Sheffield University Nova Rocket Innovative Design Engineering (SUNRIDE)

Conference Paper · October 2019

14 authors, including:

Yun-Hang Cho
The University of Sheffield

Ankita Kalra
Eindhoven University of Technology

Georgios Rontogiannis
KTH Royal Institute of Technology

Gopika Narayanankutty
The University of Sheffield

SHEFFIELD UNIVERSITY NOVA ROCKET INNOVATIVE DESIGN ENGINEERING (SUNRIDE)

Yun H. Cho[1], Jae H. Lim[1], Ankita Kalra[1], Vishan Nair[1], Georgios Rontogiannis[1], Iulius-Vladimir Seniuc[1], Andrea Schiona[1], Gopika Narayanankutty[1], Konstantinos Ioannou[1], Matthew G Lennard[1], Benjamin Appleby[2], Gary Verth[3], Istvan Ballai[3], and Viktor Fedun[4]

[1]*SunrIde team, Sheffield Space Initiative, University of Sheffield, Sheffield, South Yorkshire, United Kingdom, Email: yun-hang.cho@sheffield.ac.uk*
[2]*Sheffield Hallam University, Sheffield, South Yorkshire, United Kingdom*
[3]*Plasma Dynamics Group, School of Mathematics and Statistics, University of Sheffield, Sheffield, South Yorkshire, United Kingdom*
[4]*Plasma Dynamics Group, Department of Automatic Controls and Systems Engineering, University of Sheffield, Sheffield, South Yorkshire, United Kingdom, Email: v.fedun@sheffield.ac.uk*

ABSTRACT

Sheffield University Nova Rocket Innovation Design Engineering (SunrIde) was the first ever student-led rocketry team from the UK to participate in Spaceport America Cup (SA Cup) 2018, the largest space industry-backed annual rocketry engineering competition in the world. The main objective of the SunrIde was to design and build a high-power reusable rocket in the 10,000 ft above ground level (AGL) category with commercial-off-the-shelf (COTS) solid propulsion system. The rocket should reach the projected apogee within the smallest margin possible while carrying either a dead weight 3-unit CubeSat payload or a scientific experiment, both weighing no less than 8.8 lb (4 kg), with a 5% allowance.

Figure 1. Solidworks CAD render

The University of Sheffield team launched and recovered a self-designed rocket that reached an altitude of 10,017 ft (3,053 m) above ground level (AGL). It won the James Barrowman Award for Flight Dynamics with the most accurate altitude prediction at 99.83%. This success sets an important precedent for aspiring STEM students across the UK by encouraging them to expand their engineering skills through practical projects and increases the UKs high-power rocketry presence.

Key words: High-power rocketry; UKRA; Spaceport America Cup; SunrIde; University of Sheffield..

NOMENCLATURE

μ	Dynamic viscosity of fluid
ρ	Air density at 30,000 ft. (9144 m) = 0.467 kg/m^3
A	Inner cross-sectional area of the air-frame/compartment (in^2)
C_D	Estimated drag coefficient of an elliptical parachute = 1.50
F	Force needed to eject the compartment (N)
g	Gravitational acceleration = 9.81 m/s^2
M	Mach Number
m	Zero fuel rocket mass = 25 kg
m_b	Mass of black powder in grams.
R	Ideal Gas constant = 266 in.lbf/lbm
S	Parachute area
T	Static Temperature (Ambient)
T_b	Combustion temperature of the black powder.
V	Volume of the parachute compartment (in^3)
v	Velocity of fluid
V_D	Rocket descent speed (dependent on the stage of descent) = 30 m/s

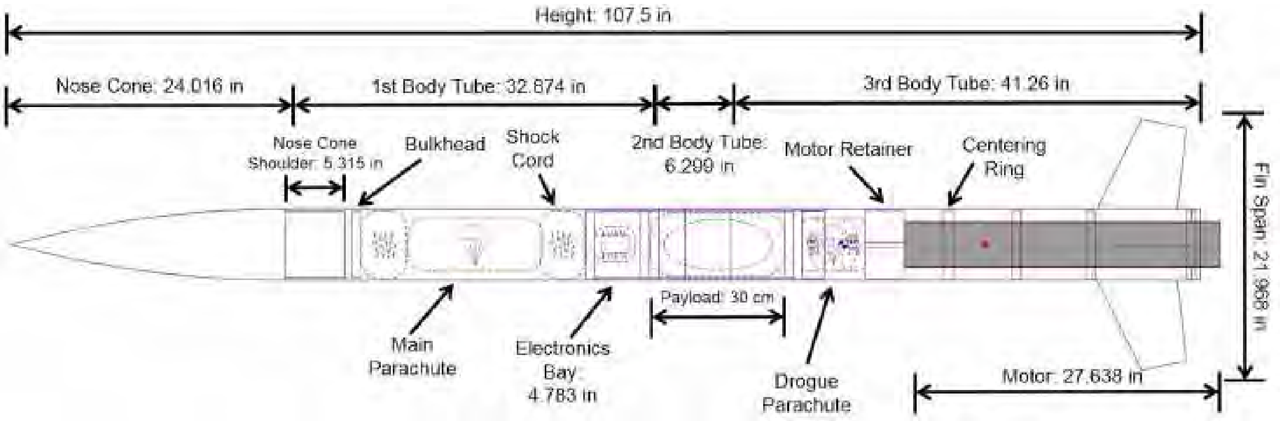

Figure 2. Rocket Architecture and Major Subsystems

1. INTRODUCTION

The SunrIde (Sheffield University Nova Rocket Innovative Design Experiment) team is a student-led rocketry team at the University of Sheffield. Inspired by the success of project SunbYte (a student led REXUS/BEXUS experiment [1]), SunrIde was founded in October 2017 with the purpose of competing in the 2018 Spaceport America Cup.
The SunrIde team consisted of 14 students from first year undergraduates to postgraduate master students. They came from five Engineering departments: Automatic Control and Systems Engineering (ACSE), Mechanical Engineering, Materials Science, Aerospace Engineering, Civil Engineering as well as the Faculty of Science's School of Mathematics and Statistics. The SunrIde project is primarily supervised and hosted by the Department of Automatic Control and Systems Engineering with support from the School of Mathematics and Statistics.
The team is funded by the Faculty of Engineering, Alumni Foundation and a Widening Participation grant at the University of Sheffield. Together with four other teams of the Sheffield Space Initiative, the projects enable a wide range of students to practice professional and technical skills from rovers and satellites to rockets.
The 2018 SunrIde team competed in the 10,000 feet category with a commercial-off-the-shelf solid motor. All the simulations of the rocket were conducted using the OpenRocket software with CAD modelling sponsored by Solidworks.

2. ROCKET DESIGN

2.1. Propulsion

For the 4 kg (8.8 lb) payload to be transported by the rocket up to an altitude of 10,000 feet, it was decided to use a single-stage M-class solid motor. The rechargeable Cesaroni Pro98 -9994M3400-P motor was selected to due its high average impulse and fast burnout time of 1.36 sec (Figure 3). The dimensions for this single-stage M-class motor are 98mm (3.86 inches) for the diameter and 702mm (27.6 inches) for the length. The motor was fixed in place using three centering rings consisting of 18 mm (0.71 inches) plywood and an aluminium motor retainer. This was calculated to be strong enough to withstand loads under launch and distribute it to the rest of the structure.

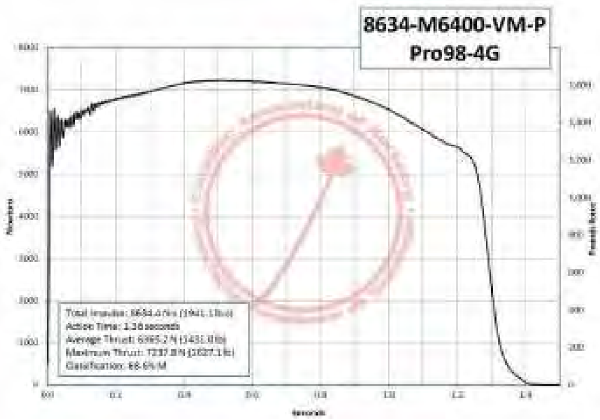

Figure 3. Cesaroni 8634-M6400-VM-Thrust curve

2.2. Air frame

The airframe consists of fiberglass coated, kraft phenolic tubing measuring 155.2 mm (6.11 inches) outer diameter and 2.79 mm (0.11 inches) wall thickness. The aft and fore section of the rocket are held together by a kraft phenolic tube coupler and contains both the payload and the electronics bay. The section of the airfame which is glued at the middle of the coupler tube measures at least 1 caliber (1 body tube diameter) on each side of the tube to ensure structural stability in flight. The nose cone was aerodynamically ogive shaped and constructed of fiberglass reinforced plastic with a wall thickness of 4 mm (0.16 inches). The fins stabilize the ascent of the rocket and prevent it from spinning while withstanding the aggressive aerodynamic forces of a supersonic launch. The rocket is equipped with 4 equally spaced fins around the airframe. This is mechanically mounted into an independent block, sliding inside the rockets aft section, along the motor tube, and through slits in the airframe. The fin block consists of two specially designed centering rings for the motor tube that compress all 4 fins longitudinally using threaded rods tightened from both ends. Additionally, dedicated aluminium square tubes were glued to the fin tabs and held apart by M6 threaded rods to act as spacers. These spacers and the centering rings slits ensure minimal transversal displacement and prevent the fins from buckling under stress. As a precaution against radial displacements, one end of the fin tab continues on the interior of the airframe tube after the slit. The fin block is fixed to the airframe using eight 3.2 x 40 mm wood screws driven into the lower centering ring. OpenRocket simulations showed that the optimal fin profile is the clipped delta shape. To prevent the fins from catastrophic fluttering mid-flight, emphasis was placed on their rigidity while minimizing mass and cross section. Among the alternatives considered for testing were glass fiber reinforced 6 mm plywood and some 2.5 mm aluminium sheets bonded together (although the latter is relatively heavier). Since preliminary epoxy lamination techniques for both sides of test plywood fins were less successful, another solution consisted of a glass fiber layers glued between two sheets of 3 mm thick plywood. The exterior edges of the fin were later smoothed to reduce drag.

2.3. Recovery subsystem

The recovery system is a dual ejection system based on the two-stage separation of the rockets airframe. Each separation stage is achieved by detonating two black powder pyrotechnic charges. These pressurize the two parachute compartments enough for the deployment to occur. The three separate rocket sections are held in place by structural inner tubes, each two body diameters in length. These are rigidly fixed to one airframe tube and friction fitted with shear pins to the other. The main parachute deployment took place at the nose cone when at apogee (approx 10,047 ft). The drogue parachute deployment occurred at the aft booster section at a lower altitude of 1,250 ft above MSL (Mean Sea Level). The three individual parts of the rocket were connected to the parachutes using rated shock cords. These absorb deployment forces and differ in length to prevent mid air, airframe collisions. The firing of pyro separation charges is controlled by a StratologgerCF programmable flight altimeter. For contingency, a redundant Eggtimer system was also installed. The altimeter precisely controlled the timing of the pyro charge cup to release the chutes. The design and dimension of the drogue and main parachutes are discussed more in the parachute design section.

2.4. StratologgerCF Deployment Altimeter

The StratologgerCF Altimeter was used in order to record the maximum altitude and the velocity achieved by the rocket. This altimeter comes with two output ports for chute deployment for drift minimization by opening the main parachute closer to the ground. The StratologgerCF gives the flexibility to deploy the parachutes at a chosen altitude. During testing, temperature, altitude and battery voltage readings from the flight was recorded at rate of 20 samples per second by the StratologgerCF. Critically, the accurate StratologgerCF also contains a built-in voltmeter allowing the altimeter to log up to 15 flights (18 minutes each) even after the battery has been removed.

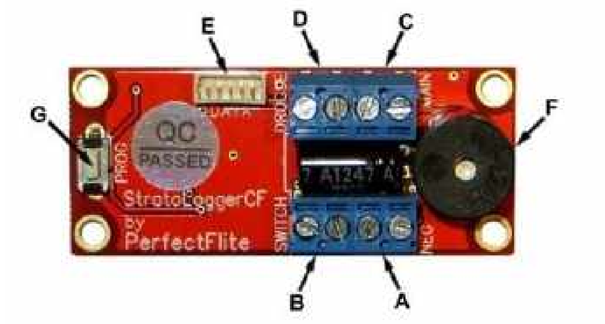

Figure 4. Stratologger

A. Battery Terminal Block.
B. Power Switch Terminal Block.
C. Main Ejection Output Terminal Block.
D. Drogue Ejection Output Terminal Block.
E. Data I/O Connector.
F. Beeper: Audibly reports settings, status, etc. via a sequence of beeps.
G. Pre-set Program Button.

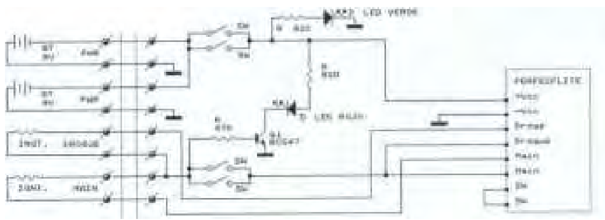

Figure 5. Stratologger circuit diagram

Figure 5 above shows the circuit diagram that powered the Stratologger. It contains the main power switch, an arming switch, and LED for visual identification for recovery. The Eggfinder TRS uses the HOPE RF module for the GPS tracking and the transmitter sends the data to the receiving computer which uses a 5 dB dipole stick antenna to retrieve the signal every second.

Table 1. Static pressure sampling holes

AvBay Diameter	AvBay Length	Single Port Hole Size	Four Port Hole Size
1.6”	6”	.032”	.020”
2.1”	6”	.048”	.025”
3.0”	8”	.113”	.057
3.0”	12”	.170”	.085”
3.9”	8”	.202”	.101
3.9”	12”	.302”	.151”
5.5”	12”	-	.286”
7.5”	12”	-	.5”

2.5. Static Pressure Sampling Holes

Sampling holes were drilled into the avionics bay aieframe to allow in-flight, external air pressure sampling by the altimeter from within the airframe. The holes are located away from the nose cone shoulder and other body tube irregularities to minimize pressure disturbances from turbulent airflow over the body tube. The four hole design minimized pressure variations due to wind currents perpendicular to the rockets direction of travel. Each hole was half the size of the previous single hole design to maintain a similar same hole area. Four static pressure sampling holes was radially placed in the avionics bay airframe at 90 degree intervals. The table below shows the predicted necessary hole size based on the Avionics bay dimensions simulated using the OpenRocket model.

2.6. Estimated Ejection Charge

To estimate the amount of black powder needed to pressurize and eject the parachute compartment, the ideal gas law equation was rearranged and used:

$$PV = mRT \tag{1}$$

$$m = PV/RT$$

$$m = FV/ART$$

Where:

m_b is the mass of gun powder in grams.
F is the force needed to eject the compartment (N)
V is the volume of the parachute compartment (in^3)
A is the inner cross-sectional area of the airframe/compartment (in^2)
R is the gas constant ($266 in - lbf/lbm$)
T = Combustion temperature

The relationship between the force, F and mass, m of the black powder was established by ground testing of the ejection system. The experiment assumed F to be 200 N. The exact dimensions of the parachute compartment was be calculated to obtain mass of the black powder. Depending on the effectiveness of mass, the quantity of the black powder was adjusted to achieve the exact force that will be needed for ejection and deployment.

2.7. General Parachute Design

Safe recovery is generally achieved by minimizing the drift. This was implemented using a dual-deployment parachute. This recovery system consists of two parachutes, a drogue and main. The drogue parachute is located in the booster section and deployed at apogee. The main parachute is located in the compartment below the nose cone, it is released when the rocket falls to 381 m (1,250 ft) MSL (Mean Sea Level). The drogue parachute ensures stabilization of the rocket and reduces the drift, whereas the main parachute is used to ensure a minimal descent velocity.

2.8. Drogue Parachute Design

The design of a parachute depends on the rocket mass and descent speed of the rocket. To achieve the initial descent rate of 30 m/s (98.42 ft/s), the required parachute sizing is to be designed from the following formula:

$$A = \frac{2gm}{\rho C_{\mathrm{d}} v^2} = \frac{2(9.8)(25)}{1.225(1.5)(30^2)} = 0.2963 m^2 \tag{2}$$

where the formula parameters are given by:
g is gravitational constant ($9.8 m/s^2$)
m is dry mass of rocket (25 kg or 55.11 lbs)
ρ is air density (1.225 kg/m^3)
C_d is drag coefficient (1.5 for typical elliptical shape)
v is chosen descent rate (30 m/s)

Finally, the the diameter of the parachute (d) is calculated simply:

$$d = \sqrt{\frac{4A}{\pi}} = 0.6142 m \tag{3}$$

2.9. Main Parachute Design

The design for the main parachute can be obtained using the same method as the drogue parachute. Here, a descent rate of 7 m/s (22.96 ft/s) is chosen, giving a result of 5.44 m^2 area, and 2.63 m for the diameter.

2.10. Parachute Material, Shock Cords and Swivel Link

The parachutes are made from rip-stop nylon to ensure durability and make the parachute more resistant to tearing. Shock cords which connect the parachute to the rocket are made of Kevlar for flame resistance. A riser is knotted along with the shock cord and is connected between the parachute and the shock cord. The riser prevents tangling of the shock cord and/or parachute. Other elastic materials were also considered for the shock cord. They are generally cheaper and more effective at absorbing the deployment impact but were not flame resistant. A composite approach can be utilised for a better performance, with the main shock cord using elastic materials but the final section connecting the rocket using Kevlar. The length of the main and drogue shock cord was approximately three times the rocket body length +10% margin for knotting. This length enables the parachute to pull away from the body and avoid zippering. A swivel link is attached between the riser and the parachute. This ensures ease of undoing bolt connections during recovery.
The parachutes are visually different from each other to assist ground-based observers in visual tracking of the rocket and post landing recovery.The drogue and main parachutes are packed in a flame resistant Nomex wadding along with risers and shock cords.

2.11. Telemetry and tracking system

For receiving real-time, in-flight data and tracking the rockets location, the Eggtimer TRS flight computer was used. The Eggfinder TRS has an Atmel ATMEGA328P-PU processor and uses 902-928 MHz ISM band. This frequency band provides high range reliability for the target altitude of 10,000 ft. The ground-station module, TeleDongle, provides USB connectivity to monitor the flight data and is compatible with any 5 dB dipole antenna. The Eggfinder TRS uses a stick antenna and with its ability to support dual deployment, will also serve as a redundancy recovery system.

3. PAYLOAD

The design procedure of the rocket starts with its functional purpose of carrying a 3U dummy or scientific payload of 4 kg and volume of 30 cm x 10cm x 10cm. Two different payloads were designed for testing. The first is an enclosed volume locked in position by M6 structural rods and bulkheads. The second is a backup and designed to be slid on structural threaded rods connected to bulkheads. However, upon design review the mechanism was altered to match primary payload so that both can interchangeable easily. The dummy payload is filled with a mixture of cement and sand to achieve 4 kg requirement. The remaining volume is then filled with Polyurea foam.

Figure 6. Backup payload

4. CONCEPT OF OPERATIONS

The Mission Concept of Operations (CONOPS) for our rocket consists of several mission phases:
1. Ignition and Liftoff:
The launch phase primarily consists of going through the pre-flight and launch checklists to ensure a safe and secure launch. All components are armed and a signal is sent to the igniters which starts the motor.
2. Powered ascent
The rocket accelerates as the solid motor burns. Motor burnout occurs at 2.92s in the flight.
3. Coasting flight
After the rocket motor burns out. The rocket continues gaining altitude but decelerates until it reaches apogee. The electronic systems monitors the altitude and the acceleration to track flight status.
4. Drogue parachute ejection charge (phase transition)
At apogee, the electronics will signal ignition of black powder charge corresponding of the drogue section. The electronics system has a complete backup in case the primary flight computer does not fire the charges.
5. Slow descent
The drogue parachute size has been calculated to guarantee a fast but controlled descent reducing drift of the rocket. The structural components have been tested to withstand the shock force and deceleration due to drogue parachute drag.
6. Main parachute ejection charge (phase transition)
At 115 seconds as the rocket approaches ground, the main parachute charges ignites and main chute deploys.
7. Landing descent
The large size of the main parachute enables a gentle touchdown. The structural components have likewise been tested to withstand the shock forces occurring from parachute deployment.
8. Landing
The rocket lands intact and safely to the ground. The GPS system signals rocket position to the team for recovery after approval from safety officers.

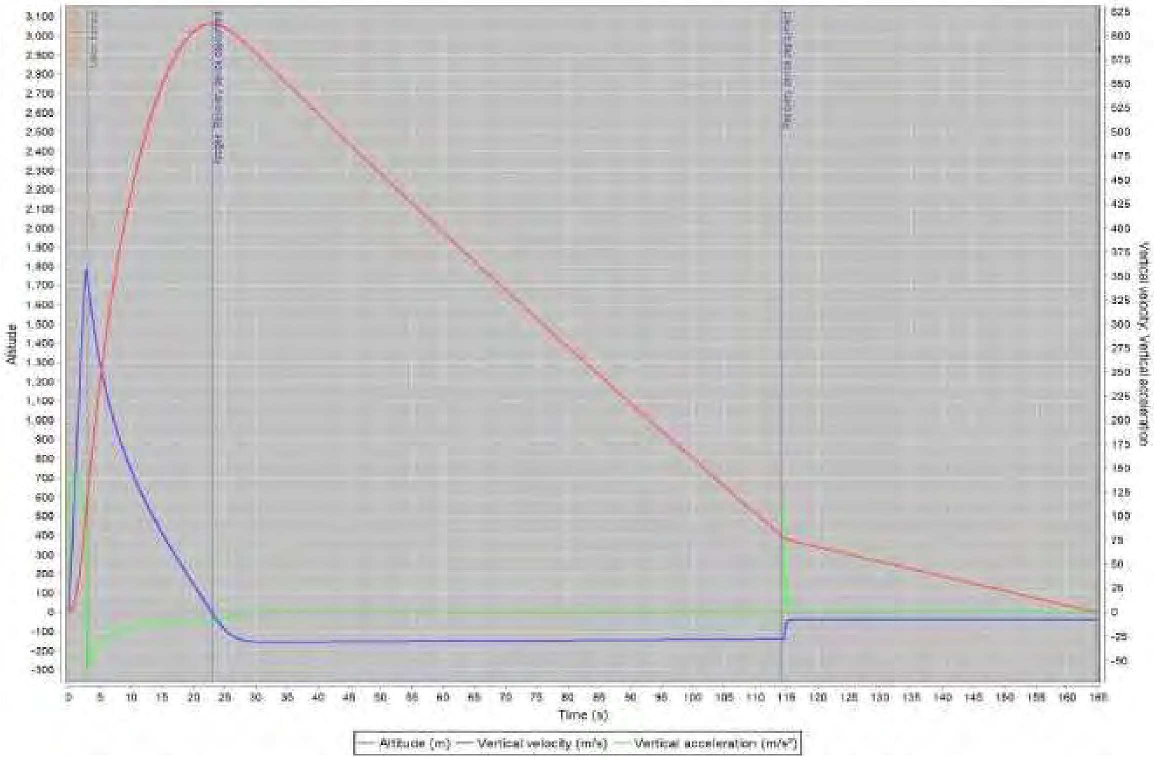

Figure 7. Mission simulation Vertical motion vs Time

5. CONCLUSIONS AND LESSONS LEARNED

The final design is comprised of a single stage rocket which weighs approximately 29 kg and is 2.73 m (107.5) in height. The single stage rocket utilised an off-the-shelf M-class solid motor and carried a 4 kg (8.8 lb) dummy payload. The rockets recovery system was a dual expulsion system based on the two-stage separation of the rockets airframe.

Some of the lessons learnt include maintaining closer communication with other Sheffield Space Initiative teams. This allows sharing of knowledge (e.g. regarding health and safety or up to date procurement practices). Furthermore, closer collaboration can bring about new opportunities that can reduce workload with technical expertise support. Finally, logistics and emotional team support play a significant role in student projects and is often a overall critical success factor.

The University of Sheffield SunrIde team launched and recovered a payload-capable rocket reaching an altitude of 10,017 ft (3,053 m). It won the James Barrowman Award for Flight Dynamics with the most accurate altitude prediction, at 99.83%. This success when combined with the achievements of the other teams at the Sheffield Space Initiative (ssi.group.shef.ac.uk), sets important precedent for aspiring students in the STEM field across the UK. The 2019 team recently exceeded 36,000 ft in this year's Spaceport America Cup setting new UK altitude record [2]. In the future, the team hope to achieve suborbital flight [3]. For more information, please visit: sunride.group.shef.ac.uk.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to Roisin Clear; the 2018 and 2019 SunrIde team; UKRA mentor Charles Simpson; funding support from Department of Automatic Controls and Systems Engineering, Interdisciplinary Programmes Office, Alumni Fund, School of Mathematics and Statistics, Faculty of Engineering, Faculty of Science and Advanced Manufacturing Research Centre at the University of Sheffield; and SHD Composite Materials Ltd, AC Composites, UK Rocketry Association and the Institute of Engineering Technology.

REFERENCES

[1] Cho Y. H., Heung S. Y. G., Verth G.,Fedun V., Sheffield University Solar Balloon Lifted Telescope (SunbYte - BEXUS 25), Proceedings of 2nd Symposium on Space Educational Activities, April 11-13, 2018, Budapest, Hungary

[2] Seniuc I.V., et al, Sheffield students win US rocket competition, Astronomy Geophysics, Volume 60, Issue 3, June 2019, Pages 3.363.37, https://doi.org/10.1093/astrogeo/atz149

[3] Aitoumeziane A., et al, 2019, Traveler IV Apogee Analysis White paper, University of Southern California Rocket Propulsion Laboratory