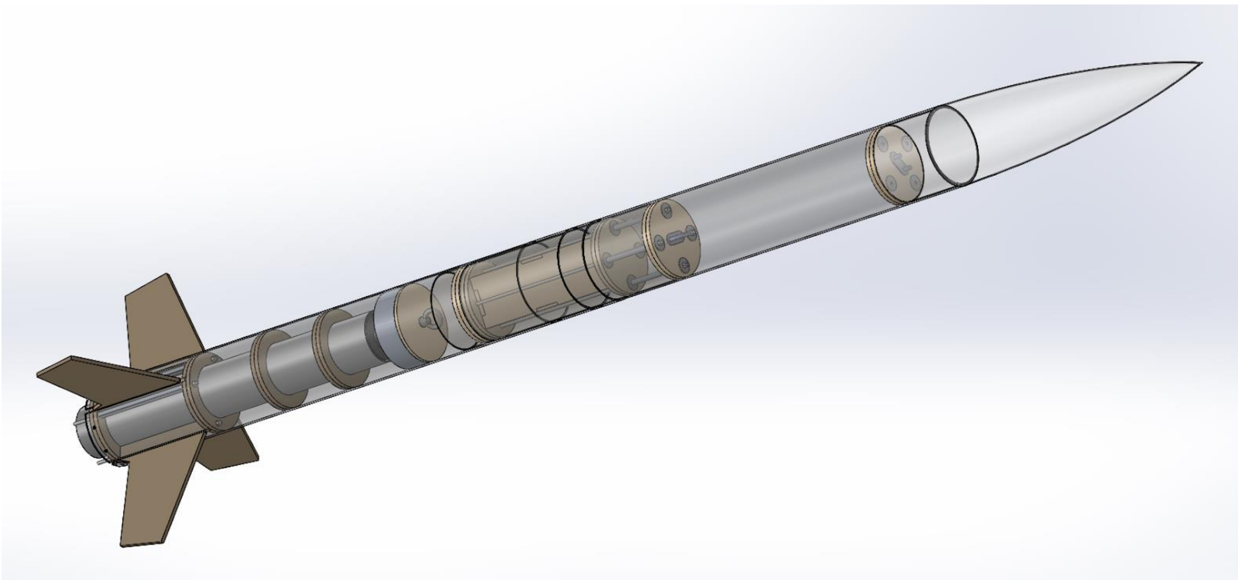
Design and Construction of a Solid Experimental Sounding Rocket, Amy

Team 40 Project Technical Report to the 2018 Spaceport America Cup



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This document presents the model, design, and the construction of the SunrIde team's competition rocket, Amy for the 2018 Spaceport America Cup. Amy is designed to be single stage rocket, reach an apogee of 10,000 feet using the commercial-off-the-shelf Cesaroni Pro98 M3400 solid motor, carries a 4 kg payload, and uses a dual deployment recovery system by altimeter (Stratologger CF and Eggtimer). The design of Amy has been guided by the design guidelines of Spaceport America Cup and the UKRA (United Kingdom Rocket Association).

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I. Introduction

The SunrIde (Sheffield University Nova Rocket Innovative Design Experiment) team is a student-led rocketry team at the University of Sheffield founded with the purpose of competing in the 2018 Spaceport America Cup. SunrIde wadrivs founded in October 2017 and began with the objective of bringing engineering skills and innovation for rocketry design for our university. The SunrIde team consists of 14 students from 1st year undergraduates to Master students, from five Engineering departments (Automatic Control and Systems Engineering, Mechanical Engineering, Materials Science, Aerospace Engineering, Civil Engineering) and the Maths and Statistics department at the University of Sheffield.

The SunrIde project is supported by the Automatic Control and Systems Engineering department and the Maths and Statistics department of University of Sheffield. The team is further funded by the Alumni Foundation grant and the Widening Participation grant, both funding committees of the University of Sheffield.

The SunrIde team is competing in the 10,000 feet category with a commercial-off-the-shelf solid motor.

All the modeling and simulations of the rocket were conducted using the SolidWorks OpenRocket software. OpenRocket is an open-source rocket performance simulator strongly recommended by many rocketry experts in the UK and the US we have discussed. This software was pivotal in designing the rocket to achieve the appropriate performance.

II. Rocket Design

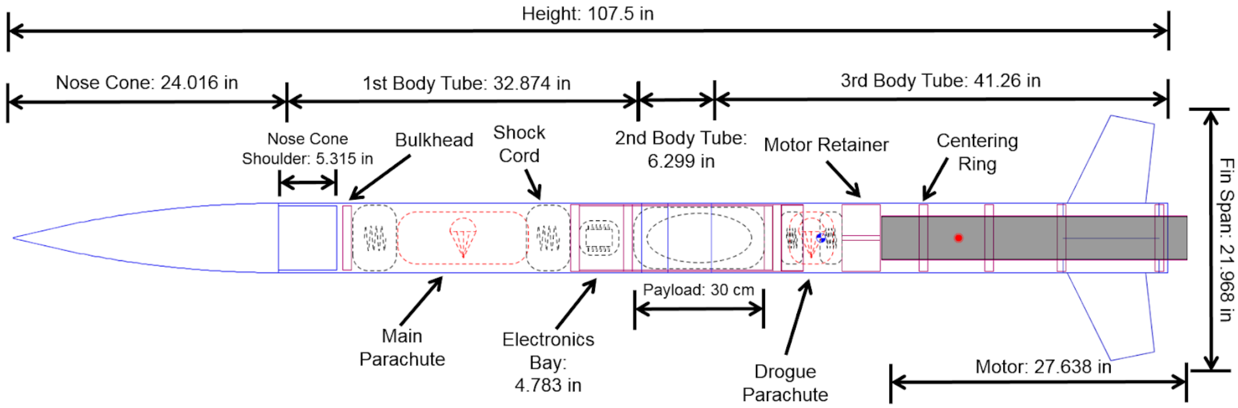

Figure 1. Rocket architecture showing all major subsystems

A. Propulsion

For the 8.8 lb payload to be transported by the rocket up to an altitude of 10,000 feet, we have decided to use a single-stage M-class solid motor. We chose to use the rechargeable Cesaroni Pro98 -9994M3400-P motor with a high average impulse and fast burnout time of 1.36 sec (Figure 2). The dimensions for this single-stage M-class motor are 98mm for the diameter and 702mm for the length. The motor is fixed in place using three centering rings made of 18 mm plywood and a motor retainer made of aluminum, which was approved to be strong enough to take the pressure developed during liftoff and distribute it to the rest of the structure.

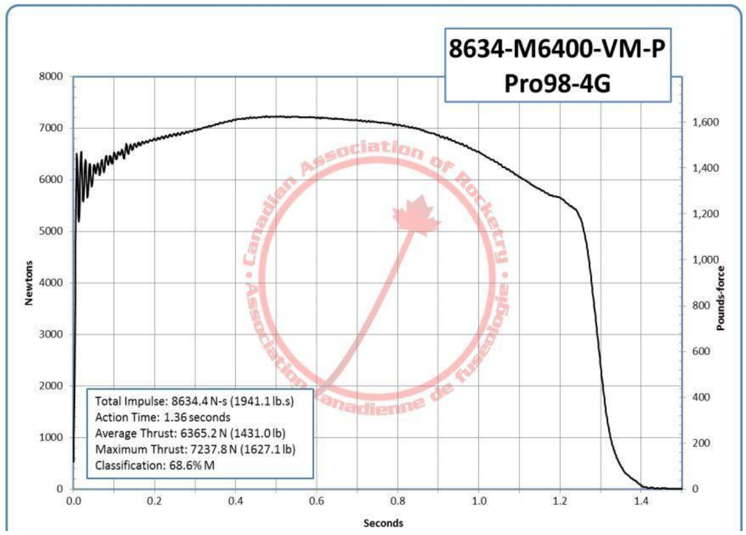

Figure 2. Thrust curve of Cesaroni 8634-M6400-VM-P motor.

B. Airframe

Body Tube

The airframe consists of fiberglass coated kraft phenolic tubing measuring 6 inches in inner diameter and 0.11 inch wall thickness. The aft and fore section of the rocket are held together by a tube coupler made of plain kraft phenolic, that contains both the payload and the electronics bay. The airframe section 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 inflight. The nose cone has the aerodynamic shape of an ogive and is fiberglass reinforced plastic, with a wall thickness of 4 mm.

Fins

The purpose of the fins is to stabilize the ascent of the rocket during ascent and prevent it from spinning, while withstanding aggressive aerodynamic forces. The current rocket is equipped with 4 fins equally spaced around the airframe, which are mechanically mounted into an independent block that slides inside the rocket's aft section at the bottom, 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, M6 threaded rods pass through dedicated aluminium square tubes glued to the fins' tabs that act as spacers to prevent them from buckling under stress. The spacers, along with the partial slits cut in the centering rings holding both ends of the fins' tabs, ensure no transversal displacement. As a precaution against any radial displacements, one end of the fin tab continues on the interior of the airframe tube for a small portion after the slit finishes. The fin block is fixed to the airframe using eight 3.2 x 40 mm wood screws driven into the bottom centering ring. Various simulation attempts in OpenRocket showed that an optimal profile of the fins for the current rocket configuration is the derived clipped delta shape. To prevent the fins from catastrophic fluttering mid flight, they need to be rigid, while maintaining as small a cross section and little weight as possible. Among the alternatives considered for testing were glass fiber reinforced 6 mm plywood and one or two 2.5 mm aluminium sheets glued together, although the latter is relatively heavier. Since preliminary epoxy lamination techniques for both sides of test plywood fins were less successful, another solution was forwarded, consisting of a median glass fiber layers glued between two sheets of 3 mm thick plywood. The exterior edges of the fin were later airfoiled to reduce the air drag.

C. Recovery subsystem

The recovery system is a dual expulsion system based on the two-stage separation of the rocket's airframe. Each separation stage is achieved by detonating two pyrotechnic charges that use black powder, which pressurize the two parachute compartments enough for the deployment to occur. The three separate rocket sections will be held in place by structural inner tubes, each two body diameters in length, which are rigidly fixed to one airframe tube, and friction fitted, with shear pins to the other. The main parachute deployment will take place at the fore section (nose cone) level when at apogee (about 10047 ft), while the drogue parachute deployment will occur at the aft section (booster) level when at the lower altitude of 1250 ft MSL (Mean Sea Level). The three individual parts of the rocket will connect to the parachutes using shock cords rated for . The shock cords differ in length as to prevent airframe collisions during descent phase, while absorbing the parachute deployment shock. The firing of the pyro charges is controlled by a programmable flight altimeter called StratologgerCF. To assure contingency, StratologgerCF will be assisted by a redundant Eggtimer system. The main altimeter controls the precise timing at which the pyro charge cups are to be fired, allowing for the main and drogue parachute deployment. The design and dimension of the drogue and main parachutes are discussed in the parachute design section. Four static pressure sampling holes will be drilled in the airframe, at 90 degree intervals around its circumference, into the avionics bay, to allow outside air pressure to be sampled by the altimeter when inflight. need to be located. This will minimize the pressure variations due to wind currents perpendicular to the rocket's direction of travel.

Dual Deployment Altimeter: StratologgerCF Altimeter

In order to record the maximum altitude and the velocity achieved by the rocket we have made use of the StratologgerCF Altimeter. The altimeter comes with two output ports for to deploy the drogue chute for drift minimization and the main parachute closer to the ground. The StratologgerCF gives the flexibility to deploy the parachutes at a chosen altitude.

During the test, we received a the temperature, altitude and battery voltage readings from the flight at rate of 20 samples per second recorded by the StratologgerCF. The decision of choosing the StratologgerCF for our altimeter is mainly because the built-in voltmeter which means the altimeter can log a data of upto 15 flights (18 minutes each) even once the battery has been removed. The data logged is accurate and precise by the industrial standards.

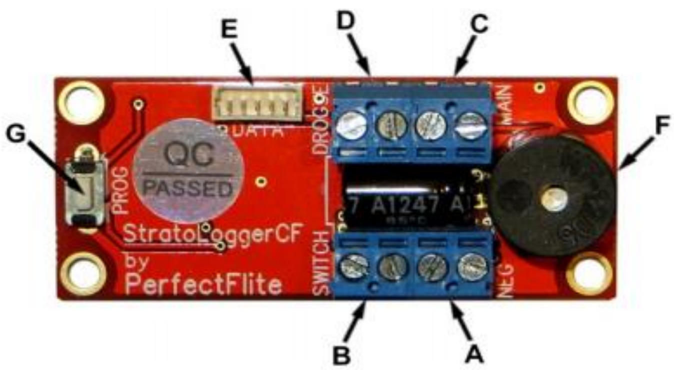

Figure 3. Stratologger

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.

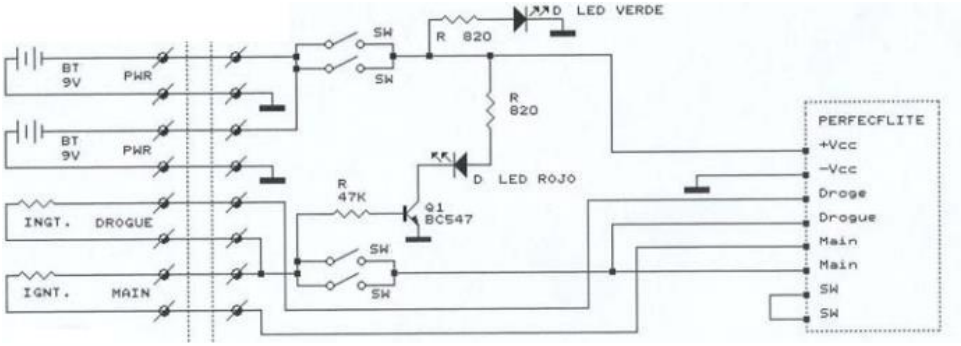

Figure 4. Stratologger circuit diagram

This figure above shows the circuit diagram that will be used to power the Stratologger. It contains the main power switch, an arming switch and LED for visual identification for the state of recovery device. The Eggfinder TRS Tx, Rx and the LCD receiver are have been chosen for the recovery of the rocket. The TRS uses the HOPE RF module for the GPS tracking. The transmitter sends the data to the receiver which uses the 5 dB dipole stick antenna to retrieve the signal once every second. This data is logged on a desktop application or smartphone (depending on the need).

Static Pressure Sampling Holes

These holes will be drilled in the airframe into the avionics bay to allow outside air pressure to be sampled by the altimeter. These holes will be as far away from the nose cone shoulder and other body tube irregularities as possible to minimize pressure disturbances being created by turbulent airflow over the body tube. Four smaller holes distributed at 90 degree intervals around the airframe’s circumference will be made instead of a single larger hole. When using four holes, each hole will be ½ the size of a single hole as noted in the table. This will minimize the pressure variations due to wind currents perpendicular to the rocket’s direction of travel.

Table 1: Static pressure sampling holes

AvBay Diameter	AvBay Length	Single Port Hole Size	Four Port Hole Size
1.6”	6”	.032”	.020” (small pinholes)
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”

The most suitable configuration shall be used depending on the dimensions of Avionics Bay once it has been fabricated. Corresponding to the OpenRocket model, the configuration highlighted above suits the best.

Estimated Ejection Charge

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

$PV = mRT$

$m = PV/RT$

$m = FV/ART$

where,
m 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 and T are the gas constant and combustion temperature of the 4F black powder.
R = 266 in-lbf/lbm
T = 3307 degrees R/ 2840 Fahrenheit (combustion temperature)
The relationship between the force F and mass m of the black powder will be established by hit and trial method during the ground testing of the ejection system. The experiment will be started with assuming F to be 200 lb. The exact dimensions of the parachute compartment will be calculated to obtain mass m1 of the black powder. Depending on the effectiveness of mass m1 the quantity of the black powder will be increased or decreased to achieve the exact force that will be needed for the ideal ejection and deployment.

General Parachute Design
Safe recovery is achieved by minimizing the drift by implementing a dual-deployment parachute. This recovery system consists of two parachutes, a drogue and main. The drogue parachute is located in the booster section, it is deployed when the rocket reaches the apogee at 10047 ft. The main parachute is located in the compartment below the nose cone, it is released when the rocket reaches 381 m (1250 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 minimized landing radius and descent velocity.

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 =(2*g*m)/(*Cd *V2)
A = (2*9.8*25*103)/(1.225*1.5*302) = 0.2963 m2

where the formula parameters are given by:
g: Gravitational constant (9.8 m/s^2)
m: Mass of rocket with empty engine (25 kg - 55.11 lbs)
ρ: Air density (1.225 kg/m^3)
C_d: Drag coefficient (1.5 for typical elliptical shape parachute)
v: chosen descent rate (30 m/s)
And the diameter of the parachute is calculated using the following formula:
d = (4*A)/ = 0.6142 m

Main Parachute Design
The design for the main parachute can be obtained using the same method as the drogue parachute. To calculate the area of the main parachute, a descent rate of 7 m/s (22.96 ft/s) is chosen, giving a result of 5.4422 m2 area, and 2.6323 m for the diameter.
The parachute dimensions will be reviewed to account for slight changes on rocket mass and configuration.

Parachute Material, Shock Cords and Swivel Link
The shape of the parachute is chosen to be elliptical as it provides more drogue coefficient and is also cost efficient. Parachute is made from ripstop nylon, as nylon material ensures durability and makes the parachute more resistant to tearing. Shock cords which connects the parachute to the vehicle, are made of Kevlar, since it’s flame resistant. A riser is knotted along with the shock cord and is connected between the parachute and the shock cord. A riser is implemented to avoid tangling of the shock cord or the parachute. Elastic materials can also be used for the shock cord, this being cheaper and more effective at absorbing the deployment impact, although they’re not flame resistant. For a better performance, the main shock cord can be made of elastic materials and the cord connecting the vehicle can be made of Kevlar.
The length of the main and drogue shock cord must be approximately three times the body length of the rocket, plus a 10 percent added for knotting, i.e. . This, to pull the parachute away from the body and avoid zippering.
A swivel link is attached between the riser and the parachute. This component will ensure unthreading of the bolted connections during recovery.

Parachute Material, Coloration and Markings

The parachutes' color and design will be different from each other, as it will 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 the risers and the shock cords.

Telemetry and tracking system

For receiving real time in-flight data and tracking the rocket's location once it has landed, the Eggtimer TRS flight computer which uses a Atmel ATMEGA328P-PU processor will be used. The Eggfinder TRS uses the RF module in the 902-928 MHz ISM band. The given band of frequency is a high range reliability for the targeted 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 the stick antenna for the given apogee of the rocket recovery. With its ability to support dual deployment and pyro charges, Eggfinder TRS will also serve as a redundant recovery system..

D. Payload subsystem

The design procedure of the rocket starts with its functional purpose of carrying a payload of mpayload=4 kg, according to CubeSat volumetric restriction of multiples of 10cm×10cm ×10cm. In other words, the payload should sum up to a volume of V=mpayload/ρcube=30 cm3 or three cubes comprising a final dimension of 10cm×10cm×30cm. There are two different payloads available for testing. The first one is an enclosed volume that is locked in position by M6 structural rods and bulkheads. The second, a backup, was initially designed to be slid on structural threaded rods connected to bulkheads but upon design revision it was changed to the newer one. The old one fits in the newer design so they are interchangeable.

The payload is filled with a mixture of cement and sand to achieve 4kg requirement. The remaining volume is then filled with Polyurea foam.

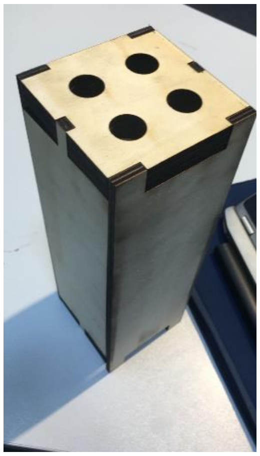

Figure 5. Backup payload

III. Mission Concept of Operations Overview

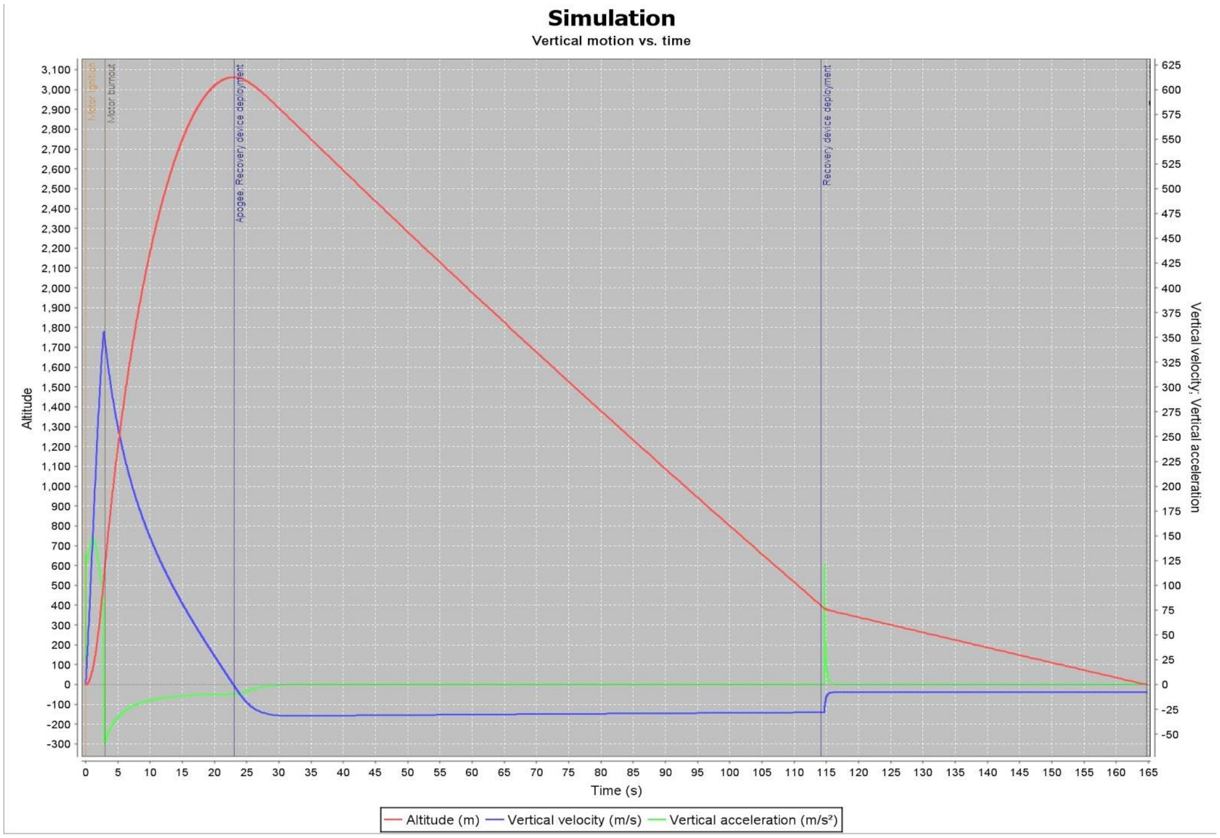

Figure 6. Mission simulation

The Mission Concept of Operations (CONOPS) for our rocket consists of several mission phases:

1. Ignition and Liftoff:

The launch phase primarily constitutes of checking through the preflight and launch checklists to ensure safe and secure launch of the rocket. At this phase, all the component are armed and the rocket launched. A signal is sent to the igniters which lights the motor.

2. Powered ascent

This phase consists of the rocket accelerating due to the Cesaroni Pro98 M3400 solid burn. Motor burnout is at 2.92s in the flight (*phase transition*).

3. Coasting flight

This phase starts the moment the rocket motor burns out. The rocket continues gaining altitude but it decelerates until it reaches apogee. The electronic systems will measure the altitude continually and the acceleration forces to determine the progression of the rocket.

4. Drogue parachute ejection charge (*phase transition*)

The electronics will signal at the correct altitude to ignite the charges of black powder corresponding of the drogue section. The electronics system has a complete backup in case the primary doesn't fire the charges. Also, the carghes have a backup in case a problem occurs.

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 forces occurring from the drag generated by the parachute.

6. Main parachute ejection charge (*phase transition*)

At 115 seconds, the electronics are set to eject the main parachute for landing of the rocket. As for the drogue parachute, backup electronics and ejection charges have been implemented.

7. Landing descent

The main parachute size has been calculated to considerably decelerate the rocket for safe landing. The structural components have likewise been tested to withstand the forces occurring from the drag generated by the parachute.

8. Landing

The rocket lands intact and safely to the ground. GPS system will signal the position of the rocket to the team to be picked up when safe and told to do so by the safety officers.

IV. Conclusions and Lessons Learned

The final design is comprised of a single stage rocket which weighs approximately 29 kg and is 107.5in in length. The rocket utilises a single-stage M-class solid motor which is bought off-the-shelf and it will carry a 8.8 lb payload. The airframe of the rocket comprises of a nose-cone, an upper and lower body tube and a coupler which are made out of fibreglass and kraft phenolic respectively. The rocket utilises 4 Aluminium fins to provide stability during flight and to allow the rocket to maintain its orientation and intended flight path. The rocket's recovery system will be a dual expulsion system based on the two-stage separation of the rocket's airframe. Each separation stage is achieved by detonating two pyrotechnic charges that use black powder, which pressurize the two parachute compartments (drogue and main) enough for the deployment to occur. The 2 parachutes are elliptical in shape and are made out of tear-resistant ripstop nylon.

Appendix A:
Systems Weights, Measures, and Perfomance Data Appendix

Table 2. Simulation results

	Specifications	**Values**	**Units**
Rocket Dimensions	Total Height	107.5	Inch
	Mass at liftoff	60	lbs
	Mass at apogee	50	lbs
	Fuselage interior diameter	6	Inch
	Fuselage exterior diameter	6.22	Inch
	Payload weight	8.8	lbs
	Fin span	21.968	Inch
	Fin thickness	0.4	Inch
	Number of fins	4	-
	Nose cone length	24.01	Inch
	Nose cone shoulder diameter	5.71	Inch
	Nose cone shoulder length	5.32	Inch
Motor Performance Pro98 Cesaroni -9994M3400-P	Total impulse	9994.5	Ns
	Maximum thrust	3421	N

	Average thrust	3983	N
	Burn time	2.92	s
	Launch mass	17.88	lbs
	Empty mass	7.37	lbs
Flight Behaviour and Characteristics/Performance comparisons	Velocity off launch rod	100	ft/s
	Apogee	10,000	ft
	Velocity at drogue deployment	92.1	ft/s
	Optimum delay	20	s
	Maximum velocity	1164	ft/s
	Maximum acceleration	15.1	G
	Time at apogee	22.9	s
	Flight time	165	s
	Ground hit velocity	24.8	ft/s
	Center of pressure (measured from the base of the rocket)	22	Inch
	Center of gravity (measured from the base of the rocket)	34	Inch
	Stability margin caliber	2	Cal

Appendix B:
Project Test Reports Appendix

The rocket systems have been tested individually on ground and together in a flight test. The flight test is carried with a lower thrust engine and without the payload focusing the test on recovery systems, electronics, reviewing on-field procedures and materials.
The flight test will be carried on before the competition.
The ground tests consisted on: bulkhead and material tests, electronic test, parachute ejection test, fin test.
Bulkhead and material test: structural component were tested against lateral and longitudinal loads ensuring adequate level of manufacturing quality was maintained. As some materials used by the team had never been used before, this test allowed for all team member to acquire necessary skill for independent work. The test was successful.
Electronic test: The team tested the electronics that was soldered. During the first test some minor issues were found, some components didn't have soldering up to standards and had to be redone. The electronics was then ground tested

simulating an ejection test and everything worked successfully.
Parachute ejection test: The purpose of the test is to size the correct quantity of black powder to pressurize the ejection compartment allowing for the ejection of the parachute. The test is carried out varying the masses of the sections below and on top to guarantee a margin of robustness for the actual flight. Multiple tests are done practicing procedures of parachute packing and safety handling black powder. The test are carried out under the supervision of the UKRA level 3 mentor.
Fin test: As for the general material test, the quality of the manufacturing was tested varying procedures and reviewing results. Strength of the fin was tested to reduce as much as possible the effect of fluttering in flight.
General procedures have been under constant review, especially since the introduction of the UKRA mentor to ensure the continuity of the project next year and the passing of the skill set and knowledge acquired to the new team.

Appendix C:
Hazard Analysis Appendix/Risk Assessment Appendix

Table 3. Risk Assessment Table

Hazard	Risk	Possible Causes	Risk of Mishap and Rationale	Mitigation Approach	Risk of Injury after Mitigation
Explosion of solid-propellant rocket motor during launch with blast	Flying debris causes injury to participants, including eye injuries or blindness	Cracks in propellant grain/ Debonding of propellant from wall/ Gaps between propellant sections and/or nozzle/ Chunk of propellant breaking off and plugging nozzle/ Motor case unable to contain normal operating pressure/ Motor end closures fail to hold	Medium; Limited testing of endurance of the equipment under hardship circumstances/ Poor evaluation and choice of materials	Test of the motor case under pressure 1.5 times the maximum expected pressure it will experience/ Visual testing for cracks on the grains, any gaps during and after the assembly/ Only trained personnel allowed in the assembly process/ Use of ductile material for the motor case/ Crew must be at least 200 feet away from the launch site	Low

Rocket deviates from nominal flight path	Comes in contact with personnel at high speed and cause severe injury/death	The stability of the rocket affected due to poor manufactured fins. The launch rail was not anchored to the ground properly, which caused a change in the angle of launch	Medium; Non-trained personnel responsible for mounting the rocket/ Possible calibration errors made due to technical problems	The fins of the rockets should be well manufactured to ensure good stability of the rocket during flight. Inspect the launch rail before launch and ensure the launch rail is anchored in the ground properly. Ensure the angle of launch rail complies to SAC's regulations	Low
Ground Fire	Could cause several skin injuries	Motor ignition and Initial Thrusting	Medium;	Ensure the launch area is not in close proximity to dry grass or plants Fire-extinguisher on-standby	Low
Catastrophic failure of motor casing; Injury to participants	Projectiles could cause injuries/ death				Medium
Charge powder catches on fire	Explosion and fire could cause skin and other injuries/ death	Powder in tight containment will catch on fire due to high pressure	Medium	Store the powder in a non-metallic container with a lid that will pop-off if powder catches on fire	Low
Recovery system fails or partially fails to deploy, rocket or payload comes	Severe body injuries/ death	Failure of stratologger in determining altitude Failure of the gps device to detect the apogee point	High	Ensure the electronics are programmed correctly Ensure parachute knots are not tied too tightly	Low

in contact with personnel					
Recovery system deploys during assembly or pre-launch, causing injury	Severe body injuries/ death				
Main parachute deploys at or near apogee, rocket or payload drifts to highway(s)	Dangerous as a distraction or cause of injury for drivers		Low	Mandatory adherence to minimum clearances from operating highway(s). No flight in elevated wind conditions.	Low
Rocket does not ignite when command is given (“hang fire”), but does ignite when team approaches to troubleshoot	Fire and projectiles from the explosion could cause serious skin or body injuries/ death	Electronic failure/ Bad electronic system design	Medium	Check of the electronics before ignition, protective goggles and clothes worn by crew members	Low
Rocket falls from launch rail during pre-launch preparations	Could cause equipment damage and also staff injuries	Improper mounting of the rocket/ Safety measures not followed	Low	Inspect and ensure the launch pins of the rocket are mounted to the launch rail	Low

Appendix D:
Assembly, Preflight, and Launch Checklists Appendix

The following must be checked before arriving at the launchpad and initiating countdown:

1. Assemble the rocket appropriately.
2. Conduct telemetry test with the rocket vehicle outside the launchpad.
3. Arrival at the launchpad: mating of rocket vehicle to the launch rail.
4. Elevate the launch rail to 84 degrees.
5. Evacuate non-essential personnel from the launch pad.
6. Insert the igniter into the engine and leads anchored to the launch pad.

<u>Arming of the rocket systems:</u>

1. Turn on power to the electronics
2. Turn on control computer.
3. Turn on telemetry and verify the transmitted signal.

4. Activate actuator circuit.

Launch:

1. All personnel evacuate from the launchpad.
2. Connect igniter to the firing circuit
3. Confirmation from RSO of a “Go for launch.”
4. Audible countdown of at least 5 seconds in 1 second intervals.

Appendix E:
Engineering Drawings Appendix

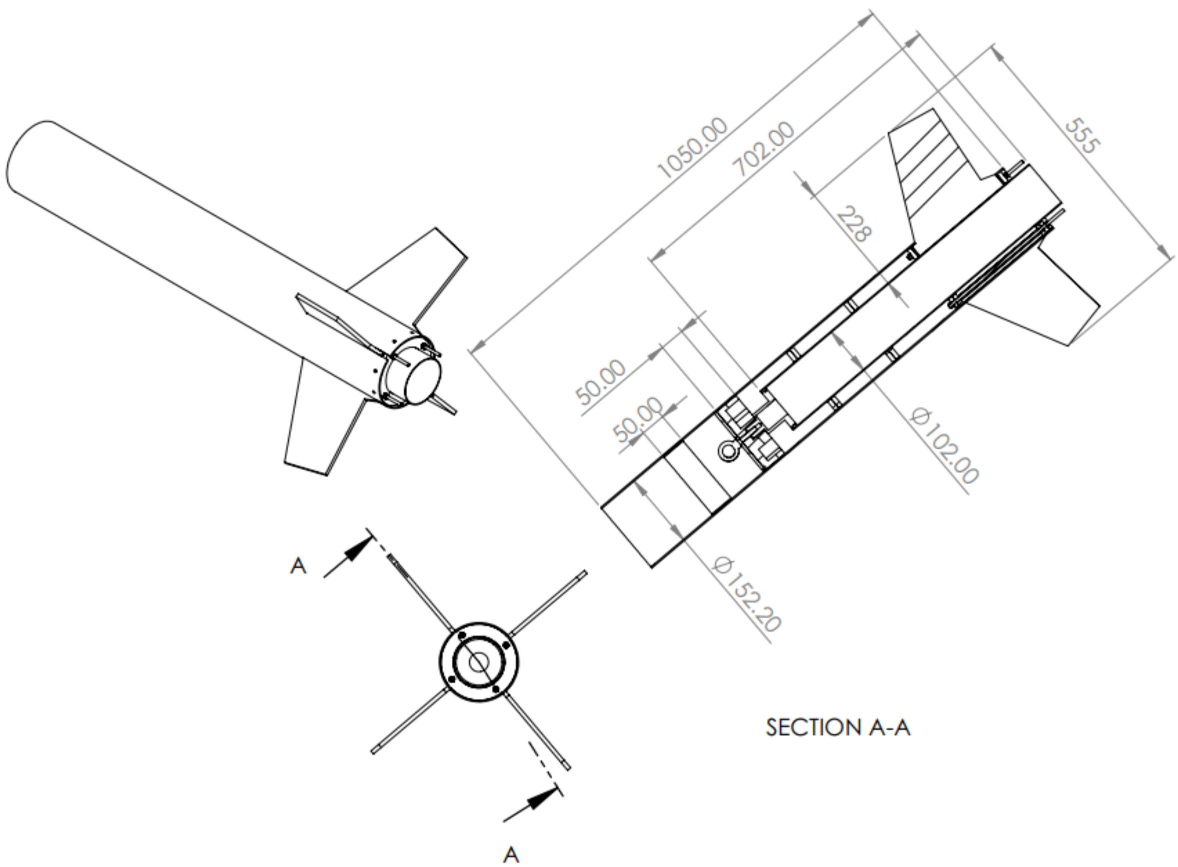

Figure 7. Technical drawing bottom section

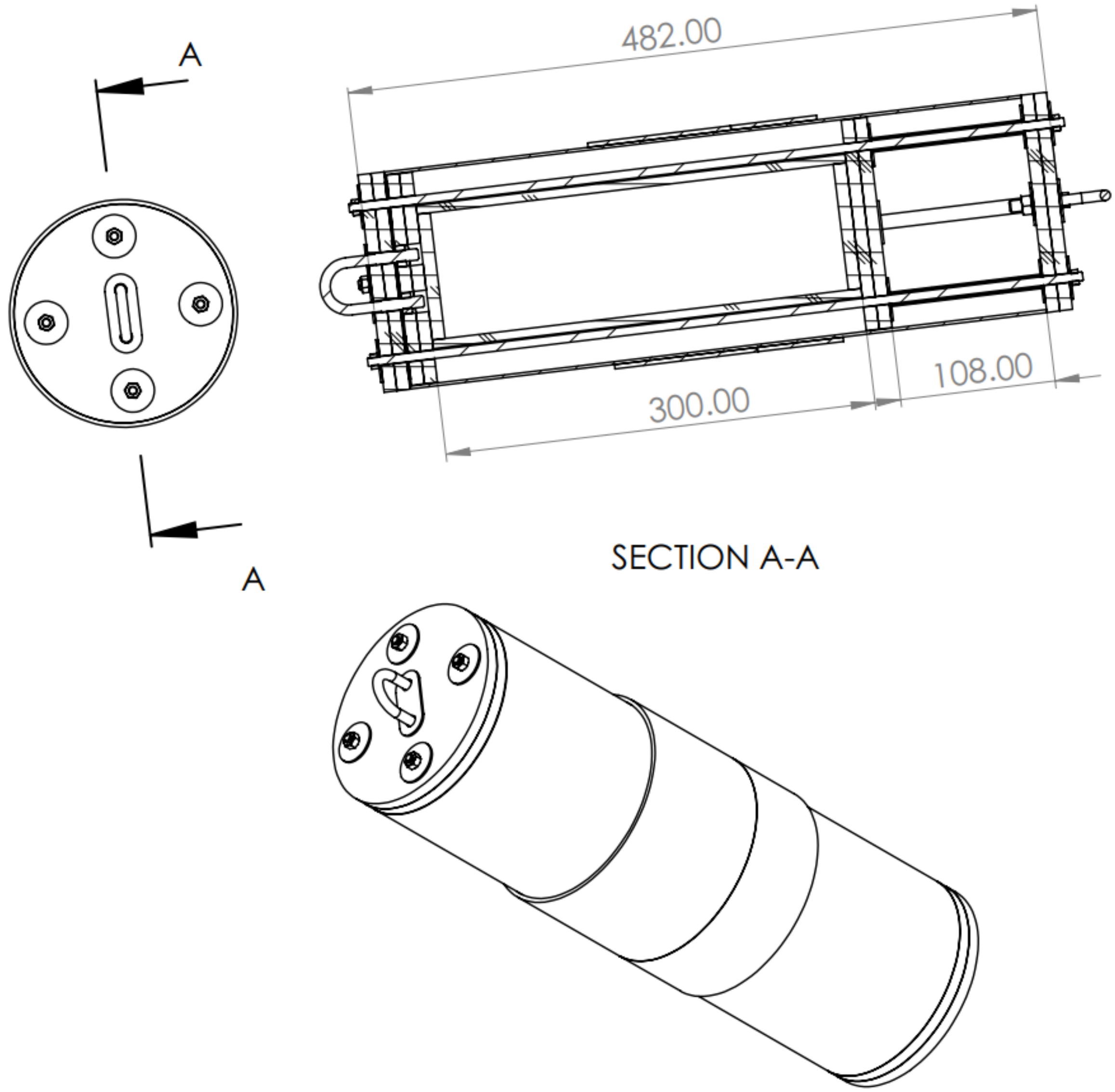

Figure 8. Technical drawing payload and electronics bay

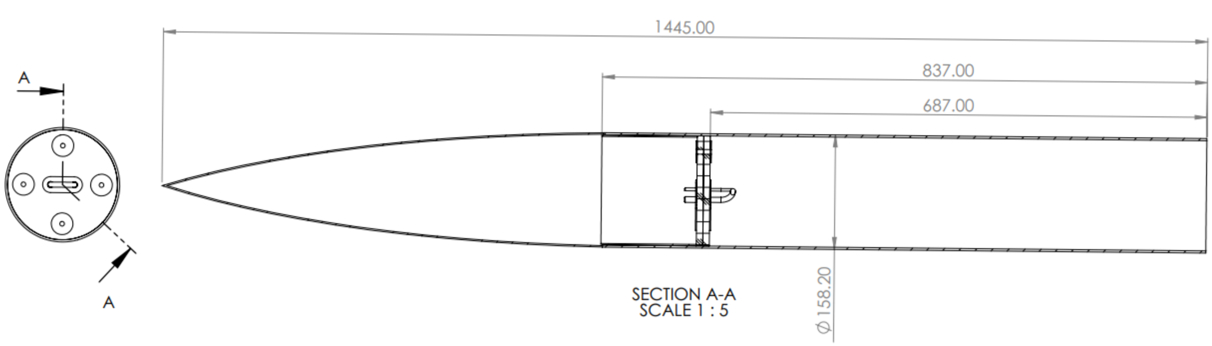

Figure 9. Technical drawing top section

Acknowledgments

The SunrIde team would like to thank the Automatic Control and Systems Engineering department of the University of Sheffield, the United Kingdom Rocketry Association (UKRA), the Alumni Foundation, and the Widening Participation Unit. We would like to also thank Dr. Viktor Fedun and Mr. Charles Simpson for their support and guidance throughout this project. We would also like to thank the staff at the iForge and the Propulsion Lab at the University of Sheffield for their supportive assistance during our project.