute enclosure

4 LAUNCH CAMPAIGN

The REXUS13/14 launch campaign took place at Esrange from the 30th of April until 10th of May 2013. The first days were spent on experiment integration and systems tests. During the final integration of the experiment at the launch campaign several issues arose. The first was an unexpected issue with the pyrocutters used in the parachute deployment, due to a high amplitude transient at power on, the pyrocutter blew and had to be replaced. To correct this, capacitors were used on the line to smooth the transient and reduce the amplitude to a safe level, after testing this correction proved successful.

Electrical transients in the circuitry affected the microcontrollers and resulted in damage occurring to two of the three that were in the system, replacements were implemented and further protection built in to ensure new damage would not occur.

With these corrections in place the experiment was passed for launch and successfully completed all communication checks and timeline runs.

StrathSat-R was launched on REXUS 13 on the 9th of May and all systems worked nominally during countdown and flight. Continuous data was received on the ground station indicating a fully functional experiment at all times. However, due to a procedure error by Eurolaunch, the two cube satellites were not ejected from the rocket at apogee. The REXUS13 payload was recovered by helicopter with both cubes still tensioned inside the rocket.

5 RESULTS AND LESSONS LEARNED

Although the modules were not deployed, multiple lessons were learned from the launch campaign. The rocket launch showed that some systems can be improved to ensure more scientific return. The first improvement will be made to the deployable of FRODO. Due to an oversized deployable, the hatch did not fit perfectly which resulted in surface melting of the FRODO deployable due to entering hot gases during launch. To solve this issue a smaller deployable and a Kapton cover is suggested. This cover will be also used for the deployable of SAM. Furthermore it is suggested to implement a working Globalstar system to increase redundancy and therefore the chance of locating the ejectables after landing. The problems with the MBed microcontrollers during the launch campaign indicated that a more reliable microcontroller should be chosen. The MBed promised simple and reliable implementation but should not be used as a flight controller due to its development for prototyping applications.

Other lessons learned [7] include:

- Take as many spare components as the budget will allow. This includes all critical components and basic components.
- Ensure selection of team members on launch campaign are appropriate, they must have extensive knowledge of the entire system and be capable of taking and implementing advanced design decisions. Especially team members with knowledge in electronics and software.
- Ensure that all procedure documents are completely up to date with the design and that all members are familiar with the procedure.
- Test system completely including critical components.
- Confirm all procedures and requirements that relate to your system, even if another is in charge of them. If your system relies on something then you must confirm it. If anything is questionable, speak up.

6 CONCLUSIONS

This paper outlined the idea behind the two deployable inflatables and their implantation for a sounding rocket experiment. The design of StrathSat-R consists of a rocket module and two ejectable cubesat-like modules that contained deployable structures. Over almost two years a team of 25 students designed, build and tested the experiment to ensure full functionality in space conditions which was proved by the REXUS13 launch in May 2013. All systems worked during the whole flight but due to a procedure error, the two cubes were not ejected at apogee preventing the functional experiment to fulfil the mission objectives. The lessons learned from this campaign have also been identified and will result in a more successful iteration of StrathSat-R in the future. Currently, the team, REXUS/BEXUS and MORABA are looking into the possibility of re-launching StrathSat-R on another sounding rocket in the near furture.

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