Deployment of a Spinning Space Web in a Micro-Gravity Environment

M. McRobb [a], T. Sinn [b], N. Smith [a], J. Skogby [c], A. Wujek [c], M. Zhang [d], J.Sun [d]

[a] School of Engineering, University of Glasgow, James Watt (South) Building, G12 8QQ, UK
[b] Advanced Space Concepts Laboratory, Department of Mechanical Engineering, University of Strathclyde, 75 Montrose Street, G1 1XJ, UK
[c] School of Information and Communication Technology, Royal Institute of Technology, Forum 105, 164 40 Kista,
[d] School of Engineering Science, Royal Institute of Technology, Osquars Backe 18, 10044, Stockholm

Suaineadh

Background

What is the mission goal of Suaineadh?

"That the collaborating students in the Suaineadh project should successfully deploy and stabilize a scalable space web in a micro-gravity environment by March 2012 to validate future investment in the concept"

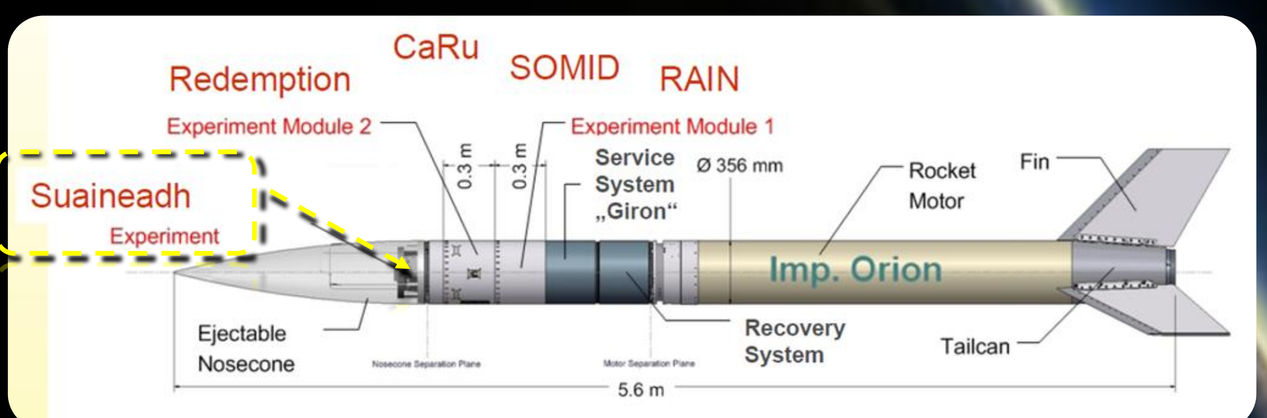
How will we achieve our goal?

In Dec' 2010, the Suaineadh team participated in the REXUS 11/12 selection workshop at the European Space Research and Technology Centre (ESTEC in Noordwijk, Holland) to compete for a place onboard a REXUS sounding rocket. "The REXUS (**R**ocket-borne **EX**periments for **U**niversity **S**tudents) programme is realised under a bilateral Agency Agreement between the German Aerospace Centre (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)".

The Suaineadh team was successful in winning a place to launch the experiment into a micro-gravity environment in March 2012 from ESRANGE, Kiruna, Sweden.

How will this technology benefit the field of science and engineering?

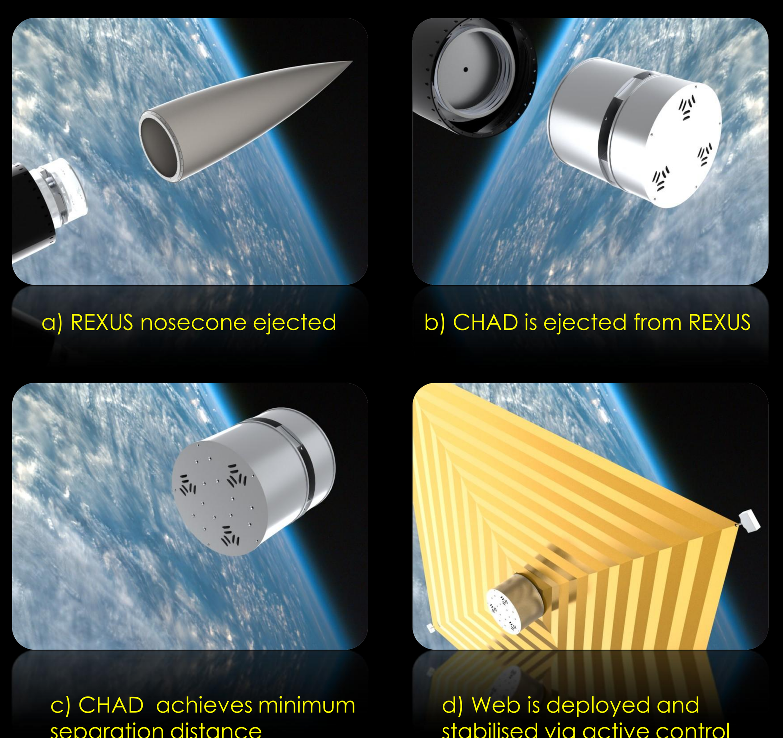
The technology being developed here will provide a *'proof of concept'* that is scalable in its design. Therefore the same concept could be used to develop much larger deployable space structures, perhaps in the regions of tens of kilometres squared whilst reducing the mass and volume normally needed for such macro scaled projects. This will reduce the amount of chemical fuel required to launch these satellites into orbit, thus potentially lowering both the costs and the carbon footprint of future space missions. In terms of applications, space webs present a vast range of exciting opportunities, including; harnessing the power of the sun as a form of propulsion i.e. solar sails (chemical free propulsion), or for turning this free and abundant source of energy into useable electricity via solar panels. On the side of the deployed structure facing back towards the earth, microwave generators could be used to transmit this energy wirelessly down to the ground. This novel concept could help solve the energy problems that the planet will soon face. Also, large scale antennas for delving deeper into the universe could be constructed and even scaffolding platforms from which to build larger space structures, possibly integrating the popular *'crawling robots'* concept. Therefore the potential benefit to the economy, industry and the field of science and engineering could literally *'be out of this world'*.



Schematic of REXUS Sounding Rocket. The Suaineadh experiment will be located in the nosecone section
Image courtesy of REXUS 11/12 User Manual

What is the Suaineadh Experiment?

The experiment objectives are to deploy a space web from a spinning central assembly by exploiting centrifugal forces and to stabilise the structure by an active control method. This is achieved using an on-board reaction wheel that transfers angular momentum from the reaction wheel to the central assembly, thus initiating spinning motion. Operational data of the mission will be accumulated visually by cameras and by on-board sensors. The experiment can be split into two distinct sections:

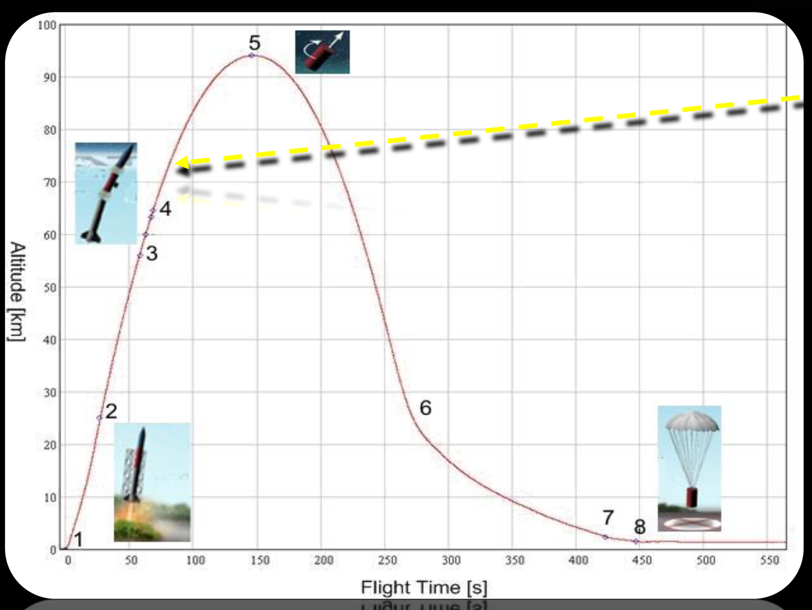


a) REXUS nosecone ejected
b) CHAD is ejected from REXUS
c) CHAD achieves minimum separation distance
d) Web is deployed and stabilised via active control

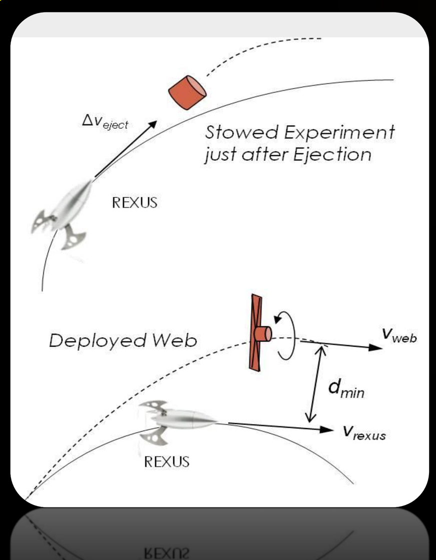
Original images created by Malcolm McRobb

<u>*Central Hub and Daughter Sections (CHAD)*</u> – this, the ejected section carries out all mission operations, including web deployment and stabilisation. CHAD consists of the central hub (mother); square web (area 4m²); and four corner masses (daughters) attached to the web. Prior to deployment; the web and corner masses are wrapped around a central channel in the central hub. The ejection of the system from the REXUS rocket occurs at an altitude of approximately 70 km, which will provide the necessary micro-gravity environment required by the experiment. Once a sufficient separation distance from REXUS has been achieved, the constraints attaching the daughter sections to the central hub are released and the deployment sequence commences. As the web approaches full deployment the reaction wheel is used to provide web stabilisation and to prevent any recoil effects.

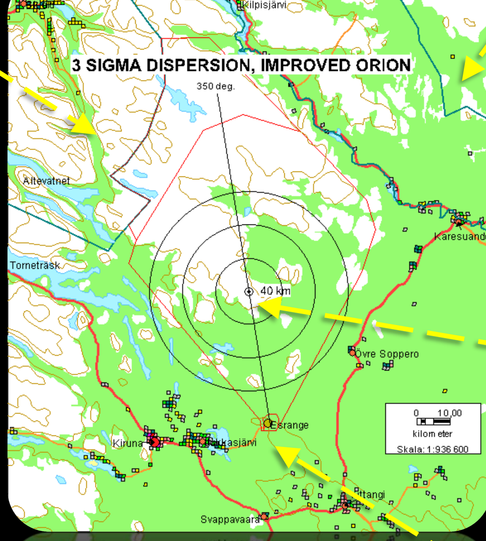
<u>*Data Storage Module (DSM)*</u> – the data accumulated by CHAD is transmitted back to REXUS via an integrated communications architecture. This data is onboard the DSM which is recovered once REXUS rocket returns back to Earth. Data acquisition of images captured by the cameras begins once REXUS has been launched and data from the Inertial Measurement Units (IMUs) on-board CHAD commences as deployment of the web is initiated. All data is transmitted to the DSM and continues until REXUS is out of range. Redundant data storage is ensured through the transmission of data from the central hub to the DSM and to ESRANGE. Additionally, data will be stored on flash drives on-board the central hub and the DSM, both of which is to be recovered using GPS and a locating beacon. The data acquired will be used to validate previous ground based analysis and simulations.



Predicted Rexus flight telemetry depicting flight time vs. Altitude
Image courtesy of REXUS 11/12 User Manual



Two stages of deployment of Suaineadh experiment



Shown above is the predicted Impact zones for the REXUS rocket. Note that it is surrounded by the Norway's and Finland's borders which both REXUS and Suaineadh MUST NOT cross. The impact zone is low population density to minimise risk to the public. Image courtesy of SSC.

Who is involved in the experiment?

Students from the University of Glasgow and Strathclyde University of the UK and KTH Royal Institute of Technology of Sweden, will collaborate in the design of the Suaineadh Experiment. The team will consist of both undergraduate and postgraduate students working under the supervision of intellectual supports from each institution. The international aspect of the team is further exemplified by the nationalities of individual team members, including; British, German, Polish, Swedish and Chinese. This form of collaboration allows for an exciting and dynamic working experience and paves the way for future partnerships.

The team members:

Mechanical Design, Fabrication, Telecommunications, Testing & Integration
Malcolm McRobb, *MEng, PhD Candidate*
John Russell, *MEng, PhD Candidate*
Andrew Feeney, *MEng, PhD Candidate*
Neil Smith

University of Glasgow

Team lead, Organisation & Outreach
Thomas Sinn, *MSc, PhD Candidate*
Johannes Weppler

University of Strathclyde Glasgow

Web Deployment Simulation & Post flight Analyses
Zhang Mengqi
Jingchao Sun

On-board Electronics
Jerker Skogby
Adam Wujek
Byron Navas, *MEng*
Guo Chen
Shuxiang Xu
Yang Sun
Martin Axelsson
Erik Axelsson
Hans Brickner

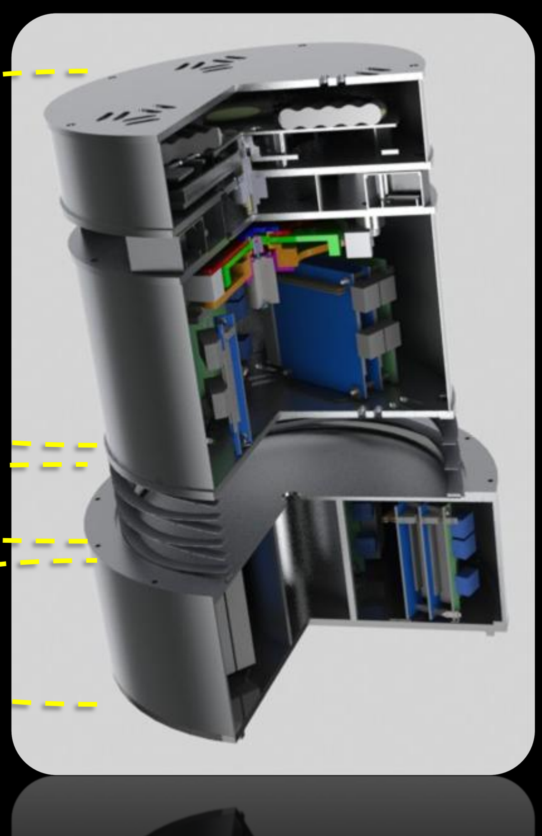
KTH Vetenskap och Konst

Where did the concept originate?

The space-web originates from the Japanese 'Furoshiki' satellite [1-3], a large net held in tension using radial thrusters or through the centrifugal forces generated by spinning the whole assembly [4]. These webs can act as lightweight platforms for the construction of large structures in space without the huge expense of launching heavy materials from Earth. Huge satellites to harness the Sun's energy as a form of propulsion or indeed for energy harvesting purposes and even antennas for further exploration of the universe may be constructed from such technology. There have been several experiments conducted on the deployment of the space web; in 2006 the deployment of a Furoshiki web by JAXA ended in a chaotic deployment sequence due to misalignment of the radial thrusters due to out of plane forces. The only successful deployments and spin stabilisation of a large space structure was the Russian Znamya-2 experiment in 1993 [5] and more recently the JAXA Ikaros Solar Sail in 2010 [6].

Experiment Design

Mechanical Design



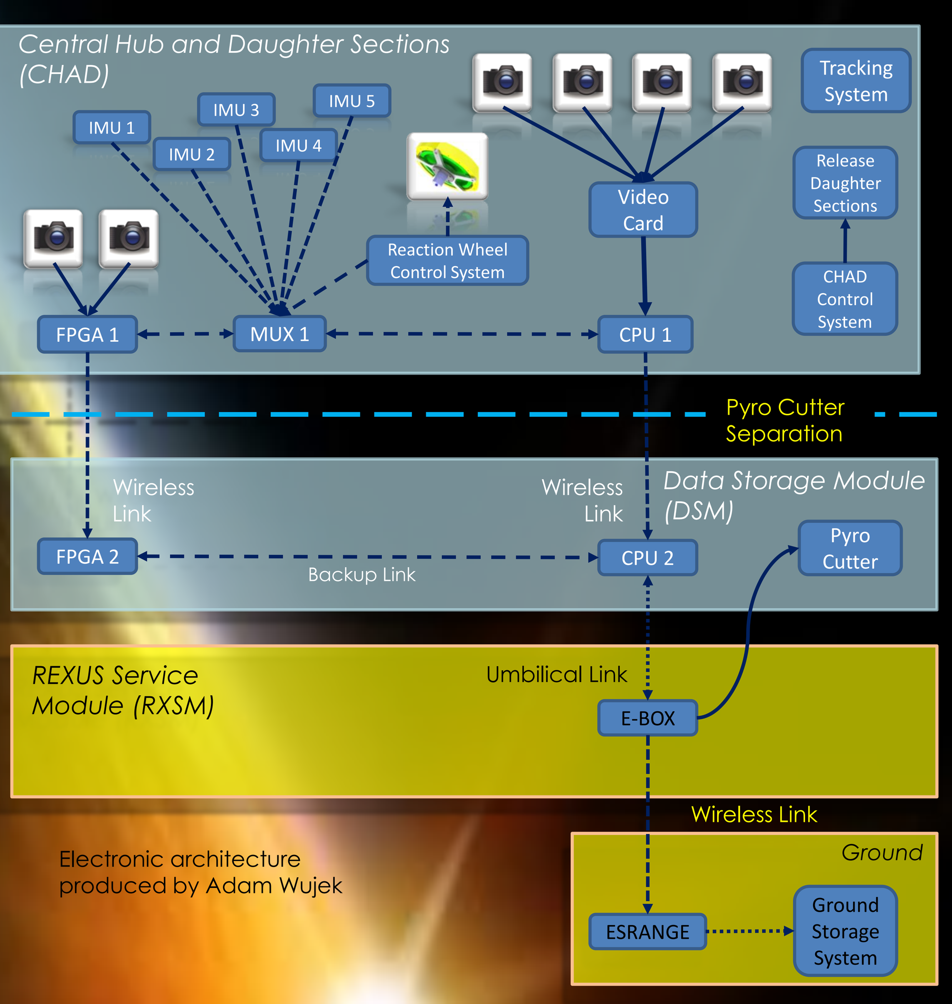
3D CAD model of complete experiment assembly
Original image created by Malcolm McRobb

The structural design requirements were defined on the basis of withstanding the mission loads during the operational lifetime of the experiment, with predefined loads relating explicitly to mission phases. Fabrication and assembly stresses were applied to the manufacture and assembly phases, while environmental loads were to be considered for the transportation and handling phase. There are three testing phases in which vibrations, shock loading, and thermal cycling predominate. Handling and stacking loads, along with pre-flight check conditions relate to the pre-launch phase and the REXUS engine acceleration. Launch vibrations, engine ground-shock, and yo-yo de-spin loads are all encountered during the launch/ascent phase. Finally, pyrotechnic separation from REXUS and web/daughter deployment, reaction wheel operation and thermal environments are all key parts of the mission operation phase. In addition to these load/phase relationships the mechanical design was closely driven by the launch vehicle requirements, which can be summarised as follows:

- Spaceflight time 180 s
- Apogee 100 km
- Maximum velocity 1.3 km/s
- Maximum acceleration 20g
- Maximum Mach number 4.3
- Maximum dynamic pressure 290 kN/m²
- Launch spin rate 4 Hz
- Vehicle bending moment 11.29 kNm
- Major axis is the roll axis
- REXUS vehicle length, mass, and diameter are 5.6m, 100 kg, and 0.356m respectively

There are four assumed quantities, namely axial and lateral load factors of 20, and the first axial and lateral natural frequencies should be greater than 25 Hz and 10 Hz, respectively. The environmental conditions under which the system must operate are; building and manufacture 20±5°C, transport as low as -30°C, systems integration 20±5°C, and the launch tower at 17±7°C, all within the pre-launch phase. The experiment will be subjected to temperatures in excess of 110°C, and 200°C, respectively, during launch and flight as a result of the REXUS thermal loadings. Post flight can again be as low as -30°C. These conditions, data, and specifications represent the criteria against which the mechanical design was undertaken.

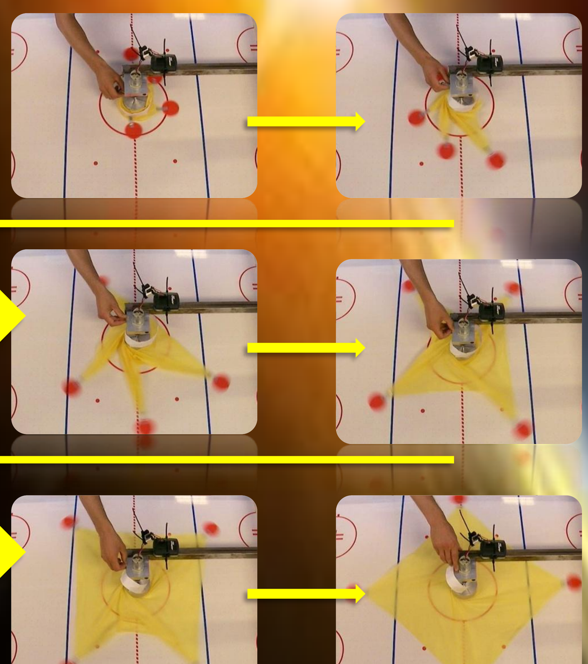
Electronic Architecture



Electronic architecture produced by Adam Wujek

The electronic systems provide two main functions. First is to control the experiments behaviour by driving actuators, second is to acquire measurements from sensors for the post flight analysis. As previously stated, to provide a secondary verification method images will be captured by cameras placed on both CHAD and the DSM. Data acquisition and control systems have been designed to be fully independent so that in the event of failure in one component, the fault will not propagate to other systems. Moreover, two data flows were designed to provide redundancy in the data acquisition system. Data accumulated by the IMUs and reaction wheel system is passed through a MUX to the central units of both data flows (CPU1 and FPGA1). Here, data is mixed with pictures captured by independent sets of cameras and stored in internal memory boards to be later passed to the DSM by two independent wireless links. At the DSM, data is again stored in non-volatile memory. To prevent whole data loss caused as a result of failures with the REXUS recovery system, portions of collected data will also be sent down to ESRANGE ground station. During each mission phase, status of the experiment and all subsystems will be monitored live by data arriving from REXUS.

Web Deployment



Still captures of fabric web deployment test on air hockey table to provide low friction surface

<u>*Deployment control law and initial spin rates after yo-yo de-spinning*</u> - The required output torque from the reaction wheel is given by the modified Melnikov-Koshelev law. This law is supposed to give an optimal deployment in terms of minimising the required energy, but also to give a short deployment time. As found by Melnikov and Koshelev, this control law is suitable for electric motors as it has the same drooping characteristics, i.e. higher torques at lower speeds, which is required for a successful deployment. For the Suaineadh experiment, the de-spinning yo-yo system is aiming to de-spin the rocket to 0.1 ± 0.08 Hz, so the window of initial spin rates is 0.02–0.18 Hz. The final desired spin rate of CHAD is 0.3 Hz (1.885 rad/s). The maximum torque capacity of the motor is 11.8 mNm at 5000 rpm. The torque applied to the hub from the reaction wheel is thus according to the modified Melnikov-Koshelev law:

$$M = max\left[0, 11.8\left(1 - \frac{\omega_h}{1.885}\right)\right] mNm$$

where ω_h is the spin rate of the hub

Simulations undertaken have shown that the higher the initial spin rate, the lower the minimum spin rate of the hub. Nevertheless, with the present control law it will be possible to accommodate initial spin rates within the specified range of 0.02 - 0.18 Hz without modifying the control law.

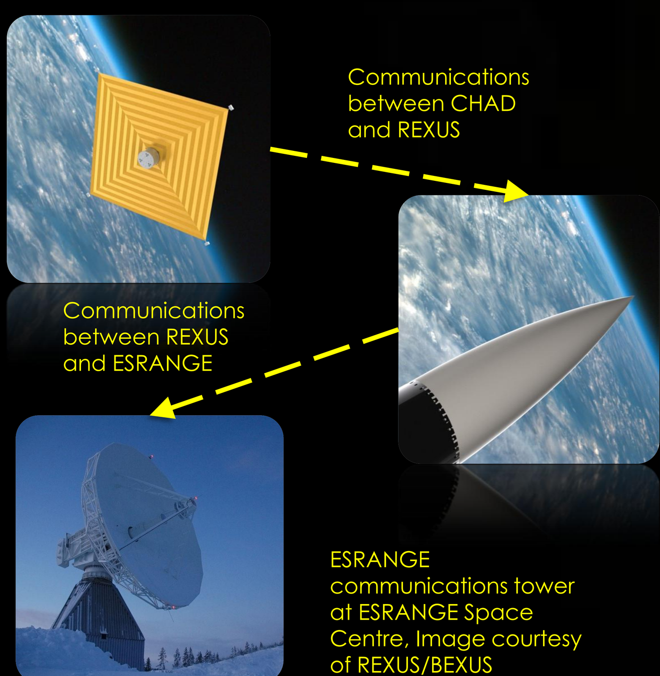
Telecommunications

<u>*Between CHAD and Data Storage Module*</u> -

- Two wireless connections at different frequencies for increased fault tolerance
- Transmission of measurements from IMUs and images from cameras
- 80 sec experimental time
- 200 sec transmission time
- 915.5 MHz frequency with 1MHz bandwidth (allocation through Swedish Telecom Authorities)
- 5.470 to 5.725 GHz bands with 40 MHz bandwidth (Permit to use at high altitudes granted by Swedish Telecom Authorities)

<u>*Between Data Storage Module and ESRANGE*</u> -

- Low speed data downlink via REXUS downlink
- Approximately every 10^{th} reading (~2.5 kbps) sent *(Serves as backup to storage on-board REXUS)*



Communications between CHAD and REXUS

Communications between REXUS and ESRANGE

ESRANGE communications tower at ESRANGE Space Centre, Image courtesy of REXUS/BEXUS

Project Management

Project management of the Suaineadh experiment is directed from Strathclyde University, UK. The experiment itself is broken into several distinct sections which makes the work distribution over all three participating institutions possible. The University of Glasgow is responsible for designing, manufacturing and testing the structure, while KTH is responsible for the simulation, electronics and software. The difficulty for the project management is to combine these closely related fields to each other to ensure on time delivery of key phases while maximising the scientific output of the mission. In order to organise the workflow more adequately, a team web site was created where the Student Experiment Documentation (SED) can be continually updated. The SED is the most important document for the project and its deliverables as it includes every detail on every subsystem of the experiment. Bi-weekly Skype conferences between each institution ensure that individual team members are achieving their goals and also allows for any outstanding issues to be discussed and resolved as a single unit. Final integration and validation of the Suaineadh experiment prior to the teams departure to ESRANGE, Kiruna, Sweden will take place at the University of Glasgow where all key team members from each institution will meet. Post launch, a final document will be created reporting on the outcome of the mission so that publications can be made to the scientific community.

Outreach

As part of the Suaineadh teams effort to publicise the project, the following measures have been undertaken:

- Publication in the 61st International Astronautical Congress, Prague, CZ, AC-10-C3.4 , 2010
- Abstract submitted for the 62nd International Astronautical Congress, Cape Town, SA, 2011
- Abstract submitted for the 2011 Space Access International Conference, Paris, France
- Article published on kosmonauta.net [7]
- Article published in the Mechanical Engineering newsletter (March 2011), Strathclyde
- Poster displayed in the House of Commons, London, UK as part of *SET for Britain 2011*
- Team blog site created [8]
- *Facebook* team page created [9]

[1] S.Nakasuka, T.Aoki, I.Ikeda, Y.Tsuda & Y.Kawakatsu: "Furoshiki Satellite" A large membrane structure as a novel space system. Acta Astronautica, 48(5-12): 461-468, 2001.
[2] S.Nakasuka, R.Funase, K.Nakada, N.Kaya & J.C.Mankins: Large membrane "Furoshiki satellite" applied to phased array antenna and its sounding rocket experiment. Acta Astronautica, 58: 395-400, 2006.
[3] S.Nakasuka, T.Funane, Y.Nakamura, Y.Nojira, H.Sahara, F.Sasaki & N.Kaya: Sounding rocket flight experiment for demonstrating "Furoshiki satellite" for large phased array antenna. Acta Astronautica, 59: 200-205, 2006.
[4] M.Gärdsback, G. Tibbert, D.Izzo: Design considerations and deployment simulations of spinning space webs. AIAA, in press, 2008.
[5] V.M.Melnikov, V.A.Kosholev. Large space structures formed by centrifugal forces. Volume 4 of Earth Space Institute Book Series. Gordon and Breach Science Publishers, India, 1998.
[6] JAXA, Ikaros leaflet.pdf, http://www.jspec.jaxa.jp/e/activity/ikarosleaflet.pdf
[7] *http://www.kosmonauta.net/index.php/Misje-bezzalogowe/Suborbitalne/rexus-12-suaineadh-cz-1.html*
[8] *http://suaineadh.blogspot.com/*
[9] *http://www.facebook.com/pages/Suaineadh-REXUS12/100114003401934*

Background image courtesy of: http://www.manywallpapers.com

EuroLaunch · DLR · esa · Rymdstyrelsen Swedish National Space Board