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LESSONS LEARNED FROM THREE UNIVERSITY EXPERIMENTS ONBOARD THE REXUS/BEXUS SOUNDING ROCKETS AND STRATOSPHERIC BALLOONS

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Over the last three years the authors have been involved in three experiments that were or will be launched on sounding rockets and high altitude balloons with the REXUS/BEXUS program (Rocket-borne / Balloon-borne Experiments for University Students). The first experiment, called Suaineadh was launched from Esrange (Kiruna, Sweden) onboard REXUS 12 in March 2012. Suaineadh had the purpose of deploying a web in space by using centrifugal forces. The payload was lost during re-entry but was recovered 18 month later in early September 2013. StrathSat-R is the second experiment, which had the purpose of deploying two cube satellites with inflatable structures from the REXUS 13 sounding rocket, was launched first in May 2013 and will be launched a second time in spring 2014. The last experiment is the iSEDE experiment which has the goal of deploying an inflatable structure with disaggregated electronics from the high altitude balloon BEXUS15/16 in October 2013. All these experiments have been designed, built and flown in a timeframe of one and a half to two years. This paper will present the lessons learned in project management, outreach, experiment design, fabrication and manufacturing, software design and implementation, testing and validation as well as launch, flight and post-flight. Furthermore, the lessons learned during the recovery mission of Suaineadh will be discussed as well. All these experiments were designed, built and tested by a large group of university students of various disciplines and different nationalities. StrathSat-R and iSEDE were built completely at Strathclyde but the Suaineadh experiment was a joint project between Glasgow and Stockholm which was especially tricky during integration while approaching the experiment delivery deadline. This paper should help students and professionals across various disciplines to build and organise these kinds of projects more efficiently without making the same, sometimes expensive, mistakes all over again.

I. ACRONYMS

ASCL	Advanced Space Concepts Laboratory
BEXUS	Balloon-borne Experiments for University Students[§§]
CDR	Critical Design Review
COTS	Commercially Of The Shelf
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)[***†††‡‡‡]
EAR	Experiment Acceptance Review
EEE	Electronic & Electrical Engineering Department[§§§****††††‡‡‡‡§§§§]
ESA	European Space Agency

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ESD	Electrostatic Discharge
FRODO	Foldable Reflective system for Omnialtitude De-Orbiting
GPS	Global Positioning System
IMU	Inertial Measurement Units
IPR	Interim Progress Review
iSEDE	Inflatable Satellite Encompassing Disaggregated Electronics
KTH	KTH Royal Institute of Technology
MAE	Mechanical and Aerospace Engineering Department
MORABA	Mobile Rocket Base (DLR)
REXUS	Rocket-borne Experiments for University Students
PCB	Printed Circuit Board
PDR	Preliminary Design Review
SAM	Self-inflating Adaptive Membrane
SED	Student Experiment Documentation
SNSB	Swedish National Space Board
SSC	Swedish Space Corporation
LO	Lift off
SOE	Start of Experiment
SODS	Start of Data Submission

II. INTRODUCTION

Space research, especially at a university is almost always theoretical because of the high costs of building and flying an actual experiment into space. Another constraining factor is time. A PhD student has in average three to four years to undertake research, too short for a 'real' space mission. REXUS/BEXUS, which stands for Rocket-borne/Balloon-borne Experiments for University Students, is a great opportunity for students from all over Europe to design, build, test and fly their own experiment. The REXUS/BEXUS program is organised and sponsored by the German Aerospace Center (DLR), the Swedish National Space Board (SNSB) and the European Space Agency (ESA) [1, 2]. Every year between 10-20 student teams are selected to fly their experiments on a sounding rocket or a stratospheric balloon. Proposals of the university teams are submitted in October outlining the basic idea of the experiment. If the proposal gets shortlisted, the team is invited to a Selection Workshop to ESTEC for the European teams and DLR Bonn for the German teams. Each shortlisted team will present their experiment to a panel of experts of ESA, DLR, SNSB and SCC. The selected teams are notified shortly after the Selection Workshop in late December and are requested to start working on the Student Experiment Documentation (SED) which is the main document for the interaction between the student teams and everyone involved in REXUS/BEXUS. The SED includes the project management, experiment description with interface definition, test plan, preparations for the launch campaign and results. The selected teams are invited to either DLR Oberpfaffenhofen (Germany) or Esrange Space Center (Sweden) for the Training Week with Preliminary Design Review (PDR) in February each year. During the Training Week the teams are provided with a variety of lectures and workshops covering all the aspects of the sounding rocket or stratospheric balloon mission. At PDR, the teams will present their detailed experiment to a panel of experts. After the Training Week, the BEXUS and REXUS program separates in order to have a BEXUS launch campaign in October the same year and a REXUS campaign in spring the following year. The Critical Design Review (CDR) is held at ESA's ESTEC for BEXUS in May/June and at DLR Oberpfaffenhofen for REXUS in June/July where the teams present their progress to a panel of experts. In the following months the teams manufacture and test their experiment until experiment delivery in September for BEXUS and November for REXUS. In between, the Interim Progress Review (IPR, BEXUS: July, REXUS: September) and Experiment Acceptance Review (EAR, BEXUS: September, REXUS: November) are held at the team's home university where two REXUS/BEXUS experts investigate the progress of the experiment. After the experiment delivery for BEXUS, the team travels to Esrange space centre for a nominally 10 day launch campaign. For REXUS, the teams are coming together twice before launch campaign in spring for Integration Week and Bench Test (both at DLR). At Integration Week (December/January), the whole experiment is tested with the service module simulator and the other experiments of the rocket. During Bench Test (January/February) all experiments are joined together and tested with the rocket's service and recovery module. Before the two week launch campaign, the full payload will perform a spin and balance test. At launch campaign, the experiment team normally has two to three days to assemble their experiment and test it thoroughly with the service module and the other experiments. Depending on the weather, the balloon/rocket can be launched as early as Day 6 of the campaign. After launch the payload will be recovered by helicopter (REXUS) or helicopter and lorry (BEXUS). Two months after launch campaign, experiment teams are requested to submit the final version of the SED which contains all up to date information and results.

II. THE EXPERIMENTS

II.I Suaineadh (REXUS 12)

On the 19th of March 2012, the Suaineadh experiment [3] was launched onboard the sounding rocket REXUS 12 from the Swedish launch base ESRANGE in Kiruna. The Suaineadh experiment served as a technology demonstrator for a novel space web deployed by a spinning assembly. Following the launch, the experiment was ejected from the nosecone of the rocket (see Figure 1)

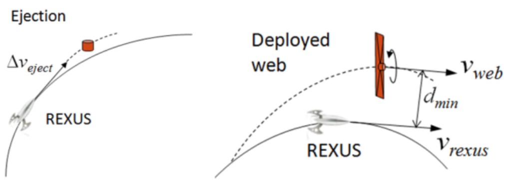

Figure 1: Conceptual deployment of web from nose-cone ejection

Centrifugal forces acting upon the space web spinning assembly were used to stabilise the experiment's platform (see Figure 2). A specifically designed spinning reaction wheel, with an active control method, was used. Once the experiment's motion was controlled, a 2 m by 2 m space web was released. Four daughter sections situated in the corners of the square web served as masses to stabilise the web by controlling the centrifugal forces acting upon them. The four daughter sections contained inertial measurement units (IMUs). After the launch of REXUS 12, the recovery helicopter was unfortunately unable to locate the ejected experiment, but 22 pictures in total were received over the wireless connection between the experiment and the rocket. The last received picture was taken at the commencement of web deployment. Inspection of these pictures allowed the assumption that a number of functions were operational after ejection, but that through tumbling of either the experiment or more likely the rocket, the wireless connection was interrupted. A recovery mission in the middle of August 2012 was only able to find the REXUS 12 motor and the main payload impact location. In early September 2013, the ejectable section was found and data recovery of the onboard data storage will commence shortly.

Figure 2: Deployed web on ground before launch

II.II StrathSat-R (REXUS 13)

StrathSat-R [4] was launched onboard REXUS 13 sounding rocket in May 2013 (see Figure 3). However, due to a procedure error of the launch provider, the two cube satellites were not ejected from the rocket. The launch provider offered the team a re-launch opportunity onboard the next REXUS mission in spring 2014.

The experiment consists of two distinct sections that are based on CubeSat architecture. The primary objective of both satellites is to deploy a structure in micro-gravity by using inflation. After inflation, the two ejectable modules (see Figure 4) have different specific objectives:

Figure 3: StrathSat-R during ground testing

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

The aim of FRODO [5] is to deploy a large, stable reflective sail from an approximately 1U CubeSat-sized pod. This is one 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 in microgravity and near vacuum conditions, to validate the passive attitude control model and to assess the behaviour of the device during re-entry.

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

The scientific objective of SAM [6] is to serve as a technology demonstrator for the residual air deployment method with a novel spherical cell element 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.

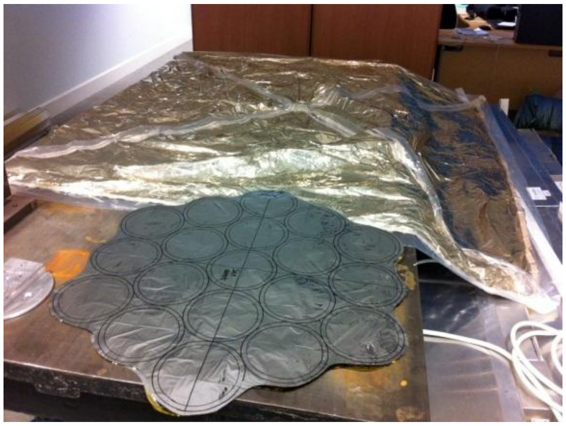

Figure 4: The two inflatable payloads, FRODO in the back and SAM in the front

II.III iSEDE (BEXUS 16)

The iSEDE experiment [7] will be launched onboard a stratospheric balloon in October 2013. The experiment has the purpose to disaggregate the electronics of a conventional satellite over the surface of an inflatable structure in order to reduce the mass. The idea is to use cellular structures as support for all the subsystems composing a typical nano-satellite. Each subsystem and component is mounted on a different cell. Cells are both individually inflated and individually controlled. The aim is to design and build a prototype for this new type of satellite, demonstrating the deployment and wireless communication among components. Furthermore, the inflatable satellites will have the ability to change their shape with embedded micro-pumps and soft robotic actuators.

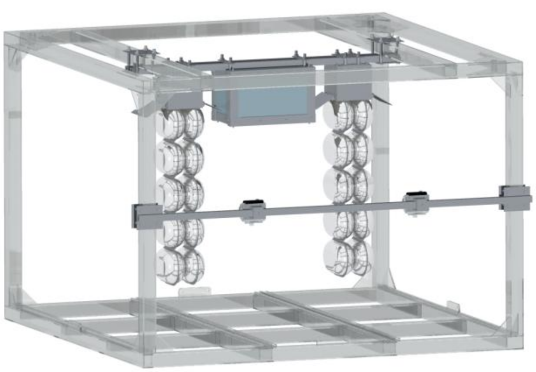

Figure 5: CAD model of iSEDE experiment inside BEXUS gondola

The idea is to have two inflatable satellites on board the BEXUS gondola and a central controller, the hub (see Figure 5). One satellite should be deployed before launch and the other deployed when the balloon reaches float altitude. When both satellites are deployed, there will be communication between the satellites and the hub. The hub will communicate with the ground station through the BEXUS E-Link. The ground station will be able to receive reports and give commands. The displacement is monitored by two Hack-HD cameras and four accelerometers on the satellite and the gondola.

III. LESSONS LEARNED

The following subchapters should give an overview on the main lessons learned of the three projects. These lessons learned should help future teams to design, build and fly their experiments.

III.I Experiment Design & Requirements

- A simple experiment that can fulfil the objectives is the best experiment.
- Learn from designs of former experiments, if available use systems that have been tested and proven in a relevant environment.
- It is important to establish and document a comprehensive list of requirements during the initiation of the project, and that these should be continuously updated where necessary
- Requirements should always be achievable within the scope of the project. If they are not, then this can lead to unnecessary diversions of resources which in turn may compromise progress.
- Proper requirements management and tracing:
    - Number requirements in multiples of 10, e.g.: 0010 0020 0030 0040 0100 0110 0200… to be able to fill in related requirements or modified requirements with intermediate numbers (011 or 012)
    - Jump to the next hundreds between clearly different types of requirements, e.g.: 0010 to 0040 requirements on system 1, 0100 to 0170 on subsystem 1.1, 0200 to 0250 on subsystem 1.2, 1000 to 1130 for software and so on. It makes it easy to read and follow, even if numbers look larger
- Keep deleted requirements, indicate just: “deleted because it was no longer needed”, or “redundant”
- Use some tool for generating the traceability matrix between requirements and tests (if no tool is available, it is easy to build an excel tool, please contact the authors for the excel traceability matrix used in StrathSat-R).
- Ensure interfaces with the rocket are rigidly defined early. As an example it was not clear how the hatches of StrathSat-R should be designed and how the ejection method should operate. Go through requirements and user manual before starting major design work and let REXUS approve the design early.
- If using a wireless communication between ejectable experimental hardware and the REXUS

rocket, then full spherical fields of view are essential so that communication is not lost during tumbling motion of either body. The REXUS rockets have since been shown to begin tumbling prior to experiment ejection, and this is the likely cause of data transmission loss between the ejectable and the rocket in the Suaineadh experiment.

- Recovery measures should be applied to any ejectable experiments where data recovery is required. This should include a parachute system and tracking facilities so that the recovery crew can locate the experiment quickly (see Figure 6)

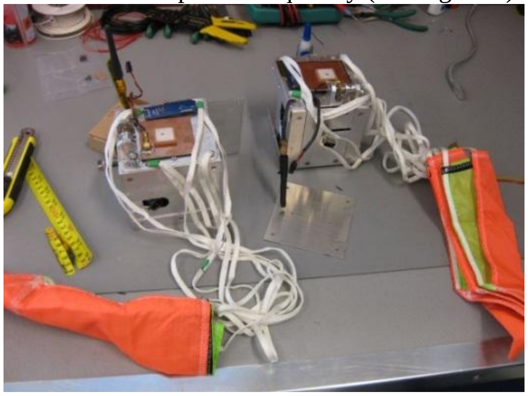

Figure 6: StrathSat-R's two cube satellites with parachute and GPS, Globalstar and radio beacon antennas

- Proposed projects must be feasible within the campaign duration provided by REXUS. Proper scheduling, including key milestones, should be used to track progress so that any deviations are highlighted as early as possible. It should be the responsibility of participating universities to observe this and to supply additional resources if necessary.

III.II Mechanical (Design & Fabrication)

- Designs for fabrication should be considered from an early stage, designs in CAD could be very expensive or even impossible to manufacture.
- Any necessary changes to design features must be identified and logged with all team members as early as possible, with actions only taken once the required modifications have been discussed and agreed with those team members that will be affected. Ultimately, severe changes must be approved by the project manager.
- An accurate list of materials should be kept and used to estimate the mass of components, sub-systems and the complete system.
- Where possible, a particular screw standard should be adopted and documented. A useful approach is to compile a list of screws, and indeed all fastener types, with their location in the experiment and number required noted. This method makes it simpler to track supplies and to ensure all necessary tools are available at all times.
- Where possible, established standards should be adopted, such as PC-104 architectures (see Figure 7), which will allow for multiple components to be stacked and subsequently mounted together. The advantage of this is that should access to these components be required, then the entire assembly may be removed together more easily.

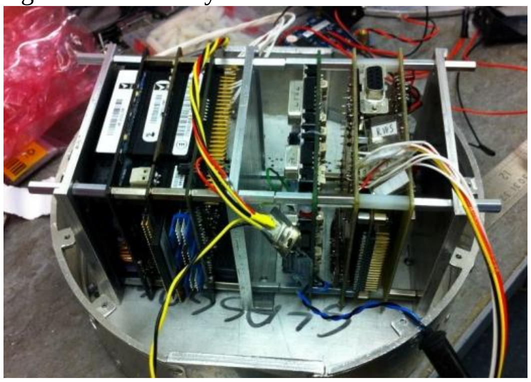

Figure 7: Suaineadh's main electronic staged based on PC-104 standards

- Use a simple, clear and flexible approach to configuration control (document, component and CAD model numbering for example). It makes life much easier later on if this is done from the start and it is suggested that REXUS define this so that all teams follow the same outline, which would make it easier for them to check documents and models.
- Manufacturing standards should be considered and applied at all points during the design process. Careful consideration must be given to this when designing with CAD software and that manufacturing tolerances are given in all technical drawings given to manufacturers.
- In a scenario where mass and volume are paramount, effort should be given to verifying the mechanical design to ensure that over-engineering is minimized. FEA (Finite Element Analysis) is a useful resource in this respect, but at least manual calculations of simplified structures should be made.
- When designing systems with extremely limited volumetric envelopes with no scope for increase, it is important to realise from the beginning of the project that the mechanical and electronic system will intrinsically influence the design of each other. This means that every effort should

be made to freeze the conceptual design of these components as early as possible, so that the impact of any future modifications is minimised as far as possible.

- If an ejectable mechanism is required, pyro cutters might be the simplest way of actuation but keep in mind that each pyro cutter can only be fired once and might be expensive to replace. Linear actuators or shape memory alloy actuators offer the advantage of repeatability which can be confirmed by continuous testing.
- Prototyping can be a useful resource for verification. Rapid prototyping is recommended for form and fit testing, whereas simplified engineering models can be used to verify mechanically loaded features.
- Where possible, design should attempt to include COTS components to reduce lead times in manufacturing. It can also be prudent to simplify designs such that the students themselves can fabricate many of the parts. This will reduce mechanical workshop costs and lead-times.
- Account for significant manufacturing delays of the university workshop and make sure to order parts from workshops outside university before summer to be able to have the parts in the early autumn. University workshop lead-times can often fluctuate throughout the academic year, and every effort should be given to track this and account for it during project scheduling.
- If possible, it is recommended that particular technicians be assigned to the project so that liaising becomes more transparent.
- Remember that constant assembly/reassembly of the experiment can lead to wear which could reduce performance.

III.III Electrical

- Instruct the mechanical team early on to include connectors/PCBs into the CAD, and to make sure that the modules are easy for members to assemble. It is easy for the separate teams to be thinking of other things at the early stages, but if you want the electronics to just slide in with minimal hassle, it requires thinking ahead..
- Design the prototype with as much functionality as possible, even things that might not be needed later on (it is easier to remove components than to add).
- Use components that are easily available almost everywhere.
- While waiting for PCB orders, test components on breadboards or similar (if possible), read their data sheets thoroughly.
- Design and order/create prototype hardware (PCBs and components) early.
- Specify rough PCB dimensions and numbers early in the project to take them into account for the structural design by the mechanical team. Figure 8 shows unforeseen complexity due to late electronic design.

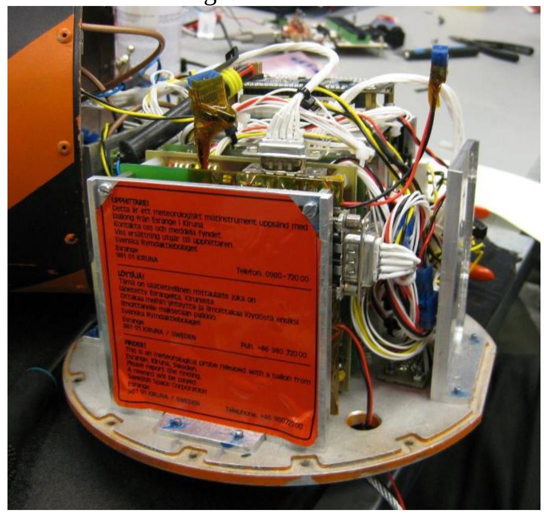

Figure 8: Large amount of required cabling of Suaineadh electronics

- Use of PCB design software with 3D model support can be extremely useful for mechanical and electrical integration.
- Order professional PCB's for custom boards for final version.
- Proper ESD protection should be used on inputs, i.e. clamping diodes.
- Series current limiting resistors on digital lines can reduce chances of pin failure.
- When performing communication between different modules a proper communication standard with support for physical protection such as shorts etc. should be used, e.g. RS232 rather than TTL
- Ensure that consideration is given to the power drops in linear regulators and that sufficient PCB heatsink is provided.
- Power systems should either be designed with an upgrade path in mind should particular areas need more power in the future. For example upgrading to more powerful cameras meant that a large increase in power was needed. Designing a method to deliver this capability early on would have helped.
- Careful consideration should be made when using COTS parts, especially prototyping modules as they may not have sufficient built in protection and they fail often.
- Don’t make the system too complicated at specification. Things will take longer than expected and a simple working system is better than a complicated non-operational system.

- If a radio beacon is used to find the ejectables: design receivers to properly receive sent data. At the launch campaign everyone is rather busy and especially if problems occur it is difficult to get a hold of the person responsible for the receiver.
- Include LEDs to help debug subsystems where possible (i.e. let you know if they are on and transferring data, see Figure 9). It may seem trivial, but anything that helps with development can save a lot of time looking for shorts or probing tracks. It improves morale for the mechanical members of the team as well.

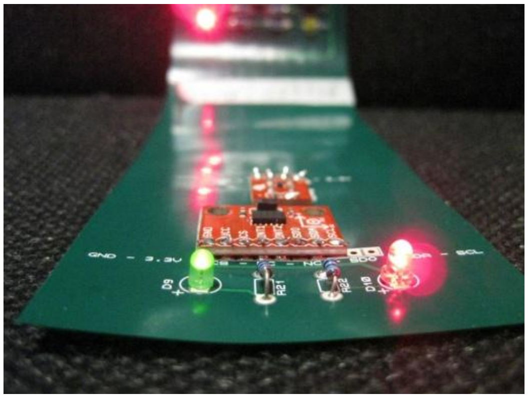

Figure 9: LEDs on iSEDE indicating power on the 3.3V and 5V line

- Make sure that there is a connector outside the experiment to directly reprogram the microcontroller inside the experiment.
- Include a dedicated debugging communication interface as a requirement to microcontrollers/ embedded systems (e.g. hardware UART). Being able to get information about the internal state of a microcontroller/embedded system can save time when developing.
- Reduce constraints where possible – e.g. do you really need the copper pour to be 0.4 mm, or could you make the board a bit more spaced out with a 1 mm gap, causing a lot less potential problems with shorting later on.
- Reduce the number of connectors wherever possible, as they were the most common point of failure in the StrathSat-R experiment. Unless you are working with a shoestring budget, spend money on a large chest for storing assorted components, and some metal flight cases for transporting items.
- Think long and hard about whether you really need anything that may increase the complexity of the design.
- Consider coating the electronics with protective lacquer.
- Buy crimping tools for D-sub connectors. It is much faster and more secure than soldering. Money spent on quality connectors is never wasted.
- Use PTFE cables which are resistant to soldering temperatures (see Figure 10)

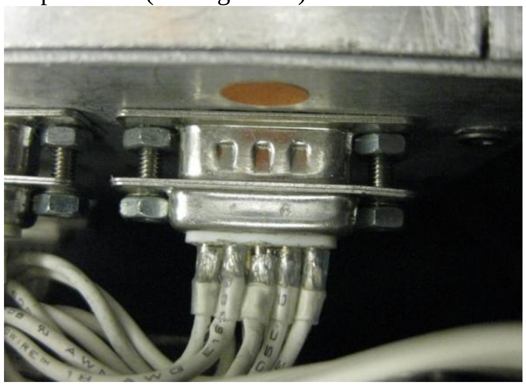

Figure 10: StrathSat-R's DSUB with PTFE cable and transparent shrinking tube for easier inspection

- Use separate fuses for each component (camera, CPU and sensors) on power distribution boards.
- When buying anything present yourself as a university representative, many times companies donate or give discounts for their products (experience shows that it is easier to get such a discounts from smaller retailers/companies).
- Always look for documentation/examples/ libraries/code when choosing sensors, communication links and other digital devices that use a specific protocol. Open hardware projects usually are a good choice. It can save lots of time that can be used to solve the real problems rather than learning how to communicate with a specific device.
- Be realistic and do not overdo the component choice, e.g., do not put in the fastest, most complex CPU if a small 8-bit will do the job just as good.
- Faulty devices connected to a data bus can mess up the whole bus, so tri-state buffers should be used.
- It is suggested to implement a working Globalstar system to increase redundancy and therefore the chance of locating the ejectables after landing.
- Have at least two people who know the electronics, of whom at least one is always present.

III.IV Software (Design, Implementation, Testing)

- Aim to use the simplest approach that will still achieve experimental outcomes.
- Implement ground support software early and make it solid. The same ground support software should be used during testing and during launch

campaign so that operator knows how to interpret readings and errors. (see Figure 11)

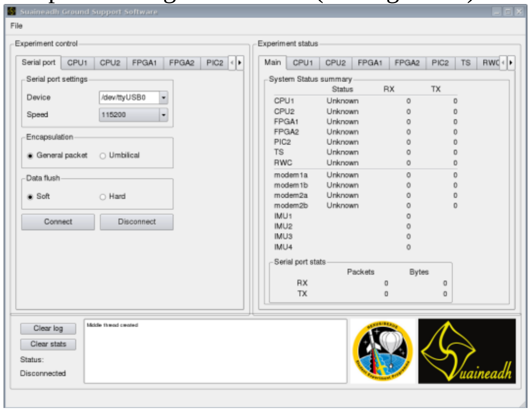

Figure 11: Ground support software of Suaineadh

- Design/hardware can change, so the software should be as portable as possible and as modular as possible.
- The most exciting design to the software engineer may not be the one that is most functional / fits with the required operation of the experiment.
- Small extra features may take a disproportionate time to implement – identify the critical path for software development early, try to estimate the time taken to complete the key features, and include a long period for full-system testing after software is complete.
- Start designing the software before anything else is built – a demo timeline could have easily been implemented before PDR for example.
- Software development should be at a sufficiently advanced stage to validate the electronic design at every prototyping stage (e.g. as soon as a new chip is ordered, the software engineer has a breadboard ready to run a simple program on). In StrathSat-R the software development lagged behind PCB design so that some subsystems were not tested until implemented in the full-system; sometimes requiring ad-hoc repairs to the PCBs.
- When specifying system elements, aim to use existing systems as much as possible (for example, a camera controlled with a microcontroller that someone on the team has used before for another project). In StrathSat-R, the team laboured to recreate a complex customised camera, with data storage etc. all tailored to the application. This was not necessary and created a lot of extra work. The reasoning behind using the design was that it was already implemented in a previous experiment (Suaineadh), but when it was realised that the cameras never actually worked, development had to be abandoned for lack of time. Therefore all extra engineering effort and custom designed parts must have good justification. As the overhead on the software/electronics front may not be worth even a large cost saving.
- Develop robust methods to simulate the interface with which you will be required to communicate as a first priority, and ensure that the timeline functions well in any possible scenario.
- Don't take it for granted that third party equipment will work and not damage your experiment.
- Use a cheap microcontroller for system development, as you are likely to break a few of them as the rest of the system develops in parallel.
- Pay attention to all aspects of the task of updating the software, and how it will be achieved. StrathSat-R encountered some problems using an online compiler for the MBed platform whenever there was a lack of wi-fi signal. Conversely, the use of an online compiler allowed remote updates when the team was split up. Another thing to think ahead about is how to reprogram the system when fully assembled – StrathSat-R utilised USB leads to each ejectable and the central module.
- Those working on the software system should have a good grasp of the requirements outlined in the SED.
- Other team members should be shown how to use the system, and made aware of major subroutines etc. so that there is not too much embedded knowledge lying with one member of the team. Ideally, several members will be able to modify the system to conform to simple changes in schedule.
- Have (at least) two people know in detail the software code, do some kind of team programming, e.g. over-the-shoulder programming: one programs while the other looks over the shoulder, and then they switch, it helps identify bugs on the spot and you are forced to write code that one person at least needs to follow. At the end both the coding styles will converge to some common ground that is easy for both and probably also other external people to understand and modify.
- Produce schematics that are laid out with the intent of allowing easy debugging, good communication between different members, and can be reused in many different situations. More care and attention in making things clear will pay off in the long run.

- Don't use different software architectures in one project.
- If using Hack-HD cameras: stop and restart them at some point during the timeline, to ensure at least a portion of the recording is stored.
- Use version control to track all changes in the software (even when only one person is working on the software). When working in a team ensure that everybody knows how to use the version control properly.

III.V Testing & Validation

- Start testing from the beginning. Do not plan the tests for the last days (or nights) before a review to allow time for required modifications.
- Have a test plan and test procedure for every test and stick to them rigidly. If things go wrong at least then one can know for sure which part of the procedure to change.
- Allocate enough extra time for anomalies that occur during testing and their fixing. Properly document a test procedure and results.
- Any changes to system designs after testing and validation must be followed by repeated tests to ensure that modifications have not compromised the operation of the experiment.
- If tests can be performed prior to CDR, this will allow for additional support from the REXUS team should complications be encountered.
- Produce a simple flight simulator (electronics in parallel with all other design).
- Produce a "fuse box" which is useful during first connection of experiment to simulator or REXUS control module.
- Focus on critical deliverables before a formal test – it doesn't matter if many of your subsystems work if the critical functions (i.e. the signal path for LO, SOE, SODS at EAR) don't work. StrathSat-R had a minor problem with optocouplers, which looked like a much worse problem to the reviewers, as there was no guarantee that the signals were received at all, when it was a simple flaw that could easily have been picked up had more targeted full-system testing been scheduled.
- Never change the output voltage of a power supply without double checking what is connected to it.
- In case your mission timeline includes pyrotechnic cutters a good alternative is to use LEDs instead (see Figure 12). However, care must be taken to ensure that no power spikes are observed when integrating actual pyrotechnic cutters as this can lead to premature deployment. It is recommended that at least three deployment tests include actual pyrotechnic cutters to ensure safe operation.

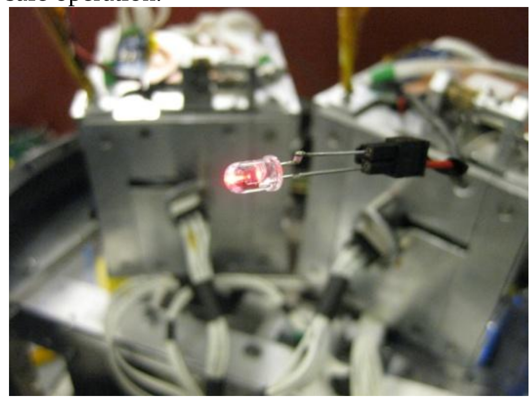

Figure 12: LED indicating pyro cutter firing of StrathSat-R

- Make a checklist that has to be read out by one team member, and carried out by another. This avoids mistakes such as leaving in the flight pins at ejection
- Ensure the consequences of tests are known by all team members – i.e. if a test will take the experiment out of action for five days, make sure the rest of the team does not need to access it.
- Complete timeline tests should be run as soon as possible to iron out any faults.
- Make sure all test equipment (e.g. vacuum chamber) is actually available, suitable, and working. For example check whether the thermal chamber can achieve the necessary temperatures.
- Don't open the thermal chamber when it's cold! Water will condense and freeze on experiment, creating water drops all over the surface when brought back to room temperature (Figure 13).

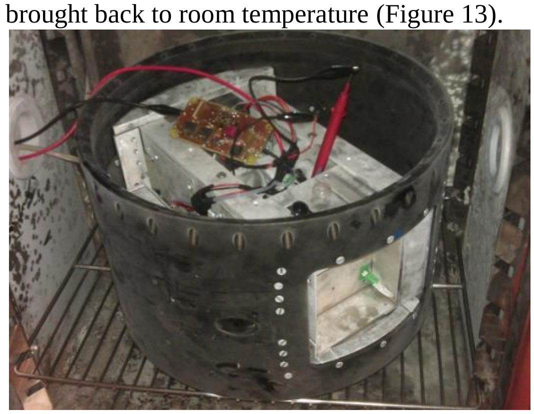

Figure 13: Freezing condensation on experiment when thermal chamber door was opened at -10C.

III.VI Workshops & Launch Campaign

- Ground everyone that is working on the experiment at Esrange; the air is very dry.

- The REXUS reviews (PDR, CDR, etc.) sometimes collide with exam periods so careful planning of the students' studies is vital to avoid that the REXUS project work affects the other courses or vice versa.
- Ensure selection of team members on launch campaign is appropriate; they must have extensive knowledge of the entire system and be capable of taking and implementing advanced design decisions.
- Make sure that there are always at least two team members that know the electronics/software at each review and official test (integration and bench test).
- When getting closer to delivery time, set a time when experiment should be good enough to fly, after that only perform timeline tests and fix bugs. The last tested timeline before a big test should always be without any problems.
- If the team is a multi-location team similar to Suaineadh, it is recommended to make the most use of the time at the workshops, possibly stay a few days longer to work as a team.
- When possible, bring hardware to the reviews (PDR and CDR), experts can give advice directly.
- The soldering course offered by ESA is a valuable workshop to learn how to manufacture space certified electronics.
- Find dedicated transport boxes for the experiment early.
- Make a project toolbox which contains everything your project may need to fix it, and which you can take to each campaign.
- Bring red tape for RBF (Remove Before Flight) items.
- When travelling to the launch campaign, it is a good idea if not everyone arrives at the same time, so team members that come later can bring missing components or tools.
- Ensure that all procedure documents are completely up to date with the design and that all members are familiar with the procedures.
- Completely test the system including critical components.
- Confirm all procedures and requirements that relate to your system, even if someone else is in charge of them. If your system relies on something then you must confirm it. If anything is questionable, speak up.
- Be confident, if you are nervous then the REXUS/BEXUS staff becomes nervous which results in you being even more nervous.
- Be honest to the other team members and the REXUS/BEXUS staff, everyone is working towards the goal of launching a functioning experiment. Let people know of problems when they occur.
- Take turns to sleep; sometimes it is unnecessary having everyone there at the same time.
- Never give up hope, the ejectable of Suaineadh was found 18 month after the REXUS12 launch.

III.VII Project Management

- Weekly meetings are obligatory to keep status updated within team.
- Try to work only with students that geographically are studying in the same campus. Communication and resolving of problems will be much easier if students from the same campus are involved in the experiment. Having meetings with all members present in the same room can't be replaced. Video- and teleconferencing are not very effective when it comes to resolving problems.
- Be aware of different time zones and switching between daylight saving time and normal time. Always schedule meetings in UTC but also write in brackets the time of each participating country to reduce confusion.
- Find a good project management tool and let all the communication go through this tool to keep track of the discussion on particular topics. Skype is recommended to use for telecons, Dropbox and Google docs are useful to share documents, Doodle.com is a great tool to schedule meetings, Facebook groups is a good tool for online communication/discussion and file sharing but everyone needs to be signed up on Facebook. Basecamp has been used by the KTH REXUS projects (SQUID [8], RAIN [9] and MUSCAT [10]).
- Generate Gantt charts with tasks to do based on feedback after reviews, this way you focus on tasks that really need to be done, rather than those you imagine may need to be done. It also keeps the goals time-constrained as there is a deadline to work towards. Mark the critical path of criteria for passing IPR, EAR etc.
- Make sure every subsystem team communicates with each other. (E.g. antennas that cannot be accommodated on the given design).
- Ensure that when people are getting a part of the project handed over to them that they understand and know everything that is going on in their field, so fewer surprises are likely to occur.
- Documentation:
    - Use some kind of configuration control. If no tool is available, or even if it is, it does not matter, use a detailed change log at the start: it saves a lot of time for reviewers at ESA/DLR, for you and your team, and it

is easy to cross-check which parts have changed and which have not.
  - Ensure that all material and parts are constantly recorded and up to date .
- When working on a big document together, it is recommended to inform the other team members of the document usage time and renaming the document with date and initials (check out a document).
- If students work on the experiment as part of their coursework, make sure that student is also available during summer.
- Have a dedicated room where the experiment can be assembled and kept without disturbance.
- Most students have not worked in such large teams together with students from other disciplines before, so an introduction to group dynamics would be advisable to avoid future problems related to, e.g. different expectations, priorities and levels of commitment within the team.
- Many students are getting course credits for their work, but it is important that both the requirements for the course and the requirements from the REXUS team are met. The team members and their supervisors need to understand that the deliverables for the project and the deliverables for the course can be two separate things. Technical reports are of courses necessary for the documentation, but more important is to build and test as quickly as possible. The report can be produced later.
- Assign a person responsible for the outreach activities. This person shall be involved with the design of the experiment, but shall not be overloaded with work. Otherwise, the outreach production and quality will suffer.
- Have dedicated supervisors that are willing to spend parts of weekends and long days to perform important tests and tasks.
- Open-minded, skilled and good team workers on both supervisor and student levels is what the REXUS/BEXUS projects need. Both supervisors and students must be prepared to work in unexpected directions not thought of from the beginning when they joined the project and be willing to quickly gain new knowledge in fields that are further away from the main studies and knowledge.

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V. CONCLUSIONS

This paper should give future experiment teams guidelines and recommendations to help them design and build an experiment more efficiently without making the same mistakes again. Overall it can be said that the main lessons learned during the three experiments is to start fabricating and testing as soon as possible because everything will take longer than expected due to unexpected problems or delays (e.g. fabrication or delivery). Specifically the development of software will take a long time and should therefore be started early.

It can be a said that the REXUS/BEXUS program is a great opportunity for students to go through an entire space project from experiment proposal over design, fabrication and testing all the way to launch.

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