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EIRSAT-1: The Educational Irish Research Satellite

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***Abstract*—The Educational Irish Research Satellite, 'EIRSAT-1', is a collaborative space project that aims to build, launch and operate the first ever Irish satellite. The EIRSAT-1 spacecraft is a 2U CubeSat incorporating three novel experiment payloads: GMOD, a gamma-ray detector; EMOD, a thermal management coating demonstration; and WBC, an attitude control algorithm. The spacecraft is currently under construction at University College Dublin and will delivered to ESA in late 2019.**

Keywords—CubeSat; gamma-ray; astronomy; materials; control

I. Introduction

EIRSAT-1 is a 2U CubeSat which is being developed by students at University College Dublin (UCD). It will be Ireland's first satellite.

The project is primarily educational in nature and aims to:

- develop the know-how of the Irish higher education sector in space science and engineering, by supporting student teams to build, test and operate the satellite;
- address skills shortages in the space sector by fostering collaboration between student teams and industry through the launch of three payloads that use innovative Irish technology;
- inspire the next generation of students towards the study of science, technology, engineering and mathematics (STEM) by launching the very first Irish satellite.

To achieve these educational aims, the EIRSAT-1 team have developed the following scientific and technical objectives for the spacecraft:

- study gamma-ray bursts (GRBs) using a bespoke gamma-ray detector to assess the capability of this technology for use on next-generation gamma-ray astrophysics missions;
- perform the first measurements on the performance of SolarWhite and SolarBlack novel surface treatments in a low Earth orbit environment;
- implement and test a wave-based control algorithm to determine its potential as a viable alternative to standard attitude determination and control methods.

The project was initiated by the Space Science and Materials Research group within the UCD School of Physics. The group has a long track record of space science and astrophysics research, especially GRBs and the development of instruments and technologies related to the detection of gamma-rays. EIRSAT-1 was proposed as a mission concept to the European Space Agency (ESA) in response to their Fly Your Satellite! (FYS) announcement of opportunity.

EIRSAT-1 brings together several strands of the Space Science group's research and educational activities. An R&D programme into the development of a gamma-ray detector using novel sensors demonstrated that the footprint of such a compact detector would be compatible with a CubeSat platform. In parallel, an educational CubeSat called 'EduCube' had been developed to train students of UCD's MSc in Space Science & Technology in systems engineering [1].

Collaboration with the UCD School of Mechanical and Materials Engineering led to the inclusion of two additional payloads. The materials experiment (EMOD) is based on UCD patented technology, while the Wave-Based Control (WBC) payload implements a novel approach to motion control which has been developed by the UCD Dynamics and Control group.

After proposal submission, the EIRSAT-1 student team was invited by ESA Education to participate in a selection workshop at ESTEC in early May 2017 to pitch their idea to a selection panel of spacecraft experts from ESA. Shortly after the workshop, EIRSAT-1 was announced as one of six CubeSats selected for the FYS programme.

II. Team Organisation

EIRSAT-1 is primarily a student-driven mission. Students are supported to take responsibility, make decisions and own the relevant parts of the programme. Students are given prominence in outreach and publicity. There is a management structure in place which is composed of a Management Board, a Mission Team, and an Academic Oversight Board. The Management Board is composed of academics from the Schools of Physics and Mechanical and Materials Engineering, student leaders, and a space-industry mentor. The Mission Team comprises graduate students working on the project and is responsible for the implementation of EIRSAT-1. Undergraduates, visiting students, and interns join the Mission Team as associate members. The Academic Oversight Board comprises the supervisors of the students who are full members of the Mission Team. The EIRSAT-1 team has adopted a policy which governs this management structure and which includes a code of practice regarding "Equality, Diversity & Inclusion" that outlines the team's ethos towards team interactions, diversity of opinion and gender balance.

The EIRSAT-1 Mission Team is currently composed of 10 students. A further 15 students that were involved in the design of EIRSAT-1 up to Critical Design Review stage. The students come from Physics, Mathematics, and Engineering backgrounds and 40% of the current Mission Team is female.

III. THE SPACECRAFT

The EIRSAT-1 spacecraft is based on Commercial Off-The-Shelf (COTS) CubeSat hardware components supplied by Clyde Space, augmented with payloads, electronic subsystems, and mechanical components, which have been designed and will be manufactured at UCD with input from industry partners. The spacecraft consists of typical electronic CubeSat subsystems which will be supplied by Clyde Space: Attitude Determination and Control System (ADCS), Electrical Power System (EPS), On-Board Data Handling (OBDH), Communications (Comms). EIRSAT-1 has two hardware payloads, the Gamma-ray Module (GMOD), the ENBIO Module (EMOD); and a software payload, Wave Based Control (WBC).

The EMOD payload includes an assembly which requires special accommodation on the exterior of the spacecraft, rendering most COTS CubeSat structures unsuitable. A Clyde Space 2U structure has been heavily modified to meet these requirements.

The design of the spacecraft was initially driven by the requirements of the GMOD payload. In order to accommodate the payload size along with the required supporting subsystems, it was determined that a 2U CubeSat would be required. Analysis of the GMOD performance (Fig. 5) indicated that a zenith pointing attitude would be optimal but that the mission would be feasible in any attitude configuration. Reaction wheels were considered and while there was sufficient mass budget and space to accommodate them, there would be insufficient power generated with body-mounted solar arrays. To use reaction wheels, the spacecraft would require deployable solar arrays. De-orbit simulations were performed for 2U configurations both with and without deployable arrays. As EIRSAT-1 will be launched from the International Space Station (ISS), atmospheric drag at this altitude, means that the lifetime of a mission with deployable arrays would be significantly reduced. These analyses demonstrated that reaction wheels are infeasible for a spacecraft of this size in a 400 km altitude Low Earth Orbit. An exploded view of the final EIRSAT-1 configuration is shown in Fig. 1, while a labelled view of the internal components is shown in Fig. 2.

A. ADCS

Although EIRSAT-1's primary objectives do not require attitude control and are achievable even when the spacecraft is tumbling, zenith pointing gives the best possible performance for the GMOD payload and has been determined to be the best compromise between the needs of both the EMOD payload and the solar arrays to be exposed to sunlight.

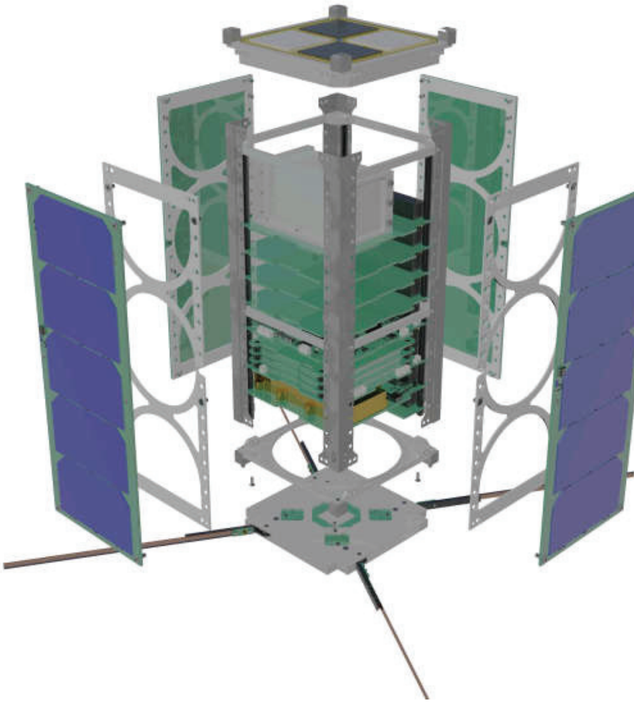

Fig. 1. Exploded view of the EIRSAT-1 spacecraft hardware.

The Attitude Determination and Control System (ADCS) consists of a magnetorquer based control system. It uses a Clyde Space ADCS Motherboard, which interfaces with magnetic coils that are integrated into the solar array PCBs, hence providing 2 × X-direction magetorquers and 2 × Y-direction magnetorquers. The baseline control algorithm for the ADCS is custom algorithm from Clyde Space designed specifically for EIRSAT-1 as this will be the first mission in which Clyde Space have performed magnetic-only control for a 2U spacecraft or for zenith/nadir pointing. The ADCS motherboard includes magnetometers and gyroscopes, utilises several external sensors such as coarse sun sensors built in to the solar arrays, and can incorporate information from the GPS module in the OBC. This hardware will also be used for the WBC experiment payload.

B. EPS

The Electrical Power System (EPS) consists of a Clyde Space 3rd generation 3U EPS motherboard, a Clyde Space 30Whr Standalone Battery, and 4 × 2U body-mounted solar cell arrays. The motherboard is designed for CubeSats larger than 1U but without deployable solar panels. The motherboard can provide power at battery voltage, 12V, 5V, and 3.3V, with latching current limiting over-current protection. Power may be supplied either directly or via switch-able power distribution modules, which are used to control power to the hardware payloads. The 30Whr battery has existing flight heritage with CubeSat deployers, such as NanoRacks, and is compatible with ISS manned flight requirements having been certified to NASA EP-Wi-032 standards. The battery has a 2s3p configuration and features additional built-in over-current and under-voltage protection independent of that functionality in the EPS module. The flight activation inhibits are implemented as MOSFETs in the battery. The solar arrays are placed on the X and Y faces of EIRSAT-1. Each array features 5 × Spectrolab UTJ cells in a

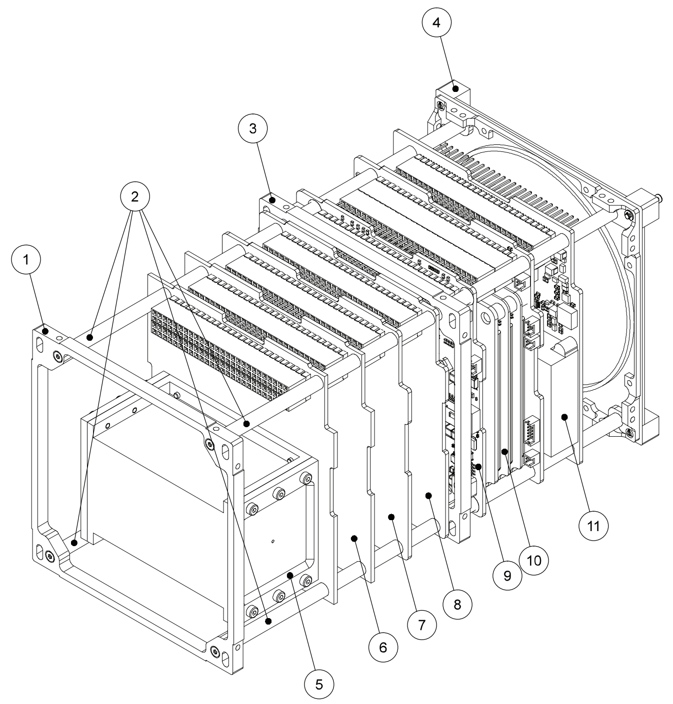

Fig. 3. Internal components. 1: Top support bracket, 2: PCB support rods, 3: Mid support bracket, 4: -Z end-cap, 5: GMOD, 6: EMOD motherboard, 7:ADCS, 8: OBDH, 9: EPS, 10: Battery, 11: Comms.

5s1p configuration for an optimal power generation of 5W per array.

C. *OBDH*

The On-Board Data Handling (OBDH) system is a Clyde Space Nanosatellite On-Board Computer (OBC). The OBC is based on a MicroSemi Smart Fusion 2 System on Chip. As the Smart Fusion 2 is flash-based, it is inherently SEU tolerant. The OBC includes other protections for radiation effects such as magnetoresistive RAM and a hardware watchdog. The OBC features a 150MHz ARM Cortex M3 processor, 8MB of EDAC protected MRAM, 4GB of NAND flash, a Micro SD card slot, and a GPS receiver. The FPGA fabric of the Smart Fusion 2 is used to create the various interfaces between the OBC and the other subsystems. EIRSAT-1 uses i2c for all inter-subsystem communication with 3 separate i2c buses used for system, comms, and payloads.

IV. GMOD - The Gamma-ray Module

GMOD is an experiment payload designed to detect cosmic gamma-ray phenomena such as GRBs which are short-lived intense flashes of gamma-rays associated with the collapse of very massive stars in the distant universe and with the merger of neutron stars [2]. It is based on the design of UCD Gamma-Ray Detector (GRD) which was developed by the Space Science and Materials Research group under contract to ESA. The GRD design utilises a 28 mm × 28 mm × 20 mm LaBr3 scintillator coupled to a 4 × 4 array of 36 mm2 SensL B-series silicon photomultipliers (SiPMs). A detailed description of the GRD can be found in [3].

GMOD is therefore the latest detector design in a series which have been developed at UCD in order to address the technical challenges of building sufficiently advanced next-generation high-energy astrophysics missions to meet the scientific requirements while being of manageable mass and complexity. These detectors benefit from several novel enabling technologies which have recently been made available to the scientific community, e.g. modern high-efficiency scintillators, SiPMs which replace bulky, high-voltage PMTs and for GMOD a dedicated SiPM readout ASIC. The SiPM Readout ASIC (SIPHRA) has been developed by Norwegian company Integrated Detector Electronics AS (IDEAS) based on the requirements of operating the UCD GRD in space [4]. SIPHRA has been incorporated into the GMOD design.

A. *Detector Hardware*

The detector assembly consists primarily the scintillator, SiPMs, the SIPHRA ASIC used to process and digitise the analog signals from the SiPMs, and a light-tight detector enclosure. An exploded view of the detector assembly is shown in Fig. 3. The scintillator is a 25 mm × 25 mm × 40 mm Cerium Bromide (CeBr3) crystal supplied by Scionix. The CeBr3 crystal is supplied by the manufacturer enclosed within a hermetically sealed unit. The housing includes a quartz window, exposing a 25 mm × 25 mm face of the crystal, allowing the scintillation light to exit.

The scintillation light is measured using 16 J-series 60035 SiPMs from SensL. The SiPMs are arranged in a 4 × 4 array which gives a very good match to the scintillator size. The array is a custom design implementing a common-anode configuration with all SiPM anodes being connected to a common negative bias supply via independent low-pass filters. The cathode of each SiPM is connected directly to the ASIC inputs via board-to-board connectors.

The analog signals from the SiPMs are digitised using the SIPHRA ASIC. SIPHRA is a 16 channel SiPM read-out IC which is used as a pulse height spectrometer in GMOD. Each of the 16 SiPM inputs have a current integrator, pulse shaper, and track & hold circuit. Additionally, a 17th channel provides the sum of the 16 inputs. Readout can be triggered by thresholds on any of the 17 channels. When triggered, the heights of all 17

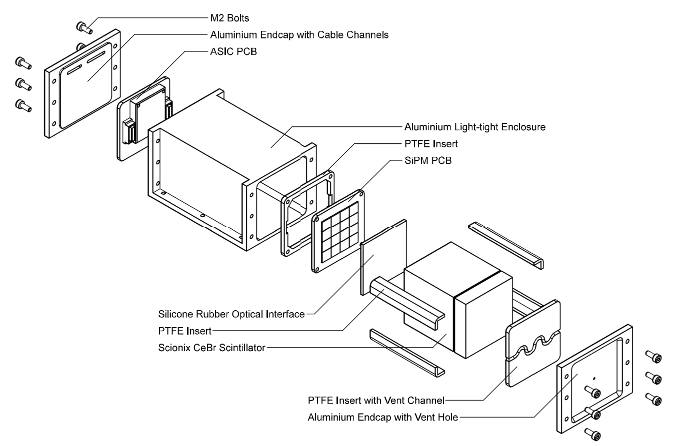

Fig. 2. Exploded view of the GMOD detector assembly.

channels are digitised by a 12-bit ADC. The 17 pulse values and trigger information are output via a high-speed serial output. SIPHRA is configured by programming its configuration registers via SPI. Configuration options include enabling of individual channels, enabling triggering and thresholds on individual channels, input offsets, pulse shaping parameters, and readout options. SIPHRA has specifically been designed for use in space applications with latch-up immunity, single event upset mitigation, and error correction, and low-power considerations. It is not expected that SEU will occur even in high radiation encountered in the South Atlantic Anomaly.

B. *Expected Performance*

GMOD's sensitivity has been simulated using the MEGAlib toolkit [5]. A simplified mass model of the EIRSAT-1 spacecraft was created and the response of the GMOD detector to a GRB spectrum with a slope of -1.1 was simulated. Fig. 4 shows the effective area of the GMOD detector as a function off-axis angle and azimuth of the source GRB. The effective area is calculated at the number of detected counts in the 50 - 300 keV range divided by the GRB flux. For each GRB in the BATSE 4B catalogue, the detection significance has been calculated. The cumulative detection significance distribution is shown in Fig. 5 at a range of spacecraft attitudes from zenith (0 degrees) to nadir (180 degrees).

Assuming the optimal zenith pointing attitude strategy and that for a single detector we would use a signal threshold of 10 sigma in order to avoid false positives, it is expected that GMOD will detect approximately 20 GRBs per year. Coincident GRB detections with other high-energy missions would allow for a lower detection threshold and therefore significantly increase the number of observed GRBs.

V. EMOD - The ENBIO Module

EMOD is an experimental payload which is designed to demonstrate and test the performance of SolarBlack and SolarWhite spacecraft surface treatments developed by ENBIO. SolarBlack and SolarWhite have been developed by ENBIO for use on ESA's Solar Orbiter mission. EMOD will measure the performance of these coatings using four 'thermal coupons'

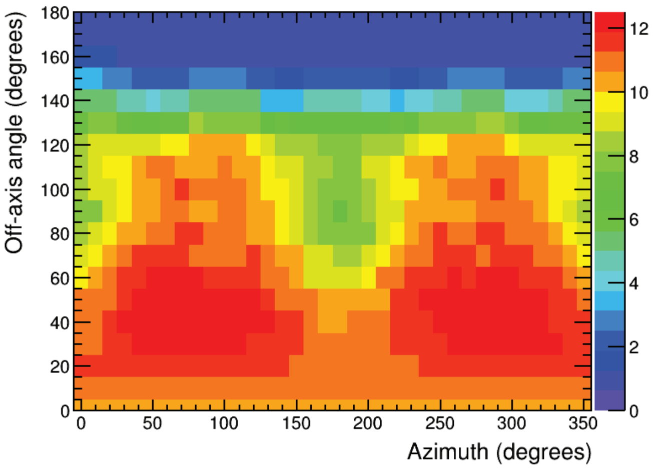

Fig. 5. Simulated effective area of the GMOD detector as a function of off-axis angle and azimuth of the source GRB.

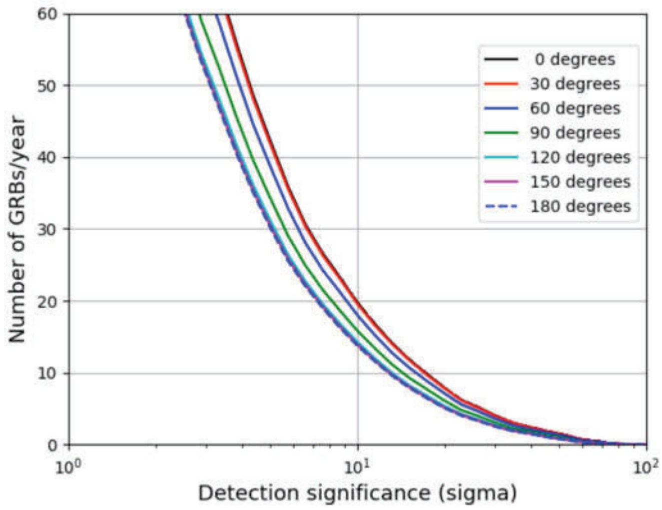

Fig. 4. Cumulative detection significance distribution of the GMOD detector for a range of spacecraft attitudes from zenith (0 degrees) to nadir (180 degrees).

which are attached to the +Z face of the spacecraft. As EIRSAT-1 orbits the Earth, the thermal coupons will be exposed to periods of solar illumination followed by eclipse which will thermally cycle the coupons. Though continuous monitoring of the temperature of the coupons as they are thermally cycled, it will be possible to characterise the coating performance and degradation.

A. *Thermal Coupon Assembly*

The coupons are made of aluminium 2024 and measure 35 mm × 35 mm × 1 mm with two coated in SolarBlack and two coated in SolarWhite. Each coupon has a RTD adhesively attached to its underside to monitor the temperature. It is important that the coupons are as thermally isolated as possible to prevent thermal energy from the spacecraft itself from influencing the temperature of the coupons. The coupons are therefore supported in a 'Thermal Coupon Assembly' (TCA) which is designed to support the coupons while insulating them from the spacecraft. The TCA is shown in Fig. 6. The coupons are suspended above a Multi-Layer Insulation (MLI) blanket using PEEK support struts. The MLI blanket and the support

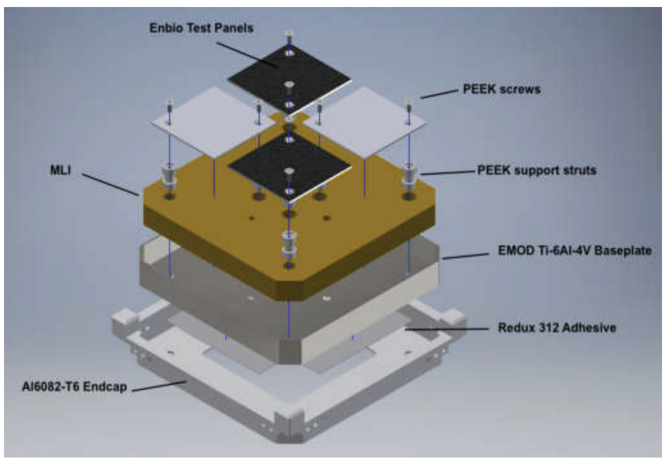

Fig. 6. Exploded view of the EMOD Thermal Coupon Assembly.

struts themselves are in turn supported on a titanium baseplate. The baseplate is adhesively bonded to a special Aluminium 6082 structural end-cap, demonstrating another ENBIO product, an adhesive primer which is based on the same process used to apply the SolarBlack and SolarWhite coatings.

VI. WBC - Wave Based Control

WBC is a novel motion control scheme that has been developed by the Dynamics and Control group at the School of Mechanical and Materials Engineering at UCD [6,7]. The WBC approach is particularly effective in controlling flexible or under-actuated systems with poorly modelled dynamics. WBC has been applied to simulations of the International X-ray Observatory and the DELIAN robotic arm as part of an ESA study and has been tested experimentally in parabolic flight. EIRSAT-1 will be the first time that WBC has been used in space.

During a series of tests, WBC will take control of EIRSAT-1's attitude to perform a number of manoeuvres designed to evaluate the performance of the control scheme. The WBC payload takes the form of a software component which runs on the OBC. The ADCS motherboard will be placed into a test mode which disables the COTS control algorithm and allows direct control of the magnetorquer actuators via i2c commands sent from the OBC.

While WBC is a motion control algorithm, as part of the WBC experiment on EIRSAT-1, students will also produce an attitude determination algorithm. This algorithm will also run as a software component on the OBC, interfacing with the ADCS motherboard to monitor sensor values. Before the WBC attitude control test manoeuvres are performed, this attitude determination part of the WBC experiment will be operated in parallel to the COTS ADC algorithm to evaluate its performance. The control test manoeuvres may then be performed using attitude solutions determined by the student-written algorithm or using solutions determined by the COTS algorithm.

Throughout the WBC control test manoeuvres, a Control Authority Watchdog will monitor the spin rate and several other parameters such as elapsed testing time. Control will revert to the COTS ADCS algorithm if any of these parameters exceeds predetermined bounds. The Control Authority Watchdog is also responsible for preventing the spacecraft from starting a WBC experiment in certain situations, e.g. if the spacecraft is in safe mode, or if the battery depth of discharge is too high.

WBC will be evaluated based on pointing accuracy, slew rate, settling time, and power consumption.

VII. The Future

Following close-out of the CDR process, the team will be focusing on production of the spacecraft engineering model and preparing for the ambient test campaign. It is anticipated that following successful spacecraft production, ambient and environmental testing, EIRSAT-1 will be delivered to ESA in late 2019. Once it has passed its Flight Readiness Review, the satellite will be launched to the ISS for deployment into Low Earth Orbit. Simulations indicate that EIRSAT-1 will de-orbit after a period of between 9 months and 2 years.

The educational aspects and opportunities of the EIRSAT-1 project will not end when the completed spacecraft is delivered for launch or even when the spacecraft de-orbits. Throughout the mission lifetime, spacecraft and science operations will be performed by students. As the mission is based around science and in-orbit engineering demonstration objectives, future generations of students will benefit from operating the spacecraft and its experiments, and from the data it produces for many years. This will allow students to learn about high-energy astrophysics, space science, and space engineering in an engaging manner which has not previously been possible in Ireland.

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