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RESULTS OF REXUS12'S SUAINEADH EXPERIMENT: DEPLOYMENT OF A SPINNING SPACE WEB IN MICRO GRAVITY CONDITIONS

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On the 19th of March 2012, the Suaineadh experiment was launched onboard the sounding rocket REXUS12 (Rocket Experiments for University Students) from the Swedish launch base ESRANGE in Kiruna. The Suaineadh experiment served as a technology demonstrator for a space web deployed by a spinning assembly. The deployment of this web is a stepping stone for the development of ever larger structures in space. Such a structure could serve as a substructure for solar arrays, transmitters and/or antennas. The team was comprised of students from the University of Strathclyde (Glasgow, UK), the University of Glasgow (Glasgow, UK) and the Royal Institute of Technology (Stockholm, Sweden), designing, manufacturing and testing the experiment over the past 24 months. Following launch, the experiment was ejected from the ejection barrel located within the nosecone of the rocket. Centrifugal forces acting upon the space webs spinning assembly were used to stabilise the experiment's platform. 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 is released. Four daughter sections situated in the corners of the square web served as masses to stabilise the web due to the centrifugal forces acting on them. The four daughter sections contained inertial measurement units (IMUs). Each IMU provided acceleration and velocity measurements in all three directions. Through this, the positions of the four corners could be found through integration with respect to known time of the accelerations and rotations. Furthermore, four cameras mounted on the central hub section captured high resolution imagery of the deployment process. After the launch of REXUS12, the recovery helicopter was unable to locate the ejected experiment, but 22 pictures 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 the experiment was fully functional after ejection, but perhaps through tumbling of either the experiment or the rocket, the wireless connection was interrupted. A recovery mission in the middle of August was only able to find the REXUS12 motor and the payload impact location.

I. ACRONYMS

BEXUS	Balloon Experiment for University Student
CHAD	Central Hub And Daughters
COTS	Commercially Of The Shelf
CPU	Computer Processor Unit
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DSM	Data Storage Module
ESA	European Space Agency
FPGA	Field-Programmable Gate Array
GPS	Global Positioning System

IMU	Inertia Measurement Unit
LO	Lift-Off signal
MORABA	Mobile Rocket Base (DLR)
PIC	Programmable Interrupt Controller
REXUS	Rocket Experiments for University Students
RWC	Reaction Wheel Controller
SNSB	Swedish National Space Board
SODS	Start Of Data Storage signal
SOE	Start of Experiment signal
SSC	Swedish Space Corporation

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II. INTRODUCTION

Large structures in space are necessary for the continuous exploration of our universe and for various space applications required to satisfy user demands today and in the future. One of largest problems nowadays lies in the transport of these structures from ground to orbit due to launch vehicle payload volume constrains. By making the space structures deployable with minimum storage properties, this constrain may be bypassed. Deployable concepts range from inflatables, foldables, electrostatic to spinning web deployment. The advantage of the web deployment is the very low storage volume and the simple deployment mechanism. The concept of a space-web, such as the Japanese ‘Furoshiki’ satellite^{1,2,3}, depicts a large net held in tension using radial thrusters or through the centrifugal forces experienced by spinning the assembly⁴. These webs can act as lightweight platforms for the construction of large structures in space without the huge expense of launching heavy structures from Earth. Utilising miniature robots that build as they crawl along the web, huge satellites to harness the Sun’s energy or antennas for further exploration of the universe may become viable when implementing space webs technology. There have been several experiments conducted on the deployment of the space webs. In 2006 the deployment of a Furoshiki web by the Japanese ended in a chaotic deployment sequence due to misalignment of the radial thrusters as a result of out of plane forces. The Russian Znamya-2⁵ experiment was the first that successfully deployed and spin stabilised large space structure. More recently, in 2010, the Japanese solar sail Ikaros⁶ was successfully deployed using thrusters to introduce spinning. The Ikaros solar sail had a 20 m diagonal and used solar winds for acceleration, solar cells on the membrane for power generation and the attitude control using the sail.

II. EXPERIMENT DESCRIPTION

II.I Overview

The Suaineadh experiment⁷ consisted of two distinct sections, the ejected part (Central Hub and Daughters – CHAD) and the Data Storage Module (DSM) which remained on the REXUS rocket. The ejected part undertook all mission operations once separation with REXUS had been achieved (Figure 1). It consisted of the central hub, the web and four daughter sections. Ejection of the experiment from REXUS occurred at an altitude of approximately 70 km and followed a pre-determined automated deployment sequence, which allowed for a safe separation distance to be achieved. The apogee of the experiment was at 86 km altitude at approximately 140 seconds into the flight.

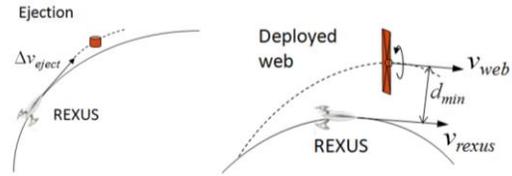


Figure 1: Conceptual deployment of web from nose-cone ejection

CHAD carried all subsystems required to achieve the mission objectives and provides stowage for the web and daughters prior to deployment. The web had the dimensions of 2 m by 2 m and was composed of ultra light and flexible braided Spectra fishing lines. Images of the deployment and stabilisation phases were accumulated by cameras located within the central hub. Data was gathered by inertial measurement units (IMUs), one IMU was located inside each of the daughter sections and another one was located inside the central hub itself. Image and data collection began two seconds before the web deployment sequence starts. The data was stored on CHAD as well as being transmitted via a wireless link to the DSM and stored there until recovery after landing. After ejection and prior to deployment, a reaction wheel was used to accelerate the central hub to a sufficient angular velocity for deployment. The daughter sections were released to initiate web deployment. Centrifugal forces acting on the released daughter sections fully deployed the web. As the deployment neared completion the reaction wheel again rotated the central hub to a sufficient velocity to reduce recoiling effects and to achieve web stabilisation. A RF-beacon was placed on CHAD to locate and recover the experiment after the mission in order to collect data.



Figure 2: Deployed web on ground before launch

II.II Mechanical

The mechanical structures of Suaineadh rely upon simplicity in design to make the most efficient use of available volume permitted by the REXUS 12 nose cone

adaptor that housed the experiment. The modular design was based around two distinct sections; the DSM and CHAD. The maximum footprint of the experiment was 0.33 m in diameter by 0.40 m in height, with a mass of approximately 12 kg. Aluminium 6082 was used to fabricate the mechanical structures, with the exception of the DSM top plate that was instead fabricated from 4 mm thick steel plate to provide additional protection during re-entry. The ultimate objective of the mechanical design was to ensure that the structure would be capable of operating in all mission loads. These may include vibration, shock loading and thermal cycling, that if amalgamated for all mission phases (manufacture, transport, storage, launch, re-entry and recovery phases), could be summarised as:

- 20-g maximum acceleration.
- 290 kN/m² maximum dynamic pressure.
- 4 Hz spin rate during launch.
- -30°C to +200°C temperature range.

The ejectable section, CHAD (see Figure 3), was designed with the requirement to be able to access all internal subsystems. In this respect, it was built in three tubular sections; the Lower Chamber, Central Chamber and the Upper Chamber. The Lower Chamber housed all electronic subsystems including data storage, modem and the reaction wheel. The reaction wheel was mounted on the underside of the top plate of the Lower Chamber in order to position the centre of gravity as close as possible to the plane of the deployed web for stability. The electronic boards themselves were mostly of PC-104 architecture, and were orientated both vertically and around the centre of the bottom plate of the Lower Chamber, such that the motor of the reaction wheel was able to extend in-between to make use of all available space.

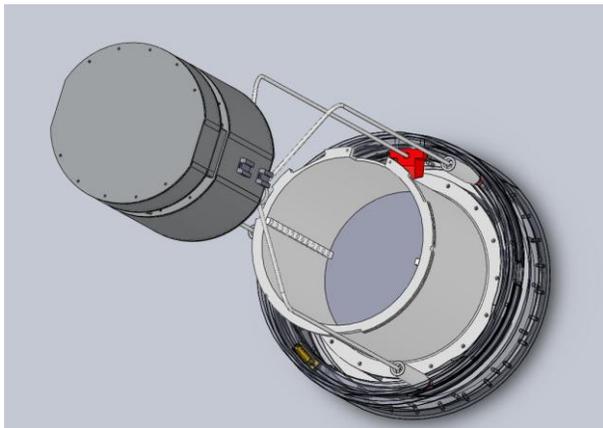


Figure 3: CHAD being ejected from the Magic Hat on the DSM

The Upper Chamber of CHAD housed the Saft battery power supply, four cameras and the Daughter Release Spine. The cameras were mounted on the inside surface of the Upper Chamber walls with the lenses extending through port holes that provide a secondary function that allowed the release of pressure during launch to satisfy the requirement for non-pressurised vessels on-board the REXUS 12 rocket. The Daughter Release Spine was responsible for simultaneous release of all four Daughter Sections at the initiation of the deployment phase. This was achieved using a single structure with four equally spaced spokes, and each with a set of two pins that extend through the bottom plate of the Upper Chamber and into the lid of each respective Daughter Section. This secured the Daughter Sections in place and prevented any significant movement during launch and spin phases. When primed into position, the Daughter Release Spine was compressed against a spring and secured by a steel cable that was also fed through a Cypress pyrotechnic cutter. Therefore, when the deployment phase was commanded, the pyrotechnic cutter activated and cut the steel cable to allow the Daughter Release Spine to rise with the subsequent retraction of the pins from the Daughter Sections. A spline shaft with fitted bearing was used to guarantee axial travel of the Daughter Release Spine with no rotation.

The main function of the Central Chamber is to create spacing between the Upper and Lower Chambers to allow housing of the Daughter Sections. The structure of the Central Chamber inherent a smaller diameter than both the Upper and Lower Chambers so that the Daughter Sections are able to be placed within the outer perimeter of CHAD. The Central Chamber also provided the attachment points for the Web and acted as a channel for which the electronic cabling can pass between the Upper and Lower Chambers. When stowed, the web itself was wrapped around the Central Chamber and secured via the previously described Daughter Release Spine mechanism. The antennas for data transfer were mounted on the top and bottom outside surface of CHAD to provide full coverage back to the DSM and REXUS 12 in the event of tumbling post ejection. However, in order to mitigate the likelihood of tumbling post ejection, CHAD was fitted with two equally spaced linear guide rails along the length of the Lower Chamber. In this way, the CHAD module could be fitted within an ejection barrel as seen in Figure 4. This barrel had four low friction linear guide carriages (two per respective guide rail) which restricted the travel of CHAD upon ejection to a linear trajectory until clearance of the barrel.

CHAD itself was primed for ejection within the ejection barrel by compressing a wave spring, and again secured via steel cable coupled with a pyrotechnic cutter. A wave spring was chosen for its ability to store

the required amounts of energy for adequate separation distance between CHAD and REXUS 12, with a minimal volume. Another critical feature of the wave spring was that it is also able to equally distribute the release of this energy around its perimeter which acted to further reduce the risk of tumbling.

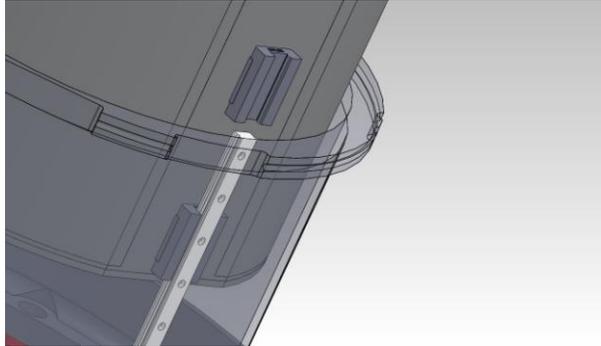


Figure 4: Guiderrails inside Magic Hat and carriages on CHAD

The DSM was responsible for receiving and storing all data transmitted from CHAD and remained on-board REXUS 12 throughout the mission. The structure was simple in design, in that the electronic components were mounted directly upon the REXUS 12 experiment module bulkhead in order to reduce the mass envelope of the experiment. To protect the components from the launch and re-entry loadings and environments, the DSM was capped by a steel plate mounted upon pillars that provided the necessary volume to house the electronics. The ejection barrel, and subsequently CHAD, was fitted axially directly on top of the DSM, both of which are easily demounted to readily allow access the DSM subsystems.

II.III Electronics & Software

Used electronics were a mix of COTS components and custom-made boards when COTS board were not available. This approach reduced design and production time of the electronics subsystem. The electronics and software for control and data acquisition was separated to allow for a more failsafe system.⁸ It also simplifies software design and testing. The main control of the experiment was done by a small microprocessor (PIC) placed on a custom made PCB in CHAD, while the data acquisition, which required more computing power, was done by more advanced CPUs and an FPGA.

To provide data acquisition from multiple sensors, i.e. IMUs, an FPGA is used. The FPGA (Cyclone IV) was placed on the DE0-Nano board. The main purpose of the FPGA was to gather the sensor data, packet, serialize and sent it to the CHAD CPU. Data was gathered at a rate of 50 Hz from the four daughter sections as well as from the Reaction Wheel Controller (RWC). To reduce the data that was needed to be sent

over the wireless link, the unnecessary information sent from the IMUs are filtered out in the FPGA before the data was packaged according to reference 8. The data streams from the IMUs were then combined into one stream and sent to CHAD CPU.

The RWC consisted of an FPGA, IMU and motor driver mounted on a custom-made board. This board controlled the reaction wheel. Two VSX-104+ boards were used in the experiment. Each board contained one SoC chip with one CPU, compatible with 486SX instruction set, using a 300 MHz system clock. Both CPUs used GNU/Linux as an operating system with custom written software.

One CPU parallel with a custom made board placed in CHAD, was responsible for capturing images from four cameras on CHAD, storing these images on two internal flash cards and sent them through wireless link to DSM. A second CPU was placed on the DSM which was the same as the one in CHAD without the custom made board. The second CPU stored all incoming data from wireless link on the two flash cards.

Both CPUs included also functionality to report its route status packets coming from other modules. Three different types of data were expected from the experiment. First, most important for post-flight data analysis were readings from the sensors, IMUs and RWC. As a secondary verification method, pictures from the four cameras onboard CHAD were recorded. The last type of data contained status information about each component. All these types of data were stored on DSM's and CHAD's flash cards.

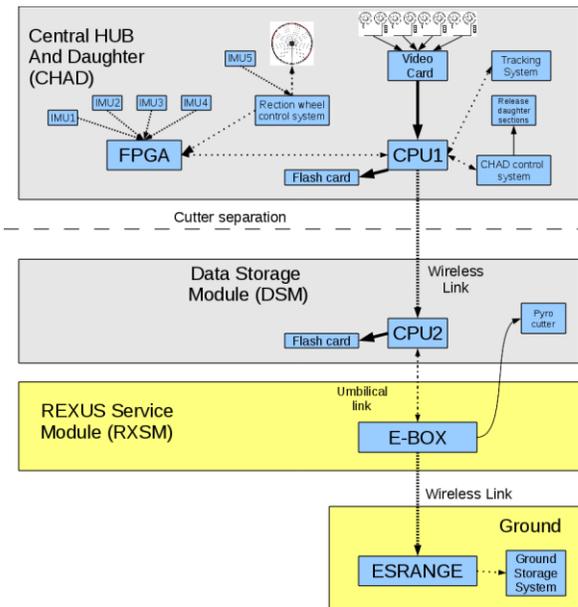


Figure 5: Schematic of Electronics

Communication

Four 915 MHz antennas were used for the telecommunication. CHAD had one on the top and one on the bottom. Two receiving antennas on the REXUS rocket were placed symmetrically on the outer rim of the magic hat ejection barrel. The size of the antenna was 31 mm × 31 mm. For a continuous communication between CHAD and DSM it was of great importance to account for possible tumbling of the rocket and of CHAD. Therefore, the antennas had to cover most of the sphere around CHAD. All antennas were denominated as printed rectangular spiral antennas. The reflection coefficient and the far-field polar plots of the antennas can be seen in Figure 6. The realized gain is -6 dBi and the bandwidth is 12 MHz. When testing the communication between two Nano IPn920 platforms (separated by 100 m) using the antennas in open space, the data rate can reach 100 kB/s. Using 900 MHz frequency requires special permission from the Swedish telecom authorities, even when transmission was to be at an altitude of several km and below one minute.

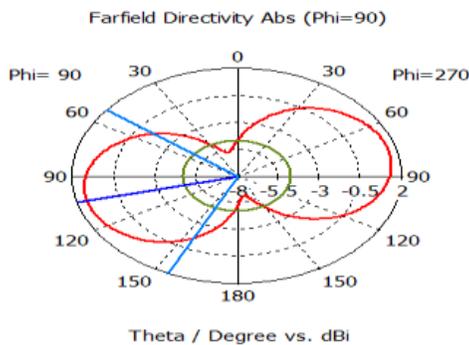


Figure 6: Polar plot of 915MHz antenna

III. LAUNCH

III.I Launch Campaign

The REXUS 11/12 launch campaign took place at SNSB's ESRANGE close to Kiruna in Northern Sweden from the 12th until the 23rd of March 2012. During the first week the Suaineadh experiment was prepared to be integrated with the other experiments and the service module from DLR MORABA. After various bench-tests and a flight simulation the Suaineadh experiment was ready for the first hot countdown on the 19th of March 2012.

III.II Launch & Mission

On the launch day, the weather added no constraints to launch. The hot countdown of T-2 hours began at 1300 local time. The Countdown proceeded without any major delays. All experiments were powered up at T-600 s, At T-565 s Suaineadh's ground support software received the first telemetry that all systems were up and running. At T-240 s the SODS (Start Of

Data Storage) signal was given and received. The switch of REXUS rocket from external power to internal batteries, which are placed in service module, was performed at T-120 s. At T=0 s REXUS 12 launched and the Suaineadh ground support successfully received notification about the LO (Lift Of) signal. SOE signal (Start of Experiment) was given at T+26 s. Suaineadh was ejected from the nosecone position of the REXUS 12 rocket at T+80 s, the ground support software indicated successful ejection, further corroborated by post mission analysis of recovered pictures. After ejection, the amount of available memory onboard the rocket should decrease with data rate of wireless link (up to 100 kB/s), which would indicate that a wireless connection between CHAD and the DSM was established. Only minor changes of free space were observed. 420 s into the flight, the Suaineadh ground support software and all the other ground stations ceased to receive further telemetry from REXUS 12. Approximately 30 minutes after lift off, the recovery helicopter team began its search for the REXUS 12 payload and Suaineadh's CHAD. After a two hour search, only the REXUS 12 payload could be recovered. Investigations into the lost signal showed that the parachute of the REXUS 12 payload malfunctioned and therefore the radio beacon were unable to function. The non-parachuted REXUS 12 payload hit the ground at terminal velocity.

III.III Postflight

After the recovery of the REXUS 12 payload, the Suaineadh team disassembled the DSM. Unfortunately, the helicopter team was unable to detect the radio beacon from CHAD and therefore did not recover the ejected section. Due to the REXUS 12 parachute malfunction, the REXUS 11 launch was postponed until November 2012.

IV. RECOVERY MISSION

IV.I Overview

The Suaineadh team embarked on a recovery mission from the 17th until 26th of August 2012 in order to search for the missing CHAD section. Shortly after the launch campaign, the experts from DLR, SNSB, ESA and ESRANGE provided the Suaineadh team with the GPS ground track of the REXUS 12 rocket, the GPS coordinates of the impact zone from the helicopter team that recovered the payload, rocket motor and nose cone. The Suaineadh team was also provided with the acceleration profile of the REXUS 12 rocket during the mission and the recovery video from the payload prior to impact.

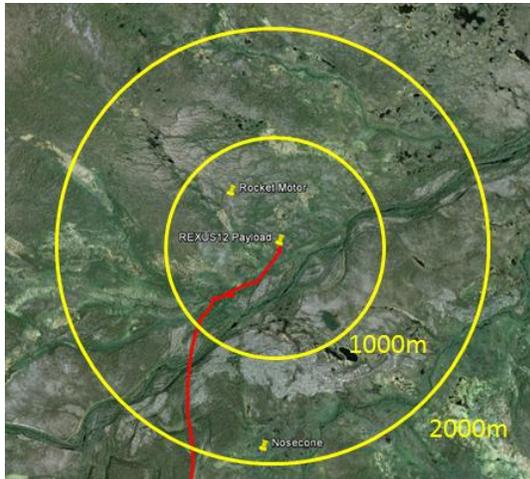


Figure 7: Landing position of REXUS12 payload, nosecone and rocket motor (source Google Earth)

With this data it was possible to estimate the approximate impact location of CHAD. The recovery expedition consisted of Suaineadh launch campaign team members and new partners from across Europe. The search began at the impact location of the REXUS payload employing a spiral search pattern. Due to the fact that the parachute of the REXUS 12 payload did not deploy, it could be assumed that CHAD may be located within close proximity to the impact site of REXUS 12. Figure 7 shows the location of the rocket motor (68.341017N, 20.979600E), the REXUS12 payload (68.336983N, 20.990333E) and the nosecone (68.320267N, 20.986750E). The ground track of REXUS12 runs along 51 km from Esrange to the impact zone (red line in Figure 7). The selection of the separation spring and bench tests on the ground indicated a velocity differential between Suaineadh and the rocket of approximately 1 m/s at Suaineadh separation. Due to the fact that the parachute of the REXUS rocket malfunctioned, the Suaineadh experiment and the REXUS payload should have followed a similar ground plane trajectory up until impact. The nose cone and the rocket motor were ejected in opposite directions. It cannot be predicted if the impact location of the Suaineadh experiment lies between the REXUS payload and the nose cone or the payload and the motor. It was decided to establish a base camp at the impact location of the REXUS 12 payload. Figure 7 shows that the payload impact position is in between the nose cone and the rocket motor location. The rocket motor impacted in a north-ward distance of 631 m with respect to the REXUS12 payload and the nose cone impact position is within a south-ward distance of 1880 m. The base camp was used as an origin point for daily missions to various locations of interest.

IV.II Mission

The recovery crew parked at Järämä, the Sami settlement north of the suspected impact zone. The 5 km walk to the base camp already showed the high density of swamp land. On the way to the base camp the REXUS12 rocket motor was found. The base camp was set up around 400m north of the original set up place because of swamp around the payload impact zone. In the following six days the recovery team tried to cover as much area as possible through swamps, forests, bushes and rivers. At the end of the week the only piece of Suaineadh that was found was a bracket which was mounted to the magic hat onboard the rocket (Figure 8).



Figure 8: Only Suaineadh part found during recovery mission: bracket from magic hat

V. RESULTS

After the recovery of the rocket on the 19th of March, 22 pictures were recovered from the internal storage module on the DSM. These 22 received pictures were recorded by the four cameras on the ejected section CHAD. These four cameras were separated by 90 degrees and therefore observed in full 360 degrees. Figure 9 shows one of the first pictures received after separation. The curvature of the Earth can be seen in two frames and the Earth and the blackness of space in the other two. The recording of the images started in between 15 to 20 s after the ejection from the rocket, depending on how long the reaction wheel took to spin up CHAD to the required spin rate. By sequencing the received images, it was possible to conclude that CHAD was indeed spinning and therefore it is concluded that the reaction wheel was operational. In the last two frames of the received images the successful release of the daughter sections can also be seen, but that it is at this point that the images cease. The reason of the data loss was likely a result of tumbling of either the ejected experiment or the REXUS12 rocket after separation.

Based on the information received over the wireless link it can be said that all the systems worked nominally at least up to the point of transmission loss and that it is suspected that a more complete data set could be stored on the CHAD data storage.



Figure 9: Picture recorded from ejected section shortly after ejection (cameras 90° apart)

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VII. CONCLUSIONS

On the 19th of March 2012 the Suaineadh experiment was launched into space onboard REXUS 12. The Suaineadh experiment had the purpose of deploying a web in space. Unfortunately, the ejected section could not be recovered by the recovery helicopter team. 22 pictures were received over the wireless link between the experiment and the REXUS rocket confirming that the experiment was fully functional with initiated spinning up after ejection. In the last two frames that were received, it could be seen that the daughters were successfully released. The wireless connection was interrupted before web deployment, likely caused by tumbling of the experiment or the rocket.

A recovery mission in mid August at the landing site was not able to recover the ejected section on which it is hoped that more data should still be stored. There remains one last hope of recovering Suaineadh during to the start of the hunting season within the impact area.

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