NC STATE UNIVERSITY

Tacho Lycos
2018 NASA Student Launch
Critical Design Review

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Common Abbreviations & Nomenclature

AGL	=	above ground level
APCP	=	ammonium perchlorate composite propellant
ARRD	=	advanced retention and release device
AV	=	avionics
BP	=	black powder
CDR	=	Critical Design Review
CG	=	center of gravity
CP	=	center of pressure
EIT	=	electronics and information technology
FAA	=	Federal Aviation Administration
FMECA	=	failure mode, effects, and criticality analysis
FN	=	foreign national
FRR	=	Flight Readiness Review
HEO	=	Human Exploration and Operations
HPR	=	High Power Rocketry
HPRC	=	High-Powered Rocketry Club
L3CC	=	Level 3 Certification Committee (NAR)
LARD	=	low-altitude recovery device
LCO	=	Launch Control Officer
LRR	=	Launch Readiness Review
LSB	=	Lazy Susan bearing
MAE	=	Mechanical & Aerospace Engineering Department
MSDS	=	Material Safety Data Sheet
MSFC	=	Marshall Space Flight Center
MSL	=	mean sea level
NAR	=	National Association of Rocketry
NCSU	=	North Carolina State University
NFPA	=	National Fire Protection Association
PDR	=	Preliminary Design Review
PLAR	=	Post-Launch Assessment Review
PPE	=	personal protective equipment
RFP	=	Request for Proposal
RSO	=	Range Safety Officer
SL	=	Student Launch
SLS	=	Space Launch System
SME	=	subject matter expert
SOW	=	statement of work
STEM	=	Science, Technology, Engineering, and Mathematics
TAP	=	Technical Advisory Panel (TRA)
TRA	=	Tripoli Rocketry Association

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1.1 Team Summary

1.1.1 Name and Contact Information

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1.1.2 Mentor Information

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1.2 Launch Vehicle Summary

1.2.1 Size and Mass

The full-scale launch vehicle will be 128.0 in. long with a diameter of 7.5 in. The rocket will have a mass of 47.1 lb on the pad, which includes 3.0 lb of nose ballast.

1.2.2 Final Motor Choice

The full-scale launch vehicle will use an AeroTech L2200G motor.

1.2.3 Recovery System

The full-scale launch vehicle will deploy a 2.0 ft drogue at apogee, a 5.0 ft parachute at 1,000 ft AGL, and a 10.0 ft main parachute at 700 ft AGL.

1.2.4 Launch Rail Size

The full-scale launch vehicle will require an 8 ft, 1515 launch rail.

1.2.5 Milestone Review Flysheet

This document was submitted separately.

1.3 Deployable Rover Payload Summary

The team has chosen to include a deployable rover as the payload for the full-scale launch vehicle. The rover will be stowed in an internal tube that will rotate freely using roller bearings (Lazy Susan bearings) attached at each end of the payload tube. The upper bearing will be attached to a centering ring aft of the main parachute compartment. The lower bearing will be attached to a bulkhead forward of the avionics bay. The payload bay will be sealed during flight by a tapered plug in the payload centering ring which will be removed with the main parachute deployment. After landing, the rover will autonomously drive at least 5.0 ft and deploy a set of solar panels to complete the payload mission.

2. Changes Made Since Preliminary Design Review

2.1 PDR Action Items

The team was not given any PDR action items to complete.

2.2 Changes Made to Vehicle Criteria

Table 2-1 lists all changes made to the full-scale launch vehicle since PDR submission. Note that this report uses the terms "launch vehicle" and "rocket" interchangeably.

Table 2-1: List of Changes Made to Full-Scale Launch Vehicle

Description of Change	Reason for Change
The rocket midsection was split into two body tube sections at the payload centering ring. The thickness of the payload centering ring was increased to 1.5 in. to ensure enough surface area for attachment of both midsections.	The team determined that access to black powder charges fixed to the forward face of the payload centering ring would be difficult without separating the midsection body tube components. The centering ring will be epoxied to the aft midsection section and the upper midsection will be attached using six wood screws.
The avionics bay was extended by 3.0 in., for a total length of 6.25 in. This also extended the lower midsection and overall rocket length by 3.0 in. to 30.0 in. and 128.0 in., respectively. The payload mass was predicted to be 2.0 lb after final assembly.	The team determined that an extension to the avionics bay was necessary to ensure enough volume for additional wires, switches, and tool access. An extension of the lower midsection also allowed for a slight increase in stability.
The rocket nosecone material was changed to plastic without a metal nosecone tip.	The team was only able to identify a single nosecone manufacturer capable of creating 7.5 in. diameter components. The nosecone will still include a 6.0 in. shoulder, but will not have a metal nosecone tip.
The rocket fin trailing edge was transitioned aft by 0.5 in. to shift the CP location afterward.	The team determined that the CP location needed to be shifted aftward due to the decrease in nosecone weight after the material transition to plastic.
Low-altitude recovery device (LARD) added to drogue shock cord line. A 60 in. parachute will be folded and bound using a Jolly Logic controller to be deployed at apogee with the drogue parachute. The LARD will remain folded until 1,000 ft AGL, when the Jolly Logic will release the parachute to open. The rocket will deploy a total of three parachutes during the descent.	The team reduced wind drift by reducing the drogue diameter, but the rocket will descend faster which would cause the main parachute to deploy at potentially unsafe speeds. To ensure the integrity of structural components and the delicate rover payload, the LARD will be deployed at 1,000 ft AGL to slow the rocket descent in two stages.

Description of Change	Reason for Change
Drogue parachute diameter reduced from 36 in. to 24 in.	A smaller drogue parachute will increase descent velocity to reduce wind drift.
Main parachute deployment altitude decreased to 700 ft AGL.	After the LARD is deployed at 1,000 ft AGL, the rocket will continue descending for approximately 300 ft before deploying the main parachute. The rocket will impact the ground under three parachutes to reduce descent velocity, and increase the chance that the rocket will land horizontally for easier rover deployment on the ground.
The nose ballast was increased to 3.0 lb.	After making all design changes listed above, additional nosecone ballast will be necessary to ensure a static margin greater than 2.0. The predicted static margin of the rocket will be 2.05 cal after final assembly.

2.3 Changes Made to Payload Criteria

Table 2-2 lists all changes made to the deployable rover payload system since PDR submission.

Table 2-2: List of Changes Made to Deployable Rover Payload System

Description of Change	Reason for Change
Total servos for rover increased to three.	To simplify mechanical design, an additional servo will be used for motion. Instead of making a gearing system controlled by one servo, each of the front wheels will be controlled by a servo.
Bluetooth communication used for rover activation.	Bluetooth communication requires only one component on the rover. It will easily be able to communicate with a team member's laptop in order to activate the rover's mission.
Payload entry seal design change	Changed the entry seal for the payload after discovering the door would not function as desired. Since the door's shape matched the centering ring's shape, the door would not open enough for the rover to deploy. The current design is now a plug constructed of birch plywood and rubber wrapped around the edge. The main parachute shock chord will be tied to a U-bolt secured in the plywood. Upon the main parachute ejection, the plug will be pulled out.

Description of Change	Reason for Change
MSP430 microcontroller instead of Arduino.	On the recommendation of local electronics experts, this microcontroller was chosen instead of Arduino because of simplicity, cost, and reliability.
Forward Lazy Susan Bearing design change	The previous design involved eight individual ball bearings in a cup that rolled in a track in the opposing piece. During subscale testing, this design was unfavorable. The current design now consists of a 3D printed cap with a track filled with ball bearings mounted to the centering ring. A PVC piece will be attached to the payload tube and will be in contact with the ball bearings. A similar design was used during the subscale launch and was more favorable.
Rover platform design change	Instead of printing housing for the latch electrical components of the payload, the components will be attached via screws. This is because the previously designed housing will not hold the updated components. Also, attaching the components without a designated housing will allow them to be attached without wire interference.

2.4 Changes Made to Project Plan

As shown in Section 8.6, the project timeline remains unchanged from PDR submission. All changes to the project verification plan are listed in Table 3-1.

3. Vehicle Criteria

3.1 Compliance to Handbook Requirements

Table 3-1, below, contains the launch vehicle requirements listed in the 2018 NASA SL handbook as well as the respective compliance actions, verification methods, and status.

Table 3-1: Full-Scale and Subscale Launch Vehicle Handbook Item Compliance

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.1	The vehicle will deliver the payload to an apogee altitude of 5,280 feet above ground level (AGL).	Based on the current design, an AeroTech L2200G will power the launch vehicle to an ideal apogee altitude of 5,280 ft AGL.	Analysis. The final weight will be calculated, and a motor will be selected based on these calculations. Analysis is detailed in Section 1.2.2.	Complete. See Section 1.2.2.
2.2	The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the altitude award winner. Teams will receive the maximum number of altitude points (5,280) if the official scoring altimeter reads a value of exactly 5,280 feet AGL. The team will lose one point for every foot above or below the required altitude.	A StratoLoggerCF altimeter will be used to record the official altitude.	Test. The StratoLoggerCF will be tested in a vacuum chamber prior to assembly and launch to ensure correct functionality.	Incomplete. Altimeter tests will occur in the week prior to launch scheduled for February 24, 2018.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.3	Each altimeter will be armed by a dedicated arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.	Both altimeters will be armed by their own key switch which will be accessible from the exterior of the airframe.	Demonstration. The team will arm the altimeters after assembly on the pad, which will be confirmed by the subsequent beeps. The checklist for this item is detailed in Section 6.2.	Incomplete. Demonstration will occur prior to launch scheduled for February 24, 2018.
2.4	Each altimeter will have a dedicated power supply.	Each altimeter will be powered by its own 9 V battery tested for conformity.	Demonstration. The team will demonstrate that the two altimeter circuits are entirely independent.	Complete. See Section 4.4.3.
2.5	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).	The altimeters will be armed by key switches and will be oriented such that they won't be disarmed by flight forces.	Demonstration. The team will demonstrate that the switches are secure when in the on position.	Incomplete. Demonstration will occur prior to launch scheduled for February 24, 2018.
2.6	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.	The rocket body will be constructed of Blue Tube to increase durability of the rocket. The main parachute will slow the rate of descent of the rocket to avoid damage upon landing.	Analysis. Body tube material will be chosen to increase durability, and parachute size will be determined by calculations to reduce impact speed and wind drift.	Complete. See Section 4.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.7	The launch vehicle will have a maximum of four (4) independent Sections. An independent Section is defined as a Section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.	The rocket will only have three (3) tethered Sections: nosecone, midsection (with payload), and fin can.	Analysis. The rocket design only requires three tethered sections to fly which will be manufactured to the specifications listed in this report.	Complete. See Section 3.4.1.
2.8	The launch vehicle will be limited to a single stage.	The launch vehicle has a single stage.	Analysis. The rocket design will include a single motor.	Complete. See Section 3.4.1.
2.9	The launch vehicle will be capable of being prepared for flight at the launch site within 3 hours of the time the Federal Aviation Administration flight waiver opens.	The team will practice assembly using detailed checklists prior to launch to ensure that assembly time does not exceed three (3) hours.	Demonstration. The team will demonstrate the capability to prepare the rocket within 3 hours by practicing assembly using detailed checklists prior to launch.	Incomplete. Demonstration will occur prior to launch scheduled for February 24, 2018.
2.10	The launch vehicle will be capable of remaining in launch-ready configuration at the pad for a minimum of 1 hour without losing the functionality of any critical on-board components.	Recovery system devices will be activated only once the rocket is on the launch pad to avoid unnecessary battery drain.	Demonstration. The team will incorporate only necessary electronics that do not exceed the available power drawn from batteries.	Complete. See Section 4.4.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.11	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated Range Services Provider.	The rocket can be launched using only a standard motor igniter.	Analysis. The team will confirm with the manufacturer that the chosen motor is capable of being launched by a standard firing system.	Complete. See Section 5.2.1.
2.12	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by Range Services).	The rocket can be launched using only a standard motor igniter.	Demonstration. The team will demonstrate that the vehicle is capable of launching using only a standard motor igniter.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
2.13	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).	The rocket uses a commercially-produced AeroTech motor.	Inspection. The team will confirm that the chosen motor is certified by NAR and/or TRA before purchase.	Complete. See Section 1.2.2.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.13.1	Final motor choices must be made by the Critical Design Review (CDR).	The team will use an AeroTech L2200G motor.	Demonstration. The final motor choice is listed in Section 1.2.2 of this report.	Complete. See Section 1.2.2.
2.13.2	Any motor changes after CDR must be approved by the NASA Range Safety Officer (RSO), and will only be approved if the change is for the sole purpose of increasing the safety margin.	The team does not anticipate any need for change to motor selection.	Analysis. The team will determine the impact of any possible high-level design changes on motor performance, and make a request for motor change only when safety can be increased.	Complete. See Section 1.2.2.
2.14	Pressure vessels on the vehicle will be approved by the RSO.	The launch vehicle will not utilize any pressure vessels.	Analysis. The team will not utilize any pressure vessels when designing the rocket.	Complete. See Section 3.3.
2.14.1	The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews.	The launch vehicle will not utilize any pressure vessels.	Analysis. The team will not utilize any pressure vessels when designing the rocket.	Complete. See Section 3.3.
2.14.2	Each pressure vessel will include a pressure relief valve that sees the full pressure of the valve that is capable of withstanding the maximum pressure and flow rate of the tank.	The launch vehicle will not utilize any pressure vessels.	Analysis. The team will not utilize any pressure vessels when designing the rocket.	Complete. See Section 3.3.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.14.3	Full pedigree of the tank will be described, including the application for which the tank was designed, and the history of the tank, including the number of pressure cycles put on the tank, by whom, and when.	The launch vehicle will not utilize any pressure vessels.	Analysis. The team will not utilize any pressure vessels when designing the rocket.	Complete. See Section 3.3.
2.15	The total impulse provided by a College and/or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).	The selected motor provides 5,104 N-s of total impulse.	Demonstration. The team will demonstrate that they did not purchase or install a motor exceeding L-class.	Complete. See Section 1.2.2.
2.16	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	Current static stability margin at point of rail exit is calculated to be 2.05 cal. No changes that would appreciably affect this are currently planned.	Analysis. The team will use multiple methods to calculate the static stability margin of the rocket at the time of rail exit to ensure that a minimum value of 2.0 is achieved.	Complete. See Section 5.1.2.
2.17	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	The has a predicted rail exit velocity of 77.3 ft/s.	Analysis. The team will use multiple methods to calculate the rail exit velocity of the rocket at the to ensure that a minimum value of 52 ft/s is achieved.	Complete. See Section 5.2.3.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.18	All teams will successfully launch and recover a subscale model of their rocket prior to CDR. Subscales are not required to be high power rockets.	The subscale rocket was successfully launched and recovered on November 18, 2018.	Demonstration. The team will demonstrate a successful launch and recovery of a subscale rocket prior to CDR.	Complete. See Section 3.4.3.
2.18.1	The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.	The subscale was designed to function as closely to the full-scale as possible at 52% of the size.	Demonstration. The team will design and fabricate a subscale rocket to confirm the design of the full-scale.	Complete. See Section 3.4.
2.18.2	The subscale model will carry an altimeter capable of reporting the model's apogee altitude.	The subscale rocket had a StrattoLoggerCF installed at launch to record the apogee altitude.	Demonstration. The team will include an altimeter capable of recording the apogee altitude on the subscale.	Complete. See Section 3.4.3.3.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.19	All teams will successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The rocket flown at FRR must be the same rocket to be flown on launch day. The purpose of the full-scale demonstration flight is to demonstrate the launch vehicle's stability, structural integrity, recovery systems, and the team's ability to prepare the launch vehicle for flight. A successful flight is defined as a launch in which all hardware is functioning properly (i.e. drogue chute at apogee, main chute at a lower altitude, functioning tracking devices, etc.).	The same rocket will be flown during the full-scale demonstration flight as the full-scale test flight.	Demonstration. The team will fly the same rocket in the full-scale demonstration flight as in the full-scale test flight.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
2.19.1	The vehicle and recovery system will have functioned as designed.	The flight and recovery system results will be analyzed thoroughly to determine whether the rocket functioned as designed.	Analysis. Flight simulations, hand calculations, and material modelling will be compared to the flight results.	Incomplete. Analysis will occur after the launch scheduled for February 24, 2018.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.19.2	The payload does not have to be flown during the full-scale test flight.	The payload is an integral part of the rocket midsection, and will be flown on the full-scale test flight.	Demonstration. The team intends to fly the full rover payload on the full-scale test flight.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
2.19.2.1	If the payload is not flown, mass simulators will be used to simulate the payload mass.	The payload will be included in the rocket. Mass simulators will be used for payload electronics, including the rover, if necessary.	Demonstration. Mass simulators will be used if the rover is not available for flight.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
2.19.2.1.1	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.	If mass simulators are used, they will be modelled to determine the most appropriate location to offset the payload CG to match the full-scale design.	Demonstration. If mass simulators are used, they will be secured in the payload section to accurately simulate the final payload CG location.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
2.19.3	If the payload changes the external surfaces of the rocket (such as with camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale demonstration flight.	The payload does not change the external surface of the rocket.	Demonstration. The payload will not change the external surface of the rocket.	Complete. See Section 3.3.4.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.19.4	The full-scale motor does not have to be flown during the full-scale test flight. However, it is recommended that the full-scale motor be used to demonstrate full flight readiness and altitude verification. If the full-scale motor is not flown during the full-scale flight, it is desired that the motor simulates, as closely as possible, the predicted maximum velocity and maximum acceleration of the launch day flight.	The full-scale motor will be flown during the full-scale test flight to demonstrate full flight readiness and altitude verification.	Demonstration. The team will use of the full-scale motor during the full-scale test launch.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
2.19.5	The vehicle must be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the same amount of ballast that will be flown during the launch day flight. Additional ballast may not be added without a re-flight of the full-scale launch vehicle.	The full-scale rocket will contain 3.0 lb of ballast in the nosecone which will be included for all ground tests and the full-scale test launch.	Demonstration. The rocket will be fully ballasted for all ground tests and the full-scale test launch.	Incomplete. Demonstration will occur prior to the launch scheduled for February 24, 2018.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.19.6	After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA Range Safety Officer (RSO).	The team will not modify any components on the full-scale rocket without concurrence of the NASA Range Safety Officer.	Inspection. The team will inspect all components after the full-scale test launch to determine if any modifications will be necessary.	Incomplete. Component inspections will occur after the launch scheduled for February 24, 2018. Exterior paint will be added to the airframe after the full-scale test launch.
2.19.7	Full scale flights must be completed by the start of FRRs (March 6th, 2018). If the Student Launch office determines that a re-flight is necessary, then an extension to March 28th, 2018 will be granted. This extension is only valid for re-flights; not first-time flights.	The primary full-scale test launch date is February 24, 2018 with a backup launch opportunity on February 25.	Demonstration. The team will complete the full-scale test launch prior to FRR submission on March 6, 2018.	Incomplete. The primary full-scale test launch date is February 24, 2018 with a backup launch opportunity on February 25.
2.20	Any structural protuberance on the rocket will be located aft of the burnout center of gravity.	The burnout CG is located 74.8 in. from the nose. The forward-most structural protuberance on the rocket is the forward rail button at 107 in. from the nose.	Analysis. The rocket design will not include any protuberances located forward of the burnout CG.	Complete. See Section 3.3.5.6.
2.21.1	The launch vehicle will not utilize forward canards.	The launch vehicle has no forward canards.	Analysis. The team will not include forward canards in the rocket design.	Complete. See Section 3.3.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
2.21.2	The launch vehicle will not utilize forward firing motors.	The launch vehicle has no forward firing motors.	Analysis. The team will not include forward firing motors in the rocket design.	Complete. See Section 5.2.1.
2.21.3	The launch vehicle will not utilize motors that expel titanium sponges.	The AeroTech L2200G motor does not utilize titanium sponges.	Analysis. The team will not use a motor with titanium sponges.	Complete. See Section 5.2.1.
2.21.4	The launch vehicle will not utilize hybrid motors.	The launch vehicle does not utilize hybrid motors.	Analysis. The team will not include a hybrid motor in the rocket design.	Complete. See Section 5.2.1.
2.21.5	The launch vehicle will not utilize a cluster of motors.	The launch vehicle uses a single AeroTech L2200G motor.	Analysis. The team will not include a cluster of motors in the rocket design.	Complete. See Section 5.2.1.
2.21.6	The launch vehicle will not utilize friction fitting for motors.	The launch vehicle motor mount is epoxied to the rocket body tube.	Analysis. The team will not use a friction fit for the motor in the rocket design.	Complete. See Section 3.3.5.2.
2.21.7	The launch vehicle will not exceed Mach 1 at any point during flight.	The launch vehicle has a predicted maximum speed of Mach 0.64.	Analysis. The team will utilize simulations to ensure that the rocket speed does not exceed Mach 1.0 during flight.	Complete. See Section 5.2.
2.21.8	Vehicle ballast will not exceed 10% of the total weight of the rocket.	The launch vehicle will contain a total of 3.0 lb of ballast at the nose, which accounts for 6.4% of the total weight of the rocket.	Analysis. The team will not include a total amount of ballast that exceeds 10% the total weight in the rocket design.	Complete. See Section 3.3.1.

3.2 Mission Statement

The team is proud to present the full-scale launch vehicle design for the 2018 NASA SL competition in the pages below. This rocket is an original design that includes efforts from team members with backgrounds in, but certainly not limited to, high-powered rocket design, structural analysis, electrical design, and slender-body aerodynamics. It is the goal of the team to always choose the rocket and payload options that require the greatest technical demand to provide a challenge to even the most veteran team members. The rocket will satisfy all the requirements listed in Section 3.1 and Section 4.1, based on the success criteria defined in Section 3.2.1, to ensure that all vehicle operations will maximize safety to crew, spectators, and the environment.

3.2.1 Mission Success Criteria

The success of the full-scale launch vehicle is based on the challenge criteria listed in Section 3.1, as well as the team-derived requirements presented in Section 8.2. The team has defined a successful rocket launch as one where the vehicle apogee is within 100 ft of 5,280 ft AGL (1 mi), the drogue parachute deploys at apogee, the LARD opens at 1,000 ft AGL, the main parachute deploys at 700 ft AGL, and the entire rocket is reusable immediately after landing. To accomplish these goals, every component of the rocket must work as designed and redundancies should be in place for each component critical to the flight. The team will rely on simulations, physical experiments, and test flights to confirm that the vehicle will be successful with regards to the above criteria for every flight. Additionally, the success of the deployable rover is dependent on the success of the launch vehicle since the rover mission starts once the rocket mission ends.

3.3 Selection, Design, and Rationale of Full-Scale Launch Vehicle

This section includes the digital models, technical specifications, and design justifications for the full-scale launch vehicle, which is shown in Figure 3-1, below.

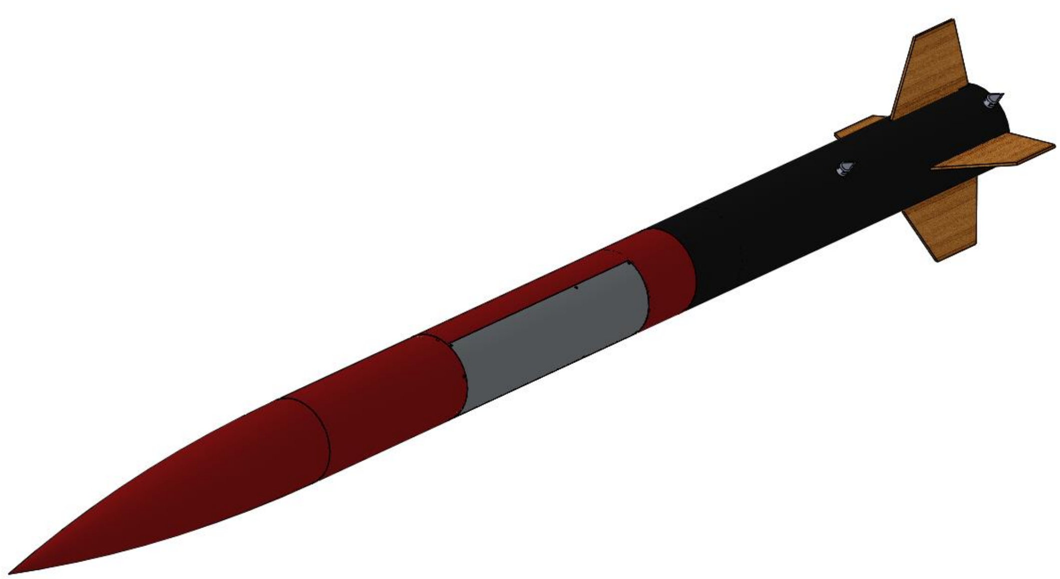

Figure 3-1: Isometric View of Full-Scale Launch Vehicle

3.3.1 Dimensions and Technical Details

The full-scale launch vehicle was designed using OpenRocket, a free software that is utilized by NAR and TRA rocketeers at all certification levels. The rocket will be 128.0 in. long with a constant body diameter of 7.5 in. after the nosecone base. A large body tube diameter was chosen to maximize the volume available within the rocket for the payload with deployable rover. The rocket will have three body Sections: nosecone, midsection, and fin can. Figure 3-2, below, shows the OpenRocket 3D schematic with body Sections labelled respectively.

Figure 3-2: OpenRocket Model with Section Labels

The current rocket configuration in OpenRocket has a predicted weight of 47.1 lb when fully assembled, which acts as the maximum allowable weight for the full-scale design. Maximum allowable weights for the payload and avionics bay are described in Sections 4.4 and 7.4, respectively. For comparison, the detailed SolidWorks model of the current rocket design has a predicted weight of 41.3 lb when fully assembled which includes accurate weights for the payload and avionics bay. Though these values do include weight approximations for the payload, avionics, and motor, they do not include weight values for body paint, epoxy, black powder charges, or fasteners. Both models will be updated continuously throughout the project timeline to reflect the latest design changes and provide up-to-date values for total mass. The team will also work on applying additional modelling techniques to include as many physical components in the OpenRocket and SolidWorks models as possible. Figure 3-3, below, shows the detailed SolidWorks model which will be compared to the OpenRocket model in Figure 3-2 for component mass confirmation.

Figure 3-3: Detailed SolidWorks Model

In its current configuration, the predicted CG location of the rocket is at a point 79.4 in. from the nosecone tip as determined using the mass approximations described above in OpenRocket. The CG location was confirmed using the detailed SolidWorks model to be 79.6 in. from the nosecone tip. Though the predicted total weights of each model differ by nearly 6.0 lb, the CG locations only differ by 0.1 in., which ensures that the stability margin is nearly identical between both models. A minimal difference in CG location between the models is highly favorable and is the result of conscious efforts to balance weights in the payload and avionics bay. The predicted CG location in each model will become more accurate as additional weights, such as body paint, epoxy, and fasteners, are added to the models throughout the design and fabrication process.

3.3.2 Body Tube Material Selection

The projected weights of the body tubes and coupler were calculated for the full-scale rocket in order to justify the use of Blue Tube on the rocket. The combined weight of the fiberglass forward airframe body tube, fin can body tube, and coupler was calculated to be approximately 7.83 lb. The combined weight of the Blue Tube forward airframe body tube, fin can body tube, and coupler was calculated to be approximately 4.23 lb. Using Blue Tube body tube components results in a weight savings of approximately 3.5 lb, nearly 10% of the weight of the rocket. Through reducing weight of the rocket, there is also a reduction of loading during flight which provides a higher margin of error for hitting the target altitude of 5,280 ft AGL.

To verify that Blue Tube would be capable of withstanding forces during flight, the compressive strength was analyzed. The principle compressive loads on the airframe are caused by inertia and drag. The peak drag force F_D was calculated using Equation 7 below:

$$F_D = \frac{1}{2}\rho V^2 C_D A \tag{1}$$

where ρ is the air density at sea level, 1.225$\frac{kg}{m^3}$; V is the peak velocity of the rocket, 219.56$\frac{m}{s}$; C_D is the drag coefficient, 0.451; and A is the frontal area of the rocket, 0.028578 m^2. This yields 380.20 N. The peak inertial load F_I was calculated using Equation 8 below:

$$F_I = ma \tag{2}$$

where m is the mass of the rocket, 19.090 kg, and a is the peak acceleration of the rocket, 142.95$\frac{m}{s^2}$. The resulting peak inertial load on the rocket is 2729.1 N. The total compressive force F_C on the rocket is given by Equation 9 below:

$$F_C = F_D + F_I = 3109.3\ N = 698.99\ lbf \tag{3}$$

The supplier of Blue Tube, Always Ready Rocketry, has provided axial crush test data for Blue Tube which is shown in Figure 3-4, below.

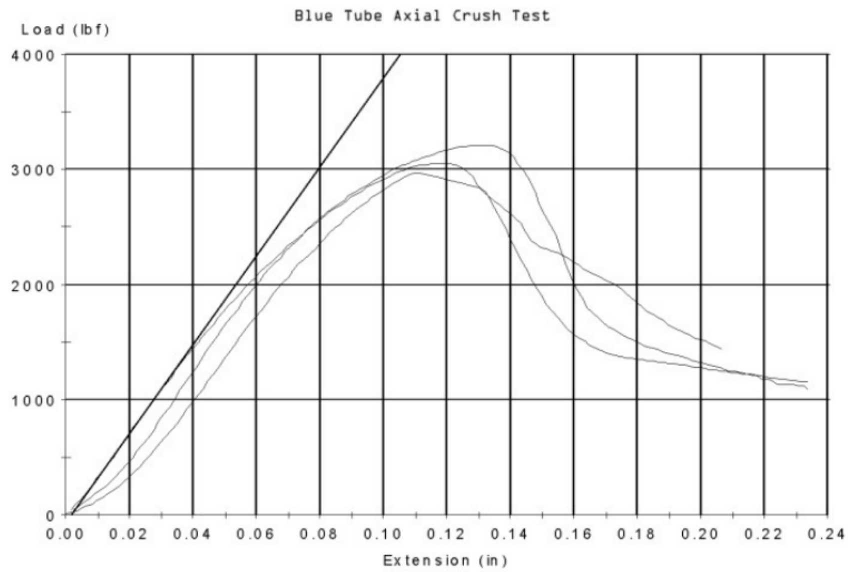

Figure 3-4: Blue Tube Axial Crush Test Data

Over three trials, the buckling load for Blue Tube was approximately 3,000 lb_f. The factor of safety for the Blue Tube airframe on this rocket was calculated to be approximately 4.3, confirming that Blue Tube is suitably strong for this application. This is also a conservative estimate, as the rocket features several bulkheads and centering rings that provide additional support. The team will conduct additional compression testing on cylindrical Blue Tube samples in order to verify the strength of the material. As one of the tests, the samples will be loaded in a hydraulic press until buckling occurs. This experiment will also grant the opportunity to quantify the strengthening effect of bulkheads, as well as the weakening effect of drilled holes and hatches in the body tube.

The rocket will have a constant body tube diameter of 7.5 in. and is reinforced with several bulkheads and centering rings throughout the vehicle. All components will be fixed to the airframe using West Systems 2-part epoxy. This epoxy was chosen for its high strength, durability, and working time. The bulkheads will be constructed using sheets of 0.25 in. aircraft-grade birch plywood. Varying numbers of sheets will be used for each bulkhead or centering ring depending on the expected loads at that location in the rocket. The launch vehicle will separate at two points: between the nosecone and midsection, and between the midsection and fin can.

3.3.3 Nosecone Design

As discussed in the PDR, the design requirements for the nosecone on the full-scale launch vehicle specified that the nosecone base had to be 7.5 in. in diameter, and that the tip could be accessible from the base to allow for the addition of nosecone ballast in the form of epoxied lead balls. Analysis on nosecone shapes led the team to choose a 5:1 ogive nosecone for use on the full-scale rocket due to its greater performance in subsonic conditions when compared to a conical nosecone with similar dimensions. Since the team does not have the precise manufacturing capabilities required to produce an original nosecone, only commercially-available nosecones were considered. After searching through catalogs of many different online rocketry retailers, the team was only able to find one nosecone that fit the required specifications. Always Ready Rocketry will supply the team with a plastic 5:1 ogive nosecone with a 7.5 in. base diameter. Assuming that the nosecone will be manufactured to a perfect 5:1 length-to-base ratio, the nosecone will be 37.5 in. long from base to tip. Figure 3-5, below, shows the plastic nosecone installed on a Blue Tube body tube taken from the website of the manufacturer.

Figure 3-5: Always Ready Rocketry Plastic 5:1 Ogive Nosecone with 7.5 in. Base Diameter

3.3.3.1 Nosecone Material Selection

The nosecone will be constructed out of plastic using a single mold to create the nosecone exterior shape and 6.0 in. shoulder. The team chose the plastic nosecone after learning that the fiberglass nosecone with metal tip described in the PDR was no longer available for purchase. A plastic nosecone also offers a significant cost and weight reduction to the launch vehicle, while remaining durable enough for multiple launches and recoveries. Since the plastic nosecone does not contain a metal tip, additional nose ballast will be necessary in the form of lead balls epoxied in the nosecone tip cavity. As shown in Figure 3-5, above, the plastic nosecone will be secured to the midsection during final assembly using multiple shear pins, described in Section 4.3.5.

3.3.3.2 Nosecone Bulkhead Design

The nosecone will feature a single bulkhead fixed into the nosecone cavity to be used as a tethering point for the main parachute. The bulkhead will consist of three circular sheets of 0.25 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 0.75 in. The aft face of the bulkhead will be fixed 3.0 in. from the base of the nosecone to allow additional volume for stowing the main parachute shock cord. Since the bulkhead will be placed inside the nosecone, OpenRocket was used to determine the outer diameter of the bulkhead to ensure that it will correspond to the inner diameter of the nosecone at its current position. Based on an assumed nosecone wall thickness of 0.08 in., the bulkhead must have a diameter 7.26 in. to fit inside the nosecone cavity. After using digital calipers to accurately measure and confirm the nosecone cavity dimensions, the plywood sheets will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine the sheets, which will then be allowed to cure for at least 24 hours under a vacuum seal.

A U-bolt will be installed through the center of the bulkhead as an attachment point for the main parachute shock cord. This will allow the nosecone section to remain tethered to the rest of the rocket during recovery rather than falling as a separate, self-contained independent section. The U-bolt shown in Figure 3-6, below, will be permanently fixed to the bulkhead during fabrication using Loctite to secure the fastening nuts on the opposite side of the bulkhead.

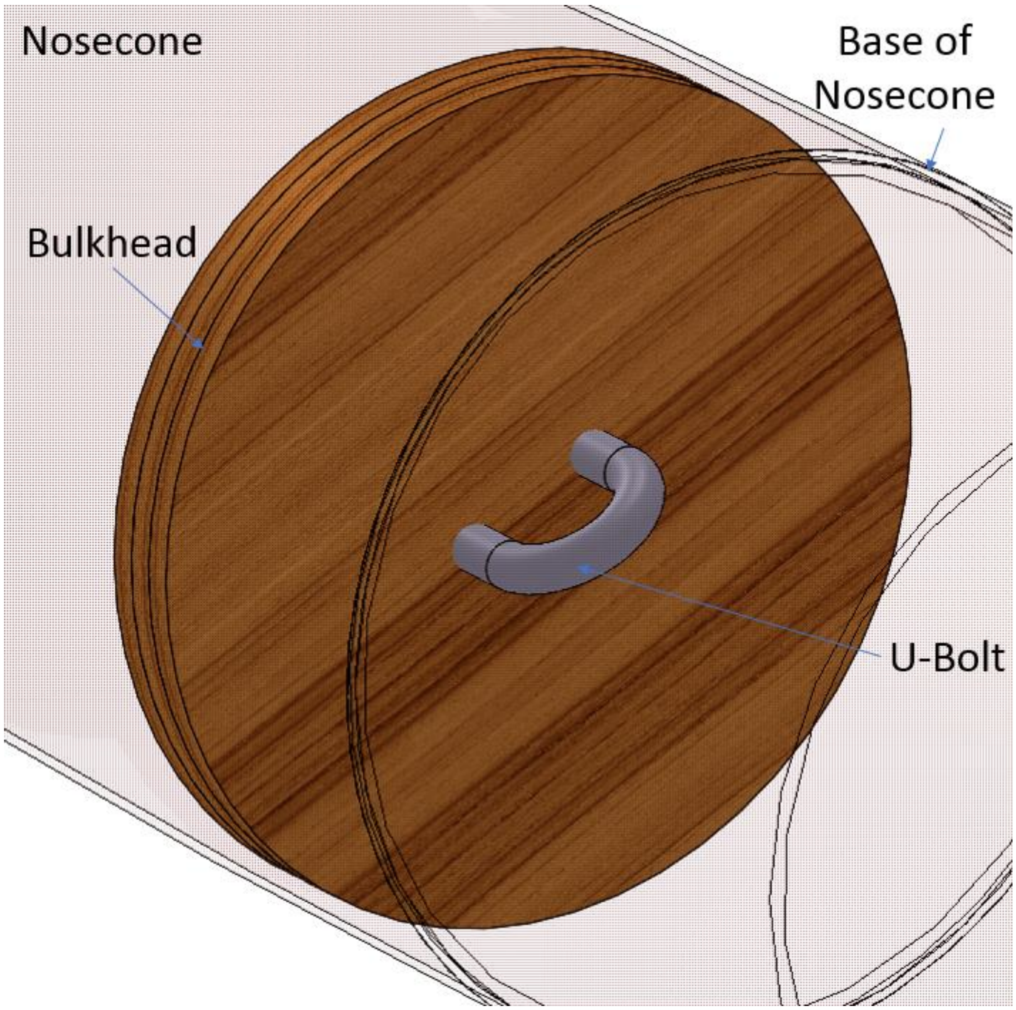

Figure 3-6: Nosecone Bulkhead

Note that once the bulkhead is installed, it will be impossible to access the interior cavity of the nosecone, therefore bulkhead installation will be one of the final steps in the rocket fabrication process.

To attach the nosecone assembly to the rocket midsection, a 6.0 in. shoulder will be included at the base of the nosecone. The nosecone and shoulder will both be made of plastic and will be formed in a single mold by the manufacturer. Shear pins will be used to secure the nosecone shoulder to the midsection body tube for launch.

3.3.4 Midsection Design

The rocket midsection, which is identified in Figure 3-2, will contain the payload bay, avionics bay, and part of each parachute compartment. The assembled midsection will be 48.0 in. long with a constant body diameter of 7.5 in. to match the base diameter of the nosecone described in Section 3.3.3. During fabrication and assembly, the midsection will be split into two lengths to allow for easier access to components in each section. The upper midsection will contain the main parachute compartment and will be 18.0 in. long. The lower midsection will contain the payload bay, avionics bay, and drogue parachute compartment, and will be 30.0 in. long. To fasten the two sections together, half of the payload centering ring will be epoxied to the lower midsection as a permanent fixture, and the upper midsection will be secured to the remaining exposed half of the payload centering ring by six wood screws. This design is described in more detail in Section 3.3.4.2. Figure 3-7, below, shows an exploded view of the midsection body tube with labels for the upper and lower midsection lengths.

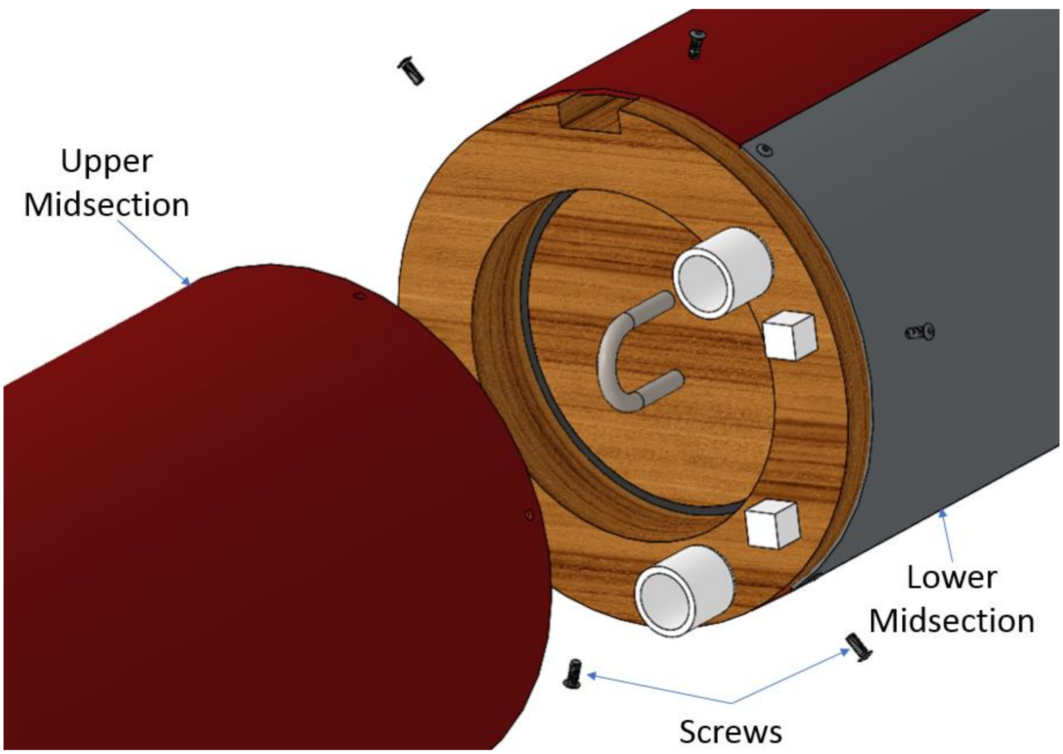

Figure 3-7: Exploded View of Midsection Body Tube Sections

Figure 3-8, below, shows the assembled midsection with labels for each internal component and subassembly.

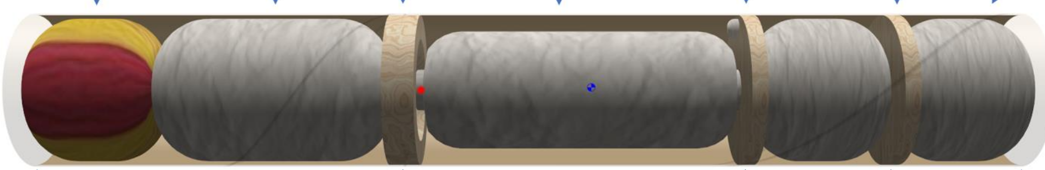

Figure 3-8: Assembled Midsection with Component and Subassembly Labels

Note that the 19.25 in. long coupler to be installed in the drogue parachute compartment is not shown in Figure 3-8, above. The coupler length will encompass the entire drogue parachute bay, and will be epoxied to the fin can leaving a 6.0 in. shoulder for attachment to the midsection. The forward end of the coupler will sit flush against the aft face of the avionics bulkhead which will be installed exactly 6.0 in. from the base of the midsection. This will allow the coupler to act as a straight edge for both the fin can and midsection to ensure that the internal components are all installed at the correct orientation during fabrication and assembly.

The main parachute will be housed in the forward parachute compartment, and the drogue parachute will be housed in the aft parachute compartment. The recovery system for the full-scale launch vehicle is described in Section 4. The avionics bay will contain the electronics sled with attached altimeters and batteries, which is discussed in Section 4.4.

3.3.4.1 Payload Bay Design

Since the payload is expected to account for a significant portion of the total rocket weight, it was determined that placing the payload bay as far forward in the midsection as possible would be most ideal. This would cause the CG position to shift forward in the rocket and would reduce the amount of nose ballast necessary to maintain a stability margin greater than 2.0. The team conducted a study to determine the maximum allowable payload weight by increasing the payload weight in steps of 0.5 lb and comparing the flight simulation results. Table 3-2, below, shows the OpenRocket flight simulation results for various realistic payload weights using an AeroTech L2200G motor and launching 5° from vertical on an 8 ft launch rail with no windspeed.

Table 3-2: OpenRocket Flight Simulation Results for Varying Payload Weight

Payload Weight (lb)	Rocket Weight (lb)	Nose Ballast (lb)	Apogee (ft AGL)
6.0	46.1	3.00	5,562
6.5	46.5	2.88	5,526
7.0	46.9	2.75	5,489
7.5	47.3	2.69	5,446
8.0	47.7	2.56	5,408

The results in Table 3-2 confirm that the amount of nose ballast necessary to maintain a stability margin of at least 2.0 will decrease as the payload weight increases. Since the OpenRocket model does not include the weight of body paint, epoxy, and fasteners, the team decided that a simulated apogee of approximately 5,500 ft AGL was reasonable for this stage in the design. The rocket model with a 7.0 lb payload weight reached 5,489 ft AGL using the simulation settings, which is why it was designated as the maximum allowable weight. As discussed in Section 7.4.1, the current payload model has a predicted weight less than 7.0 lb, but the team expects this value to increase as more components are added to the design. The OpenRocket and SolidWorks models will be updated continuously throughout the project to ensure greater accuracy in the flight simulation results.

3.3.4.2 Payload Centering Ring Design

Since the payload will remain fixed within the midsection for the entire flight, it was necessary to add a bulkhead to either end of the payload bay shown in Figure 3-8. The forward end of the payload will be fixed to the rocket body by a 1.5 in. thick centering ring that also acts as the point of separation between the upper and lower midsection body tubes identified in Figure 3-7.

Since the centering ring will have to hold the payload in place while also acting as an attachment point for the upper midsection and access hatch, it was necessary to design the ring to be thick enough to secure these components and still maintain structural strength to survive launch and recovery. The payload centering ring will consist of six rings of 0.25 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 1.5 in. The outer diameter will match the inner diameter of the body tube, approximately 7.3 in., and the inner diameter will be 5.0 in. to allow clearance for the rover to deploy after landing. After using digital calipers to accurately measure and confirm the body tube dimensions, the plywood rings will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine the rings, which will then be allowed to cure for at least 24 hours under a vacuum seal.

The forward face of the payload centering ring will act as the lower end of the main parachute bay. A pair of PVC blast caps will be installed on this face using West Systems 2 part epoxy at the base. Since the difference between the inner and outer diameters of the ring will be approximately 2.5 in., only blast caps with base diameters of 0.75 in. or less will be used to store the main parachute black powder charges. A wire terminal with two ports will be fixed adjacent to each of the blast caps to act as the connection point for the e-match wire being fed into the respective blast cap. The blast cap and terminal pairs will be labelled “P” for primary and “S” for secondary. A small hole will be drilled at a point between the two blast cap and terminal pairs to allow altimeter wires to be fed around the payload bay and into the main parachute compartment. These wires will be color-coded and labelled primary and secondary to ensure proper connection to their respective wire terminal. When assembling the rocket for the launch, this hole will be sealed using plumber’s putty to ensure that no ejection gases can escape into the payload bay.

Since the payload centering ring will be supporting the payload bay, upper midsection, and access hatch, the team determined that it would not be suitable to also add an attachment point for the main parachute to the forward face. Instead, the main parachute shock cord will be fed through a small, rectangular cutout on the outer edge of the payload ring which will be open and accessible by the removable access hatch described in Section 3.3.4.6. The cutout will be 0.75 in. wide and 0.25 in. deep which will allow ample room for the 0.50 in. shock cord described in Section 4.3.2. When closing the access hatch, the shock cord will be held taut in the cutout and then sealed with plumber’s putty to ensure that no ejection gases can escape into the payload bay. Figure 3-9, below, shows the payload centering ring with blast caps and terminals, as it would be installed in the rocket body tube.

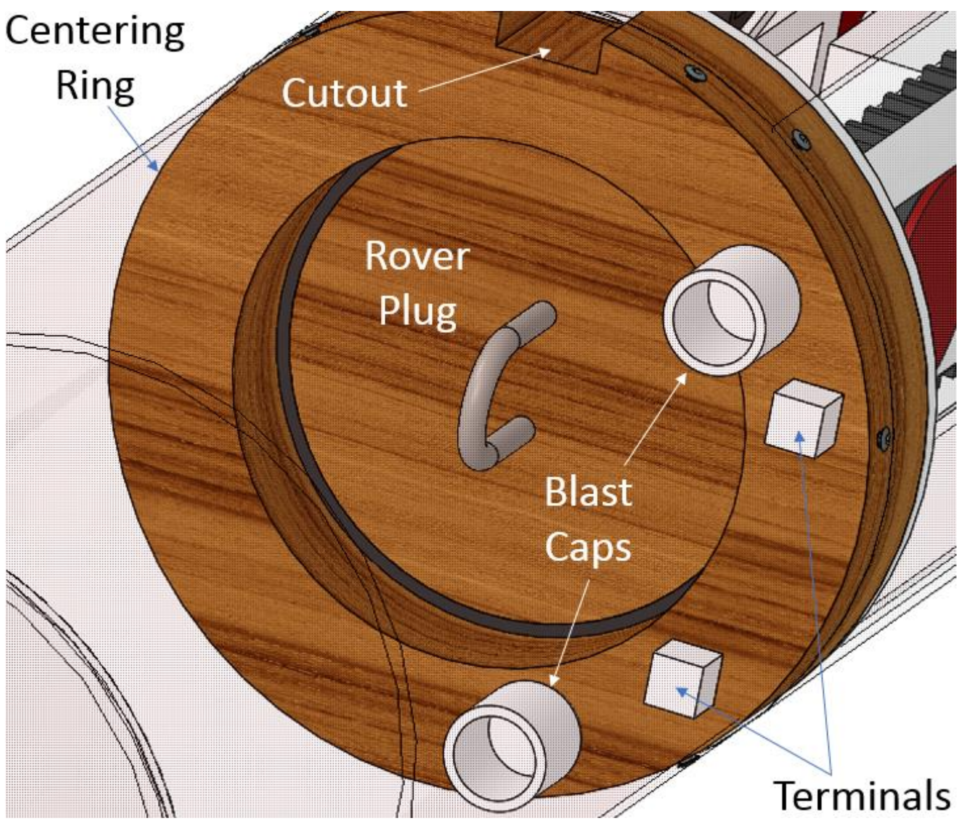

Figure 3-9: Payload Centering Ring Assembly

As shown in Figure 3-9, above, the rover bay will be sealed off during flight by a removable plug. The PDR design called for a hinged door at the rover bay entrance, but it was determined through simulation that the door would be unable to open past 30° from vertical before making contact with the inner diameter of the payload centering ring. The plug will consist of two circular sheets of 0.25 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 0.5 in. After creating the plug body, a weather-resistant rubber seal will be glued to the outer edges to ensure an airtight seal. The outer diameter of the plug body with seal will be equal to the inner diameter of the payload centering ring. After using digital calipers to accurately measure and confirm the body tube dimensions, the plywood rings will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine the rings, which will then be allowed to cure for at least 24 hours under a vacuum seal. Figure 3-10, below, shows the SolidWorks model of the plug with a rubber seal along the outer edge.

Figure 3-10: Rover Bay Plug

During assembly, the plug will be placed over the rover bay opening to the main parachute compartment and pushed into the hole until it is flush against the upper payload bearing. When the main parachute black powder charges fire, the gas expansion will push against the upper face of the plug to make it even tighter against the payload bearing. The plug will protect the rover from any negative effects due to the rapid gas expansion in the main parachute compartment during each black powder charge explosion. Additionally, the plug will act as the divide between the payload bay and main parachute compartment to ensure that no gases are able to escape into the payload bay volume which may cause the charges to be ineffective in separating the nosecone and deploying the main parachute.

A U-bolt will be installed through the center of the plug body to allow its removal following nosecone separation. A small loop will be made in the main parachute shock cord approximately 5.0 ft from the end of the main parachute aft shock cord. A metal, approved carabiner will be used to connect the shock cord loop to the plug U-bolt. As the shock cord is pulled out of the compartment, it will also pull the plug out of the payload centering ring to open the rover bay. The plug is designed to be lightweight to reduce any complications with the shock cord, and will remain tethered to the shock cord during descent.

The team intends to build a model plug prior to full-scale fabrication to practice its installation and removal to ensure that the design is practical. The team also intends to build a model of the midsection with a mock parachute compartment and mock payload bay. A centering ring will be placed between the sections and each compartment will be closed using removable bulkheads at each end. An active altimeter will be placed in the rover bay and sealed using a plug identical to the one described above. A black powder charge will be ignited in the mock parachute compartment to simulate a recovery event. Following each test, the force required to remove the plug will be measured using a handheld fish scale, and the altimeter data will be analyzed to determine if any pressure changes were present during each black powder detonation. The team will use these results to finalize the design of the plug before fabricating the full-scale launch vehicle.

3.3.4.3 Payload Bulkhead Design

The payload bulkhead will act as the aft attachment point for the payload tube, and will separate the payload and avionics bays. The payload bulkhead will consist of three circular sheets of 0.25 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 0.75 in. After using digital calipers to accurately measure and confirm the body tube dimensions, the plywood sheets will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine the sheets, which will then be allowed to cure for at least 24 hours under a vacuum seal.

As described in Section 3.3.4.2, the payload bulkhead will act as an attachment point for the main parachute shock cord to ensure that the nosecone and midsection remain tethered during recovery. A U-bolt will be installed through the bulkhead on the side of the tube that is accessible by the access hatch. The U-bolt shown in Figure 3-11, below, will be permanently fixed to the bulkhead during fabrication Loctite to secure the fastening nuts on the opposite side of the bulkhead.

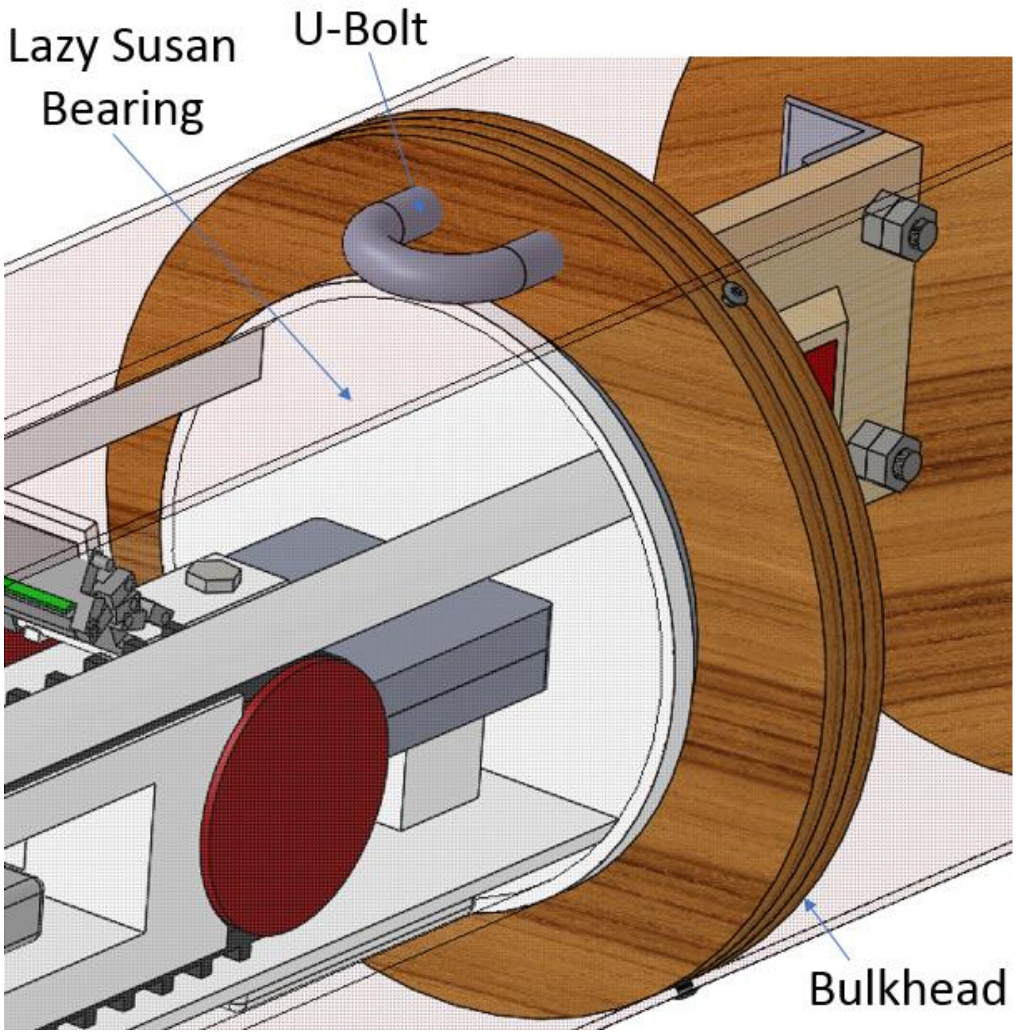

Figure 3-11: Payload Bulkhead

During rocket assembly, team members will be able to easily locate and attach the shock cord to the payload bulkhead U-bolt when the access hatch, described in Section 3.3.4.6, is removed. To further secure the hatch during flight, two screws will be used to fix the hatch to the payload bulkhead outer edge. This will ensure that the hatch remains flush with the rocket body to minimize any negative effects on surface drag during flight.

3.3.4.4 Avionics Bay Design

The avionics bay will contain all the electronics necessary to operate the recovery systems on board the full-scale launch vehicle which are described in Section 4.4. The team utilized the relatively large diameter of the rocket body to design an avionics package ("sled") that could fit horizontally in the avionics bay, rather than the more conventional vertical installation. The avionics bay will be 6.25 in. long, measured between the bulkhead faces on either end of the bay, which corresponds to an internal volume of 143. 6 in^3. The avionics sled design shown in Section 4.4.1

confirms that this open volume is large enough to contain all the necessary electronics for flight.

Two holes will be drilled through the body tube wall of the avionics bay to allow for the installation of two key switches that will enable the team to power on or off the electronics from the exterior of the rocket. The key switches will be permanently fixed to the rocket body using epoxy on the interior side of the hole. The exterior portion of the key switches will be minimized to reduce any negative effects on surface drag. Ideally, the exterior portion of the key switches will be made flush with the rocket body exterior surface. The team will also ensure that the key switches are not installed in-line with the launch rail buttons to enable access to the switches when placed on the launch rail. Four small holes will be drilled wall of the avionics bay at even increments around the circumference of the body tube to act as pressure relief and static ports for the altimeters.

3.3.4.5 Avionics Bay Bulkhead Design

The avionics bay bulkhead will separate the avionics bay from the drogue parachute compartment at the aft-most end of the midsection. The avionics bay bulkhead will consist of three circular sheets of 0.25 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 0.75 in. After using digital calipers to accurately measure and confirm the body tube dimensions, the plywood sheets will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine the sheets, which will then be allowed to cure for at least 24 hours under a vacuum seal.

A U-bolt will be installed through the center of the avionics bay bulkhead as the forward attachment point for the drogue parachute shock cord. This will allow the midsection to remain tethered to the fin can during rocket recovery. The U-bolt will be permanently fixed to the bulkhead during fabrication using Loctite to secure the fastening nuts on the opposite side of the bulkhead.

The aft face of the avionics bay bulkhead will be installed exactly 6.0 in. from the bottom edge of the midsection to allow enough clearance for the fin can coupler described in Section 3.3.5. This face will also act as the upper end to the drogue parachute bay. A pair of 0.75 in. diameter PVC blast caps will be installed on this face using West Systems 2 part epoxy at the base. A wire terminal with two ports will be fixed adjacent to each of the blast caps to act as the connection point for the e-match wire being fed into the respective blast cap. The blast cap and terminal pairs will be labelled “P” for primary and “S” for secondary. A small hole will be drilled at a point between the two blast cap and terminal pairs to allow altimeter wires to be fed around the payload bay and into the main parachute compartment. These wires will be color-coded and labelled primary and secondary to ensure proper connection to their respective wire terminal. When assembling the rocket for the launch, this hole will be sealed using plumber’s putty to ensure that no ejection gases can escape into the payload bay. Figure 3-12, below, shows the avionics bay bulkhead with PVC blast caps, wire terminals, and U-bolt installed.

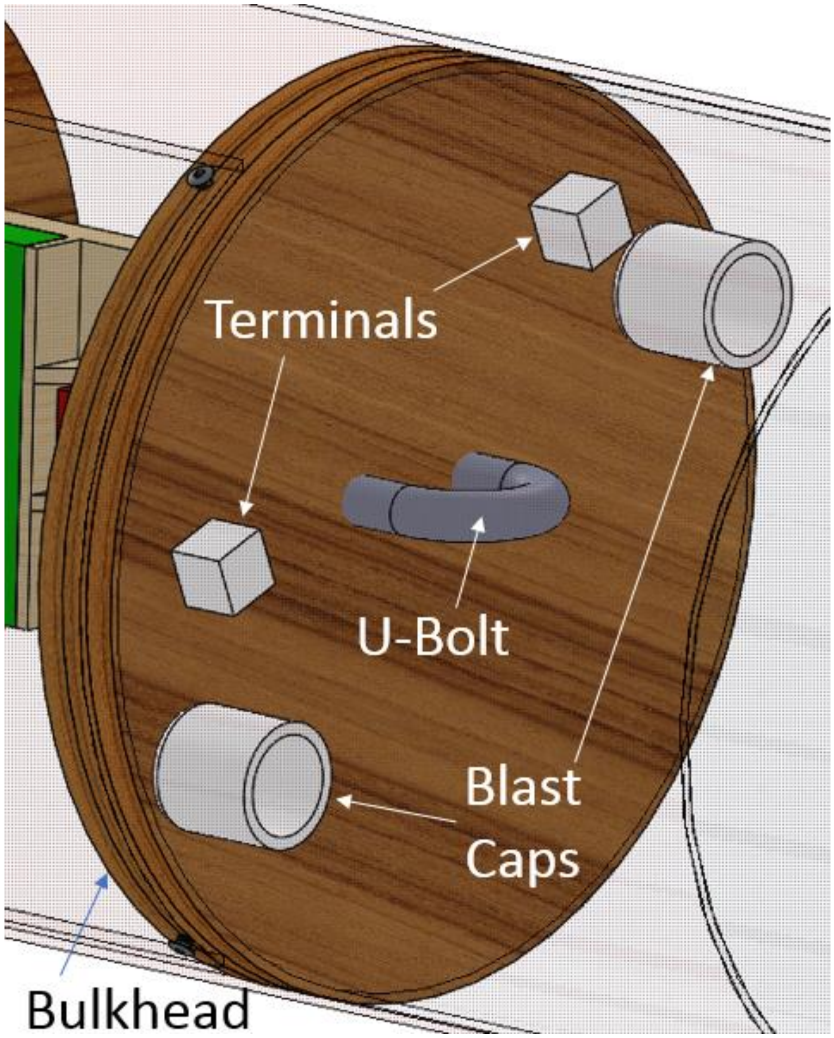

Figure 3-12: Avionics Bay Bulkhead

The avionics bay bulkhead will act as the aft attachment point for the access hatch described in Section 3.3.4.6. The access hatch will be cut out of the body tube to leave only 0.5 in. of the outer edge of the avionics bay bulkhead exposed. The remaining bulkhead thickness of 0.25 in. will be covered by the midsection body tube to ensure a filleted epoxy seal around the drogue parachute bay. Two screws will be used to fix the hatch to the avionics bay bulkhead during assembly. This will ensure that the hatch remains flush with the rocket body to minimize any negative effects on surface drag during flight.

3.3.4.6 Midsection Access Hatch Design

The rocket midsection will feature a removable hatch that will allow access to the payload bay and avionics bay during assembly. The hatch will be cut from the midsection body tube to ensure that it remains flush and even with the body tube surface when attached for flight. The top of the hatch will be cut from the edge of the body tube, and the bottom of the hatch will stop 6.25 in. from the bottom for a total length of 23.75 in. The hatch will be 7 in. wide when viewing the rocket as a flat plane; this corresponds to a curvature of 115.5°. The hatch will be measured and sketched on the Blue Tube surface before being cut out using a handheld Dremel tool. The team will practice cutting spare pieces of Blue Tube before attempting to cut the actual hatch. Figure 3-13, below, shows an exploded view of the hatch over the fully assembled rocket.

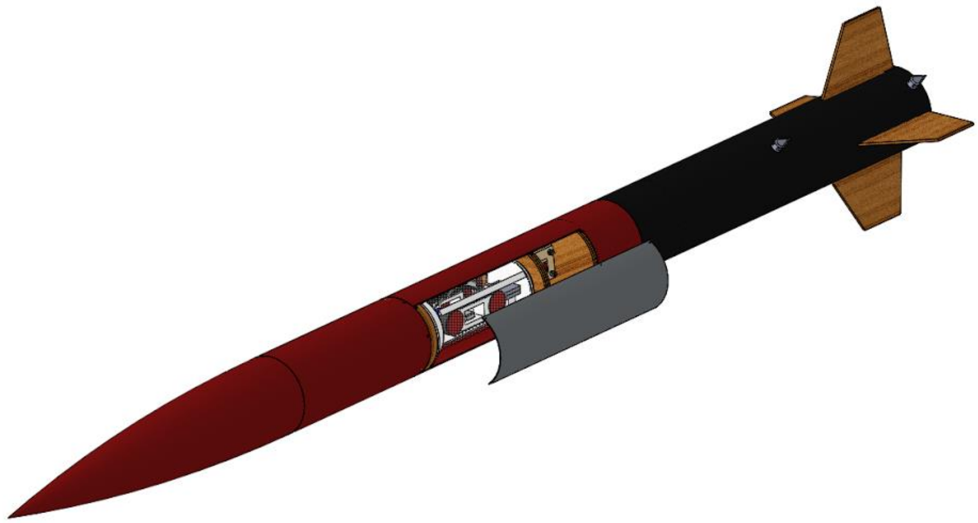

Figure 3-13: Exploded View of Midsection Access Hatch

When removed, the hatch opening will allow team members to access the U-bolt attached to the payload bulkhead for use when assembling the main parachute shock cord. Team members will also have full access to the avionics bay, as well as all altimeter wires leading to the drogue and main parachute compartments. Due to the wide body diameter of the midsection airframe, access to the avionics bay and wires will no longer be limited to only members with small hands, which was a major complication when assembling the subscale rocket.

The hatch will be secured to the midsection via a total of six screws. The two top screws will fit into the payload centering ring, the two middle screws will fit into the payload bulkhead, and the two bottom screws will fit into the avionics bay bulkhead. Before drilling any screw holes, the team will practice using spare Blue Tube components to determine how far hole can be drilled from the edge before damaging the body tube material. The access hatch on the subscale rocket was permanently damaged after overtightening the screws too close to the material edges. Figure 3-14, below, shows an exploded view of the hatch and screw placement over the assembled midsection.

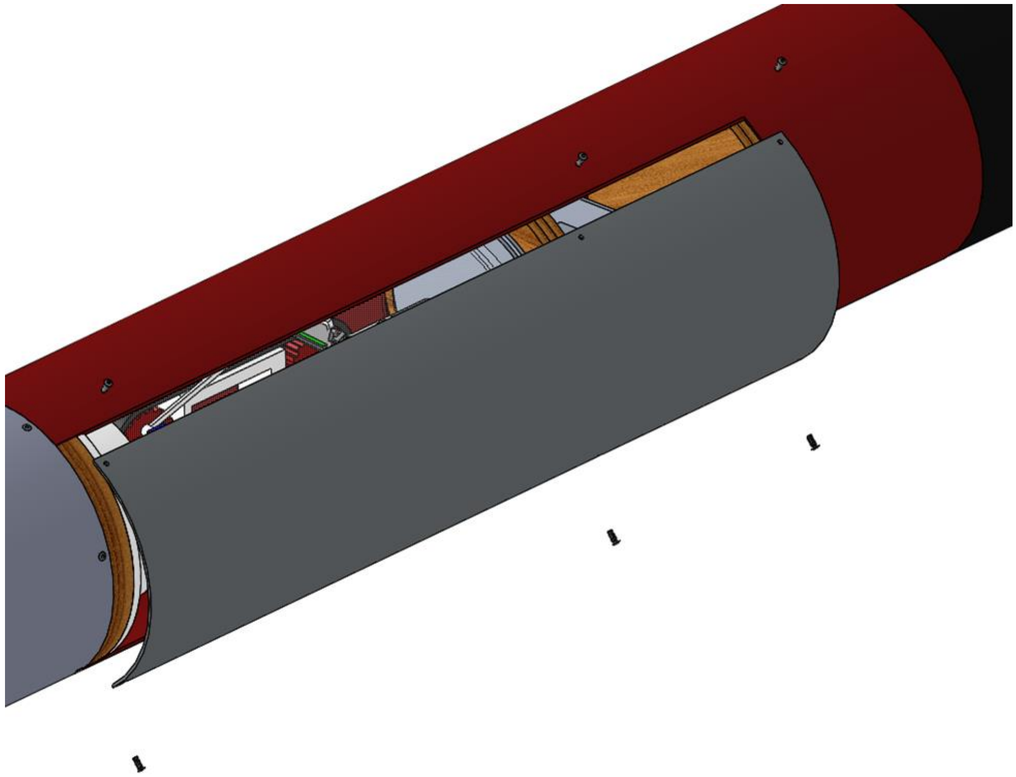

Figure 3-14: Exploded View of Midsection Access Hatch with Screw Placement

As described in Section 4.4.1, the access hatch will also include two holes toward the bottom to install the key switches necessary to operate the altimeters.

3.3.5 Fin Can Design

The fin can on the full-scale launch vehicle will be 41.0 in. long and will contain the drogue parachute compartment, motor, and mounted fins. As described in Section 4.3, the drogue parachute compartment will contain two parachutes: the drogue parachute for deployment at apogee, and the Low-Altitude Recovery Device (LARD) for deployment at 1,000 ft AGL. A 19.25 in. coupler will encompass the entire length of the inner wall of the drogue parachute compartment, as described in Section 3.3.4. The coupler will be epoxied such that a 6.0 in. shoulder will extend out of the top of the fin can for insertion into the midsection during assembly. The fin can will be secured to the midsection during final assembly using multiple shear pins, described in Section 4.3.5. Figure 3-15, below, shows the fin can with all components labelled.

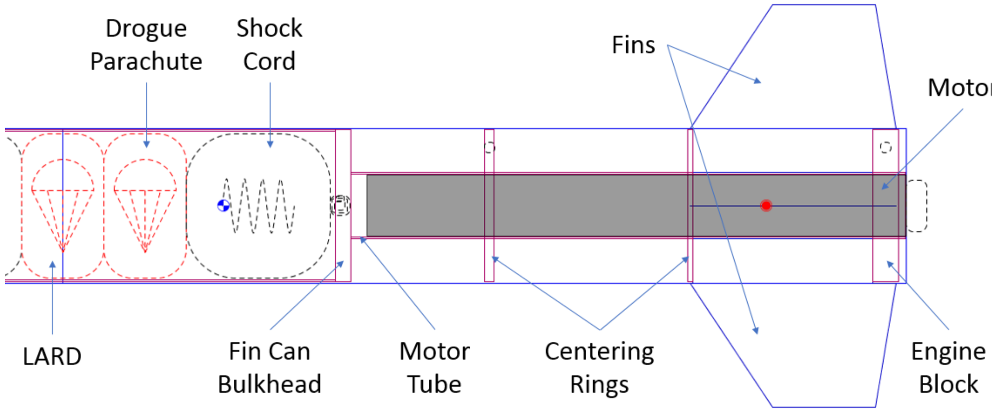

Figure 3-15: Fin Can with Component Labels

As shown in Figure 3-15, above, the fin can will have four fins attached through slots cut in the body tube and secured using epoxy fillets at their intersection lines with the body tube. The fin can body tube was purchased from Always Ready Rocketry and will have pre-cut fin slots to aid in mounting the fins.

3.3.5.1 Fin Can Bulkhead Design

The fin can bulkhead will separate the drogue parachute compartment and the motor bay, which contains the motor tube, centering rings, and motor. The bulkhead will consist of three circular sheets of 0.25 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 0.75 in. The forward face of the bulkhead will be fixed 13.25 in. from the upper end of the fin can and will act as the aft end of the drogue parachute compartment. After using digital calipers to accurately measure and confirm the body tube dimensions, the plywood sheets will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine the sheets, which will then be allowed to cure for at least 24 hours under a vacuum seal.

A U-bolt will be installed through the center of the bulkhead as the aft attachment point for the drogue parachute shock cord. This will allow the fin can to remain tethered to the midsection during rocket recovery. The U-bolt shown in Figure 3-16, below, will be permanently fixed to the bulkhead during fabrication using Loctite to secure the fastening nuts on the opposite side of the bulkhead.

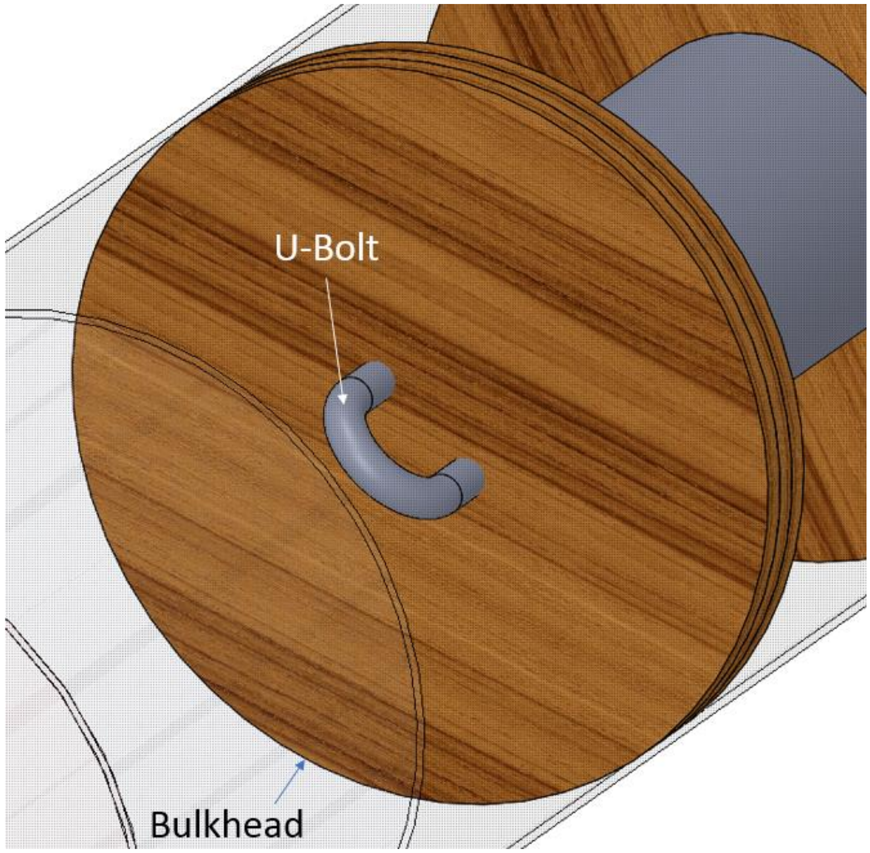

Figure 3-16: Fin Can Bulkhead

Once the fin can bulkhead is installed, the entire motor bay will become inaccessible, so it will be one of the final components to epoxy during fin can fabrication.

3.3.5.2 Motor Tube Design

The motor tube is designed to transfer the loading from the rocket motor retainer to the body tube via centering rings and an engine block. The motor retainer will be fixed to the aft end of the motor tube, and the inner diameter will exactly match the outer diameter of the motor casing. This will allow the motor casing to slide into the tube and be secured using the retainer which will act as the single point of contact between the motor casing and the rest of the rocket. The motor tube is one of the most critical components that will be installed on the rocket, and much caution will be used when handling, installing, and securing the motor tube during fabrication.

The motor tube will have a length of 27.0 in., which is 0.8 in. longer than the motor casing to ensure that the motor casing will be able to fit vertically in the fin can with room to spare. The bottom surface of the motor tube will be level with the bottom of the fin can body tube, and will extend out from the engine block by 0.375 in., which is further explained in Section 3.3.5.4. Identical to the rocket airframe body, the motor tube will be Blue Tube, which is described in Section 3.3.2.

The motor tube will be attached by epoxy to both centering rings, the engine block, and four fin tabs. The designs for the centering rings, engine block, and fins are detailed in Sections 3.3.5.3, 3.3.5.4, and 3.3.5.5, respectively. The entire motor tube and fin assembly will be fabricated outside of the body tube and left to cure over several days. Figure 3-17, below, shows each of the epoxy areas along the length of the motor tube, with motor removed for clarity, as green regions.

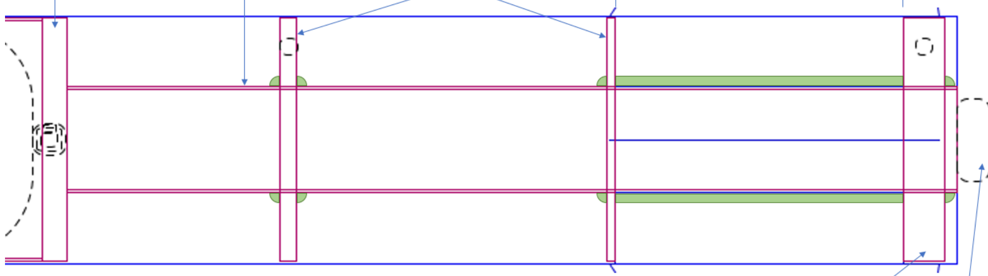

Figure 3-17: Motor Tube with Epoxy Areas Highlighted

After allowing at least 24 hours to the epoxy to cure, the entire motor tube assembly will be slid into the fin can body tube and epoxied in place by the aft face of the engine block and by fillets around each fin. Once installation is complete, the entire motor tube will be inaccessible by the team, so it is imperative that extra caution is taken when cutting, dimensioning, handling, and installing motor tube components.

The team is confident that this configuration of motor tubes, centering rings, fin tabs, and engine block will transfer the load from the motor retainer to the outer body tube in a safe and effective manner. The team will perform load simulations on the SolidWorks model with this configuration to confirm that the rocket will be able to withstand all applied forces of flight.

3.3.5.3 Motor Tube Centering Ring Design

The motor tube will have two attached centering rings to secure the motor from within the fin can. The forward centering ring will consist of two rings cut out of 0.25 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 0.5 in. The aft centering ring will consist of a single ring cut out of 0.25 in. aircraft-grade birch plywood. The outer diameter of each ring will match the inner diameter of the fin can body tube described in Section 3.3.5. The inner diameter of each ring will match the outer diameter of the motor tube described in Section 3.3.5.2. After using digital calipers to accurately measure and confirm the body tube dimensions, the plywood rings will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine the upper centering rings, which will then be allowed to cure for at least 24 hours under a vacuum seal. Figure 3-18, below, shows the dimensions for the centering rings with respect to the fin can bulkhead and engine block.

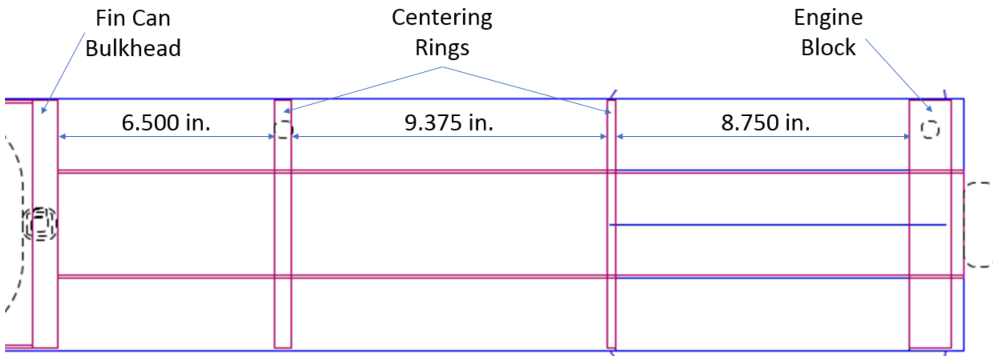

Figure 3-18: Location of Centering Rings Along Motor Tube

The forward centering ring will be installed as the uppermost support for the motor tube, since the motor tube itself will not be fixed to the fin can bulkhead. As described in Section 3.3.6.5, the motor tube and centering rings will be assembled before insertion into the fin can. This method will ensure that all motor tube components and fins will be aligned correctly, but it will be impossible to epoxy the aft centering ring to the inner wall of the body tube during fabrication. However, the upper face of the forward centering ring, the lower face of the engine block, and each of the fins will be epoxied to the body tube. This configuration will allow team members to fabricate the motor tube components with more precision, while still also allowing forces to transfer from the motor tube to the body tube.

To ensure the proper alignment of the fins during fabrication, the aft centering ring and top layer of the engine block will have rectangular cutouts that match notches on the fin tabs in the same location. The fin tab notches will be able to fit into the centering ring holes to ensure their proper spacing and orientation along the motor tube. This setup relies on the engine block being level once attached to the motor tube, so the team will take great care to ensure that the engine block does not settle or slip when curing. Figure 3-19, below, shows a centering ring layer with rectangular cutouts for the fin tab notches.

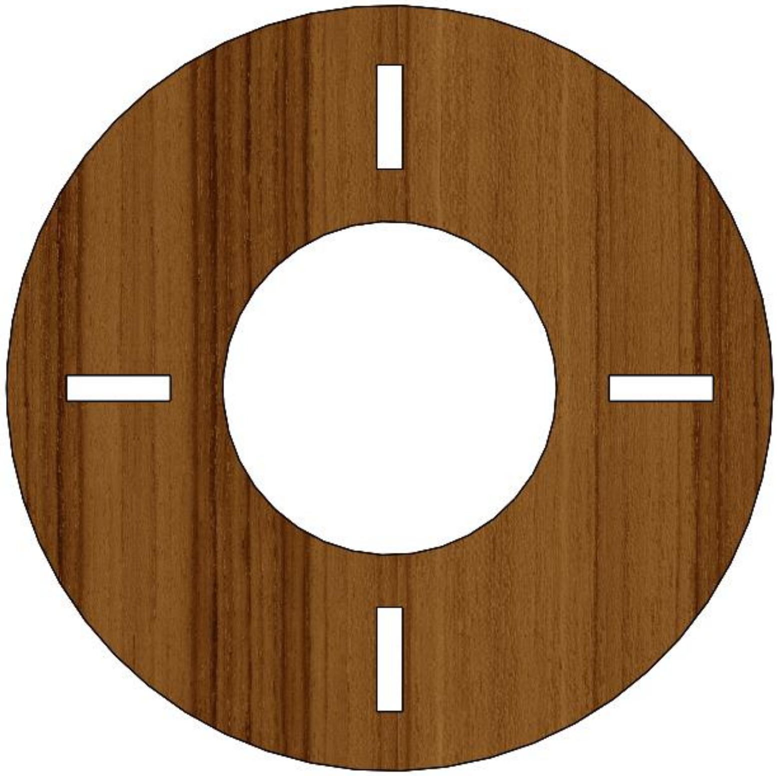

Figure 3-19: Motor Tube Centering Ring with Cutouts for Fin Tab Notches

To ensure that the fins remain aligned during the fabrication process, the team will use an external jig to align the fins exactly 90° from each other. The jig will be designed to fit around the motor tube, engine block, and aft centering ring so that the entire assembly can be epoxied together and set aside to cure for at least 24 hours before continuing fabrication.

3.3.5.4 Engine Block Design

The engine block is designed to withstand the largest expected forces from the motor during flight, and it will transfer loads directly from the motor retainer to the outer body tube. The engine block will consist of five rings cut out of 0.25 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 1.25 in. The outer diameter of each ring will match the inner diameter of the fin can body tube described in Section 3.3.5. The inner diameter of each ring will match the outer diameter of the motor tube described in Section 3.3.5.2. After using digital calipers to accurately measure and confirm the body tube dimensions, the plywood rings will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine the upper centering rings, which will then be allowed to cure for at least 24 hours under a vacuum seal.

As described in Section 3.3.6.5, the engine block will be the first component epoxied to the motor tube during assembly. The engine block lower face will be recessed into the fin can body tube by 0.125 in. to allow the motor tube to extend past the engine block to remain level with the bottom of the fin can. A flanged motor retainer will be installed over the motor tube and will be fixed to the engine block face by special wood screws. The dimensions of the retainer, including the necessary recess between the engine block and bottom of the fin can, were provided by the manufacturer, AeroPack. Figure 3-20, below, shows the engine block with motor retainer fixed in place after fabrication.

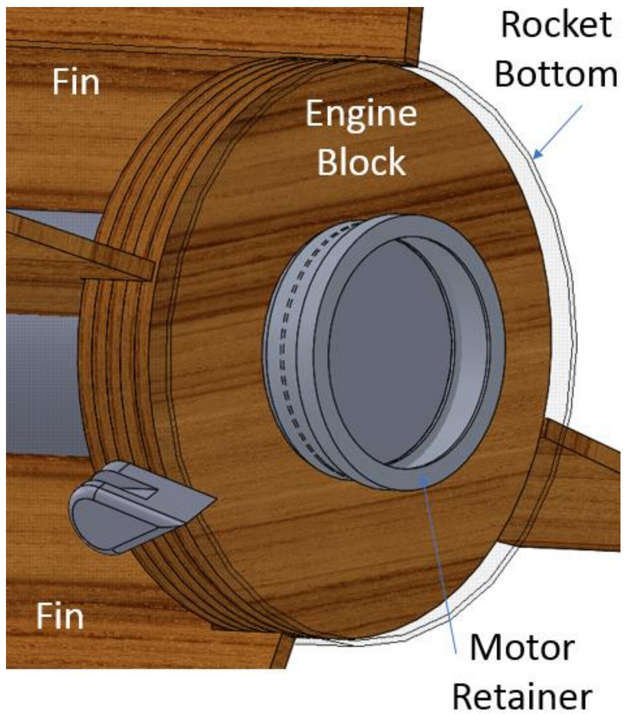

Figure 3-20: Engine Block and Motor Retainer

Once the motor retainer is installed on the engine block, the motor casing will be able to slide into the motor tube during assembly. A retainer cap will then be screwed on to secure the motor within the motor tube immediately prior to launch.

3.3.5.5 Fin Design and Mounting

The rocket fins are critical to controlling the rocket stability during ascent, but require precise fabrication to limit any errors in manufacturing and installation. The surface area, cross-sectional shape, and location of the fins control the location of the CP along the length of the rocket, which is described in Section 5.1.1. The greatest effect on CP can be observed when the fins are installed at the aft-most end of the rocket, which also increases the stability margin by pushing the CP closer to the tail if the CG remains unchanged. There are numerous sources of conflicting information regarding fin shapes and sizing available in books and online, so the team relied on advice from mentors and results from OpenRocket flight simulations to design the fins.

Alan Whitmore, one of the team mentors identified in Section 1.1.2, offered the following advice to the team when asked about fin sizing:

1. Straight lines are easier to design, cut, and install than curved lines.
2. Any part of a fin that extends beyond the bottom of the body tube will be more likely to break off at impact, thus eliminating rocket reusability.
3. The most durable fins have forward swept trailing edges with the rear of the root chord starting some small distance from the bottom of the body tube.
4. Fins with a span that exceeds the root chord length will be more subject to the negative effects of fin flutter during flight.
5. Fins with a span less than half of the root chord length generally do not perform very well during flight.
6. The most common fin design for high-powered rockets is the clipped delta.

Applying the above advice, the launch vehicle fins will be trapezoidal, each with a root chord of 10.0 in., a tip chord of 5.0 in., and a span of 6.0 in. The leading edge of each fin will be swept back by 2/3, or 2.0 in. of sweep for every 3.0 in. along the span, to increase high-speed aerodynamic performance. The trailing edge of each fin will be swept forward by a slope of 1/6, or 1.0 in. for every 6.0 in. along the span, to increase the impact durability, and thus reusability, of the rocket. The rocket will feature four identical fins installed at 90° increments around the circumference of the fin can. Figure 3-21, below, shows the dimensions of each fin as well as dimensions for the fin tabs that will be used to attach the fins to both the motor tube and fin can body tube.

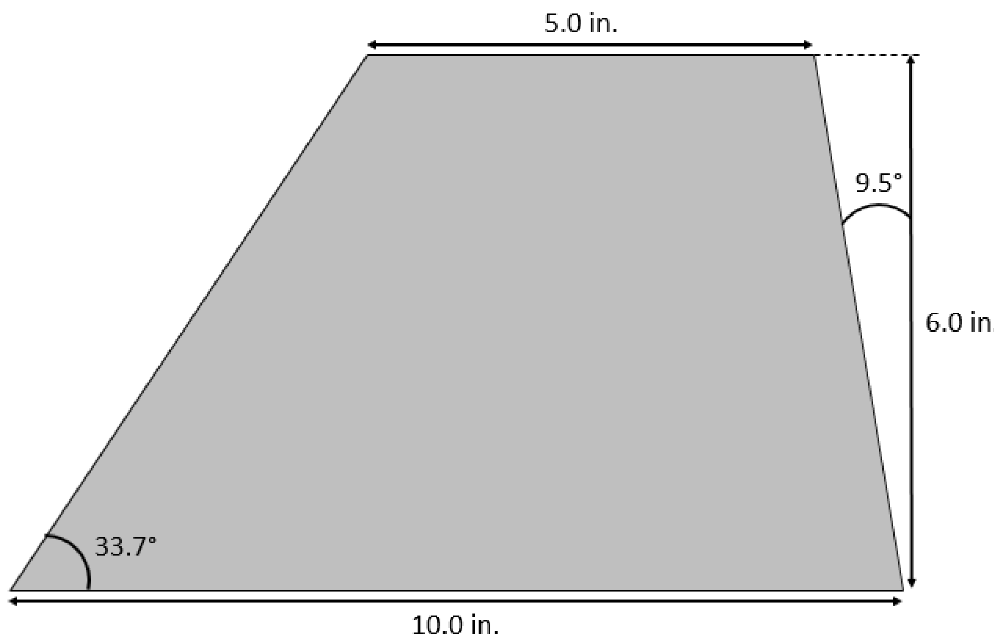

Figure 3-21: Fin Dimensions

Each fin will be installed as described in Section 3.3.6.5, with fin tabs being used to better secure each fin to the rocket body tube as well as to aid in transferring the loads from the motor to the body tube. Each tab will be 8.75 in. long to match the length between the lower face of the aft centering ring and the upper face of the engine block. The depth of the tabs will equal the length between the outer walls of the motor tube and body tube, approximately 2.25 in. Figure 3-22, below, shows all fin and fin tab dimensions.

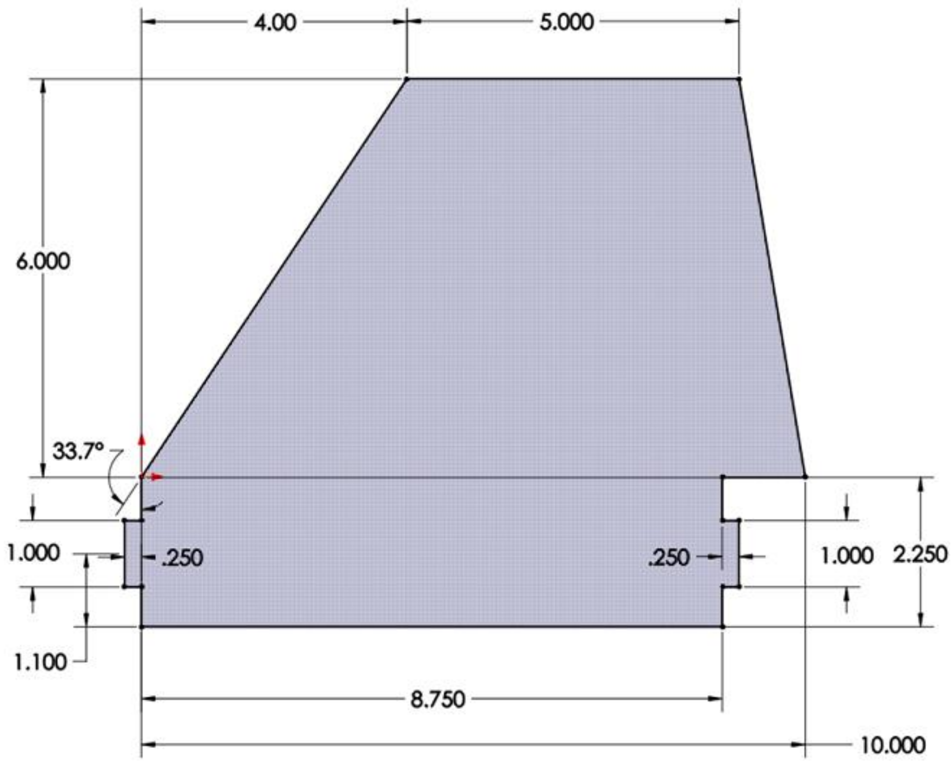

Figure 3-22: Fin Tab Dimensions

Each fin will consist of two cutouts of 0.125 in. aircraft-grade birch plywood sandwiched together using epoxy for a total thickness of 0.25 in. The team is confident from experience that fins of this thickness will be durable enough to survive multiple flights. Using two sheets reduces flutter during flight, and the simple manufacturing method allows for extra fins to easily be created in the event of failure. After using digital calipers to accurately measure and confirm the body tube and motor tube dimensions, the plywood fins will be cut out using a laser cutter. West Systems 2 part epoxy will be used to combine two cutouts for each fin, which will then be allowed to cure for at least 24 hours under a vacuum seal.

3.3.5.6 Launch Rail Buttons

Two rail buttons will be installed on the exterior surface of the body tube to secure the full-scale launch vehicle on the vertical rail for launch. It is desirable to place rail buttons close to the tail of the rocket so that the rail can guide the vehicle in the vertical direction for as long as possible. It is also important that the rail buttons be installed at strong points in the rocket body as the entire weight of the rocket will be supported by the buttons while on the rail prior to launch. The team has chosen to use airfoil-shaped rail buttons to decrease the drag penalty from attaching asymmetrical components to the exterior of the rocket.

The forward rail button will be installed at the forward motor tube centering ring, and the aft rail button will be installed at the engine block. The rail buttons will only be installed after allowing at least 24 hours for all epoxied elements in the motor tube to cure. To install each rail button, a pilot hole will be drilled through the body tube and ring. The rail buttons will then be screwed in through the pilot holes using the manufacturer-recommended screws. The rail buttons will be installed on the opposite side of the rocket as the access hatch, described in Section 3.3.4.6, to ensure that the team can access all flight-critical components even while the rocket is resting on the launch rail prior to launch.

3.3.6 Fabrication of Launch Vehicle

This section contains high-level instructions for fabricating the full-scale launch vehicle.

3.3.6.1 Bulkhead Fabrication

All bulkheads will be constructed using sheets of 0.25 in. thick aircraft-grade birch plywood. Additional sheets will be epoxied together using West Systems 2 part epoxy in areas of increased loading such as the motor mount and payload bulkhead. The epoxied bulkheads will remain under vacuum for 24 hours to allow the epoxy to fully cure. All bulkheads and centering rings are cut from sheets of plywood using a laser cutter. The bulkheads and centering rings will be positioned upright in the main body tubes at their correct location. The placement will be maintained using shims, dowels, and/or clamps to stabilize the bulkheads while the epoxy cures.

A drill press will be used to create any holes needed through a bulkhead or centering ring. The hole size and placement will depend on which components will be attached. When installing U-bolts, the fastening nuts will be secured using Loctite after installation is complete.

3.3.6.2 Fin Fabrication

The fins will be constructed out of two sheets of 0.125 in. aircraft-grade birch plywood epoxied together using West Systems 2 part epoxy. The outline of the fins will be cut from sheets of plywood using a laser cutter. The sheets will be epoxied together and held under vacuum for 24 hours to allow the epoxy to fully cure.

To increase aerodynamic performance, the exterior edges of the fins will be sanded to a rounded bevel using a belt sander and angle guides to create.

3.3.6.3 Nosecone Fabrication

The exterior of the nosecone will be sanded using 220 grit sandpaper, then successively finer grit sandpapers up to 2000 to guarantee a smooth surface finish. The nosecone will be thoroughly cleaned with mineral spirits prior to receiving primer then paint to finish.

3.3.6.4 Midsection Fabrication

The upper and lower sections of will be cut using a band saw to 18 in. and 30 in., respectively. The access hatch will be cut out of the lower section using a hand Dremel tool and cutting wheel. The avionics bay bulkhead will be installed first, then the payload bulkhead. After installing the payload and ensuring that it is in its final state, the payload centering ring will be installed. Once the epoxy has cured for at least 24 hours, holes will be drilled through the upper midsection and hatch to attach them via screws to their respective bulkheads.

The exterior surface of Blue Tube has a spiral ridge caused by the filament-wound construction technique. Wood filler will be applied to this ridge then sanded smooth using 220 grit sandpaper, then successively finer sandpaper up to 2000 grit. 3M Sanding Primer will be used to create a fine surface finish. The exterior surface will be cleaned thoroughly with mineral spirits prior to adding primer and paint to finish.

3.3.6.5 Fin Can Fabrication

The fin can body tube section will be cut to a length of 41 in. using a band saw. The fin slots will be laser cut by the supplier, Always Ready Rocketry, and will require small cuts to be made at the bottom of the tube to remove the remaining tabs. The engine block will be epoxied to the motor tube and left to cure for at least 24 hours. The fins will be aligned around the motor tube using the aft centering ring, engine block, and an external jig. These components will be epoxied together as one assembly and then will be left to cure for at least 24 hours. The forward centering ring will be epoxied to the motor tube and the entire assembly will be left to cure for another 24 hours. After curing for another 24 hours, the entire motor tube assembly will slide into the aft end of the fin can to align with the fin slots. The upper face of the forward centering ring, the lower face of the engine block, and the fins will all be epoxied to the body tube. After letting the fin can cure for at least 24 hours, the fin can bulkhead will be epoxied through the top of the fin can. The rail buttons will be aligned and installed at their respective locations along the fin can. Finally, the body tube exterior surface will be prepared and painted as described in Section 3.3.6.4.

3.4 Design, Fabrication, and Flight Results of Subscale Launch Vehicle

This section includes the technical specifications, fabrication methods, and flight results for the subscale launch vehicle, named *Very Nuts II*, shown in Figure 3-23, below.

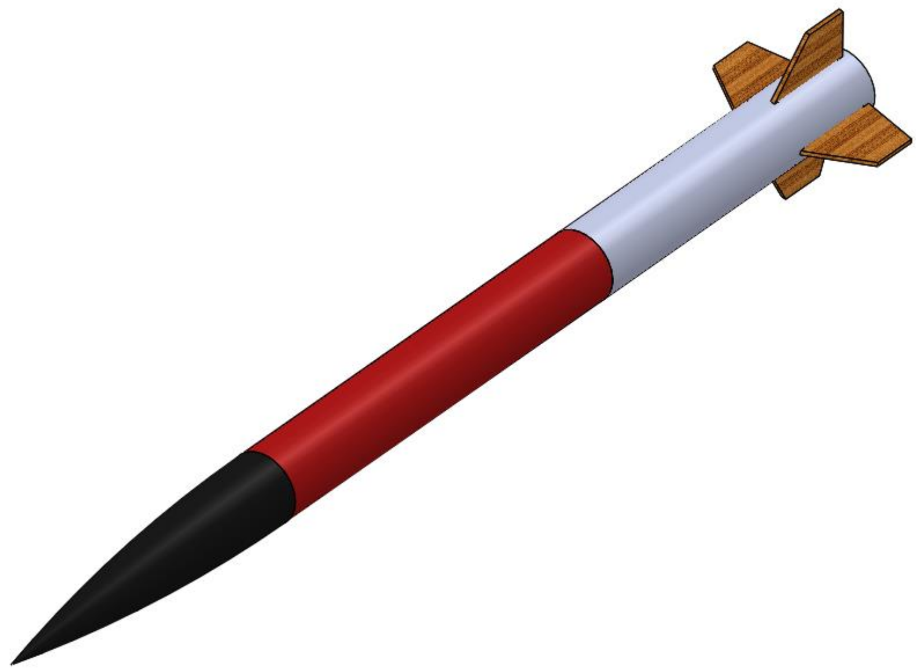

Figure 3-23: Isometric View of the Subscale Launch Vehicle

3.4.1 Dimensions and Technical Details

The subscale launch vehicle is 65.0 in. long with a constant body diameter of 3.9 in. after the base of the nosecone, and has identical sections to the full-scale rocket: nosecone, midsection, and fin can. Figure 3-24, below, shows the OpenRocket schematic with body sections labelled respectively.

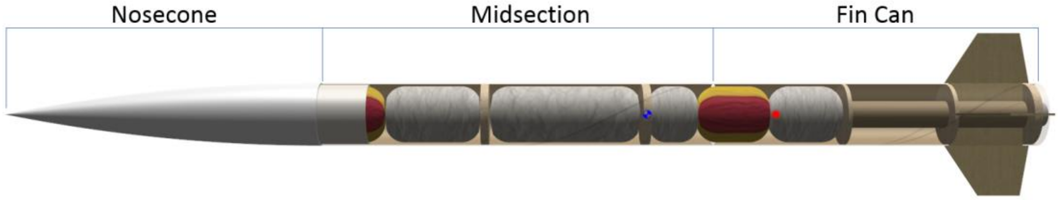

Figure 3-24: Subscale OpenRocket Model with Section Labels

After final assembly, the rocket weighs 9.1 lb, which is less than the predicted weight in OpenRocket of 9.6 lb. The SolidWorks model had a predicted weight of 8.9 lb, which is less than the actual weight. This difference can be attributed to the fact that the OpenRocket model was updated to include weight approximations for body paint and epoxy, which the SolidWorks model omitted. Figure 3-25, below, shows the SolidWorks model with each component modelled as a mass block for total weight and CG confirmation.

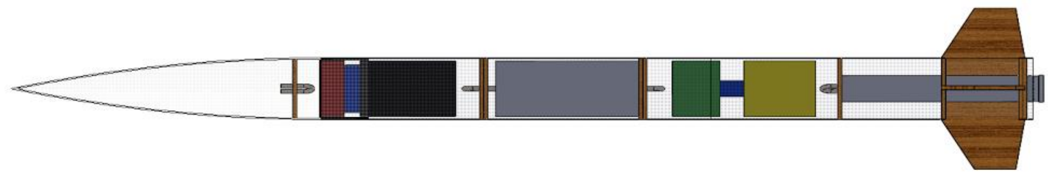

Figure 3-25: Subscale SolidWorks Model

After assembly, the CG location on the subscale rocket was located balancing the entire rocket on a rope, then measuring the distance to that location from the nose. It was determined that the CG was located at a point 39.8 in. from the nose which is 1.2 in. more aft than the predicted location of 38.6 in. from the nose using OpenRocket. Though the CG is more aft than predicted, it is still within an allowable range for a stability margin greater than 2.0, as explained in Section 3.4.1.3. The subscale did not use any ballast to alter its final CG location prior to flight.

3.4.1.1 Subscale Design Scaling

The subscale rocket was designed and fabricated to be a scaled-down model of the full-scale rocket described in Section 3.3. The team began designing the subscale by choosing a 3.9 in. body diameter to allow enough internal volume for the payload, avionics, and parachutes, while still being wide enough that most team members would be able to fit their hands down the body tube for black powder charge preparation. The ratio of subscale to full-scale body tube diameters is 3.9:7.5, or 52%. This ratio was also directly applied to the subscale nosecone which matches the 5:1 ogive shape of the full-scale nosecone as described in Section 3.3.3.

The total length of the subscale was also chosen by the above ratio against the PDR full-scale rocket design. In the PDR, the full-scale was 125 in. long, so the subscale was designed to be 65.0 in. long by applying the 52% scale factor. As described in Section 3.3.1, the current full-scale design is 128.0 in. long which corresponds to a ratio of lengths of 65:128, or 51%. Though the subscale is not scaled exactly to the current full-scale design, it is within a margin that can still be considered reasonable.

The team took great efforts when designing the subscale midsection to apply the 52% scale factor to each dimension, but most components had to be shifted slightly in the final design to allow enough space for the onboard payload. Table 3-3, below, shows each dimension with its subscale length, full-scale length, and corresponding scale factor percentage.

Table 3-3: Scale Factors of Subscale Midsection Component Lengths

Component or Subsection	Subscale Length (in.)	Full-Scale Length (in.)	Scale Factor (%)
Midsection body tube	24.50	48.00	51
Main parachute compartment	9.50	20.25	47
Access hatch	12.25	23.75	52
Drogue parachute compartment	11.75	19.25	61

As shown in Table 3-3 above, most of the major dimensions in the subscale midsection fall within +/- 5% of the desired 52% scale factor applied to the rest of the design.

The subscale fins were designed to apply the 52% scale factor when compared to the full-scale fin dimensions. The subscale fins have a root chord length of 5.20 in., tip chord of 2.6 in., and span of 3.12 in., which are all 52% the total length of their respective dimension in the full-scale design. The subscale fins also feature a 33.7° swept leading edge and a 9.5° forward-swept trailing edge.

3.4.1.2 Payload Design

The subscale payload housing consisted of a 3D printed forward bearing cap made of ABS plastic, a 3D printed Lazy Susan bearing made of ABS plastic, a 2.75 in diameter acrylic tube, 3.77 in diameter centering ring made of birch plywood for support. All of these components were constrained between two birch bulkheads secured together with 0.25 in threaded rods.

The subscale payload was designed to promote free rotation of the payload during flight. This was done by having the two LSB systems at the forward and aft ends of the payload. The free spinning tube contained two wooden rails epoxied to the inside of the tube, which held in place a 3D printed ABS plastic sled. A BeagleBone Black computer was attached to the sled. A BNO 055 Absolute Orientation Sensor and a BMP 180 Barometric Altimeter were attached to the BeagleBone to provide sensory input, and a HobbyTiger Lipo Battery attached to a DROK Voltage Regulator powered the Beagle Bone. The Lipo battery, which was the heaviest component, was housed in a slot at the bottom of the sled to offset the center of gravity from the central axis of the tube. The Beagle Bone Black was programmed to measure the roll rate and orientation of the tube, to allow the team to see how an internal free spinning tube affects the rocket's orientation. Figure 3-26 shows an isometric view of the subscale payload, including the avionics sled which was housed in the same bay, just below the payload. The BeagleBone Black, voltage regulator, barometric altimeter, and orientation sensor is shown in black, pink, blue, and orange respectively. The payload sled is shown in purple, and the avionics sled is shown in light brown. On the Avionics sled, the Stratologger CF and Entacore AIM USB 3 altimeters are shown in red and green respectively.

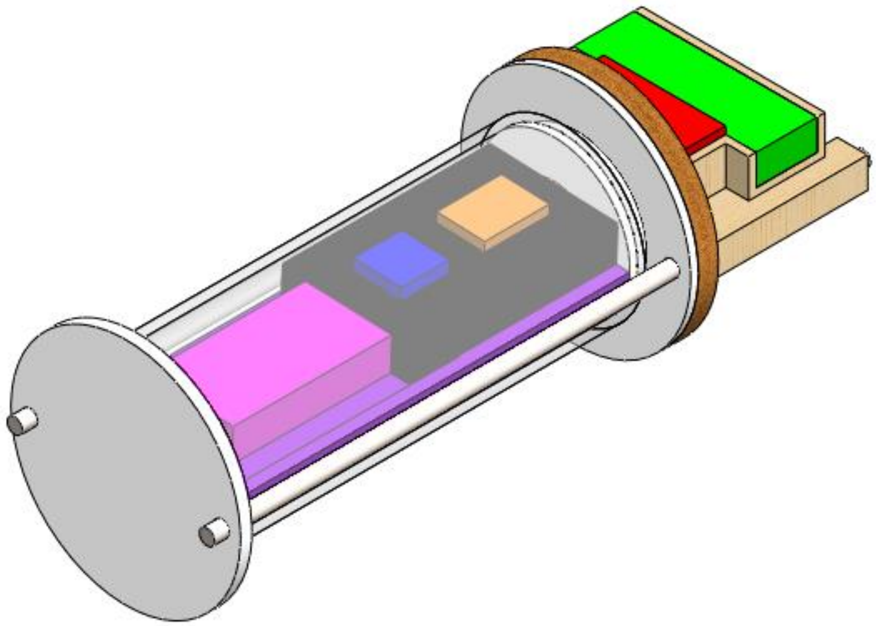

Figure 3-26: Isometric view of Payload and Avionics Sled

3.4.1.3 Flight Stability

The subscale CP location was predicted by OpenRocket to be located 48.2 in. from the nose and was confirmed using Barrowman's Method, which is described in Section 5.1.1. The difference between CG and CP locations is 8.4 in. Figure 3-27, below, shows the final CP and CG locations on the subscale launch vehicle after assembly.

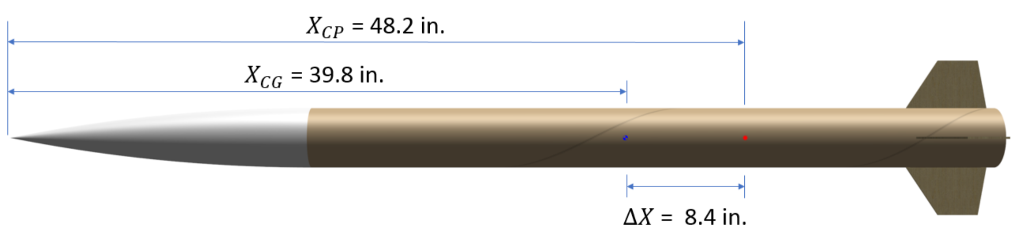

Figure 3-27: Subscale OpenRocket Model with CG and CP Locations Shown

The subscale rocket stability margin was calculated to be 2.2 cal, which exceeds the minimum value of 2.0 as listed in Table 4-1. During flight, the stability margin will continue to increase as the motor propellant is burned away. Section 5.1.2 contains the necessary equations for stability margin, as well as detailed analysis regarding how the stability margin will change throughout a rocket flight.

3.4.2 Fabrication of Launch Vehicle

This section contains high-level instructions for fabricating the subscale launch vehicle.

3.4.2.1 Bulkhead Fabrication

All bulkheads were constructed using sheets of 0.125 in. thick aircraft-grade birch plywood cut using a laser cutter. Bulkheads or centering rings with multiple sheets were epoxied together using West Systems 2 part before being allowed to cure under a vacuum seal for at least 24 hours. When fixing the bulkheads or centering rings in the rocket body, shims, dowels, and clamps were used to hold the bulkhead or centering ring in place and the entire assembly was set aside to cure for at least 24 hours. A drill press will be used to create any holes needed through a bulkhead or centering ring for U-bolts, wire access, or screw holes.

3.4.2.2 Fin Fabrication

The fins were constructed out of two sheets of 0.125 in. aircraft-grade birch plywood that were cut using a laser cutter. The sheets were epoxied together using West Systems 2 part epoxy and left to cure under a vacuum seal for at least 24 hours. To increase aerodynamic performance, the exterior edges of the fins were sanded to a rounded bevel using a belt sander and angle guides.

3.4.2.3 Nosecone Fabrication

The exterior of the nosecone was sanded using 220 grit sandpaper, then successively finer grit sandpapers up to 2000 until a smooth finish was achieved. Then the nosecone was thoroughly cleaned with mineral spirits prior to receiving primer then paint to finish. Two coats of red spray paint were added to the nosecone.

3.4.2.4 Midsection Fabrication

The phenolic body tube was cut using a band saw to a length of 24.5 in. and the top and bottom edges were sanded to achieve a level surface on each end. The access hatch was measured and cut out from the midsection body tube using a hand Dremel tool and cutting wheel. The 8.0 in. long coupler was epoxied into the bottom of the midsection so that a 4.0 in. shoulder extended out of the bottom to be inserted in the fin can. The payload aft bulkhead was epoxied against the top edge of the coupler in the midsection and a bubble-level was used to ensure the bulkhead was level in the body tube.

During assembly prior to launch, two metal rods were inserted through the payload bay and fastened at one end to the payload bulkhead. After securing the payload and avionics bay on the metal rods, a forward bulkhead was fastened to the top of the rods to separate the main parachute compartment and payload bay. The access hatch was closed by screwing the top corners into the forward bulkhead and the bottom corners into the payload bulkhead.

The exterior surface of the body tube was thoroughly cleaned with mineral spirits prior to receiving primer then paint to finish. Two coats of black spray paint were added to the midsection body tube, and two coats of white spray paint were added to the hatch. This contrast was chosen to allow the team to estimate the roll rate during flight when watching video of the launch.

3.4.2.5 Payload Fabrication

The phenolic tube was cut to length using a band saw. The sled was 3D printed in 3 separate pieces using AVC plastic, then epoxied together using Loctite plastic epoxy. The sled turned out slightly taller than was required, so the top of the sled was sanded down on the belt sander until it was the correct height. To create the inner tube rails, two 0.25 in. by 0.25 in. wooden beams were sanded on the belt sander to fit the curved surface of the tube. The inner tube was sanded to create a rough surface for bonding, and the sled was covered in painters tape. The rails were placed into the sled channels, covered in Loctite plastic epoxy, then the sled was inserted in the tube. Once the epoxy dried, the sled was removed and the rails remained epoxied in place. Plastic stand offs where screwed into the top of the sled to secure the BeagleBone Black and voltage regulator onto the surface. The orientation sensor and barometric altimeter were soldered to a BeagleBone Black hood, which was attached to the top of the BeagleBone. The Lipo battery was placed into the slot at the bottom of the sled.

The payload was assembled by sliding the forward bulkhead on the two threaded rods and securing it down with lock washers on the forward side and nuts on the aft side. Next, the forward bearing cap was slid on and filled with 3 mm ball bearings. One nut was threaded on each threaded rod to secure the cap. After the electronics sled was inserted into the sled, it was connected to the bearing cap. The aft end Lazy Susan bearing was filled with more ball bearings and was connected to the aft end of the tube. The centering was placed against the aft bearing system and then secured using two more nuts. The avionics sled was then secured on the threaded rods. The entire payload was then secured to the forward bulkhead that was previously secured inside the launch vehicle using lock washers and nuts.

3.4.2.6 Fin Can Fabrication

The phenolic body tube was cut using a band saw to a length of 20.25 in. and the top and bottom edges were sanded to achieve a level surface on each end. The rail button positions were measured and marked using a plumb bob with string marked in half-inch increments. The fin slots were measured along the fin can exterior and cut out using a hand Dremel tool and cutting wheel.

The motor tube was sanded and clamped to allow the centering ring, fins, and engine block to be attached together. The team did not use any external jig to mount the fins, and the result was that the fins were all tilted slightly. After consulting with the mentors, the fins were determined safe for flight and the entire motor tube assembly was slid into the fin can. The engine block, fins, and centering ring were epoxied to the fin can body tube and left to cure at least 24 hours. The fins were given tip-to-tip fillets at their point of contact with the outer wall of the body tube for added strength.

The exterior surface of the body tube was thoroughly cleaned with mineral spirits prior to receiving primer then paint to finish. Two coats of black spray paint were added to the fin can body tube, and two coats of white spray paint were added to the fins.

3.4.2.7 Black Powder Sizing

The subscale primary black powder charges for both drogue and main weighed 1 g. The charge sizes were tested and successfully separated both sections. The ground tests were completed once the rocket was manufactured.

The rocket was assembled using the checklist and laid on purple and pink construction foam. The wires for the charges were attached to a manual blast device, which was battery operated. With instructor supervision, the charges completed the separation for the drogue section.

The main section test was not completed until launch day, due to the lack of the bulkhead in the nosecone as the team was waiting to install ballast. The main test was completed in the same way with foam on the ground and the safety officer and mentor present.

The equations used to calculate the amount of black powder were the same as in Equation 3. The sections properly separated in flight, though the wiring of the avionics was backwards, and the events occurred simultaneously. Both redundant charges were 1.5 g each. The calculations proved to be successful for subscale separations so the same methods were used for full-scale calculations.

3.4.3 Flight Results

This section contains the predicted data and the flight results from the maiden flight of the subscale rocket.

3.4.3.1 Launch Day Conditions

The subscale rocket was launched on November 18, 2017 from a field outside of Bayboro, NC located at 35.172°N, 76.832°W. The field is operated by the local NAR prefect and all launches are covered by an FAA waiver to 16,000 ft MSL. All three team mentors listed in Section 1.1.2 were present at the launch to help the team assemble the rocket and prepare for launch.

The team was ready to launch at approximately 3:30 pm EST which, unfortunately, corresponded with the strongest winds of the day. The New Bern airport, located approximately 13 mi from the field, reported windspeeds of 10 knots (11.5 mph) with gusts up to 20 knots (23.0 mph). Since the launch site is a large, flat field, the localized windspeeds were assumed to be slightly greater. The team observed several rockets drifting far downrange even without the use of drogue parachutes.

The subscale was equipped with a dual-deploy recovery system, which was set to deploy the drogue parachute at apogee and the main parachute at 800 ft AGL.

3.4.3.2 Predicted Flight Model

The subscale OpenRocket model was updated to have the same weight and CG location as the subscale rocket, itself. A flight simulation using OpenRocket was setup using steady 11 mph winds with a heading of 200°, as reported by the New Bern Airport weather statement. OpenRocket does not have an option for including gusting winds, and the effects of any wind gusts during flight would be difficult to predict regardless. The drogue and main parachutes in the OpenRocket model were set to deploy at apogee and 800 ft AGL, respectively. The simulated rocket was fired from an 8 ft launch rail angled 5° from vertical in the downwind direction. Figure 3-28, below, shows a co-plot of flight time versus rocket altitude and vertical velocity.

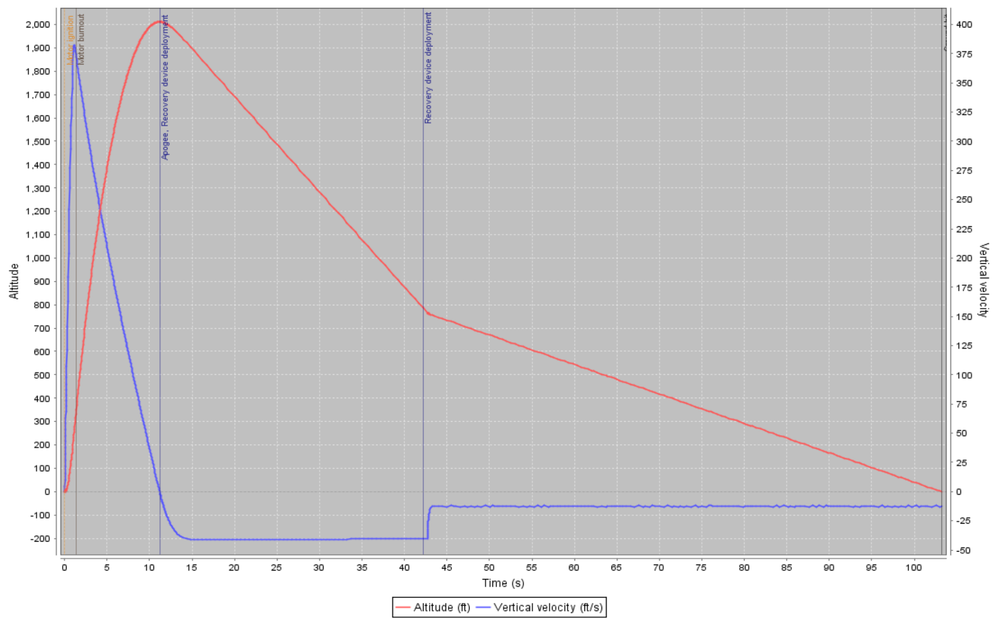

Figure 3-28: Subscale Flight Simulation of Altitude and Vertical Velocity

The OpenRocket flight simulation predicted an apogee of 2,011 ft AGL, which is almost exactly on the goal altitude of 2,000 ft set by the team. The maximum vertical velocity was predicted to be 386 ft/s, which is equivalent to Mach 0.35. The impact velocity of the subscale was predicted to be 13.5 ft/s. These predicted values are all within safe levels for flight of the subscale rocket. The simulation also indicates a total flight time of approximately 103 seconds with drogue and main parachute deployment at 11 and 42 seconds, respectively.

As discussed in Section 3.4.3.4, the main parachute and drogue parachute both deployed at apogee during the actual subscale flight. To simulate these conditions, the main parachute in the OpenRocket model was set to also deploy at apogee and the simulation described above was rerun. Figure 3-29, below, shows a co-plot of flight time versus rocket altitude and vertical velocity for the dual-deployment-at-apogee flight simulation.

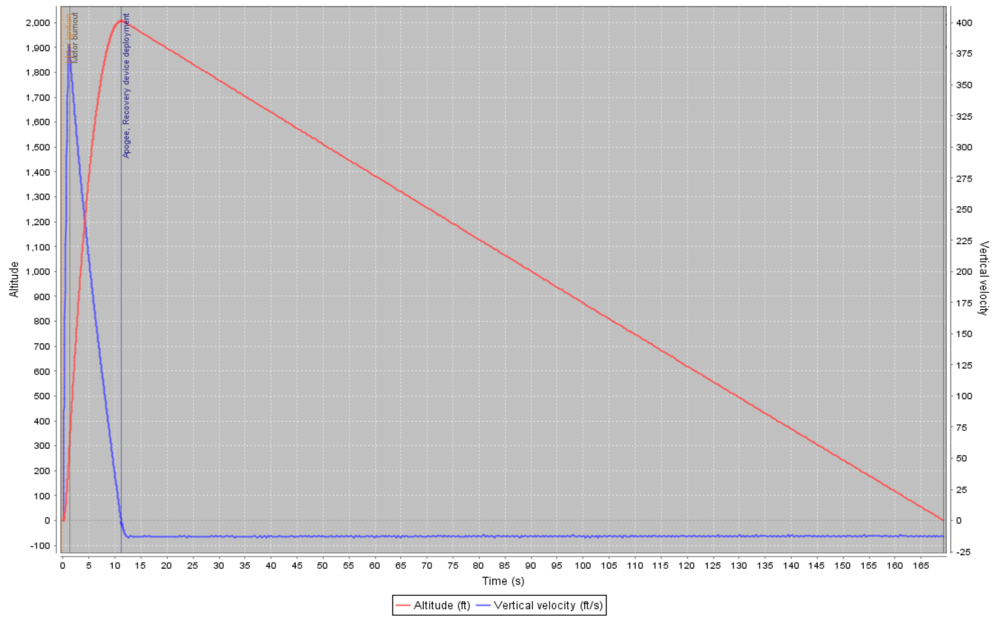

Figure 3-29: Subscale Flight Simulation of Actual Launch

The OpenRocket dual-deployment-at-apogee flight simulation predicted an apogee of 2,006 ft AGL, which is almost exactly on the goal altitude of 2,000 ft set by the team. The maximum vertical velocity was predicted to be 386 ft/s, which is equivalent to Mach 0.35. The impact velocity of the subscale was predicted to be 12.4 ft/s. When compared to the nominal flight simulation in Figure 3-28, this simulation has an almost identical apogee, equal maximum velocity, and slower ground impact velocity. The simulation also indicates a total flight time of approximately 169 seconds with drogue and main parachute deployment at 11.2 seconds. These results still indicate safe flying conditions for the subscale, but with a much longer descent time than the nominal flight conditions.

3.4.3.3 Actual Flight Model

Flight data was recorded during the subscale launch by the onboard StratoLoggerCF altimeter. Figure 3-30, below, shows a co-plot of data points taken from the StratoLoggerCF for flight time versus rocket altitude and vertical velocity.

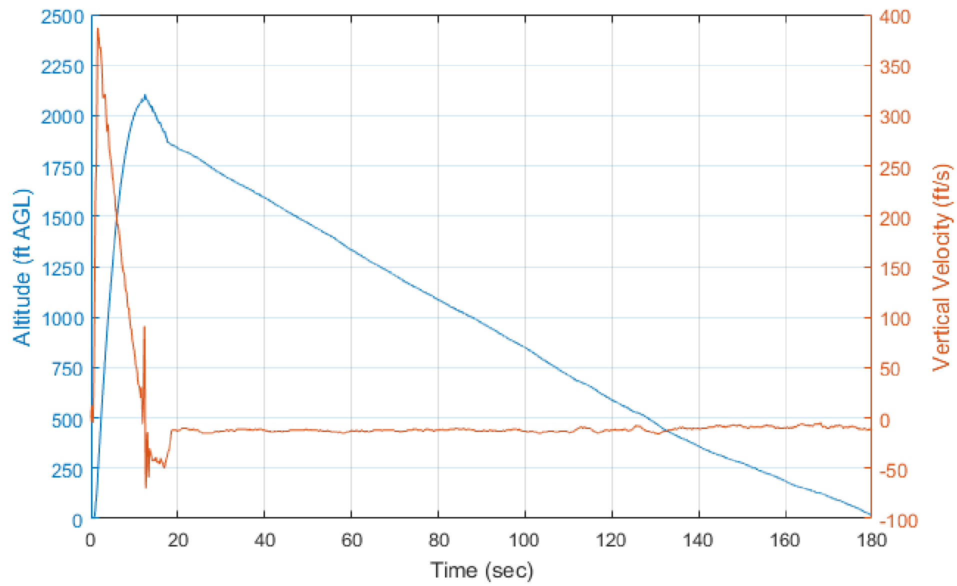

Figure 3-30: Subscale Flight Profile

The StratoLoggerCF data indicates an apogee of 2,093 ft AGL, which is greater than the goal altitude of 2,000 ft set by the team prior to launch. The maximum vertical velocity was measured to be 387 ft/s, which is equivalent to Mach 0.35. The impact velocity was measured to be 8 ft/s. The total flight time was 181.7 seconds with drogue and main parachute deployment at 11.9 seconds. These results are very similar to those predicted by OpenRocket as shown in Figure 3-29. Table 3-4, below, shows the predicted and actual flight profile results with the error value included as a percentage.

Table 3-4: Comparison of Predicted and Actual Subscale Flight Results

Condition	Predicted Value	Actual Value	Percent Error
Apogee	2,006 ft	2,093 ft	4.2 %
Max Velocity	386 ft/s	387 ft/s	0.0%
Impact Velocity	12.4 ft/s	8 ft/s	55%
Parachute Deployment	11.2 s	11.9 s	5.9%
Total Flight Time	169.3 s	181.7 s	6.8%

When comparing the simulation and actual flight results, the simulated value for apogee is within 5% error of the actual flight value. The predicted value is nearly 100 ft less than the actual value which is important to consider when reviewing other OpenRocket simulations. Since the team is design the full-scale rocket for a target altitude of 5,280 ft AGL, it can be assumed that the predicted apogee will be within 5% of the actual apogee.

The predicted and actual values for maximum velocity are only different by 1 ft/s, which indicates a high level of accuracy within OpenRocket for predicting flight velocity and acceleration during the motor burn phase. However, OpenRocket has a much higher level of error when predicting the descent velocity and ground impact velocity of the rocket. It can be assumed that the OpenRocket values for descent and ground impact velocity will be greater than the actual flight values.

The predicted and actual values for the time to apogee and the total flight time are also within reasonable levels of error. The difference between the OpenRocket simulation and actual flight data is only 0.7 seconds for time to parachute deployment, which corresponds to only 5.9% error. The values for total flight time have a larger difference of 12.4 seconds, which corresponds to 6.8% error. These values still contain reasonable levels of error, and the predicted values can be used when checking the hand calculations for flight time.

These conclusions will be tested again by comparing the predicted and actual flight profiles for the full-scale test launch scheduled for February 24, 2018.

3.4.3.4 Rocket Recovery

Though the subscale rocket flight is considered a success, the rocket did experience an in-flight issue when the drogue and main parachute both deployed at apogee. Though this mishap did not cause any damage to the vehicle, it did drift much further from the pad than predicted which complicated recovery efforts at the field. Due to strong winds at the field, the rocket drifted approximately 1.36 mi away from the pad before making impact. Figure 3-31, below, shows the total distance between the pads and rocket impact area, which was still within the safe limits of the launch field.

Figure 3-31: Subscale Wind Drift

After recovering the rocket, the team discovered that the drogue parachute redundant terminal on the Entacore altimeter had been wired to the main parachute primary black powder charge. During fabrication and practice assembly, the altimeter wires were labelled with “MP”, “MS”,”DM”, and “DS” for main primary, main secondary, drogue main, and drogue secondary, respectively. Though the wires were labelled, they were also all identical in color and size which is likely the cause of the issue.

To avoid this issue on the full-scale rocket, the altimeter wires will be color-coded and kept separate from the other payload wires. The team has purchased small toolboxes that will be used to store payload and avionics wires and components separately. These toolboxes will be included in the assembly checklists to ensure that the wires are identified and installed correctly on the full-scale rocket. The team will also coordinate practice assembly sessions to give team members more experience with identifying and installing wires in the correct orientation.

3.4.3.5 Payload Results

During payload assembly, the orientation sensor came unattached from the beagle bone black hood. The team lacked any way to reattach the orientation sensor by soldering, so it was reattached with electrical tape. This attachment method proved, and the orientation sensor lost connection with the BeagleBone during flight. As a result, no usable data was recovered.

3.4.4 Impact to Full-Scale Launch Vehicle Design

The subscale flight was a success, and the team intends to apply the lessons learned during fabrication, assembly, and launch to the full-scale rocket. The design of subscale was an accurate scale model of the full-scale design, and the subscale design was proven to be flightworthy and structurally sound at the launch. Beyond rocket design, the team also gained experience in launch planning which will be crucial to the success of the full-scale vehicle. Table 3-5, below, contains a list of the design impacts to the full-scale as a result of experiences when designing, fabricating, assembling, and launching the subscale rocket.

Table 3-5: Full-Scale Launch Vehicle Design Impacts after Subscale Launch

Issue	Effects on Subscale Rocket	Impact to Full-Scale
Rail buttons and hatch installed on same side	The hatch and attached altimeter switches were not accessible once placed on the launch rail.	Rail buttons and access hatch will be on opposite sides of the rocket.
Quality of 3D printed components were less than ideal	Components had to be printed multiple times until the component did not warp or break.	The team redesigned payload components to decrease the time necessary to print and to increase individual print quality.
Fins were not precisely aligned during fabrication	The fins experienced uneven applied forces during flight, which increased the roll rate of the rocket.	An external jig will be used to align fins while they are epoxied to the motor tube. The fin tabs will also have notches to attach each fin to the centering ring and engine block.
Rail buttons were not secured to any centering rings or bulkheads	The rail button damaged the body tube while on the launch rail as it could not support the entire weight of the rocket.	The forward rail button will be screwed into the forward centering ring and the aft rail button will be screwed into the engine block.

Issue	Effects on Subscale Rocket	Impact to Full-Scale
Altimeter and black powder charges were mis-wired	The main parachute and drogue parachute both deployed at apogee.	All altimeters will be color coded and only team members with assembly experience will wire flight electronics.
Small piece of wadding was still smoldering after ejecting from rocket during nosecone ejection testing	The rocket was undamaged, but the foam used to hold the rocket in place was melted. Mentor Chuck Hall had to use some of his own coffee to put out the “blaze.”	The team has purchased a small fire extinguisher that will be present for all future ejection tests.

3.4.4.1 Estimation of Drag Coefficient

The drag coefficient for the subscale rocket was predicted by OpenRocket to be an average of 0.42 during the ascent phase of flight. A C_D less than 0.5 is desirable for high-powered rockets and the value calculated by OpenRocket is reasonable. The magnitude of total drag acting on the rocket is the result of a combination of factors including paint, finish, fin epoxy fillet radii, nosecone shape, and body diameter. Since the subscale is an 52% scale model of the full-scale, the negative drag effects from the nosecone shape and body diameter will still exist on the full-scale rocket. However, the team intends to reduce surface drag on the full-scale rocket by using wood filler to smooth any edges along the Blue Tube surface created by the overlapping tube plies. The body tube will then be sanded and painted with at least two coats to create a smooth finish. The fin intersections with the fin can body tube will be filleted using thickened epoxy to create a large radius of curvature. By adding these body finishing methods to the full-scale, the team is confident that the drag coefficient will be less than the subscale rocket. The drag coefficient for the full-scale rocket was predicted by OpenRocket to be an average of 0.41, which confirms the above conclusion.

4. Launch Vehicle Recovery Systems

4.1 Compliance to Handbook Requirements

Table 4-1, below, contains the launch vehicle recovery system requirements listed in the 2018 NASA SL handbook as well as the respective compliance actions, verification methods, and status.

Table 4-1: Full-Scale Launch Vehicle Recovery System Handbook Item Compliance

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
3.1	The launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue-stage descent is reasonable, as deemed by the RSO.	The launch vehicle will use a dual deploy recovery system which utilizes a drogue parachute at apogee and a main parachute at 500 ft AGL.	Demonstration. The team will use the dual deploy recovery system at the full-scale test launch. The team will demonstrate successful deployment of both parachutes at their designated altitudes.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
3.2	Each team must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full-scale launches.	Successful ground ejection tests were completed prior to launch of the subscale rocket. Similar tests will be conducted on the full-scale rocket prior to launch to determine the necessary charge size to ensure separation for each events.	Test. The team will conduct ground ejection tests prior to the subscale and full-scale test launches. The charge size and location will not change after testing is complete.	Subscale: Complete. See Section 3.4.2.7. Full-scale: Incomplete. Tests will occur prior to the launch scheduled for February 24, 2018.
3.3	At landing, each independent Sections of the launch vehicle will have a maximum kinetic energy of 75 ft-lb$_f$.	The launch vehicle will separate into three tethered sections during descent. The nosecone, midsection, and fin can kinetic energy at impact were calculated to be 21.10 ft-lb, 46.04 ft-lb, and 46.99 ft-lb, respectively.	Analysis. The team will use simulations and hand calculations to confirm that each section of the rocket will impact with less than 75 ft-lb of kinetic energy.	Complete. See Section 5.3.2.
3.4	The recovery system electrical circuits will be completely independent of any payload electrical circuits.	The avionics bay will be separated by thick bulkheads on either side to ensure that there is no interaction between flight-critical electronics and the onboard payload.	Analysis. The payload and avionics bay will be designed independently of each other and strict electrical schematics will be used to ensure that there is no interaction between components.	Complete. See Section 3.3.4 and Section 4.4.2.
3.5	All recovery electronics will be powered by commercially available batteries.	Only unused, tested 9 V batteries will be used for each launch.	Demonstration. The team will only use unused, tested 9 V batteries for each launch.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
3.6	The recovery system will contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers.	The dual deploy recovery system relies on two commercially-available altimeters for parachute deployment and altitude confirmation. The StrattoLoggerCF is primary and the Entacore is secondary.	Analysis. The team will design the rocket electrical system to utilize two altimeters: one StrattoLoggerCF and one Entacore. These altimeters will be completely independent of each other to increase redundancy and reliability. Strict electrical schematics will be used when wiring altimeters.	Complete. See Section 4.4.
3.7	Motor ejection is not a permissible form of primary or secondary deployment.	Parachute deployment will only occur as a result of altimeter-controlled black powder charge detonation.	Analysis. The team will not rely on a motor ejection charge to deploy parachutes.	Complete. See Section 4.2.
3.8	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	Nylon shear pins will be used to secure parachute compartments for launch. Ground tests will be used to ensure that black powder charges are large enough to ensure separation.	Demonstration. The team will only use Nylon shear pins to secure parachute compartments for launch. The team will also demonstrate that the shear pins will shear at each deployment event.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
3.9	Recovery area will be limited to a 2500 ft. radius from the launch pads.	The launch vehicle is predicted to drift a maximum of 2,500.4 ft laterally from the launch pad in 20 mph winds.	Analysis. The team will use simulations and hand calculations to confirm that lateral drift is within allowable limits for launch.	Complete. See Section 5.3.1.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
3.10	An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent Section to a ground receiver.	All rocket sections will remain tethered during descent and recovery. A BigRedBee BRB 900 GPS unit will be housed in the payload bay to allow tracking from a ground receiver.	Demonstration. The team will include a GPS tracker in the rocket to allow for ground tracking after landing. This system will be used for the full-scale test launch.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
3.10.1	Any rocket section, or payload component, which lands untethered to the launch vehicle, will also carry an active electronic tracking device.	All launch vehicle sections will be tethered.	Analysis. The team will design the rocket to keep all sections tethered together during descent and landing.	Complete. See Section 4.2.
3.10.2	The electronic tracking device will be fully functional during the official flight on launch day.	The team will use a functional BigRedBee BRB 900 GPS unit on the official launch day flight.	Test. The team will test the GPS unit prior to launch, and will bring backup components to each launch.	Incomplete. Testing will occur prior to the launch scheduled for February 24, 2018.
3.11	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	The recovery system electronics will be stowed in a separate avionics bay from all other onboard electronics. The recovery system will be wired independently of other onboard electronics.	Analysis. The recovery system will be designed independently of all other onboard electronics and stowed in a separate compartment in the rocket.	Complete. See Section 3.3.4 and Section 4.4.2.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
3.11.1	The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.	The recovery system electronics will be stowed in the avionics bay which is surrounded by bulkheads on either end.	Analysis. The rocket design will include a separate compartment for the recovery system electronics, labelled "avionics bay."	Complete. See Section 3.3.4.
3.11.2	The recovery system electronics will be shielded from all onboard transmitting devices, to avoid inadvertent excitation of the recovery system electronics.	The flight-critical electronics will be separated from the rest of the payload section by 0.75 in. thick bulkheads on either side of the avionics bay.	Demonstration. The team will confirm that the altimeters are not affected by payload electronics using ground tests and a full-scale launch prior to the competition launch.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.
3.11.3	The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system.	The rocket payload does not contain any magnetic wave generating devices.	Analysis. The team will not include any magnetic generating devices on the rocket.	Complete. Section 4.4.5.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
3.11.4	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.	The flight-critical electronics will be separated from the rest of the payload section by 0.75 in. thick bulkheads on either side of the avionics bay.	Demonstration. The team will confirm that the altimeters are not affected by payload electronics using ground tests and a full-scale launch prior to the competition launch.	Incomplete. Demonstration will occur at the launch scheduled for February 24, 2018.

4.2 Description of Recovery Events

Figure 4-1 below displays an overview of the recovery system for the full-scale rocket. The main components of the system are integrated to contribute to 2 successful separation events, releasing a total of 3 parachutes. the first separation deploys the drogue parachute at apogee as required, while releasing a contained recovery device still restricted using a Jolly Logic Chute Release (the Low Altitude Recovery Device – so named as to not be confused with a drogue or pilot chute). The second separation releases the main parachute.

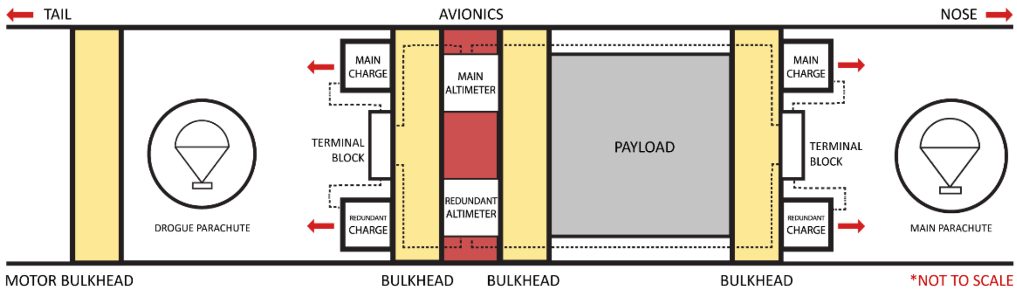

Figure 4-1: Recovery System Diagram

Successful recovery system performance begins in the avionics bay. The avionics bay houses two altimeters: the main altimeter and the redundant altimeter. The redundant altimeter is included for the event that the main altimeter fails.

At an apogee of 5,280 ft AGL, a signal is sent from the main altimeter to the terminal block in the drogue compartment. The terminal block relays the signal through an E-match to a small PVC cap housing enough black powder to complete the first separation, covered by 3M blue painters tape to secure the E-match within the cap. The calculations for the exact black powder charge sizes are in Section 4.3.5and will be defended with ground ejection tests prior to launch. The transmitted signal will cause the first separation to occur, and the drogue parachute will release. One second later the redundant altimeter will send a signal through the terminal block in the drogue compartment to an E-match inserted into a second, equivalent black-powder charge. This event releases the drogue parachute should there be an interruption or failure in the main system charge.

The addition of the Low Altitude Recovery Device (LARD) is the most notable design change to the recovery system included in the CDR. The LARD is included to reduce impulse when the main parachute is deployed. To reduce drift, the drogue parachute size was reduced. Without the LARD, the main would deploy at a descent velocity of approximately 70 ft/s, defended later with OpenRocket simulations. The main deployment would cause the payload to suddenly jolt 180 degrees. The latch restricting the rover has a 1.5 lb allowable force limit, discussed in Section 7.4. The LARD is a larger parachute to be deployed prior to the main parachute, slowing down the vehicle to a descent of 28.4 ft/s and will allow for the main to deploy and the rover to remain secured in the payload with no significant forces. At this point, the first separation of the recovery system is complete.

The second step of the recovery system is a successful second separation and release of the main parachute. For the full-scale launch vehicle, the second separation will occur at 700 ft

AGL. At 700 ft AGL, the main altimeter will send an electrical signal through the payload bay, to the terminal block in the compartment housing the main parachute. The signal will transmit from the terminal block through an E-match connected to a PVC cap filled with an appropriately sized black powder charge, secured with 3M blue painters tape. This charge will pressurize the main cavity and forcefully separate the nosecone from the midsection of the rocket. This event releases the main parachute deployment bag, which allows for more time between the unfurling of the shroud lines and the main parachute opening, thereby decreasing the impulse from the parachute opening. One second later, the redundant altimeter will send a signal through the terminal block to a second E-match connected to a second, identical PVC cap. The calculations for charge sizes are included in Section 4.3.5 and will also be defended with ground ejection tests prior to launch. At this point, the second, main separation of the recovery Section is complete.

4.2.1 Electrical Schematic for Recovery System

Shown below is Figure 4-2, a block diagram of the recovery system responsible for the deployment of the drogue parachute, low altitude recovery device, and main parachute.

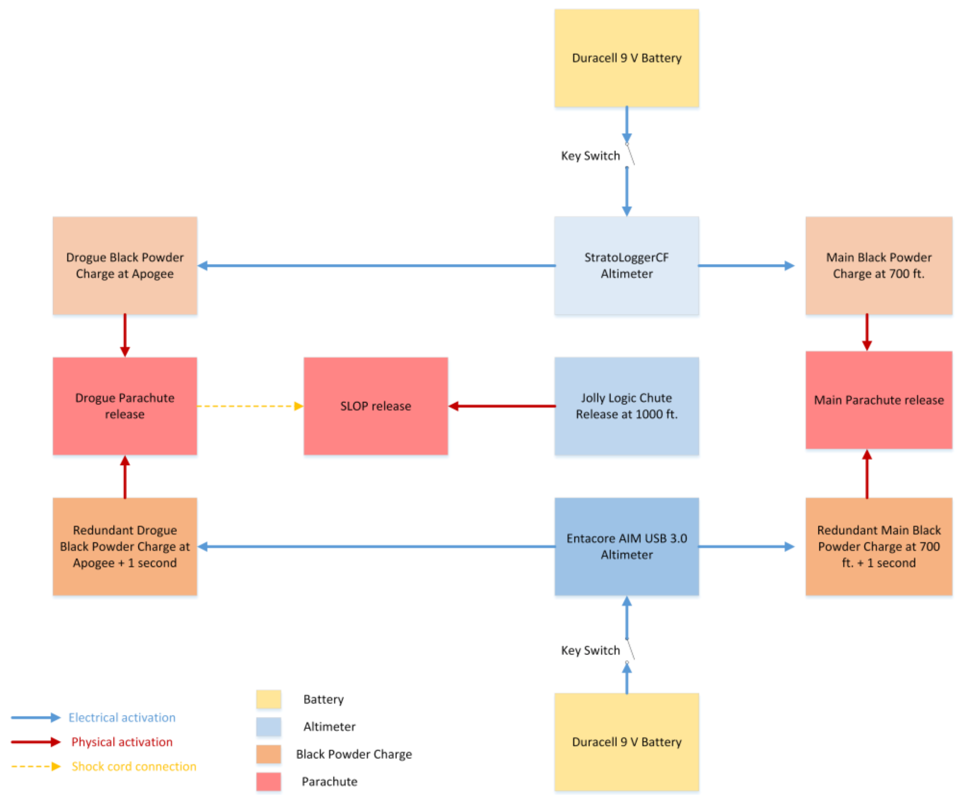

Figure 4-2: Recovery Electrical System

4.3 Recovery System Design

A pre-reefed parachute was chosen for the main parachute. The Fruity Chutes Iris Ultra Compact parachutes employ reefing of the inner diameter shroud lines. Reefing these lines changes the shape of the parachute during descent. In changing the shape of the parachute, the coefficient of drag C_d is increased. The coefficient of drag for the un-reefed, elliptical parachute is 1.5, where the coefficient of drag of a reefed parachute with the same diameter is 2.2.

The focus of the drogue parachute was to find a small parachute to minimize wind drift. For this reason, an elliptical parachute with C_d of 1.5 was chosen. This selection is expanded on in Section 4.3.1.

The Low Altitude Recovery Device (LARD) will be a Fruity Chutes Iris Ultra Compact 60 in. parachute. The LARD will attach to the same shock cord line as the drogue, will release during the drogue release, but will be retained by a Jolly Logic Chute Release until desired deployment altitude.

4.3.1 Drogue Parachute

For the full-scale recovery system the team focused on the safe recovery and execution of the rover mission following landing. The team focused on the electronics-heavy payload and the influence of wind drift with the use of various parachute sizes and their respective deployment altitudes. Parachute sizing for both the drogue and main parachutes is mission critical.

The drogue parachute will introduce drag at apogee during it’s deployment; this is the point where vertical velocity is 0 ft/s. At apogee, after all of the motor propellant has burnt on ascent, all of the forces on the rocket are momentarily balanced. Though a large parachute deployed at apogee would promote a soft, safe landing and a recoverable, reusable rocket as listed in requirement 2.18 of the 2018 NASA SLI Handbook, the effect of deploying a large parachute at approximately 5280 ft AGL could result in a landing position outside of the recovery range. Wind drift restrictions are posted in requirement 3.9 of the 2018 NASA SLI Handbook, which limits landing distance from the launch pad to a 2500 ft radius.

For drogue sizing, the C_{d_d} will be 1.5 for an elliptical parachute. The following equation can be used to determine the equilibrium descent velocity for parachutes of specific surface areas:

$$C_{d_d} = \frac{2mg}{V_{ed}^2 S_0 \rho} \quad (4)$$

where m is the mass of the body falling beneath the parachute, which is the empty rocket weight of 38.2 lb or mass of 1.19 slugs, g is the coefficient of gravity 32.174 ft/s^2, V_{ed} is the terminal velocity of the falling mass with the drogue, S_0 is the surface area of the employed drogue, and ρ is the air density, .002377 slugs/ft^3. In order to determine the size of parachute needed, the team focused on minimizing drift, and therefore the team did not set a limiting bound or minimum descent velocity / terminal velocity limit for the weight falling beneath the drogue.

To minimize drift beneath the drogue parachute, a parachute size of 24 in. was selected. This size changed since the PDR, where a 36 in. parachute was going to be utilized, but due to the decrease in drift with the decrease of drogue size, a Fruity Chutes 24 in. elliptical chute was selected. The terminal velocity of the rocket beneath the drogue will be 93.2 ft/s. The descent velocity beneath the drogue is high, but the following paragraph explains how the team implemented a design change to safely bring the rocket to the ground, and ensure that the rover mission will be completed.

The high-speed drogue prepares the Low Altitude Recovery Device to be deployed at a speed of approximately 93.2 ft/s, which OpenRocket warns to be high speed, however the drift limitation requires the drogue size of 24 in. The size is already relatively small and the team decided not to go any smaller due to this warning and other calculations included in the next section to determine descent velocity bounds beneath the Low Altitude Recovery Device and especially beneath the main parachute.

4.3.2 Low-Altitude Recovery Device (LARD)

The advantage of implementing the Low Altitude Recovery Device is that the forces transferred to the payload and rover body, especially the latching mechanism safely securing the rover in place, are reduced and the orientation of the landing payload is nearly 180 degrees (horizontal), and parallel with the ground. This orientation will help ensure that the launch vehicle housing the payload and rover will land in an optimal position to allow the rover to exit the launch vehicle and successfully complete the mission.

The concern prior to implementation, for example without the LARD and with a larger drogue, was that even with the next highest drogue (30 in.) the main parachute would deploy during a descent velocity of at minimum 69 ft/s. OpenRocket warned of high speeds for recovery device deployment, but the team's main concern was the forces jolting the rocket body that could be introduced during re-orientation of the midsection, following the deployment of the main chute. These forces could introduce potential electrical and mechanical issues within the payload and decrease the chance for a successful rover mission.

The Low Altitude Recovery Device (LARD) is a Fruity Chutes 60 in. Iris Ultra Standard Parachute. The LARD was previously used by the team as the main parachute in the subscale launch and has been used by the team in previous years. There is no damage to the parachute, but the reuse allows the team to continue compliance of the team-derived requirements. The LARD will be attached along the same shock cord as the drogue but will have a delayed release through the use of a Jolly Logic Chute Release. The parachute will be deployed at 1000 ft AGL. Beneath the LARD, the rocket body will fall at 28.5 ft/s for 300 ft, before the Main parachute deploys at 700 ft AGL.

4.3.3 Main Parachute

At 700 ft AGL, the main separation will eject the main parachute allowing it to deploy fro the deployment bag. A deployment bag is being used to slow down / delay the deployment of the chute, further reducing the opportunity for wind drift. A similar equation to the drogue calculation will be used:

$$C_{d_m} = \frac{2mg}{V_{em}^2 S_{0_m} \rho} \tag{5}$$

but the terminal velocity of the falling weight beneath the main parachute, V_{em}, will be set as a maximum of 15.38 ft/s the maximum impact velocity for a kinetic energy of 75ft-lbf, calculated in Section 5.3.2. The chosen style of parachute C_{d_m} is 2.2 as shown above. Figure 4-3, below, shows the predicted descent velocities of Iris Ultra Standard parachutes of various diameters.

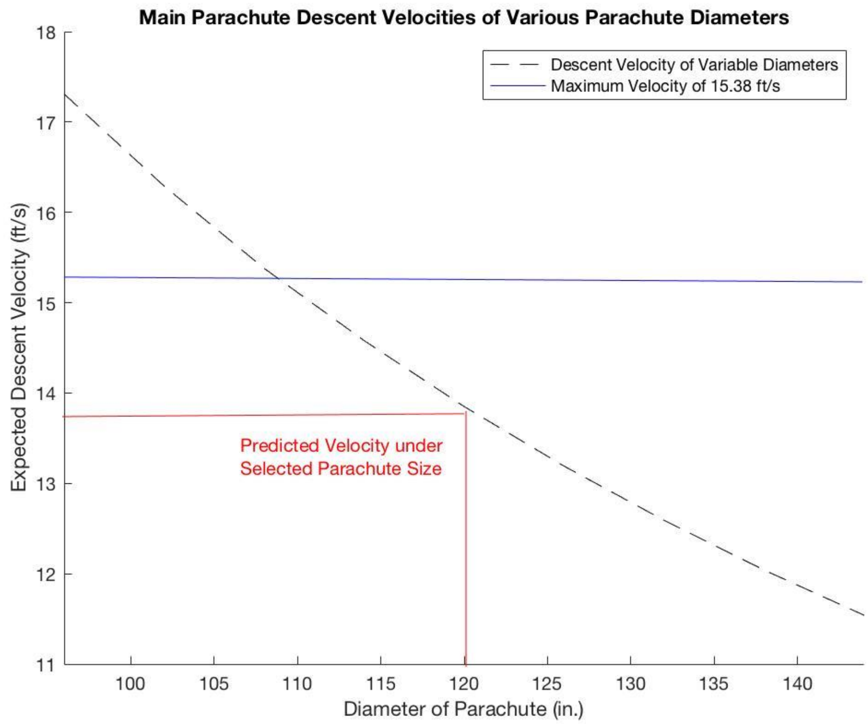

Figure 4-3: Full-scale Main Sizing vs. Descent Velocity Prediction

From Figure 4-3, for the maximum impact velocity of 15.38 ft/s (the maximum descent velocity for the total falling body weight to be within the kinetic energy limit) a parachute diameter of at least 108 in. is required. For a safe landing, and to account for any weight variances in construction, the Iris Ultra Compact 120 in. parachute will be used for the main parachute and will allow for a descent velocity of 13.85 ft/s, which is below the maximum impact velocity of 15.38 ft/s. The descent and impact velocity predicted by OpenRocket simulations is 13.55 ft/s, .3 ft/s more than the calculated descent velocity from the Fruity Chutes descent rate calculator. The predicted kinetic energies of each Section at landing are included in the Table 4-2 below.

Table 4-2: Full-Scale Predicted Kinetic Energy Values at Impact

Body Section	Mass (slugs)	Maximum Descent Velocity (ft/s)	Kinetic Energy at Landing (ft-lbf)
Nose Cone	0.22	13.85	21.10
Midsection	0.48	13.85	46.04
Fin Can	0.49	13.85	46.99

4.3.3.1 Parachute Reefing Alternative

During the PDR and subscale launch, an alternative of employing reefing to utilize variable drag during main parachute deployment was considered. After further research it was decided that pre-reefed parachutes (i.e. the Fruity Chutes Iris Ultra Standard parachute) would be used instead. Due to lack of experience with the technology and inability to locate proper parts/ inadequate timing for experiments, the team decided not to reef our own parachutes. This idea will be researched further and hopefully used in the team's future, as the technology could reduce transferred forces through shroud lines and drastically reduce wind drift.

In place of reefing, the LARD (above) is being implemented to decrease forces on payload and to reduce stress on rover and latching mechanisms.

4.3.4 Shock Cord Sizing

For the full-scale launch vehicle, both separations will require 480-in of ½-in tubular Kevlar shock cord in each compartment. The chosen shock cord is 2200 lb strength from Giant Leap Rocketry and will withstand the opposing forces from ejection and black powder forces explained in Section 4.3.5. Figure 4-4 below is a diagram for shock cord arrangement during separation.

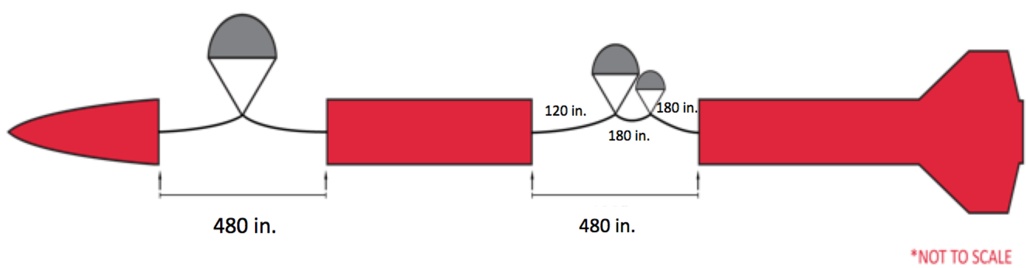

Figure 4-4: Full-Scale Shock Cord Sizing Diagram

The main parachute will be attached halfway along the shock cord, 240 in. from the nosecone bulkhead.

There will be 9 quick links reused from the subscale launched, which have been used by the team in several launches. There is a quick link at each attachment point and for the drogue and LARD chutes to attach the Nomex Cloths.

The main parachute will employ the use of a deployment bag. A 7.5 in. Fruity Chutes deployment bag will store the main parachute and the shroud lines in a z-formation in order to delay the inflation of the parachute canopy.

The LARD is attached ahead of the drogue towards the nosecone, approximately 120 in. from the midsection's aft avionics bulkhead. The drogue will be attached 180 in. aft of the LARD, to avoid tangling during the deployment of the LARD. The drogue is attached 180 in. from the fin can bulkhead.

4.3.5 Black Powder Sizing

Black powder ejection methods will be used for the full-scale section separations. Goex 4F black powder will be used in both ground testing, and ejection separations in flight. In order to determine the mass of black powder that is required to complete each separation, the following equation is used:

$$m_{main} = 0.006 * 20.25\ in. * (7.34\ in.)^2 = 6.6\ g$$
$$m_{drogue} = 0.006 * 19.00\ in. * (7.34\ in.)^2 = 6.2\ g \quad (6)$$

where m is the mass in grams, 0.006 is a constant for converting in^3 to grams and is also related to the amount of pressure in the filled cavity, in this case 15 psi, L_{sect} is the length of the body Section in inches that must move in order to separate and D_{sect} is the diameter of the Section in inches.

Figure 4-5 below is a diagram of the lengths of Sections for the full-scale, and the separation lengths.

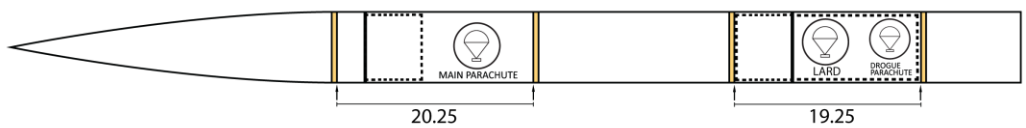

Figure 4-5: Full-Scale Separation Sections and Charge Compartments

For both the main and drogue compartments, the amount of black powder seemed high, but in order for the black powder to occupy the full cavity volumes and eject the parachutes to complete the separations and recovery stages, a primary main charge of 6.6 g and a primary drogue charge of 6.2 g will be used. Using the assumed pressure of 15psi, the ejection force can be calculated as:

$$F = P * A \quad (7)$$

where F is the ejection force, P is the pressure that occupies the Section volume and A is the area of the forward bulkhead, opposite of the charge.

$$F = 15 \frac{lb}{in.^2} * \left(\pi \left(\frac{7.34\ in}{2}\right)^2\right) = 635\ lbf \quad (8)$$

During the drogue separation the ejection force will maximize at 635 lbf. With this data, the number of sheer pins needed is determined. The familiar shear pins used are 4-40 Nylon, typically 0.5 in. length. One 4-40 Nylon sheer pin can handle a maximum force of 76 lb. As the number of shear pins is increased, the force is required to shear the pins is additive. The number of shear pins that can be used is limited in that the force required to break the shear pins must not exceed 635 lb. In the drogue section, (4) 4-40 Nylon shear pins ½ in. long will require a force of 304 lb to separate and release the drogue chute, shock cord and LARD.

Similarly, the 6.6 g charge meant to complete the main separation will produce a larger force of 730 lb, but the same number and size of shear pins will be acceptable, as the force will still overcome the 304 lb of shear force required to remove the pins and complete the main separation, ejecting the main parachute.

To ensure the redundant charges separate, they will be .5 g heavier,

$$m_{redundant\_main} = 7.1\ g$$

$$m_{redundant\_drogue} = 6.7\ g$$

4.4 Avionics Design

The launch vehicle will contain a single avionics bay which will house all recovery system electronics, except the Jolly Logic Chute Release which will be mounted directly on the LARD parachute. The AV bay will be 6.25 in long, and will contain a sled which will be placed into the bay through the removable hatch on the body tube. The AV sled will hold two 9 V Duracell batteries, one Entacore AIM USB 3.0 altimeter, and one StratoLoggerCF altimeter. Two different brands of altimeters will be used to avoid the possibility of both altimeters failing due to a common manufacturer's defect. The StratoLoggerCF and Entacore AIM USB 3.0 altimeters were chosen because the team has successfully used those altimeters in the past. The altimeters will be independently powered by dedicated 9 V batteries. The Duracell brand was chosen for the batteries because the team conducted an experiment in a previous year which found that Duracell brand batteries generally deviated from 9 volts less than other brands.

The StratoLogger will be designated as the official competition altimeter because unlike the Entacore, it does not require two wires to be connected to the same terminal, making it less likely to disconnect and lose power midflight. The StratoLogger will be wired to the two main ejection charges: one for the separation of the fin can for drogue deployment and one for the separation of the nosecone for main deployment. The altimeter will be programmed to activate drogue deployment at apogee and main deployment at an altitude of 1000 ft. The Entacore altimeter will be wired to two backup charges, one for each separation event, and will be programmed to activate on a 1 s delay compared to the main charge. The 1 s delay is added to the redundant charges to avoid over pressurizing the tube and damaging bulkheads or the body tube. A delay of 1 s has been used by the team before and has proven to be sufficient. An additional parachute, the low altitude recovery device, will be ejected with the drogue parachute but remain folded until it is released using a Jolly Logic Chute Release at 1000 ft.

The Jolly Logic will be armed prior to placing the LARD into the rocket. The two altimeters responsible for drogue and main deployment will be armed with a dedicated key switch accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad. The switches will be capable of being locked in the ON position for launch, but will not be armed until the vehicle is erected on the launch rail to avoid battery drain and premature black powder detonation. Since each altimeter has a dedicated battery and switch, the two systems will operate on separate circuits and will be independently redundant.

4.4.1 Avionics Sled

Since PDR, the AV bay has been lengthened from 3 in to 6.25 in. For this reason, the AV sled has been completely redesigned with accessibility in mind. The front of the AV sled when fully assembled with altimeters and batteries installed is shown in Figure 4-6:

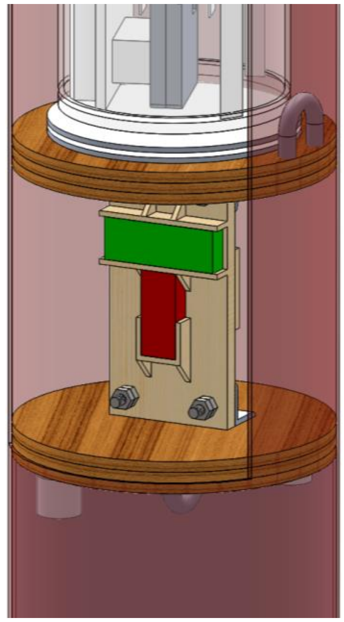

Figure 4-6: Front View of Avionics Sled

The rear view of the fully assembled AV Sled is shown in Figure 4-7:

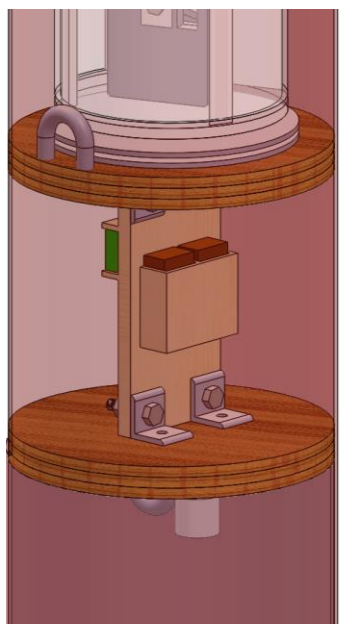

Figure 4-7: Rear View of Sled Back

The exploded view of the AV sled assembly shown in Figure 4-8 illustrates how the sled will be put together prior to launch:

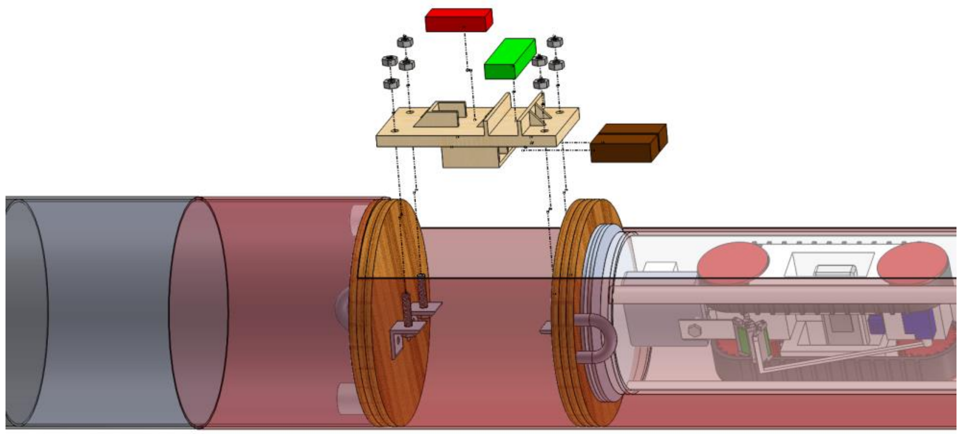

Figure 4-8: Exploded View of Avionics Sled

The dimensions of the AV Sled are shown in Figure 4-9:

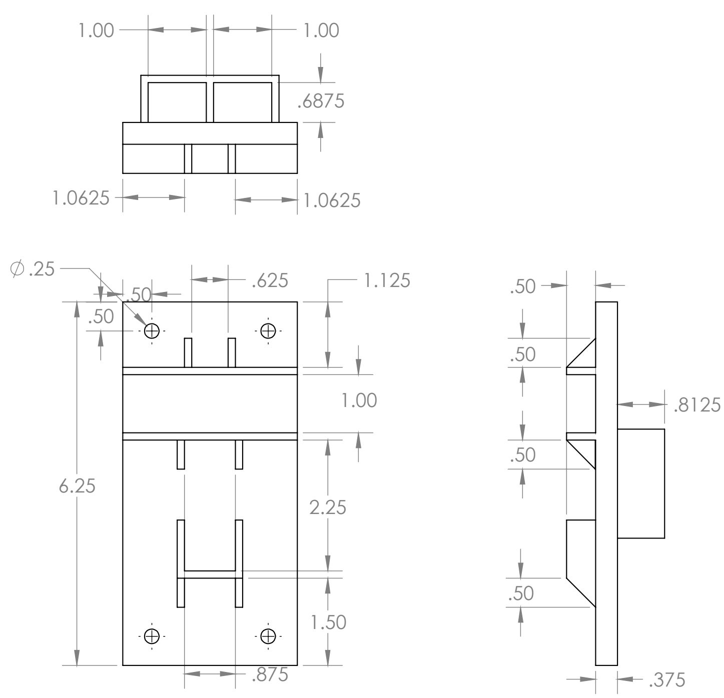

Figure 4-9: Avionics Sled Dimensions

In Figure 4-6, Figure 4-7, and Figure 4-8, the StratoLoggerCF altimeter is shown in red and the Entacore AIM USB 3.0 altimeter is shown in green. The two 9 V Duracell batteries are shown in brown. A major reason for this sled design choice was that it allows both altimeters to be viewed face up from the hatch, providing for easy wiring directly to the terminals and a clear view of the wiring. Designs where the altimeters do not face the hatch require the use of wire connectors, which have been unreliable for the team in the past. The sled will be constructed out of laser cut 0.125 in. aircraft birch plywood, using finger joints and wood glue to hold the pieces together. Plywood was chosen because it is readily available, easy and quick to work with, and relatively light. The main platform of the sled will be constructed with 3 sheets of plywood for extra strength, giving a thickness of 0.375 in. This will not result in excess weight, which will be discussed in Section 4.4.2 below.

The side of the sled facing the hatch will contain two slots for the altimeters. The slots will provide additional support to the altimeters during flight without blocking terminals or coming into contact with the electronics. The altimeters will be mounted onto the face of the sled using small plastic standoffs at their designated attachment points to keep electronic components from contacting the sled surface. The side of the sled facing away from the hatch will contain two slots to hold two 9 V batteries. To prevent the batteries from falling out of their slot or getting disconnected during flight, each battery and battery cap will be tightly zip tied to its enclosure using small holes drilled into the sled. During assembly and prior to a launch, the altimeters and batteries will be secured to the sled before the sled is inserted into the AV Bay.

Inside the AV Bay, four aluminum 1 in. by 1 in. L brackets will be permanently screwed to the forward and aft fixed bulkheads, two to each bulkhead. The brackets will be oriented so that the outer face will face the hatch. A bolt will be placed through each bracket, pointing towards the hatch, and the head of each bolt will be permanently epoxied to the inner face of the L bracket. During assembly, the sled will be mounted onto the four bolts, one on each corner, then secured with two locked nuts. This design for mounting the sled was chosen over the common two rod method because the current design with its easily accessible fasteners will be quicker to assemble.

4.4.2 Avionics Bay Weight

The goal weight of the AV bay is 2 lb. SolidWorks estimates that the unloaded sled will weigh 0.11 pounds. This estimate assumes pine density for the plywood using standard SolidWorks libraries. All other components that will be in the AV Bay are available on hand, and the weight of each was measured with a scale. The breakdown of weights in the AV bay is shown in Table 4-3.

Table 4-3: Avionics Bay Component Weights

Component	Quantity	Weight (lb)
Plywood Sled	1	0.11
Stratologger CF	1	0.02
Entacore AIM USB 3.0	1	0.03
Duracell batteries, 9V	2	0.20
Key switches	2	0.22
Battery caps	2	0.01
Wire (ft)	2	0.07
Terminal blocks	2	0.03
L brackets	4	0.08

Component	Quantity	Weight (lb)
Bolts	4	0.08
Nuts	8	0.09
Screws	4	0.01
Standoffs	6	0.003
	Total:	**0.96**

The combined weight of all components in the AV bay is estimated to be 0.96 lb, well under the 2 lb limit. The estimate does not include wood glue or epoxy which will add to the weight. Even with additional weight, it is unlikely that the AV bay will reach its weight limit. After the AV bay and payload bay are fully constructed, the final weight will be measured. If the final weight is still significantly under the target goal weight, a ballast will be added to the AV and payload bays.

4.4.3 Electrical Schematic for Avionics Sled

Below is Figure 4-10, a block diagram of the recovery system responsible for the deployment of the drogue and main parachutes. This figure demonstrates that the system will be independently redundant.

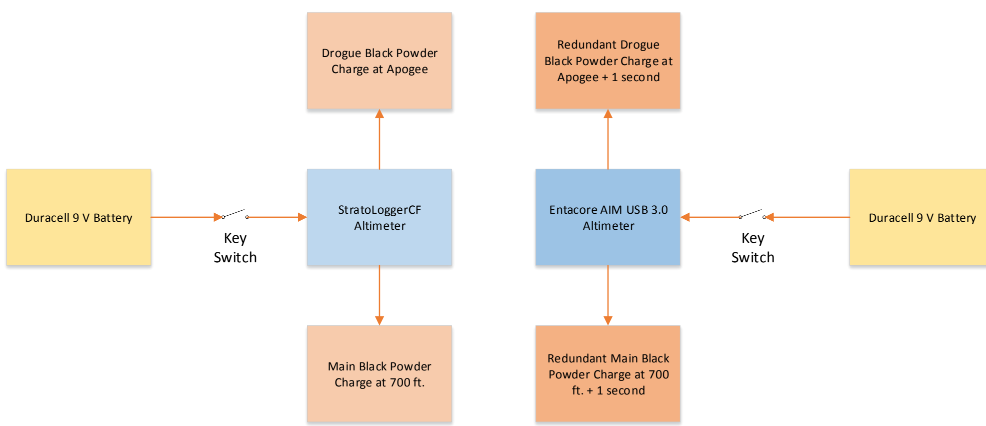

Figure 4-10: Avionics Bay Electrical System Block Chart

4.4.4 Avionics Bay Pressure Sampling Holes

The airframe of the avionics bay must contain static pressure sampling holes to allow the altimeters to sample outside air pressure. The holes will need to be large enough to accurately sample the outside air pressure, but small enough to avoid pressure variation due to wind currents. Since the StratoLoggerCF will be used as the competition altimeter, the StratoLoggerCF manual will be used for porthole sizing to ensure optimal performance. The StratoLoggerCF manual recommends four portholes placed at 90 degrees, each having a diameter calculated with Equation 6, where D is the AV bay diameter and L is the AV bay length:

$$Port\ hole\ diameter = D^2 * L * 0.0008 \qquad (9)$$

Given a body tube diameter of 7.5 in. and an AV bay length of 6.25 in., each of the four pressure sampling holes will be of approximately 0.28 in. diameter. After drilling, the area around the portholes will be sanded to ensure there are no raised edges which might prevent smooth airflow over the holes.

4.4.5 Location Tracking

GPS tracking of the full-scale rocket will be done by a BigRedBee BRB 900 transmitter. A BRB 900 transmitter will be used because it does not require an amateur radio license, and the team has successfully used them in the past. The BRB 900 is a self-contained system with an internal battery, GPS receiver, and 900 MHz spread spectrum transmitter. An LCD display will receive the coordinates of the rocket in real time. The GPS will be mounted onto the nosecone bulkhead, behind the parachute.

The parachute and deployment bag will protect the transmitter from the ejection charge, and there will be sufficient space to extend the whip antenna along the rocket body. The parachute and the AV bay will be separated by two bulkheads, the payload, and a parachute, which will provide sufficient shielding from EM waves for the recovery system to not experience interference from the GPS. The payload deployment system makes use of a radio receiver operating on the 400 MHz spectrum. Since the two systems operate on different frequencies, there should not be any interference, however, both systems will be tested in close proximity to each other to ensure that no unexpected interference will occur.

5. Mission Performance Predictions

5.1 Flight Stability Predictions

This section contains flight stability predictions and analysis from full-scale OpenRocket simulations and hand calculations.

5.1.1 Center of Pressure

According to the OpenRocket model, the CP location of the rocket in its current configuration is at a point 94.9 in. from the nosecone tip. This value was computed automatically by the software at Mach 0.3, which corresponds to the approximate average Mach number of the rocket from launch to apogee.

The Barrowman's Method, which defines a simple algebraic method for calculating the CP position on a subsonic rocket, was applied to confirm the OpenRocket prediction for CP position. Barrowman's Method allows the rocket to be split into three parts: nosecone, transition, and fins. Since the rocket does not include a transition section, only the nosecone and fin equations were considered. The coefficient for nosecones C_N can be defined as a constant equal to 2. The arm length for any ogive nosecone X_N can be defined as:

$$X_N = 0.466L_N \tag{10}$$

where L_N is the length of the nosecone. Using L_N = 37.5 in., X_N was calculated to be 17.475 in. The coefficient for fins C_F can be defined as:

$$C_F = \left(1 + \frac{R}{S+R}\right)\left[\frac{4N\left(\frac{S}{d}\right)^2}{1+\sqrt{1+\left(\frac{2L_F}{C_R+C_T}\right)^2}}\right] \tag{11}$$

where R is the radius of the rocket body, S is the fin semi-span length, N is the number of included fins, d is the diameter of the rocket body, L_F is the fin mid-chord line length, C_R is the fin root chord length, and C_T is the fin tip chord length. Using R = 3.75 in., S = 6.0 in., N = 4, d = 7.5 in., L_F = 6.185 in., C_R = 10.0 in., and C_T = 5.0 in., C_F was calculated to be 7.719. The equation for the arm length of the fins X_F can be defined as:

$$X_F = X_B + \frac{X_R}{3}\frac{(C_R+2C_T)}{(C_R+C_T)} + \frac{1}{6}\left[(C_R+C_T) - \frac{(C_R C_T)}{(C_R+C_T)}\right] \tag{12}$$

where X_B is the distance from nosecone tip to fin root chord leading edge and X_R is the fin sweep length measured parallel to the rocket body. Using X_B = 116.5 in., X_R = 4.0 in., C_R = 10.0 in., and C_T = 5.0 in., X_F was calculated to be 120.2 in.

The equation for CP position of the entire body is a weighted average of the coefficient for each component, and can be defined as:

$$X_{CP} = \frac{C_N X_N + C_F X_F}{C_N + C_F} \tag{13}$$

The CP position was calculated to be 99.1 in. from the nosecone tip, which is 4.2 in. aft of the CP position from OpenRocket. This is a significant difference, and equates to an increase of 0.56 cal to the stability margin. However, this disparity can be explained by comparing the complexity of the OpenRocket calculation to the simplicity of the Barrowman's Method. When calculating the CP position, OpenRocket considers effects due to flight speed, nosecone shape, nosecone length, body diameter, body length, fin shape, fin location, fin leading edge shape, and surface roughness due to body paint. Compared to Barrowman's Method, which only considers nosecone shape, nosecone length, fin shape, and fin location, the OpenRocket calculation is much more advanced and can be considered more accurate. Though Barrowman's Method was used to approximately confirm the CP position, the OpenRocket prediction for CP position was used when calculating the rocket stability margin and determining the amount of ballast necessary for stable flight.

The equation for the stability margin of a rocket S_M can be defined as:

$$S_M = \frac{X_{CP} - X_{CG}}{d} \tag{14}$$

Where X_{CP} and X_{CG} are the distances from nosecone tip to the rocket CP and CG, respectively, and d is the rocket outside diameter. Stability margin is measured in calibers, where one caliber is equal to the rocket outside diameter. Using the results from OpenRocket, X_{CP} = 94.9 in. and X_{CG} = 79.5 in., the stability margin was calculated to be 2.05 cal. Since this value is the stability margin of the rocket after full assembly and before launch, it exceeds the handbook requirement (see Table 4-1) that the rocket must have a stability margin of at least 2.0 when exiting the launch rail since the stability margin will only increase during flight. Figure 5-1, below, shows the CG and CP locations on the OpenRocket model.

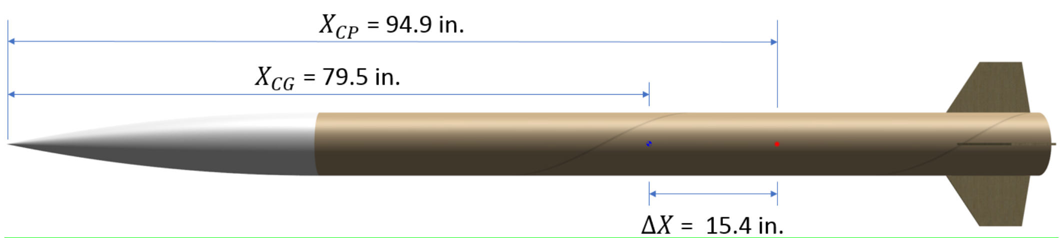

Figure 5-1: OpenRocket Model with CG and CP Locations Shown

As component weights are updated throughout the remainder of the project, the nose ballast will be modified in the OpenRocket model to ensure that the CG is less than 79.9 in. from the nosecone tip, which corresponds to the minimum allowable stability margin of 2.0. Detailed analysis of how the stability margin will change throughout the flight is shown in Section 5.1.2.

5.1.2 Stability Margin

As the motor burns and ejects mass, the CG will translate forward in the rocket, thereby increasing the stability margin throughout the entire powered phase of flight. However, a large stability margin is not required as it may cause the rocket to pitch off-course due to an external perturbation such as a gust of wind. Once perturbed, the rocket flight will become unpredictable which is not ideal in any scenario. To increase spectator safety and confirm that the rocket will perform as expected, the team investigated how the stability margin changed during flight. Table 5-1 below, shows the results of this investigation, which shows the rocket stability margin as a function of rocket mass and CG location for the ascent profile.

Table 5-1: Stability Margin at Various Events during Flight

Wind Condition (mph)	Event	Stability Margin (cal)
0	Rail Clearance	2.08
	Burnout	2.75
	Apogee	5.30

Figure 5-2, below, shows the stability margin as a function of flight time and altitude for the ascent profile.

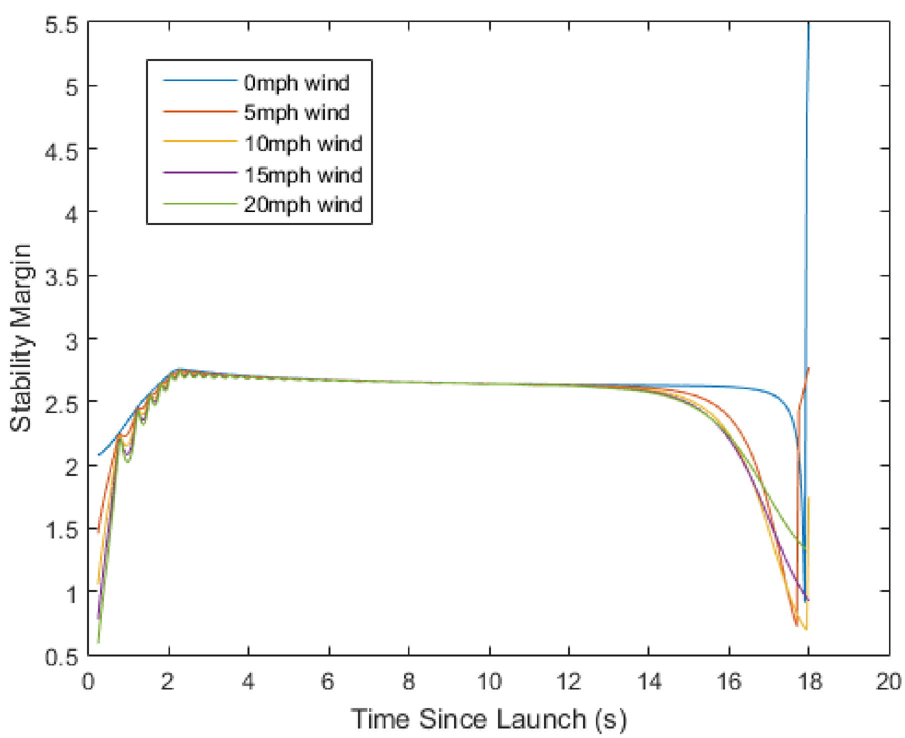

Figure 5-2: Time vs. Stability Margin

Stability margin, the distance between the center of gravity and the center of pressure, increases in an oscillatory motion for one quarter of the time to apogee. After engine burnout, the margin remains relatively constant until before apogee where it drops dramatically then rises at apogee.

5.2 Flight Profile Predictions

This section contains analysis of the OpenRocket flight simulations of the full-scale launch vehicle.

5.2.1 Simulated Flight Profiles

The team has relied on flight simulation results to determine the effectiveness of the full-scale launch vehicle design. Figure 5-3, below, shows the results from one of these simulated launches, where the location was set to Huntsville, AL and windspeed was a constant 10 mph, launching from an 8 ft launch rail angled 5° from vertical.

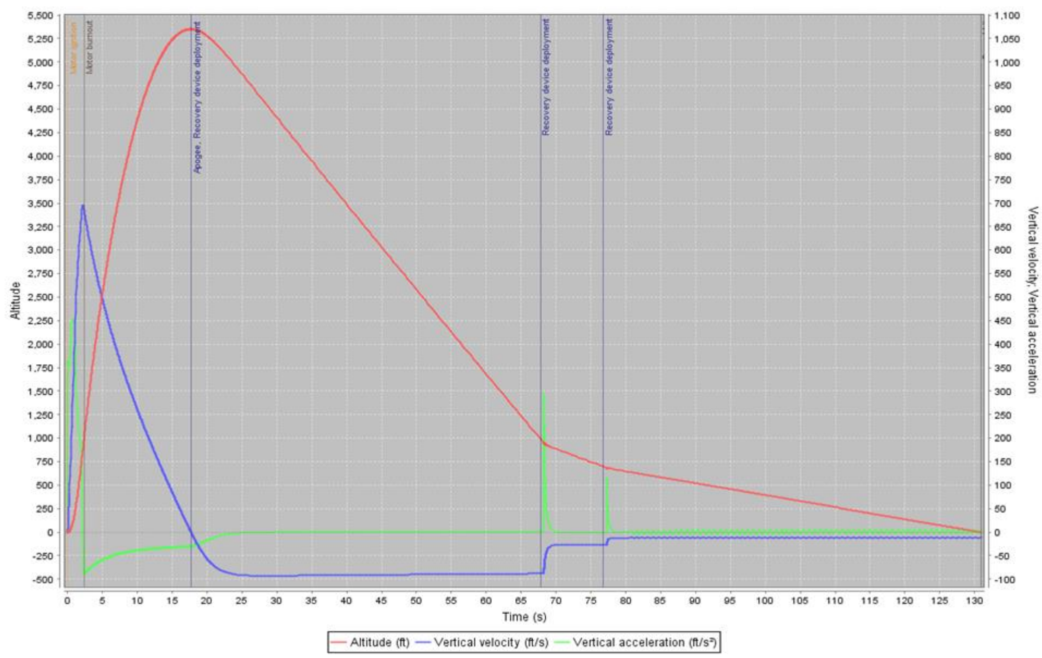

Figure 5-3: OpenRocket Simulation with 10 mph Winds at Huntsville, AL

Figure 5-3, above, shows that the rocket motor will burn out at approximately 2.4 seconds to let the rocket coast for another 15 seconds until reaching apogee at 5,351 ft AGL. The total flight lasts 131 seconds and the ground impact velocity is 13.6 ft/s, well below the limit assigned in Section 5.3.2. The team is confident that the numerous flight simulations run using OpenRocket are reasonable to use when iterating the rocket design.

Table 5-2, below, shows the results for various flight simulations using the same environmental parameters described above.

Table 5-2: OpenRocket Simulation Results for Varying Winds

Wind Speed (mph)	Apogee (ft AGL)	Flight Time (s)	Impact Velocity (ft/s)
0	5,467	131	13.5
5	5,461	132	13.6
10	5,351	131	13.6
15	5,426	131	13.6
20	5,400	131	11.9

The simulation results show that the rocket has a very predictable and steady flight pattern. Regardless of wind speed, the apogee never deviates more than 120 ft, and the impact velocity is never greater than 13.6 ft/s. The team is confident that the rocket will perform as expected, and will continue to use OpenRocket simulations to observe the effects that any small change may have on the overall design.

5.2.2 Motor Thrust Curve

The chosen contender for the full-scale motor was the AeroTech L2200GP, with the motor thrust curve shown below in Figure 5-4.

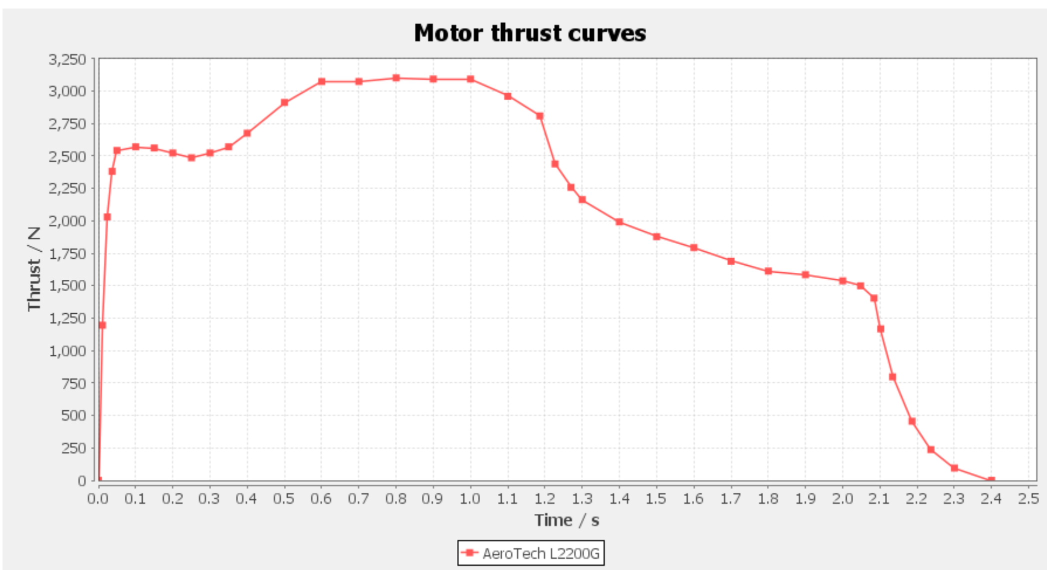

Figure 5-4: AeroTech L2200GP Motor Thrust Curve

From the thrust curve in Figure 5-4, the performance provides the highest max thrust 3,100 N and the total impulse of 5,104 N-s in less burn time (2.4 s), stabilizing the rocket quickly during flight.

5.2.2.1 Motor Thrust-to-Weight Curve and Ratio

From the thrust-to-weight curve in Figure 5-5 below, the thrust-to-weight ratio can be determined for the selected AeroTech L2200G motor.

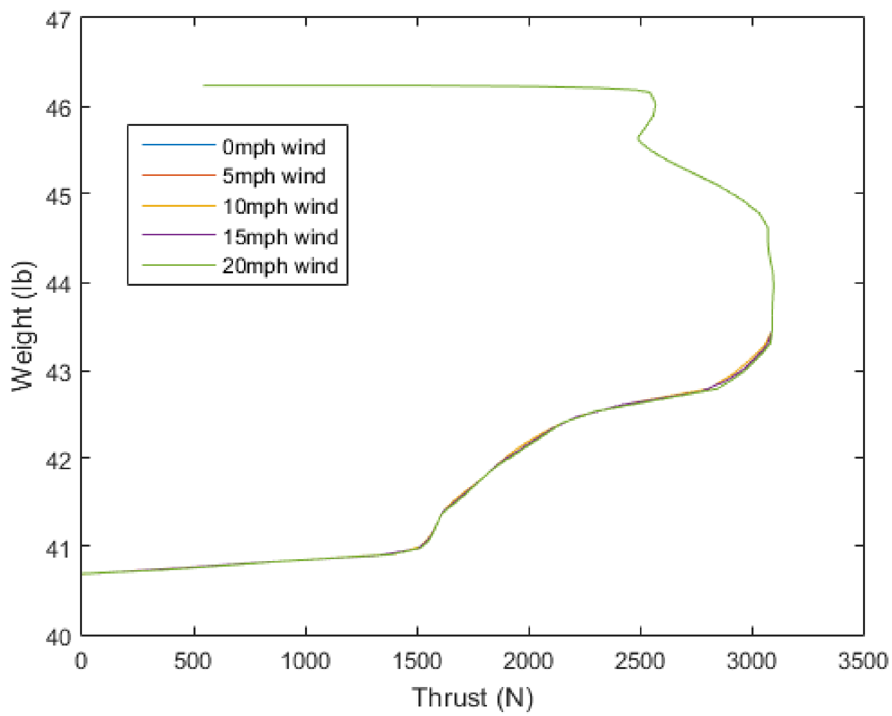

Figure 5-5: AeroTech L2200G Motor Thrust-to-Weight Curve

To calculate the thrust-to-weight ratio Equation 6 is used

$$\frac{T}{W} = \frac{Max\ Thrust}{Max\ Weight} \tag{15}$$

and both values can be taken from the data in Figure 5-7, which came from OpenRocket simulations and manufacturer data. After converting the maximum rocket weight from pounds to Newtons, the ratio is calculated below as

$$\frac{T}{W} = \frac{3100N}{209.51N} = 14.97 \tag{16}$$

5.2.3 Launch Rail Exit Velocity

The rail exit velocity requirement 2.17 of the 2018 NASA SLI Handbook sets a lower limit of 52 ft/s for the exit speed of the rocket from the launch rail. In order to determine the launch speed of the full-scale design, the locations of rail buttons and the size of the launch rail were determined.

Equation 17, shown below, is the equation for launch rail exit velocity:

$$V_{exit} = \sqrt{\frac{2L(T - W\sin\theta)}{m}} \tag{17}$$

where L is the distance the top rail button travels before leaving the rail (ft) and is equivalent to:

$$L(in.) = L_{rail}(in.) - d_{rb_{aft}}(in.) \tag{18}$$

which is equivalent to the difference in the length of the rail and the distance between the top most rail button and the aft most point of the rocket. For the full-scale:

$$L = 8\ ft - 1.67\ ft = 6.33\ ft = 96\ in. - 20\ in. = 76\ in.$$

and T is the average thrust (lbf) over the first instant of flight, taken from Open Rocket simulation. The predicted values for both subscale and full-scale motors are provided below:

$$T = 2243\ N = 504.25\ lbf$$

W and M are the weight and mass of the launch vehicle, listed below**:**

$$W = 47.1\ lbf$$

$$m = 1.46\ slugs$$

$$W_{empty} = 41.5\ lbf$$

where W_{empty} is the weight of the rocket just at apogee before the drogue is ejected. The impact mass

$$W_{mi} = 38.2\ lbf$$

is the mass minus the propellant and minus both parachutes and shock chords.

θ is the angle of the launch rail from horizontal, which is typically 85 degrees from horizontal for launch purposes for both full-scale and subscale.

$$\theta = 85°$$

With this information, MATLAB is used to analyze the rail exit velocity, and is plugged in below for clarification. The MATLAB code is included in Appendix A.

$$V_{exit} = \sqrt{\frac{2 * (6.33\ ft) * (504.25\ lbf - (47.1\ lbf)\sin(85°))}{1.46\ slugs}}$$

$$V_{exit} = 77.3\ \frac{ft}{s}\ and\ 77.3\ \frac{ft}{s} \geq 52\frac{ft}{s}$$

5.2.3.1 Alternative Calculation

OpenRocket Simulations predict that the rocket will leave the launch rail with a V_{exit} of 78.06 ft/s. This number is lower than the hand calculation (above) but still higher than the minimum NASA requirement of 52 ft/s. The difference comes from a margin of error in the simulation.

5.3 Recovery Profile Predictions

This section contains analysis of the recovery flight profile for the full-scale launch vehicle.

5.3.1 Variable Wind Drift Calculations

To defend requirement 3.9 of the 2018 NASA SLI Handbook, where recovery distance must remain within a 2500 ft radius of the launch pad, wind drift calculations are completed to predict performance in various wind conditions. To simulate wind drift for 0 mph, 5 mph, 10 mph, 15mph and 20 mph winds, two methods of calculations are used; OpenRocket simulations provided drift distances and descent times and then to compare, hand calculations were completed with the equation below:

$$d_{drift}\,(ft) = t_{descent}\,(s) * V_{wind}\left(\frac{ft}{s}\right) \tag{19}$$

where d_{drift} is the lateral distance at landing from the launch pad, $t_{descent}$ is the time the rocket Sections take to reach the ground from apogee and V_{wind} is the wind speed converted to ft/s from mph. the lateral drift distance is the result of the addition of the drogue to main drift and the main to landing drift. The mathematical results from method 1, OpenRocket simulation predictions are included in Table 5-3, below.

Table 5-3: OpenRocket Simulation Wind Effect on Altitude and Drift

Wind Speed (mph)	Predicted Altitude (ft AGL)	Descent Time (s)	Wind Speed (ft/s)	Lateral Drift Distance from OpenRocket (ft)
0	5467	114.1	0.00	7.6
5	5461	114.5	7.33	589.1
10	5351	113.3	14.67	1321.5
15	5426	113.5	22.00	1851.7
20	5400	112.9	29.33	2500.4

It is seen from the values above that all wind speeds keep the drift distance with in the allowable 2500 ft.

The predicted altitudes during various wind speeds are all above the goal apogee of 5,280 ft AGL, but the rocket design being simulated is before paint, ballast, and any variable weight changes during construction of the full scale.

Figure 5-6, below, shows a plot of the drift distances in feet, per the OpenRocket Simulation results.

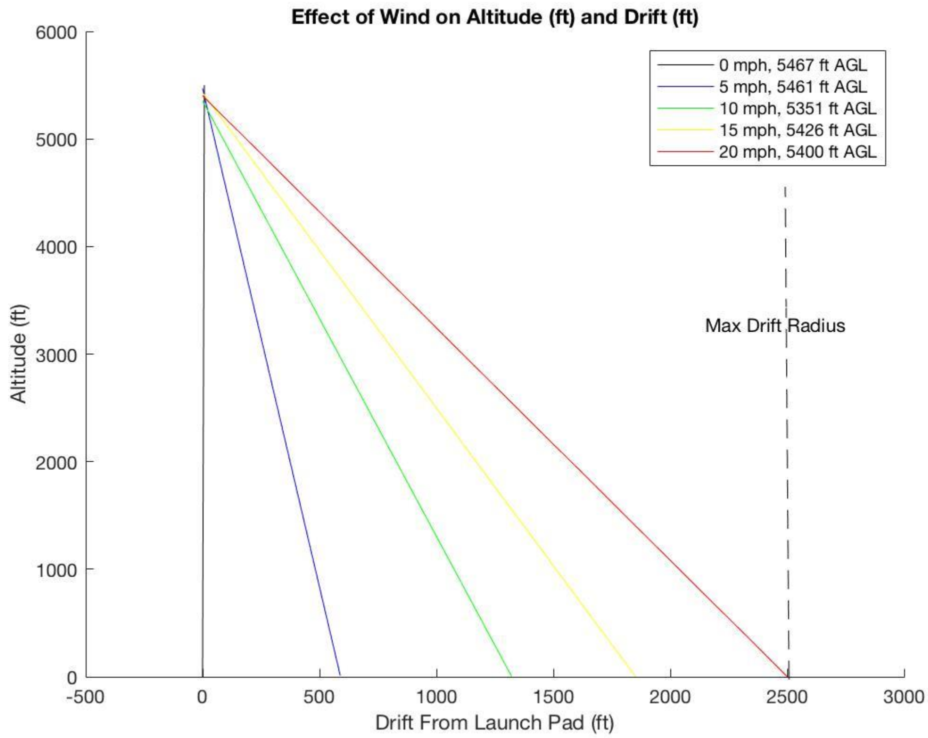

Figure 5-6: Full-scale Effect of Wind on Altitude and Drift from Launchpad

These values correspond to the predicted OpenRocket altitude and drift values Figure 5-7, below, shows a plot of the surrounding areas for lateral drift distances.

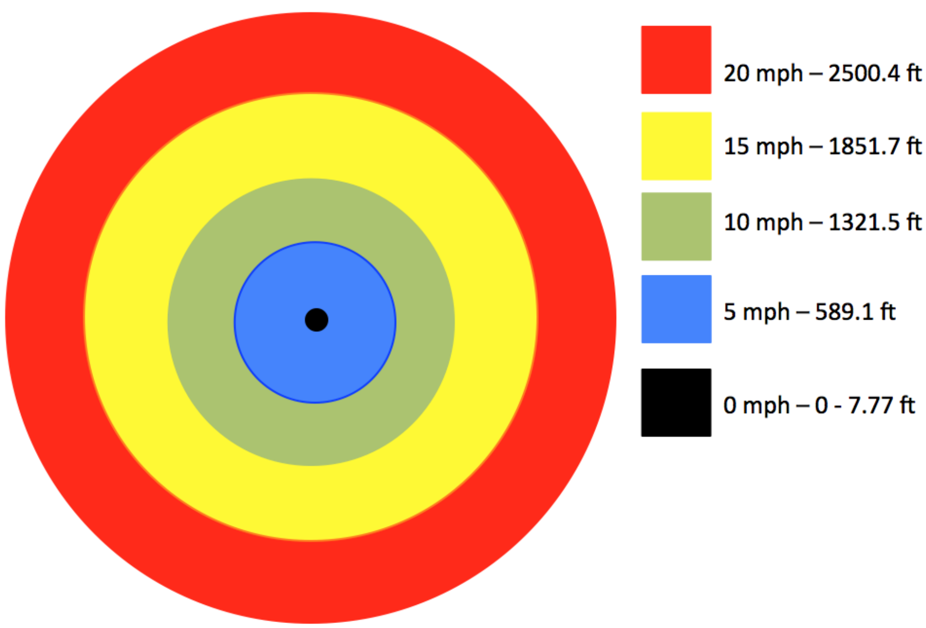

Figure 5-7: Radial View of Wind Drift Lateral Distances from Launch Pad

5.3.1.1 Alternative Calculations

Table 5-5 below includes the hand calculations for Wind Drift.

Table 5-4: Hand Calculations - Wind Effect on Drift

Wind Speed (mph)	Predicted Altitude (ft AGL)	Descent Time (s)	Wind Speed (ft/s)	Lateral Drift Distance Hand Calculation (ft/s)
0	5280	104.35	0.00	0.00
5	5280	104.35	7.33	764.9
10	5280	104.35	14.67	1530.8
15	5280	104.35	22.00	2295.7
20	5280	104.35	29.33	3119

It is seen from the values in Table 5-2 that with wind drift of 20 mph the range is approximately 600 ft over the limit. This is due to the assumption that 20 mph winds will be constant in one direction on the rocket upon descent. The calculations were modified in Table 5-2 with an assumption that the altitude will be 5280 and that the descent time will be the same for all wind speeds. Another factor not accounted for is the use of a deployment bag for the main parachute, which will delay the deployment of the main parachute. The descent times were calculated taking the predicted descent velocities for the falling body beneath each recovery device, and dividing the distance travelled between each recovery event.

5.3.1.2 Design Alterations to Accommodate Excessive Wind Drift

Since the PDR, the drogue parachute size was decreased from 36 in. to 24 in. in order to allow for higher descent and less drift between apogee (during the drogue deployment), the LARD deployment, and the main deployment. The deployment altitude for the LARD is now 1000 ft and the deployment altitude for the main parachute changed from 1000 ft to 700 ft, also to decrease potential for wind drift. The hand calculations are still higher than the allowed limit, but we are confident that this is due to the assumption that the wind will be constant at 20 mph, in a constantly straight direction, which is not likely to be the case.

5.3.2 Kinetic Energy at Landing

To address the kinetic energy requirement 3.3 within the 2018 NASA SLI Handbook, maximum impact velocities for each individual section are determined from the masses of each of the sections in order to set a limit for terminal velocities. Limiting the terminal velocities establishes an upper limit for the impact velocity/descent rate of the falling rocket body, and will ensure that the falling rocket body will land with a kinetic energy less than the established maximum requirement.

Using MATLAB for analysis, the maximum impact velocities of each Section of the falling rocket body, with parachutes, can be defined as:

$$KE = \frac{1}{2} m V_i^2 \rightarrow V_i = \sqrt{\frac{2KE}{m}} \quad (20)$$

where KE is kinetic energy, m is mass, and V_i is the impact velocity. Using the assigned kinetic energy of 75 ft-lbf and the known empty rocket mass of 1.19 slugs, the maximum allowable descent velocity of all section masses combined was calculated as 11.22 ft/s.

Table 5-5 below contains the masses of each of the three separate body Sections, as required by Section 3.3 in the 2018 NASA SL Handbook limits the individual Sections' kinetic energies at landing.

Table 5-5: Maximum Descent Velocity of Body Section

Body Section	Mass (slugs)	Maximum Descent Velocity (ft/s)
Nose Cone	0.22	26.11
Midsection	0.48	17.67
Fin Can	0.49	17.496

The MATLAB code for kinetic energy calculations is included in Appendix A. Using the minimum of the body Section's descent velocity requirements, 17.496 ft/s, parachute sizes are determined. The kinetic energy for each section and the resulting main parachute selection is included above in Section 4.3.3.

6. Safety

6.1 Compliance to Handbook Requirements

Table 6-1, below, contains the safety requirements listed in the 2018 NASA SL handbook as well as the respective compliance actions, verification methods, and status.

Table 6-1: Launch Vehicle Safety Handbook Item Compliance

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
5.1	Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.	The Pre-Flight Checklist provided by TRA will be utilized in conjunction with the checklists that will be created by the Team Leads	The latest version of the checklist is included in Section 6.2.	Complete.
5.2	Each team must identify a student safety officer who will be responsible for all items in Section 5.3.	The club shall designate a member to be the safety officer.	Erik Benson has been designated the team's safety officer.	Complete.
5.3	The role and responsibilities of each safety officer will include, but are not limited to, handbook items 5.3.1-5.3.4, below.	The safety officer will review the required handbook items frequently ensuring all are adhered to, as well as meeting any expectations set upon the position by the club.	See Below	Complete.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
5.3.1	Monitor team activities with an emphasis on safety during: Design of vehicle and payload Construction of vehicle and payload Assembly of vehicle and payload Ground testing of vehicle and payload Sub-scale launch test(s) Full-scale launch test(s) Launch day activities Recovery activities Educational engagement activities	The assembly and construction of the vehicle will be monitored at all times by officers if not the safety officer. Ground testing will be conducted in a manner that is approved by the HPRC mentors and in accordance with safety procedure. All launch activities will be conducted in accordance with the wishes of the RSO and advice of our mentors.	The safety officer is responsible for providing the safety briefing to all the club members.	The safety officer has given the safety briefing at one of the meetings.
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	The safety officer will advocate the continued adherence to the vision of the Team Leads and the current design	The safety officer will be present during construction, assembly, launch, and recovery activities.	The safety officer has been a part of these processes for subscale and will continue involvement for full-scale development
5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	All relevant documents will pass through the safety officer before modifications are made, reevaluating after any unexpected occurrences.	The safety officer is directly involved with the safety process.	Complete.

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
5.3.4	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	The safety officer will oversee the safety sections of all reports, personally verifying all information in relevant sections is accurate.	The safety officer is directly involved in the writing of the report.	Complete.
5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch Initiative does not give explicit or implicit authority for teams to fly those certain vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.	The safety officer will notify the local rocketry club's prefect about any upcoming launches as well as any relevant changes to the rocket design, ensuring strict compliance to all local rules and regulations before any flight. The club will utilize the knowledge of their mentor Alan Whitmore, the prefect of the local rocketry club.	The safety officer will be the team's direct communication line to the NAR Staff and RSO at the competition.	HPRC continues to have open communication will all relevant parties.

6.2 Launch Operation Procedures

The following pages contain the subscale rocket checklist which will be updated and adapted for use with the full-scale rocket. The checklist is to be completed by two team members during assembly: one checker and one observer.

VERY NUTS II Launch Checklist

Key:

PPE Required

Explosive - DANGER

Night Before Checklist:

1. Charge batteries:
    a. Payload: HobbyTiger blue lipo (2)
    b. Handheld Drill: DeWalt drill batteries (2)
2. Test 9V batteries:
    a. Use multimeter to select (4) batteries that contain *at least* 9.0V
3. Measure and store black powder charges:
    a. (2) primary black powder charges
    b. (2) redundant black powder charges
4. Coordinate carpool plans and confirm cars/drivers
5. Encourage:
    a. Full night of sleep
    b. Large breakfast before leaving
    c. Clothes that protect against weather (sunscreen, heavy coat, hat, etc.)
    d. Packing the night prior to launch

Packing List:

1. Nosecone
2. Midsection:
    a. Hatch with (4) screws
    b. Payload supplies (see payload checklist)
    c. Avionics bay supplies (see avionics checklist)
    d. Hatch switches installed
3. Fin can:
    a. Retainer ring
    b. Rail buttons
4. Recovery box:
    a. Main parachute: 60in Iris Ultra Compact
    b. Drogue parachute: 18in Elliptical
    c. Main parachute nomex sheet
    d. Drogue parachute nomex sheet
    e. Main parachute shock cord with loop
    f. Drogue parachute shock cord with loop
    g. Rubber bands

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   h. (8) quicklinks
   i. (5) paper for funnels
   j. Scotch tape
5. Avionics box:
   a. (6) e-matches (Hall)
   b. Extra rotary switches
   c. (6) tested 9V batteries
   d. Extra wires
   e. E-match test switch and wire
   f. Black electrical tape
   g. Blue painter's tape
   h. Small gram scale
   i. Shear pins
   j. Circle stickers
   k. Altimeters:
      i. (2) StratoLoggerCF #
      ii. (2) Entacore #
   l. StratoLoggerCF user manual
   m. PerfectFlite computer connection wire
   n. Micro-USB to computer USB wire
   o.
   p. Black screwdriver kit:
      i. Black screwdriver with red tip
   q. Ask Eugene
6. Payload box:
   a. Hatch
   b. (2) threaded rods
   c. Payload tube with epoxied bearing
   d. Forward payload bulkhead
   e. Forward bearing cap
   f. Payload centering ring
   g. Payload center bearing
   h. Payload sled
   i. (20) ¼" nuts
   j. (10) ¼" lock washers
   k. (2) bags of ball bearings
   l. Adjustable wrench
   m. Vice grip pliers
   n. Straight forceps
   o. Curved forceps
   p. Paper funnel

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q. (4) Hatch screws

7. Motor reload:
    a. AeroTech I435T-14A motor reload kit (yellow tube)
    b. RMS 38/600 motor casing with capped forward seal (Alan/Hall)
    c. Propellant sleeve
    d. Silicone grease
    e. Motor ignitor (Alan)
8. DeWalt battery-powered drill
    a. (2) charged batteries
9. Black drill bit case
10. Folding table
11. (2) paper towel rolls
12. (2) clipboards with pens
13. First-aid kit
14. Water bottles
15. Red box with extra screws
16. Launch day toolbox:
    a. (4) safety glasses
    b. Gloves:
        i. Nitrile
        ii. Heavy duty (yellow)
    c. Baby wipes
    d. Baby powder
    e. Band-aid box
    f. (2) trash bags
    g. Zipties
    h. Powered drill charged battery
    i. Blue painter's tape
    j. Black electrical tape
    k. Black duct tape
    l. Black powder containers:
        i. Large container
        ii. (2) red main containers
        iii. (2) green drogue containers
    m. Multimeter
    n. WD-40
    o. Mallet
    p. Screwdriver kits:
        i. Blue kit
        ii. Clear box with extra screws
        iii. Extra shear pins

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q. (2) scissors
r. Forceps
s. Multitool in black case
t. Set of allen wrenches (red plastic)
u. Vaseline
v. Wire cutters
w. (2) Needle-nose pliers
x. Set of vise grip pliers
y. Tape measure
z. Rope for measuring CG
aa. Handheld fish scale
bb. (3) black pens
cc. (2) sharpie markers
dd. (2) walkie-talkies
ee. Thick dowel rod
ff. (2) putty containers
gg. Ejection testing switch
hh. Sandpaper of varying grit

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Payload Checklist:

1. Required items:
    a. Payload box
    b. Rocket midsection
    c. Avionics box
2. Fit (2) ¼" nuts on each threaded rod
3. Fit both threaded rods through forward payload bulkhead with attached nuts on non-charge side of bulkhead
    a. Do not stick the threaded rods through the hole marked with an X
    b. Only a small amount (less than ½ inch) of threaded rod should stick out
4. Fit (1) ¼" lock washer over each rod on the charge side of the forward bulkhead
5. Fasten (1) ¼" nut over each lock washer
    a. Screw each nut on so that the face of the nut is flush with the end of the rod
6. Tighten the two nuts on each rod on the non-charge side of the bulkhead with a wrench
7. Slide the forward bearing cap against the upper nut with the bearing track facing away from the bulkhead and aligning the X-marked holes
8. Fasten (1) nut on each rod to secure the bearing cap
9. Build payload tube:
    a. Place payload sled flat with sled side up
    b. Place voltage regulator over standoffs with IN/OUT terminals aligned with IN/OUT
    c. Use (3) screws to secure voltage regulator on standoffs
        i. Only screw in standoffs labelled using a number value
        ii. Do not use the standoff marked with an X
    d. Find wire labelled as "BBB Connector"
    e. Screw red wire lead into OUT+ terminal
    f. Screw black wire lead into OUT- terminal
        i. Use another team member to ensure wire leads are secured in place
    g. Find wire labelled as "Battery Connector"
    h. Screw red wire lead into IN+ terminal
    i. Screw black wire lead into IN- terminal
        i. Use another team member to ensure wire leads are secured in place
    j. Find BeagleBone Black and attachable cape
        i. Attach cape to top of BeagleBone Black
        ii. Put (4) screws through corner holes and secure with small nuts
        iii. Startup BeagleBone Black
    k. Align standoff screws with payload sled holes
        i. Ethernet port should face the voltage regulator
        ii. Entire assembly will be friction fit on sled, do not tighten
    l. Slide LiPo battery into sled port with wire side facing out
    m. Battery wires should lay in the slot next to the voltage regulator

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n. Connect battery to voltage regulator using yellow plug
o. Connect voltage regulator to BeagleBone Black
p. Compress wires on top of electronics
q. Slide payload into tube (fits perfectly)

10. Fill the forward bearing cap with enough ball bearings to fill entire track:
    a. Hold payload structure with track facing upright
    b. Use forceps and pliers to place individual ball bearings
11. Install the complete payload tube into the bearing cap between the threaded rods
    a. Ensure that the payload tube sits flat on the ball bearings
    b. If the payload tube does not sit flat, remove or add ball bearings accordingly
12. Apply enough pressure on the tube to prevent the ball bearings from falling out and flip the entire payload structure over
    a. Continue applying pressure against the ball bearings until the payload is complete
13. Fill the center bearing ring with enough ball bearings to fill entire track:
    a. The cap should be filled before placing on the payload structure for ease of use
    b. Use forceps and pliers to place individual ball bearings
14. Slide the center bearing ring over the threaded rods with the ball bearings side up
    a. The bearing should sit flat against the end of the payload tube to lock it in place
    b. If the payload tube does not sit flat, remove or add ball bearings accordingly
15. Slide the centering ring up the threaded rods until it is against the center bearing ring
    a. Ensure holes marked with X line up for later wiring
16. Hold payload assembly and set aside
17. Build avionics sled:
    a. Place StratoLogger altimeter over standoffs labelled "StratoLogger"
        i. Align parachute terminals facing aft (see label on back)
    b. Place Entacore altimeter over standoffs labelled "Entacore"
        i. Align miniUSB port facing forward (see label on back)
    c. Place (2) fresh 9V batteries into battery slots with terminals facing forward
        i. +/- battery terminals should aligned with the +/- symbols
    d. Place 9V battery caps over each battery
    e. Feed (1) ziptie through each hole next to the batteries
        i. Wrap each ziptie around the entire payload sled and over the battery
        ii. Tighten ziptie to secure altimeters and batteries
        iii. Ensure ziptie heads are flush next to the batteries
    f. Clip extra length of ziptie at each head
    g. Connect red lead from Battery 1 to Entacore terminal between V+ and V-
        i. Tighten lead in terminal using small screwdriver
    h. Connect black lead from Battery 1 to Entacore V- terminal
        i. Tighten lead in terminal using small screwdriver
    i. Connect black lead from Battery 2 to StratoLogger NEG terminal
        i. Tighten lead in terminal using small screwdriver

j. Connect red lead from Battery 2 to terminal adjacent to NEG terminal
    i. Tighten lead in terminal using small screwdriver
18. Slide avionics sled down the threaded rods until the top is against centering ring
    a. Ensure avionics sled A-side matches A-side on forward bulkhead
19. Fit (1) ¼" nut over each threaded rod to secure the avionics sled and centering ring
    a. Ensure that the nut is tight enough to keep ball bearings from falling out, but also loose enough to allow the payload tube to rotate freely
20. Wire main parachute electronics:
    a. Find wire labelled "Main P" and feed wire through holes marked with an X
        i. Connect forward end to terminal block labelled "PI"
            1. Split wire and secure each lead into terminal block side
        ii. Connect aft end to StratoLogger MAIN and adjacent terminals
            1. Tighten leads in terminal using small screwdriver
    b. Find wire labelled "Main S" and feed wire through holes marked with an X
        i. Connect forward end to terminal block labelled "SI"
            1. Split wire and secure each lead into terminal block side
        ii. Connect aft end to Entacore A and adjacent terminals
            1. Tighten leads in terminal using small screwdriver
21. Place payload aside and find the midsection aft payload
22. Wire drogue parachute electronics:
    a. Find wire labelled "Drogue P" and connect leads to terminal block labelled "PI"
        i. Tighten leads in terminal using small screwdriver
        ii. Hang wires out of hatch opening for later use
    b. Find wire labelled "Drogue S" and connect leads to terminal block labelled "SI"
        i. Tighten leads in terminal using small screwdriver
        ii. Hang wires out of hatch for later use
23. Assemble main parachute e-matches **(see Main Parachute Black Powder checklist)**
24. Assemble drogue parachute e-matches **(see Drogue Parachute Black Powder checklist)**
25. Connect hatch rotary switches to altimeters
    a. Ensure rotary switches are turned to OFF during installation
    b. Green switch should connect to the Entacore
        i. Connect green lead to SWITCH terminal, black lead to adjacent
    c. Red switch should connect to StratoLogger
        i. Connect red lead to V+ terminal, black lead to adjacent
26. Slide payload into forward opening of midsection with avionics sled at the bottom
    a. The A-side on the bulkhead and avionics sled should face the hatch opening
    b. DO NOT insert payload all the way to the bottom of the midsection tube
    c. Align threaded rods with aft midsection bulkhead holes
27. Wire drogue parachute electronics:
    a. Find wire labelled "Drogue P" and connect lead ends to StratoLogger DROGUE and adjacent terminals

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        i. Tighten leads in terminal using small screwdriver
    b. Find wire labelled “Drogue S” and connect lead ends to Entacore B and adjacent terminals
        i. Tighten leads in terminal using small screwdriver

28. Slide payload threaded rods through aft midsection holes until line on forward payload bulkhead lines up with forward hatch opening
29. Use putty to seal both sides of forward payload bulkhead
30. Use putty to seal all wire holes
31. Place hatch over the opening with forward side up and align holes
32. Use (4) wood screws to secure hatch to midsection
    a. DO NOT over-tighten screws too much as they will damage the phenolic tubing

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Main Parachute Black Powder Charge Assembly (Primary and Secondary):

1. Required items:
   a. Avionics box
   b. Safety glasses
   c. Small scale
2. Ensure ALL altimeters and rotary switches are set to the OFF position
3. Unscrew all terminal blocks on the forward payload bulkhead
4. Primary charge:
   a. Remove plastic protective e-match cover from e-match
   b. Remove pre-cut wire insulation from end of e-match
   c. Separate the two leads
   d. Make a 180° bend (U-turn) in each lead approximately 1 cm in length
   e. Place exposed e-match leads into terminal block labelled "P"
      i. NOTE: altimeter wires should already be connected to other end of the terminal blocks
   f. Tighten down the screws in the "P" terminal block
   g. Place e-match head within the blast cap labelled "P"
      i. Ensure that the wire is curved over the outside edge of the blast cap and that the head is flat on the cap bottom
   h. Tape the e-match wire to the outside of the of the blast
   i. Carefully pour **1.0g** of black powder into the "P" blast cap over the e-match head
   j. Fill the remaining space in the blast cap with a balled-up paper towel
      i. NOTE: the paper towel should fill the space, but not be packed in tightly!
   k. Place small (2-3 in.) strips of black electrical tape on top of the "P" blast cap to cover the blast cap completely
      i. NOTE: do not layer the electrical tape and ensure all edges are covered
   l. Wrap electrical tape all the way around the outside of the blast cap to keep the top layers tight
5. Redundant charge:
   a. Repeat the above steps with the following changes:
      i. Use terminal block labelled "S"
      ii. Use **1.5g** of black powder

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Drogue Parachute Black Powder Charge Assembly (Primary and Secondary):

1. Required items:
    a. Avionics box
    b. Safety glasses
    c. Small scale
2. Ensure ALL altimeters and rotary switches are set to the OFF position
3. Unscrew all terminal blocks on the forward payload bulkhead
4. Primary charge:
    a. Remove plastic protective e-match cover from e-match
    b. Remove pre-cut wire insulation from end of e-match
    c. Separate the two leads
    d. Make a 180° bend (U-turn) in each lead approximately 1 cm in length
    e. Place exposed e-match leads into terminal block labelled "P"
        i. NOTE: altimeter wires should already be connected to other end of the terminal blocks
    f. Tighten down the screws in the "P" terminal block
    g. Place e-match head within the blast cap labelled "P"
        i. Ensure that the wire is curved over the outside edge of the blast cap and that the head is flat on the cap bottom
    h. Tape the e-match wire to the outside of the of the blast
    i. Carefully pour **1.0g** of black powder into the "P" blast cap over the e-match head
    j. Fill the remaining space in the blast cap with a balled-up paper towel
        i. NOTE: the paper towel should fill the space, but not be packed in tightly!
    k. Place small (2-3 in.) strips of black electrical tape on top of the "P" blast cap to cover the blast cap completely
        i. NOTE: do not layer the electrical tape and ensure all edges are covered
    l. Wrap electrical tape all the way around the outside of the blast cap to keep the top layers tight
5. Redundant charge:
    a. Repeat the above steps with the following changes:
        i. Use terminal block labelled "S"
        ii. Use **1.5g** of black powder

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Drogue Parachute Recovery Assembly:

1. Required items:
    a. Recovery box
    b. Fin can
    c. Midsection
    d. Drogue parachute
    e. Small nomex cloth
    f. Drogue parachute shock cord
    g. (2) nylon 4-40 shear pins
    h. (3) quicklinks (one small, two large)
    i. (2) rubberbands
    j. Adjustable wrench
2. Remove all rubber bands holding parachute fabric and shroudlines, but not shock cord
3. Use (1) quicklink (small) to attach nomex cloth to shock cord parachute loop
4. Use same quicklink to attach drogue parachute eye-bolt to shock cord parachute loop
    a. Final check that no rubber bands are on parachute or shroudlines
5. Tighten quicklink by hand, then use a wrench to secure
6. Fold FWD length of shock cord accordion-style and secure with a single rubber band
    a. DO NOT make rubber band too tight and not covering any part of parachute
7. Fold AFT length of shock cord accordion-style and secure with a single rubber band
    a. DO NOT make rubber band too tight and not covering any part of parachute
8. Attach quicklink to each end of shock cord using the loops
9. Install drogue parachute black powder charges **(see Drogue Black Powder Checklist)**
10. Attach FWD quicklink to midsection aft bulkhead U-bolt and tighten by hand
11. Have a second team member confirm the quicklink is secured to the midsection aft bulkhead U-bolt by visual inspection and pulling on shock cord
12. Attach AFT quicklink to fin can bulkhead U-bolt and tighten by hand
13. Have a second team member confirm the quicklink is secured to the fin can bulkhead U-bolt by visual inspection and pulling on shock cord
14. Fold and roll drogue parachute and wrap shroudlines around until tight
    a. Final check that all rubber bands are removed from parachute and shroudlines
15. Wrap nomex cloth around rolled parachute like a burrito
16. Carefully insert the AFT shock cord length into fin can cavity
17. Carefully insert the FWD shock cord length into the midsection cavity
18. Carefully insert the wrapped parachute into the space between stowed shock cords
19. Slide midsection coupler into fin can cavity using inner symbols to align holes
20. Cut (2) 4-40 nylon shear pins to size and insert into shear pin holes until tight
21. If shear pins are loose, place small piece of electrical tape over shear pin heads
22. Fin can and midsection should be able to hold their own weight from shear pins alone

11

Main Parachute Recovery Assembly:

1. Required items:
    a. Recovery box
    b. Nosecone
    c. Midsection
    d. Drogue parachute
    e. Large nomex cloth
    f. Main parachute shock cord
    g. (2) nylon 4-40 shear pins
    h. (3) quicklinks
    i. (2) rubberbands
    j. Adjustable wrench
2. Remove all rubber bands holding parachute fabric and shroudlines, but not shock cord
3. Use (1) quicklink to attach nomex cloth to Kevlar shock cord at parachute loop
4. Use same quicklink to attach main parachute at same shock cord loop location
    a. Check again that no rubber bands are on parachute or shroudlines
5. Tighten quicklink by hand, then use a wrench to secure
6. Fold FWD length of shock cord accordion-style and secure with a single rubber band
    a. DO NOT make rubber band too tight and not covering any part of parachute
7. Fold AFT length of shock cord accordion-style and secure with a single rubber band
    a. DO NOT make rubber band too tight and not covering any part of parachute
8. Attach quicklink to each end of shock cord using the loops
9. Install main parachute black powder charges **(see Main Black Powder Checklist)**
10. Attach FWD quicklink to nosecone bulkhead U-bolt and tighten by hand
11. Have a second team member confirm the quicklink is secured to the nosecone bulkhead U-bolt by visual inspection and pulling on shock cord
12. Attach AFT quicklink to midsection forward bulkhead U-bolt and tighten by hand
13. Have a second team member confirm the quicklink is secured to the nosecone U-bolt by visual inspection and pulling on shock cord
14. Fold and roll main parachute and wrap shroudlines around until tight
    a. Final check that all rubber bands are removed from parachute and shroudlines
15. Wrap nomex cloth around rolled parachute like a burrito
16. Carefully insert the AFT shock cord length into midsection forward cavity
17. Carefully insert the FWD shock cord length into the nosecone cavity
18. Carefully insert the wrapped parachute into the space between stowed shock cords
19. Slide nosecone shoulder into midsection cavity using inner symbols to align holes
20. Cut (2) 4-40 nylon shear pins to size and insert into shear pin holes until tight
21. If shear pins are loose, place small piece of electrical tape over shear pin heads
22. Nosecone and midsection should be able to hold their own weight from shear pins alone

12

Motor Assembly:

1. Required items:
    a. AeroTech I435T-14A reload kit
    b. AeroTech RMS 38/600 motor casing with forward seal
    c. Lube
    d. Needle-nose pliers
    e. Baby wipes
2. Follow instructions for motor assembly from L3 mentor
3. Unscrew motor retainer and slide motor casing into motor tube
4. Secure motor casing using retainer screw
5. Use another team member to ensure motor retainer screw is tight

13

Launch Pad Procedure:

1. Required items:
    a. Fully assembled rocket with payload and motor installed
    b. Motor igniter
    c. 6ft x 1515 launch rail
    d. Small, black screwdriver with red tip
    e. Blue painter's tape
    f. Safety glasses
    g. Launch rail lubricant
    h. Stepladder (if necessary)
2. Grease rocket rail buttons and launch rail track
3. Carefully slide rocket onto launch rail
4. Rotate launch rail into upright position and lock into place
    a. Rocket must be pointed downwind and 5° from vertical
5. Use another team member and L3 mentor to confirm launch rail is locked
6. Take team picture in front of rocket
7. All non-essential personnel must be directed to leave the launch pad
    a. All individuals remaining at launch pad must wear safety glasses
8. Arm both altimeters:
    a. Turn forward rotary switch to the ON position
    b. Turn aft rotary switch to the ON position
    c. Confirm that both altimeters are beeping correctly:
        i. Ask Eugene
9. Insert igniter fully into motor tube
10. Tape igniter into place at the bottom of rocket
11. Confirm that launch pad power is cut off
12. Connect igniter to launch pad power
13. Ensure pad continuity
14. All personnel must navigate to safe locations behind launch table
15. LAUNCH!

14

6.3 Launch Vehicle Safety Analysis

This section contains analysis of hazards to personnel and the environment, as well as analysis of failure modes, effects, and criticality.

6.3.1 Personnel Hazard Analysis

Table 6-2, below, contains the specific hazards that members of the team and others may face. Table 6-2 also details the strategies used to combat the associated risks of each hazard with its confidence.

Table 6-2: Personnel Hazard Analysis

Category	Concern	Mitigation	Confidence
Operational	Assembly and Handling of Motor	Minimal individuals will be allowed contact with the motor. The primary handlers of the motor would be the safety officer and club advisors. In unforeseen circumstances another club officer may be necessary but unlikely. The directions of the manufacturer will be followed strictly	The motor will be in optimal conditions to perform to specifications due to the proper care given by the adherence to the instructions of the manufacturer in addition to guidance given by HPRC club advisors.
	Transport and Handling of the Launch Vehicle	The launch will consistently be supported by multiple points of contact in effort to reduce the risk of damage to the body or internal components. This will be paid special attention to when being transported to and from road vehicles.	With these concerns and wishes expressed to all members, an effective pool of members will be available at any moment to be called upon or take initiative at any time that a need may arise.
	Launch Vicinity	Careful management of all personnel and bystanders present at the launch site and enforcing the rule, specifically the safe distance, will be necessary at all launches.	These actions will promote a safe launch and allow officials to maintain focus on other launch related tasks.

Category	Concern	Mitigation	Confidence
Operational	Location	The team will only launch at NAR/TRA approved launch sites. The team plans to launch its subscale and full-scale rockets at the Bayboro, NC launch site which meets the minimum range requirements described. The final, competition launch will occur at another NAR/TRA approved launch site near Huntsville, AL.	This will ensure the launches are able to be safely conducted with the expectation that all other safety protocols are followed.
Rocket Construction	Sharp Objects	When construction is happening on the rocket or adjustments must be made, care will be taken to make everyone in the vicinity aware that sharp objects are out. Additionally, the sharp objects will be store in consistent locations to mitigate the possibility of wounds while searching for objects.	With attention paid to sharp objects, preventable injuries due to them will be reduced and a safe, clean working environment can be guaranteed.
	Hot Objects	When construction is happening on the rocket or adjustments must be made, care will be taken to make everyone in the vicinity aware that hot objects are in use. When objects that can be heated are not in use they will be stored away to eliminate risk.	To limit use of hot objects to a minimum and heightening awareness to their us, preventable injuries can be brought to a minimum.

Category	Concern	Mitigation	Confidence
Rocket Construction	3D-Printer	The 3D Printer as a computer controlled device can perform unintended actions. As such no member without recognized experience with the HPRC 3D Printer should not interact with it whatsoever without direct supervision of a member with experience.	Using experience as a barrier of usage, personal injuries such as mechanical pinching or burns can be limited as well as causing costly damage to the 3D printing unit.
	Laser Cutter	The laser cutter is under the care of the Entrepreneurship Initiative group on campus which requires a regimented certification class to use it. HPRC members will take the certification class and abide by EI's policies at all times.	With EI's policies followed HPRC can effectively keep injuries due to the laser cutter to a minimum.
	Airborne Hazards	Some of the materials that HPRC uses can create fumes or airborne particulates. When these materials the member using it must first verbally identify the hazard and then begin use once all members in the vicinity are wearing masks.	With the appropriate use of masks the risk of respiratory injury is greatly reduced.

6.3.1.1 Personnel Reference Material

Table 6-3, below, contains descriptions of various lab items and what personnel protective equipment (PPE) is required when handling each item.

Table 6-3: Personnel Protective Equipment Reference Material

Item Description (hyperlink)	Mentor or Safety Officer required?	Required PPE				
		Safety Glasses	Mask	Gloves	Earplugs	Covered Clothing
Dewalt Power Drill DC 759	No	No	No	No	No	No
Dewalt Power Sander D26450	No	Yes	No	No	No	No
Delta Belt Sander 90183	No	Yes	No	No	No	No
Craftsman 137.216020 Scroll Saw	No	Yes	No	Yes	No	No
Delta Band Saw 28-180	No	Yes	No	Yes	No	No
GOEX Black Powder	Yes	Yes	No	Yes	No	No
Klean-Strip Acetone	No	No	Yes	Yes	No	No
West System 105 Epoxy Resin	No	No	Yes	Yes	No	No
West System 206 Slow Hardener	No	No	Yes	Yes	No	No
Fiberglass Fabric	No	Yes	Yes	Yes	No	Yes
Batteries	No	No	No	No	No	No
Cotton Flock	No	Yes	Yes	Yes	No	No
Baby Wipes	No	No	No	No	No	No
Igniters	Yes	No	No	No	No	No
Liquid Nails	No	No	No	No	No	No
Glass Microspheres	No	Yes	Yes	Yes	No	No
WD-40	No	No	No	No	No	No
Blue Tube	No	No	No	No	No	No

6.3.2 Environmental Impact Analysis

Table 6-4, below, contains analysis on how the team will impact the environment to complete the challenge, as well as any environmental concerns that may provide a hazard to personnel or the launch vehicle.

Table 6-4: Environmental Impact and Hazard Analysis

Environmental Concern	Hazard	Mitigation	Confidence
Cloud Cover	Cloud cover can obscure the rocket creating an uncertain and therefore unsafe condition when the rocket is airborne.	NAR Safety Code does not allow for launches into cloudy conditions	Without the rocket flying into cloud cover almost all risk associated with obscured flying is mitigated.
Precipitation	Precipitation usually accompanied with cloudy conditions (see above). Precipitation puts the electrical components at higher risk of being damaged.	Use weather forecasts to find a launch date with favorable conditions. Waterproof materials will be brought to shelter the rocket and its components.	With the vehicle protected from the elements the conditions will enable the best chances for launch as well as contributing to reducing launch accidents.
High Wind	NAR Safety Code prohibits launching in wind conditions exceeding 20 miles per hour and if launched the rocket may become unrecoverable	Use weather forecasts to find a launch date with favorable conditions and conditions will be checked at launch conditions	With the launch occurring under acceptable conditions launch accidents will be reduced.
Water Features	The rocket when launched may land in a water feature and would become unrecoverable or damage the rocket.	Choose a launch site that has no or minimal water features in the feasible landing area.	Without water being an obstacle for rocket retrieval the recoverability of the rocket is increased as well as the level of safety of the retrieval team.

Environmental Concern	Hazard	Mitigation	Confidence
Severe Weather	Challenging weather to include precipitation can pose a risk to the well-being of attendees as well as the safety of the launch vehicle	NAR and TRA regulations regarding severe weather will be followed to ensure a safe and responsible launch	Without members and the vehicle exposed to dangerous conditions the performance and level of safety of HPRC will be increased.
Severe Cold	Cold temperatures can cause power sources to discharge more rapidly and can weaken the structural integrity of the rocket itself.	Use weather forecasts to find a launch date with favorable conditions. If the outdoor temperatures are determined to be detrimental, thermally shelter the rocket and components.	If electronics are not subject to extreme temperatures, the risk of a rocket malfunction due to an avionics failure is reduced.
Severe Humidity	The moisture in the air can compromise the integrity of the black powder charges as well as affecting the calibration of altimeters.	Keep components and charges stored in optimal conditions prior to the launch.	Without the electronics being exposed to atmospheric moisture, the risk of a rocket malfunction due to an avionics failure is reduced.
Severe UV Exposure	UV exposure can be detrimental to the integrity of adhesives used on the rocket as well as degrading the material of the parachute.	Limit the amount of direct sunlight that are experienced and periodically inspect the rocket.	With the vehicle sheltered from unnecessary UV radiation the integrity of the rocket is more likely not to be compromised and therefore safer.
Hard Landing Surface	Hard surfaces can damage the rocket upon landing	Choose an appropriate launch site that has soft surfaces for the rocket to land on	Without the danger of debris or mechanical damage on the vehicle landing the risk to bystanders is reduced.

Environmental Concern	Hazard	Mitigation	Confidence
Trees	The rocket and parachute may become lodged into the trees making the recovery difficult or even impossible.	Read the conditions with the intention to reduce if not eliminate the risk of the rocket landing in a wooded area.	Without the risk of the rocket falling upon retrieval the risk to bystanders is reduced.
Bystanders	Bystanders on the ground could be injured by parts of the rocket or not following the directions of the RSO.	All members must abide by the safety regulations as well as imposing them upon all bystanders.	With bystanders kept in an area where their safety can be controlled more easily the overall risk is reduced.
Catastrophic Motor Failure	Fire can result and could spread to field	The motor will be handled with proper care in accordance with manufacturer guidelines and HPRC policies. A fire-extinguisher will also be present at every launch and energetic test.	With energetics kept in optimal conditions and the preparations to react in the event of an incident the impact on the local environment as well as bystanders is reduced.
Chemical and/or Acid Leakage	May deteriorate the local Ecosystems	Materials will be purchased from reputable sources to minimize defective components. After a launch component will be inspected with the purpose of verification that it is suitable for subsequent launches. If a component is not flyable it will be disposed of according the MSDS standards.	With chemicals contained and disposed of in the recommended manner HPRC can reduce impact on the ecosystem in addition to contributing to the safety of human health.

Environmental Concern	Hazard	Mitigation	Confidence
Paint Application	Paint fumes can degrade the atmosphere and if ingested can harm humans	When substantial painting is performed the paint-booth will be used so that fumes are handled correctly. The detriment to environment is negligible due to the small scale of the project.	With paint fumes kept in a controlled setting the environmental impact will be negligible and the impact on humans is mitigated.
Waste Production from Materials	Scraps of excess materials such as wires, plastics, and wood could be ingested by scavengers as well as reduce the safety of lab personnel	All members will be held responsible for maintaining a clean workspace and after using materials an inspection will be conducted to ensure that all waste created is disposed in the proper manner	With the excess materials generated from the HPRC project disposed of properly the impact on the local environment is minimal and the safety of the individuals is maintained.

6.3.3 Failure Modes, Effects, and Criticality Analysis (FMECA)

See Section 11 (Appendix B) for FMECA tables relevant to this project.

7. Payload Criteria

7.1 Compliance to Handbook Requirements

Table 7-1, below, contains the deployable rover experimental payload requirements listed in the 2018 NASA SL handbook as well as the respective compliance actions, verification methods, and status.

Table 7-1: Experimental Payload Handbook Item Compliance

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
4.1	Each team will choose one design experiment option from the following list: target detection, deployable rover, or landing coordinates via triangulation.	The team has chosen option 2: the deployable rover.	Demonstration. The team will construct a rover and will not perform the other experiments.	Complete.
4.2	Additional experiments (limit of 1) are allowed, and may be flown, but they will not contribute to scoring.	The team has chosen not to perform additional experiments.	Demonstration. The team will construct a rover and will not perform the other experiments.	Complete.
4.3	If the team chooses to fly additional experiments, they will provide the appropriate documentation in all design reports, so experiments may be reviewed for flight safety.	The team has chosen not to perform additional experiments.	Demonstration. The team will construct a rover and will not perform the other experiments.	Complete.
4.5	Deployable rover challenge requirements.	See below.		

Handbook Item	Description of Requirement	Compliance	Verification Method	Status
4.5.1	Teams will design a custom rover that will deploy from the internal structure of the launch vehicle.	The rover is custom designed and 3D printed in order to meet all the requirements.	Analysis. The custom rover will be 3D printed and assembled by the team.	Incomplete. The rover is still under construction.
4.5.2	At landing, the team will remotely activate a trigger to deploy the rover from the rocket.	An RN-42 Bluetooth module connects with a laptop and receives a signal from the laptop.	Demonstration. The team will use Bluetooth to wirelessly communicate with the rover.	Incomplete. The rover is still under construction.
4.5.3	After deployment, the rover will autonomously move at least 5 ft. (in any direction) from the launch vehicle.	The motors that are responsible for the rover's motion remain active long enough for the rover to move 5 ft.	Demonstration. The two servos will rotate such that the treads are pulled around the housing, causing forward motion.	Incomplete. The rover is still under construction.
4.5.4	Once the rover has reached its final destination, it will deploy a set of foldable solar cell panels.	A sail system is deployed by an arm controlled by a motor on top of the rover.	Demonstration. A servo activated after the rover reaches it's final destination will rotate an arm which unfurls the solar panels.	Incomplete. The rover is still under construction.

7.2 Mission Statement

The payload is a custom designed rover, which is to deploy from the internal structure of the launch vehicle upon remote triggering. During flight, it is housed in the payload tube, which is rotating about a Lazy Susan bearing system. Upon landing, the payload tube self-rights, and the electric latch keeping the rover in the tube is unlocked. At the same time, the rover exits the payload tube is to autonomously drive 5 ft in any direction and deploy foldable solar cell panels upon reaching the final resting point. The solar panels will be deployed using a rotating arm with folded panels attached. As the arm rotates, the panels unfurl. The experiment is considered to be successful when the rover deploys from the launch vehicle, travels the required distance, and deploys the solar cells with minimal damage.

7.2.1 Mission Success Criteria

The experiment is considered to be successful when the rover deploys from the launch vehicle, travels the required distance, and deploys the solar cells with minimal damage.

7.3 Selection, Design, and Rationale of Deployable Rover

To meet the requirements outlined in Section 4.5 of the NASA Student Launch handbook, the team chose to design a rover with tracks. This was done to maximize traction, power efficiency, and volume efficiency. When compared to wheels, treaded tracks allow for greater grip when driving over rough terrain and are less susceptible to getting stuck. Tracks also require less power to achieve similar performance to wheels, and the space inside the tracks' housings can be utilized for additional storage. During flight, the rover is kept in place by an electronic rotary latch at the rear of the rover and by slots above the rover. The latch prevents longitudinal motion within the payload tube, and the slots keep the rover from moving laterally. Upon landing, the self-righting payload tube will rotate into the correct orientation due to the center of gravity of the entire payload offset from the axis of rotation. A radio signal will be sent to the payload to unhook the latch, and Bluetooth module will be used to activate the rover after landing is confirmed. The rover will utilize two motors controlling the rotation of both front wheels, thus pulling the tracks around their housings to drive the rover forward. The motors will remain active long enough for the rover to travel at least 5 ft laterally from the payload landing site, and then it will stop in place. To meet the requirement of deployable solar panels, an arm will be attached to a servo on top of the rover, and the rotation of the servo will turn the arm and unfurl the panels.

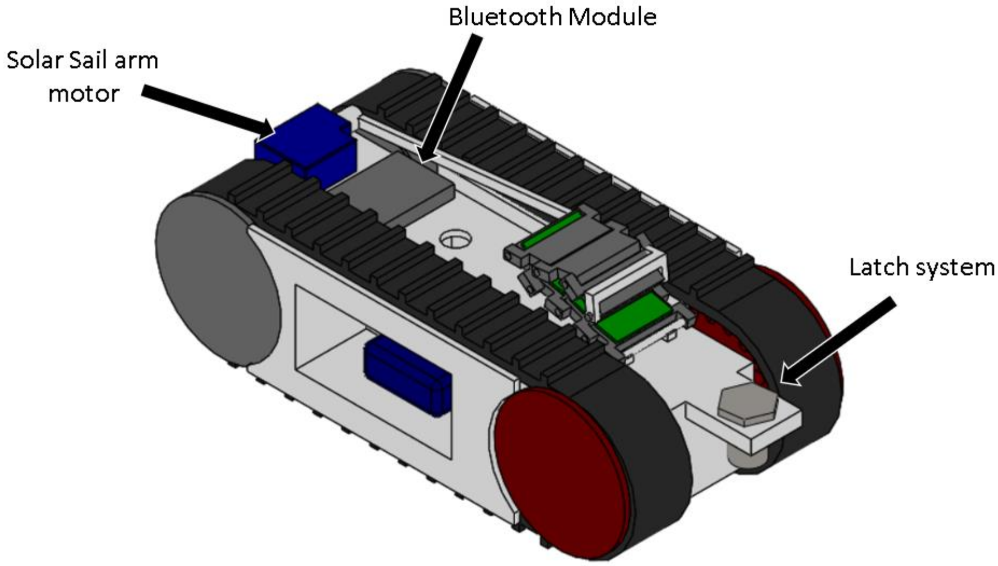


Figure 7-1: Current Rover Model with Solar Panels Stowed

The electronic rotary latch, attached to the sled, wrap around the latch screw and will unlatch when it receives a signal from the team upon landing.

The rover body will consist of two 3D printed shells and two track housing pieces designed to hold all the electronics. These electronic components include an MSP-EXP430G2, RN-42 Bluetooth Module, a 4AA battery pack, and three servos. The main body will be printed in two pieces to simplify the process of inserting components and minimize the likelihood of defects during printing. The geometry of the body, specifically the axle slots, makes it difficult to print in one piece, so splitting it in half reduces the possibility of printing malfunctions taking place in high risk areas. The team decided to 3D print rather than use other methods because 3D printing allows for rapid prototyping and is much simpler than traditional manufacturing methods. Changes can be made quickly and at a low cost, and they can be tested in a timely manner. The shell design will allow for quick and easy rover assembly, and the track housing pieces will protect the electrical components from dirt and debris after exiting the payload.

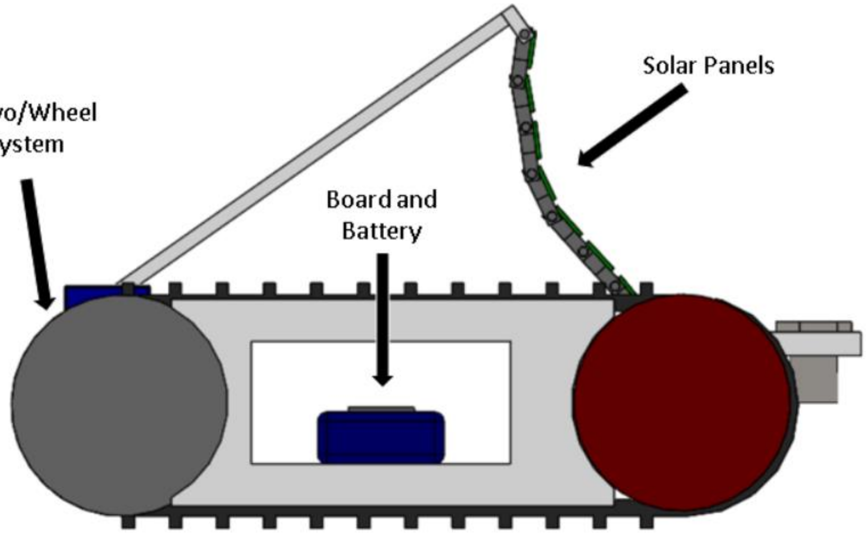


Figure 7-2: Side View of Current Rover Model – Main Body Interior

A more space efficient design was created after running into sizing issues with the initial proposal design. The main body interior allows for sensitive components such as the MSP-EXP430G2 to be stored away from potential hazards.

7.3.1 Dimensions and Technical Details

Due to size constraints set forth by the payload tube dimensions, the rover is constricted to 9 in. in length, 3.8 in. in width, and 2.2 in. in height with solar panels stowed and 5.5 in. when solar panels are deployed.

7.3.1.1 Material Selection

An MSP-EXP430G2 was chosen for its simplicity, cost, and reliability. Extensive literature is available for team members not experienced in programming to become familiar with its operation, and it was also recommended after consulting with local electronics experts. The rover will use three FS90 servos: two for motion and one for the solar panel arm. These were chosen because of their reliability, size, and output power. An RN-42 Bluetooth module will be used because of the simplicity it allows. The module will be paired with a laptop which will activate everything for the rover to operate. A 4AA battery pack will be used to power all electronics onboard and will have the power capacity necessary to keep the system alive while waiting on the launch pad.

Table 7-2: Rover Parts List

Part	Material	Weight (lb)	Quantity	Total Weight (lb)
Body	ABS	0.360	1	0.360
Opening	ABS	0.160	2	0.320
Wheel	ABS	0.120	2	0.240
Servo Wheel	ABS	0.080	2	0.160
Tread	Rubber	0.170	2	0.340
Arm	ABS	0.010	1	0.010
Front Axle	ABS	0.020	1	0.020
Rear Axle	ABS	0.020	1	0.020
Latch Screw	Steel	0.020	1	0.020
Screw Guide Bottom	ABS	0.010	1	0.010
Screw Guide Top	ABS	0.010	1	0.010
Panasonic - BSG AM-1456CA Solar Panels	n/a	0.002	7	0.014
Accordion	Paper/ Plastic	0.010	1	0.010
FEETECH FS90R	n/a	0.020	3	0.060
4AA Battery Pack (batteries included)	n/a	0.250	1	0.250
MSP-EXP430G2*	n/a	0.055	1	0.055
RN-42 Bluetooth Module	n/a	0.006	1	0.006
Misc. Wires (estimate)	n/a	0.020	1	0.020
			Total (lb)	**1.925**

**Estimated using comparable microcontrollers*

7.3.2 Rover Movement

The rover will use a total of three FEETECH FS90 servos. Two of these will be used for forward motion. These servos will be activated after the latch has opened and will cause the front wheels to rotate which will in turn pull the tracks around their housings. The rubber tracks will grip on the rough terrain that the rover will likely face and generate forward motion. Once construction of the rover is complete, its capabilities will be tested including its ability to traverse steep inclines and large objects.

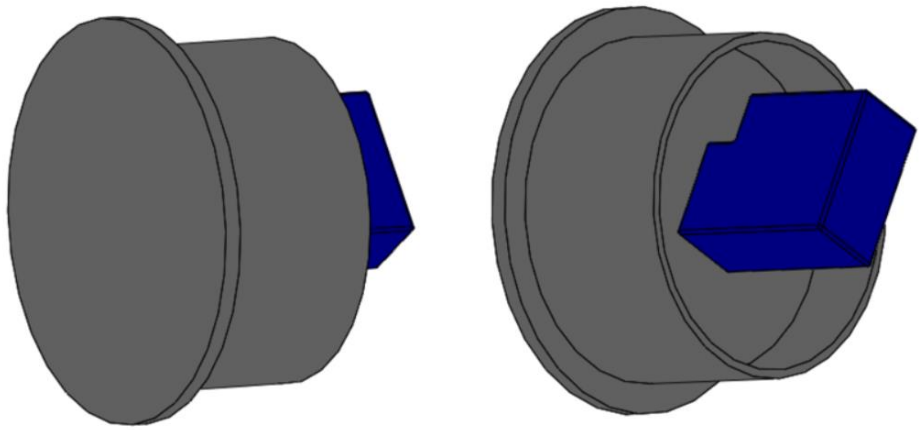


Figure 7-3: Front wheel with FEETECH FS90 servo

7.3.3 Solar Panel Deployment

In order to meet the requirements of deployable solar panels, the rover must contain a folded set of solar panels that deploy after reaching its destination. In this design, called the "Solar Sail," the solar panels are folded in an accordion style. To create the accordion, the panels are mounted either on a foldable surface such as paper or plastic or attached to links that can be stowed in a folded state. One end of the accordion is attached to a rotating arm spanning the length of the rover that is controlled by a servo at the front. The other end of the accordion is linked to the body of the rover at the rear. In its stowed position, the arm is parallel with the rover, and the panels are folded and not receiving sunlight. In its deployed position, the arm is upright with the solar panels extended, resembling the sail of a ship.

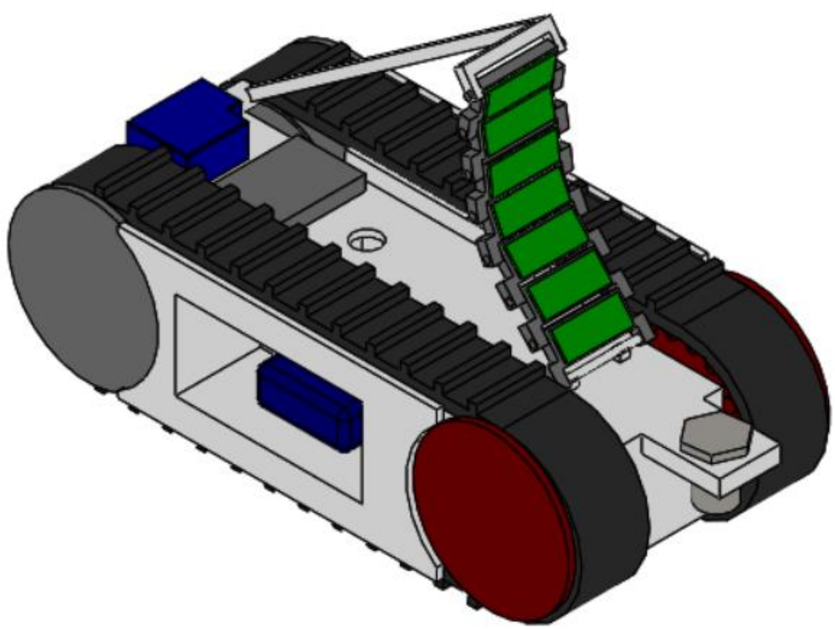


Figure 7-4: Current Rover Model with Solar Panels Deployed

When the servo activates, it will rotate the arm, thus deploying the solar panels. Although no power will be generated by the solar panels, this serves as an analogue of a real solar panel deployment.

The Panasonic - BSG AM-1456CA solar cells were selected because of their small size, light weight, and low cost. The solar cell can ship quickly and in large quantities. Its size and weight are ideal because they will not require large amounts of torque to be lifted out of the folded position, so a small servo can still be used. This keeps the weight of the entire rover low.

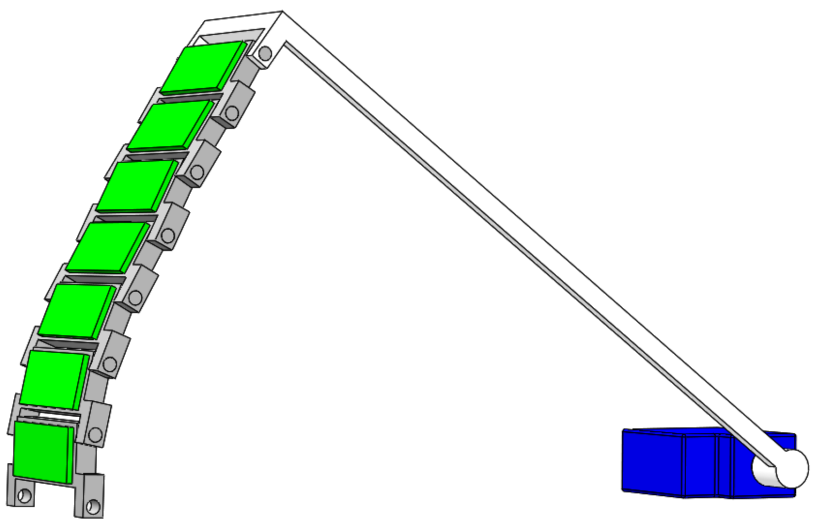


Figure 7-5: Close up view of Solar Sail arm

The solar panels will deploy after the rover reaches its final destination. The linkages modeled are currently a placeholder for the accordion method, which could not be modeled due to limitations in SolidWorks.

All parts from the rover mass table that are relevant to the function of the solar panel deployment contribute a small percentage to the overall weight of the rover.

Table 7-3: Weight Estimate for Sail System

Part	Material	Weight (lb)	Quantity	Total Weight (lb)
Arm	ABS	0.010	1	0.010
Panasonic - BSG AM-1456CA Solar Panels	n/a	0.002	7	0.014
Accordion	Paper/ Plastic	0.010	1	0.010
FEETECH FS90R	n/a	0.020	1	0.020
			TOTAL	0.054

7.3.4 Rover Electronics

For the rover to perform completely autonomously, the on-board microcontroller must be pre-programmed to run through its mission of at least 5 ft of travel and solar panel deployment. This means that there are five key events that need to happen for a successful rover mission:

1. Bluetooth activation
2. Front servos run for allotted time
3. Front servos stop after allotted time
4. Solar Sail servo activates
5. Solar Sail servo stops after deploying the sail

Since this is a mission with few operations, a relatively simple microcontroller was chosen to handle the tasks.

7.3.4.1 Computer

The MSP-EXP430G2 can be programmed and easily tested on the MSP430 Development Kit. After it has been confirmed that the code works as expected, the microcontroller can be removed from the Development Kit and placed on a breadboard to allow for further manipulation. Its operating voltage is between 1.8V and 3.6V.

Figure 7-6: MSP-EXP430G2 Development Kit

7.3.4.2 Remote Activation System

For the rover to be considered successful, it must be remotely activated upon landing. The team decided to use a Bluetooth module that is to be linked with a laptop. The RN-42 Bluetooth module was selected because of extensive resources from Texas Instruments that detail how the Bluetooth communication works between the module and the MSP-EXP430G2. It operates between 3.0V and 3.6V.

Figure 7-7: RN-42 Bluetooth Module

7.3.4.3 Driving Servos

All three servos will be FEETECH FS90 Continuous Rotation servos. These are space efficient yet powerful enough to move the rover the necessary distance, and they pair well with the MSP-EXP430G2..

Figure 7-8: FEETECH FS90 Continuous Rotation Servo

7.3.4.4 Battery

Currently, the power is provided from a battery pack containing 4AA alkaline batteries.

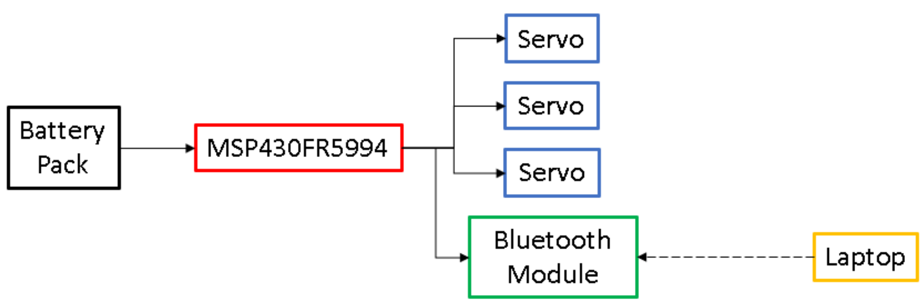


Figure 7-9: Block Diagram of Electronics

The battery provides power to the microcontroller which connects to the servos and Bluetooth module, and t Pictured below is the electrical diagram of all the rover's electronics, and the Bluetooth module communicates wirelessly with the laptop.

7.3.5 Operational Procedure

After programming the microcontroller, attach it to the breadboard and then connect the two motion servos and Bluetooth module to the microcontroller. Apply power to then board to ensure that all connections are firm and provide power to necessary components. Place the assembly in the bottom half of the rover body and position the servos in the proper openings. Slide the rear axle into its slot and adhere the top half of the rover to the bottom half. Route the sail servo's wires through the top hole and connect it to the microcontroller then attach the sail to the servo. Slide the front wheels onto the servos and the rear wheels onto the axle.

7.3.6 Performance Predictions

It is difficult to predict the performance capabilities of the rover at this point in development. Once construction is complete, the team will be able to run tests on the rover ranging from Bluetooth capabilities to terrain navigation.

7.4 Payload Integration in Full-Scale Launch Vehicle

This section contains the technical specifications and design justifications for the payload bay design that will house the rover during flight.

7.4.1 Dimensions and Technical Details

The payload integration for the full-scale launch vehicle will weigh 6.27 lb, including rover, according to SolidWorks. The total length of the payload is 17.5 in. from bulkhead to bulkhead. The design of the payload has the center of gravity below the lateral axis to ensure the payload stabilizes in the optimal position during the descent and landing. Figure 7-10 is an isometric view of the payload in its entirety.

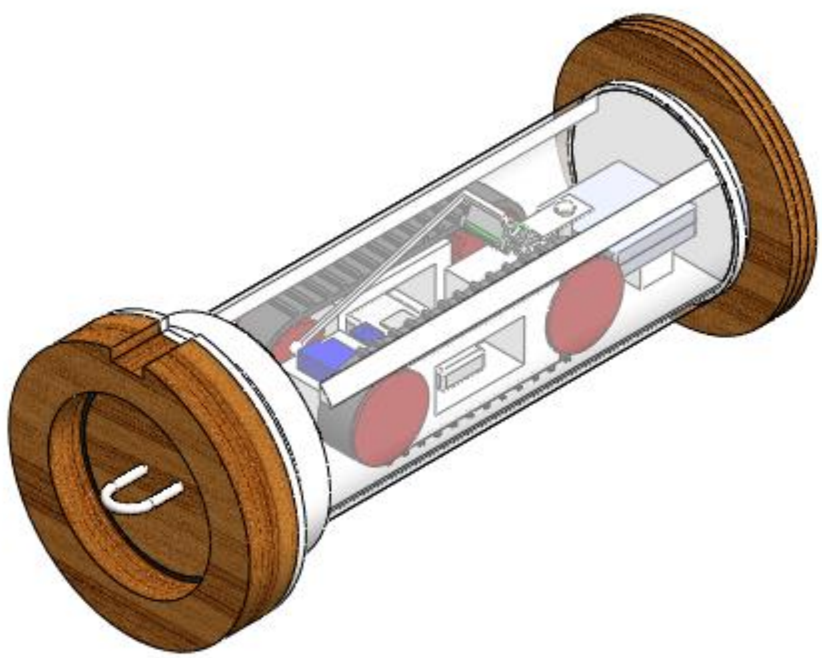


Figure 7-10: Isometric View of Payload

7.4.1.1 Payload Structure

The rover will be enclosed in an acrylic tube with an outer diameter of 5.25 in. with .125 in. walls from ePlastics (part number ACRCAT5.250ODX.125). Acrylic plastic is strong, easy to work with, and light. It has a shear modulus of 129 ksi and a density of 0.043 lb/in^3, according to SolidWorks Material Database. The design of the tube is to be attached to two Lazy-Susan bearings (LSB) which will prevent the payload from moving with the body of the rocket during flight. This means the payload housing will not be a rigid body. The intent of this design is to keep the payload in a constant position in the case the rocket spins during flight and descent. At the aft end of the tube, there will be a birch plywood disk attached to the interior wall flush with the end for the aft LSB attachment. Since the LSB's are attached in between the forward centering ring and the aft bulkhead, the payload structure will not be removable. However, discussed later in Section 7.4.1.4, the rover payload will be removable.

7.4.1.2 Forward Lazy Susan Bearing Design

The forward LSB system is a combination of a 3D printed bearing carrier and a PVC connector that connects the acrylic tube to the bearings to allow roll. The 3D printed piece is an original design and attaches to the forward centering ring. It will consist of ABS plastic. Figure 7-11 is a section view of the forward LSB design:

Figure 7-11: Profile of Sketch for the Forward LSB Revolved 360°

The team chose to 3D print the forward LSB instead of buying a manufactured system because it fit the team's design of the payload. The design has a required inner diameter of 5 in. to allow the rover to exit. This bearing carrier will be attached to the forward centering ring by eight ¼"-16 screws.

The PVC plastic tubing comes from a 5 inch Schedule 40 PVC Coupling SxS from Home Depot (Model # 429-050) and will be adhered to the payload tube with 0.1 inch overhang. It will be cut to a 1.125 inch length to allow optimum contact surface as well as minimize unnecessary weight. Epoxy resin will be used to attach the PVC to the acrylic to ensure a secure bonding. This PVC piece will have contact with the 5 mm VBX ball bearings in the 3D printed carrier to allow the payload to roll when necessary. PVC was selected because it is more cost effective than acrylic with the amount needed for the design. PVC also is a hard and durable plastic meaning with will not fracture at any point during flight.

A foam ring with an inner diameter of 5.25 in. and an outer diameter of 5.5 in. will be attached between the payload tube and the PVC piece. This will act as a spacer to fill the gap between the tube and PVC piece.

Figure 7-12 illustrates the entire forward LSB system with the PVC, foam, and tube interactions.

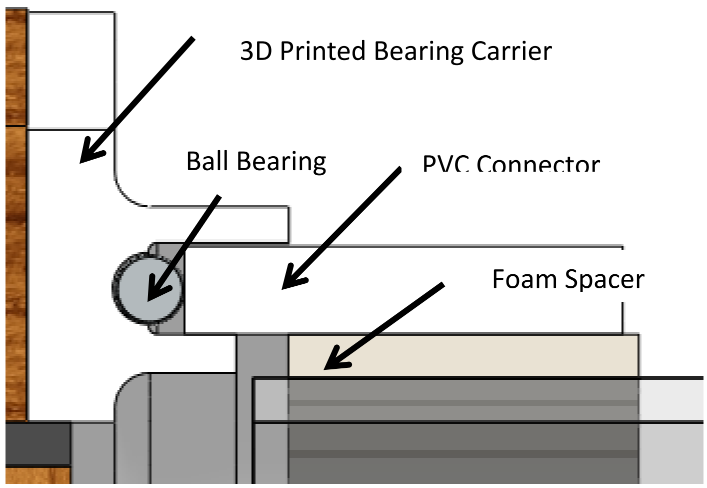


Figure 7-12: Interactions Between All Components of the Forward LSB

The team is considering creating the forward LSB bearing carrier out of aluminum. Changing the material to alumium will make the the component stronger and will reduce the amount of friction acting on the ball bearings. This will be fabricated by a member of the team. The weight of the part will increase to 0.74 lb increasing the weight of the payload 0.46lb.

7.4.1.3 Aft Lazy Susan Bearing Design

The aft LSB system will be a 120mm Lazy Susan Aluminum Bearing Turntable Bearings from VXB Bearings (Product Code: KIT12876). Figure 7-13 is an image of the bearing, provided by VXB.com:

Figure 7-13: Image of the Aft Lazy Susan Bearing from VXB Bearing

It can be seen that the design of the bearing consists of two concentric rings. The outer ring will attach to the aft bulkhead and the inner ring will attach to the tube insert. The outer diameter of the bearing is 120 mm (4.72 in.), the inner diameter is 60 mm (3.36 in.) and the thickness is 9.5 mm (0.37 in.). Figure 7-14 is a full-section view of the bearing provided by VXB.com:

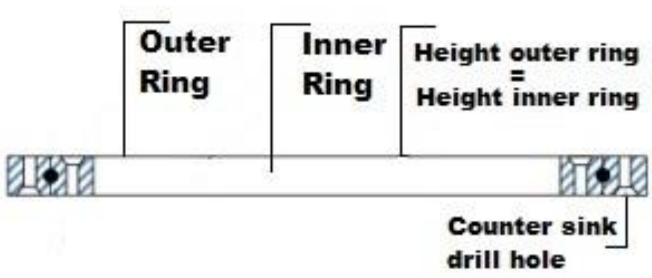


Figure 7-14: Full-Section View of the Aft LSB

It can be seen in the section view that the bearings are enclosed between the rings. Also, the screws will be used to attach the bearing to the bulkhead and the tube insert.

The two bearing systems will allow the offset center of gravity bring the rover to rest in the upright position when the launch vehicle lands to permit easy deployment.

7.4.1.4 Rover Latch Design

The rover will be secured in the lateral direction using a Southco R4-EM 6 Series Electronic Rotary Latch. Figure 7-15 illustrates the latch that will be used:

Figure 7-15: Southco R4-EM 6 Series Latch

This latch is an electrically-actuated latch. It will be secured via 0.22 inch screws through two through holes that are present in the latch. After the launch vehicle lands, the latch will be remotely triggered to release, allowing the rover to exit the vehicle body.

7.4.1.5 Rover Support

The rover is going to be secured between a platform and braces. The platform is a continuous extruded piece that fits the curve of the tube's interior face. The top edge of the platform is 1.25 in. from the horizontal axis. This design allows the platform to sit easily in the tube. The front face of the platform fills the entirety of the tube below the top edge. The part is extruded back an inch into the tube while tapering off to the thickness. This design will protect the latch electronics The thickness of the tube is .25 in. which allows it to be strong enough to support the while not requiring a large amount of material that would increase the payload weight.

The rover will be supported from above by a pair of braces. These braces have a curved face that matches the curve of the tube and extend the length of the tube. They will be attached to the tube above the rover treads so that they are just touching them. These braces, in addition to the platform below, will secure the rover between them to keep it from moving off the platform during flight. The braces will be 3D printed with ABS plastic because the design is a custom design that will be easily printed.

While the braces are attached to the tube walls, the platform is not. This is intended to have the platform removable. This is designed as such so that the team is able to properly set up the rover and the electronics prior to launch. Figure 7-16 is a side view of the rover supported between the platform and the upper braces.

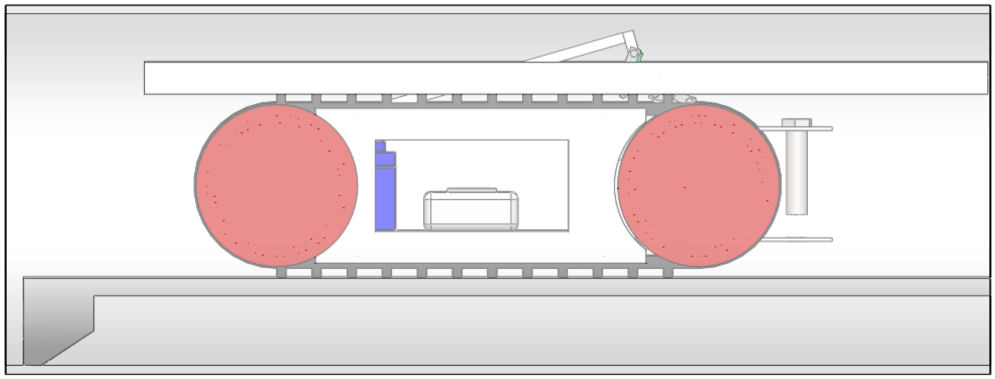


Figure 7-16: Side View of Rover Resting Between Platform and Upper Braces

7.4.2 Payload Electronics

The Southco latch will require a remote control receiver and a wireless key fob to operate.

7.4.2.1 Electronic Latch

As discussed in Section 7.4.1.4, the rover will be secured with a Southco R4-EM 6 Series Electronic Rotary Latch. The cam inside the latch is controlled by a DC motor connected of an actuator. This latch can either be manually opened and closed or controlled by a wireless key fob. The team chose to use the wireless key fob instead of using the rover to open to latch to guarantee rover deployment.

7.4.2.2 Receiver

The latch will be controlled by a key fob provided by Southco. This fob is paired with the EA-R02-RF Wireless Remote Controller. Figure 7-17 shows the EA-R02-RF Wireless Remote Controller.

Figure 7-17: Southco EA-R02-RF-Wireless Remote Controller with Key Fob and Wires

This key fob has both lock and unlock buttons to control the latch. The controller's case is constructed of injection molded ABS plastic. It requires 12 volts DC to operate. The controller operates at a frequency of 433.92 MHz. It can operate at temperatures ranging from -20 to 80 °C (-4 to 176 °F). The standard atmospheric temperature at the rocket's approximate expected apogee altitude of 5000 ft is 41.17 °F which is safely well within the controller's operational range. The key fob will open release the latch at a distance up to 60 feet from the controller. The key fob uses two Type CR2016 3VDC batteries.

7.4.2.3 Battery

The Southco R4-Em- Series 6 latch and the EA-R02 RF Controller require an input power supply with a voltage between 12 V and 24 V. Energizer A23 12V batteries will power the latch and controller. The batteries will be mounted on LanLan A23 Battery Clip Holder Box Case. Figure 7-18 is an image of the LanLan battery clip.

Figure 7-18: LanLan A23 Battery Clip Holder Box Case

The LanLan battery clip holder has positive and negative connectors. The positive wire will connect to the red power connector pin on the latch and the negative wire will connect to the black pin connector the RF Wireless receiver. Figure 7-18 is the electronics diagram of the payload latch.

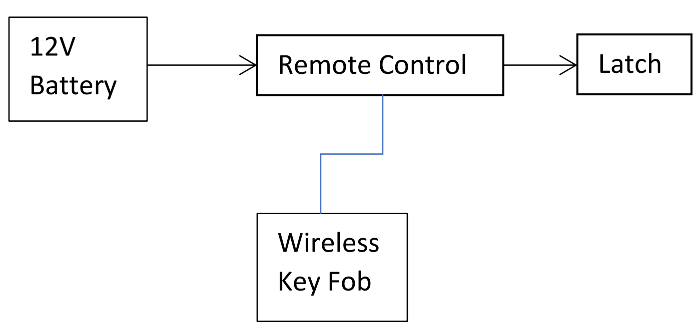


Figure 7-19: Payload Latch Electrical Diagram

The weight of all parts of the payload excluding the rover and launch vehicle structures are list below in Table 7-4.

Table 7-4: Weight Estimate for Payload Integration system

Part	Material	Weight (lb)	Quantity	Total Weight (lb)
Payload Tube	Acrylic	1.22	1	1.22
Rover Platform	ABS Plastic	0.62	1	0.62
Tube Bearing Mount	Birch	0.12	1	0.12
Upper Rover Support Braces	ABS Plastic	0.04	2	0.08
VXB 120mm LSB	1060 Aluminum	0.50	1	0.50
Forward LSB bearing carrier	ABS	0.28	1	0.28
PVC Contact	Schedule 40 PVC	0.27	1	0.27
Foam Spacer	Blue Foam	0.01	1	0.01
5 mm Ball Bearing	Chrome	0.004	91	0.36
Southco R4-EM 6 Series Latch	Multiple	0.18	1	0.18
Southco EA-R02 Remote Controller	ABS Plastic	0.21	1	0.21
A23 Battery	Lithium	0.02	1	0.02
Plug Disk	Birch	.21	1	.21
Rubber Gasket	Rubber	0.04	1	0.04
U-bolt	201 Annealed Stainless Steel	0.23	1	0.23
			TOTAL	**4.35**

8. Project Plan

8.1 Project Verification Plan

The updated verification plan listed is in Table 3-1.

8.2 Team-Derived Requirements Verification Plan

Table 8-1, below, contains the compliance plan for team-derived requirements.

Table 8-1: Team-Derived Requirements and Verification Plan

Subsystem	Description of Requirement	Verification Method	Status
Recovery	Prioritize Hardware available to decrease budget.	For the LARD parachute, quick links, and shear pins are examples of hardware currently available and were prioritized before purchasing new materials. This process of taking inventory of available parts will continue during full-scale construction. Shear pins were readily available and are being used, the parachute for the LARD is the same parachute as the subscale main parachute, which was used in previous years. The quick links are being reused from previous years. All of these parts are in good, working condition and in the end will save the team money.	Complete. See Sections 4.2 and 4.3.
Recovery	Utilize deployment bag for the main parachute.	A Fruity Chutes 7.5 in. deployment bag is being utilized in order to delay the deployment and inflation of the main parachute following the main separation. The deployment bag requires the shroud lines to be inserted and woven in a z-formation and therefore delays the time that it takes for the shroud lines to fully extend and the canopy to inflate.	Complete. See Section 4.3.3.

Subsystem	Description of Requirement	Verification Method	Status
Recovery	Decrease wind drift through the employment of a third parachute, the Low Altitude Recovery Device (LARD).	A third parachute (LARD) is being installed along the shock cord of the drogue compartment. The LARD will be located 120 inches from the aft bulkhead of the midsection and 180 in. from the drogue parachute. The LARD will decrease the amount of motion and force transferred from the main parachute deployment to the rover latching mechanism. The rover latching mechanism may only withstand 1.5 lb of force. With the LARD, the midsection avoids a 180 degree maneuver to re-orient once the main parachute is deployed. The LARD parachute is a 60 in. Iris Ultra Standard parachute, and was used as the main parachute for the subscale rocket.	Complete. See Section 4.3.2.
Structures	Minimize cost of materials by using leftovers or currently available materials when possible.	Buckling experiment will be conducted using leftover Blue Tube samples from previous projects. Experiment will consist of axially compressing three Blue Tube cylindrical sections until buckling occurs in a hydraulic press. By using small samples, the team will avoid purchasing extra Blue Tube.	Incomplete. Demonstration and experimentations will be completed prior to launch, 02/24/2018.
Rover	Complete a completely custom body with no pre-manufactured parts.	The body, axles, and wheels of the rover will be 3D printed by members of the team and tested for strength and functionality. The team-manufactured parts will be tested and compared to pre-manufactured part performance. The parts will be incorporated and tested for mission completion to ensure that they perform as intended.	Incomplete. Manufacturing, assembly, and experimentation will be completed prior to launch, 02/24/2018.

8.3 Required Testing

Table 8-2, below, includes the plans for all futures tests to be completed prior to full-scale launch.

Table 8-2: Full-Scale and Subscale Launch Vehicle Handbook Item Compliance

Subsystem	Test	Plan for Test
Recovery	Black powder ejection testing	The predicted black powder size will be pre-measured and inserted into the finished full-scale rocket. The rocket will complete ground testing with pink and blue foam and an external, manual testing device. The main charges will be tested and are predicted to be successful.
Payload	Payload plug ejection testing	During the black powder ejection test for the main parachute, the plug will be inserted in the payload centering ring with the shock chord looped around the U-bolt. This test will follow the Black powder ejection test procedure. It will determine if the seal created by the rubber gasket will not interfere with the rover ejection.
Avionics	Altimeter testing	Each altimeter will be tested inside a clear vacuum chamber. The altimeter will be powered via a 9V battery and an LED light will be wired to the ejection terminals to signal current flow. The pressure in the vacuum chamber will then be adjusted to simulate a full flight cycle. The LEDs will be observed to confirm they fire at the appropriate times: apogee, apogee delay, descent, or descent delay.
Avionics	GPS testing	The BigRedBee GPS unit will be powered on and taken by a team member on the NC State bus system which can be tracked using a GPS based cell phone app. The BigRedBee unit will then be synced to Google maps and compared to the tracking of the bus tracking phone app.

8.4 Budget

Table 8-3, below, contains a line item list of all projected expense for the team to compete in the 2017-18 NASA SL challenge.

Table 8-3: Weight Estimate for Sail System

	Item	Quantity	Price per Unit	Item Total
Subscale Rocket	4" Phenolic Airframe Tube	2	$20.99	$41.98
	4" Phenolic Tube Coupler	1	$4.99	$4.99
	4" Plastic Nose Cone Standard	1	$23.95	$23.95
	Aircraft Spruce Domestic Birch Plywood 1/4"x4x4	2	$56.38	$112.76
	¼" Threaded Rods	2	$4.54	$70.00
	Rail Buttons	1	$7.35	$7.35
	U-Bolts	4	$2.96	$11.84
	I435T Motor	2	$55.99	$111.98
	Motor Casing (subscale)	1	$240.00	$240.00
	Motor Retainer	1	$33.50	$33.50
	12" Motor Mounting Tube MMT-1.525 (38mm)	1	$5.49	$5.49
	StratoLogger Altimeters	2	$55.00	$110.00
	Entacore Altimeters	2	$115.00	$230.00
	Key Switches	2	$12.00	$24.00
	1 in PVC Pipe Caps	4	$0.83	$3.32
	Acrylic Tubing (OD 2.75", 1/8" thick)	1	$43.27	$43.27
	Terminal Blocks	3	$7.00	$21.00
	3mm Ball Bearings (1000 count)	2	$8.22	$16.44
	Adafruit BNO055 10DoF sensor	1	$28.05	$28.05
			Subtotal:	**$1,139.92**
Full-Scale Rocket	Fiberglass 7.5" Filament Wound Metal Tip	1	$170.00	$170.00
	7.5"x 0.08 wall x 12" Blue Tube ARR Standard Coupler	2	$30.00	$60.00
	7.5" x 0.08 wall x 48" ARR Airframe Blue Tube	2	$90.00	$180.00
	Aircraft Spruce Domestic Birch Plywood 1/8"x4x4	3	$50.00	$150.00
	Aircraft Spruce Domestic Birch Plywood 3/8"x2x4	2	$70.00	$140.00
	Rail Buttons	4	$2.50	$10.00
	U-Bolts	3	$1.00	$3.00
	Aerotech L2200G-P	2	$250.00	$500.00
	Motor Casing	1	$390.00	$390.00
	3" G12 Fiberglass Filament Wound Tube 48" Long	1	$91.00	$91.00
	Motor Retainer	1	$25.00	$25.00
	Wires	1	$30.00	$30.00
	Connectors	1	$20.00	$20.00
	StratoLogger Altimeters	2	$55.00	$110.00
	Entacore Altimeters	2	$115.00	$230.00

	Item	Quantity	Price per Unit	Item Total
Full-Scale Rocket	BRB 900 Transmitter	3	$200.00	$600.00
	Key Switches	2	$12.00	$24.00
	Blast Caps	4	$2.50	$10.00
	Terminal Blocks	3	$7.00	$21.00
	E-matches	-	$20.00	$20.00
	Black Powder (lb)	1	$30.00	$30.00
	Sanding Sealer (qt)	1	$17.00	$17.00
	Epoxy and Hardener	1	$50.00	$50.00
	Paint	1	$30.00	$30.00
	Nuts (box)	1	$5.50	$5.50
	Screws (box)	1	$5.00	$5.00
			Subtotal:	**$2,921.50**
Payload	5.25" x .125" Wall Acrylic Tube	1	$145.00	$145.00
	LiPo Batteries	2	$15.00	$30.00
	Servo Motor	1	$20.00	$20.00
	Arduino Nano	1	$22.00	$22.00
	120mm Lazy Susan Bearing	2	$9.37	$18.74
	Southco R4-EM 4&6 Series Electronic Rotary Latch	1	$45.00	$45.00
	1” Brass Hinges (4 pack)	1	$6.28	$6.28
			Subtotal:	**$287.02**
Rover	Arduino Pro Mini 238	1	$9.95	$9.95
	XBee Pro 900 XSC S3B Wire Rx	1	$66.95	$66.95
	FS90 Servo	2	$4.95	$9.90
	Turnigy 1000mAh 25 20C LiPoly Pack	1	$4.73	$4.73
	1" Wide Molded Track Set	1	$82.00	$82.00
	Panasonic-BSG AM-1456CA	7	$1.55	$10.85
			Subtotal:	**$184.38**
Recovery	Jolly Logic Chute Release	1	$130.00	$130.00
	36 in. Standard Elliptical Parachute	1	$89.00	$89.00
	120 in. Iris Ultra Compact Parachute	1	$685.00	$685.00
	7.5” deployment bag	1	$69.00	$69.00
	Kevlar Shock Cord (yd) (fullscale)	28	$4.34	$121.52
	¼” Kevlar Tube Shock Cord (yd) (subscale)	20	$2.84	$56.80
	Quick Links	5	$1.25	$6.25
			Subtotal:	**$1,157.57**
Travel	Student Hotel Rooms (price per day)	4	$791.70	$3,166.80
	Mentor Hotel Rooms (price per day)	3	$1,178.10	$3,534.30
	Van Rental (2 vans, 1,144 miles each)	2,288	$0.69	$1,578.72
	Gas	-	-	$686.40
			Subtotal:	**$8,966.22**

	Item	Quantity	Price per Unit	Item Total
Promotional	T-Shirts	25	$15.00	$375.00
	Polos	25	$30.00	$750.00
	Pens	500	$0.24	$120.00
	Stickers	500	$0.26	$130.00
			Subtotal:	**$1,375.00**
Other	Incidentals (replacement tools, hardware, safety items)	-	-	$1,000.00
	Shipping Costs	-	-	$750.00
			Subtotal:	**$1,750.00**
			Total Expenses:	**$17,781.61**

8.4.1 Funding Plan

The team receives funding from multiple NC State University organizations as well as the North Carolina Space Grant (NCSG).

The Engineering Technology Fee (ETF) fund from the MAE department at NC State provides monetary support to any student organizations that satisfy the Senior Design project curriculum requirements. Since the NASA SL project will complete the requirements for the Aerospace Engineering Senior Design course, the team will receive approximately $2,000 from the ETF fund for the entire school year.

The Engineers' Council (E-Council) at NC State University is a student-led organization that oversees events hosted by the College of Engineering. E-Council also allocates funds to different engineering organizations through a proposal, presentation, and appeals process that occurs twice per school year. This academic year, HPRC has received $850 from E-Council for the Fall session. A similar request of $900 will be placed for the Spring session, given that the E-Council budget remains the same.

The NC State University Student Government Association's Appropriations Committee is responsible for distributing university funds to campus organizations. The application process is similar to E-Council with a proposal, presentation, and an in-person interview. This academic year, HPRC has received $865 for the fall session. A similar request of $950 will be made for the Spring and should be received given that Student Government's budget remains the same.

The Department of Mechanical and Aerospace Engineering at NC State has committed to paying up to $6,000 dollars of HPRC's travel costs for the year. At the moment, this covers the cost of hotels in Huntsville during the NASA SL competition.

In addition to funding through NC State organizations, the North Carolina Space Grant will provide a large amount of monetary support to the club. NCSG has awarded the team $5,000 for group participation and $3,000 for senior design to participate in the 2018 NASA SL competition.

Our sponsor, Southco, has offered to provide the electronic latches and additional equipment required for our full-scale payload design.

With the funding described above, HPRC's working capital for the academic year is $19,565. About half of this, $10,470, has been spent on subscale and travel; leaving $9,095 for full-scale fabrication, promotional materials, and incidentals. Full-scale fabrication is projected to cost $4,450, promotional materials is $1,375, and incidentals and shipping is $1,750. These estimated values leave $2,785 extra for incidentals.

These totals are listed in Table 8-4, below, which compares the projected costs and incoming grants for the 2017-18 school year.

Table 8-4: HPRC Projected Funding for 2017-18 School Year

Organization	Fall Semester Amount	Spring Semester Amount	School Year Total
E-Council	$850.00	$900.00	$1,750.00
SGA Appropriations	$865.00	$950.00	$1,815.00
NC Space Grant	-	-	$8,000.00
ETF Fund	-	-	$2,000.00
MAE Department	-	-	$6,000.00
		Total Funding:	**$19,565.00**
		Total Expenses:	**$17,781.61**
		Difference:	**+$1,783.39**

8.5 Outreach

Each outreach event is planned differently to correspond with the STEM topics requested by the outreach coordinator or contact. Most outreach events include a presentation on the club, NASA SL details, and a topic in rocket design, STEM, general aerodynamics, or all three. After the presentation, there is a hands-on demo that varies according to the specific event. Most hands-on demos teach participants to build and fly their own water bottle rockets. After each flight, participants are encouraged to make changes to their design to compare the effects of adding fins or nosecones, and how the level of water, "propellant," affects the flight. This exposes students (and often parents) to the engineering design cycle that is integral to the field. For the current school year, upcoming demos will include more small experiments to teach participants about other topics including Newton's Laws of Physics, thermodynamics, and dynamics.

8.5.1 Completed Events

This section contains information about completed outreach events.

8.5.1.1 NASA Langley Research Center Open House

Members of NC State University's (Tacho Lycos) team went to NASA Langley Research Center to represent North Carolina Space Grant as part of the NASA Langley Research Center's Open House celebrating their 100-year anniversary. Members of the club set up a table with rockets in the Kid Zone from previous years to answer questions that participants may have. In addition, the club had a small hands-on activity in which participants could make a straw rocket and learn about

Newton's Laws through launching the straw rockets. Figure 8-1, below, is a team photo at the team booth in the Kid Zone.

Figure 8-1: Isometric View of Full-Scale Launch Vehicle

8.5.1.2 2017 JY Joyner Science Go-Round

Members of the Tacho Lycos team attended Science Go-Round, a STEM event hosted by JY Joyner Elementary. This event was set up like classes with groups of students rotating through different classrooms to see presentations. For each class, a short presentation was given on rocket design and how water bottle rockets work. Following the presentation, the class was broken up into groups where each group made their own water bottle rocket. After construction was completed, members of the team assisted in launching their water bottle rockets.

8.5.2 Upcoming Events

This section contains information about upcoming outreach events. The team is continually adding new outreach events to the schedule to build a diverse STEM network in the Raleigh area.

8.5.2.1 2018 Astronomy Days

Tacho Lycos will continue its support of Tripoli Rocketry Association by helping at their booth during Astronomy Days hosted by the North Carolina Museum of Natural Science. Using past rockets as examples of completed projects, the team will talk to the general public about high-powered rockets and Tacho Lychos' participation in NASA SL.

8.5.2.2 2018 Weatherstone STEM Expo

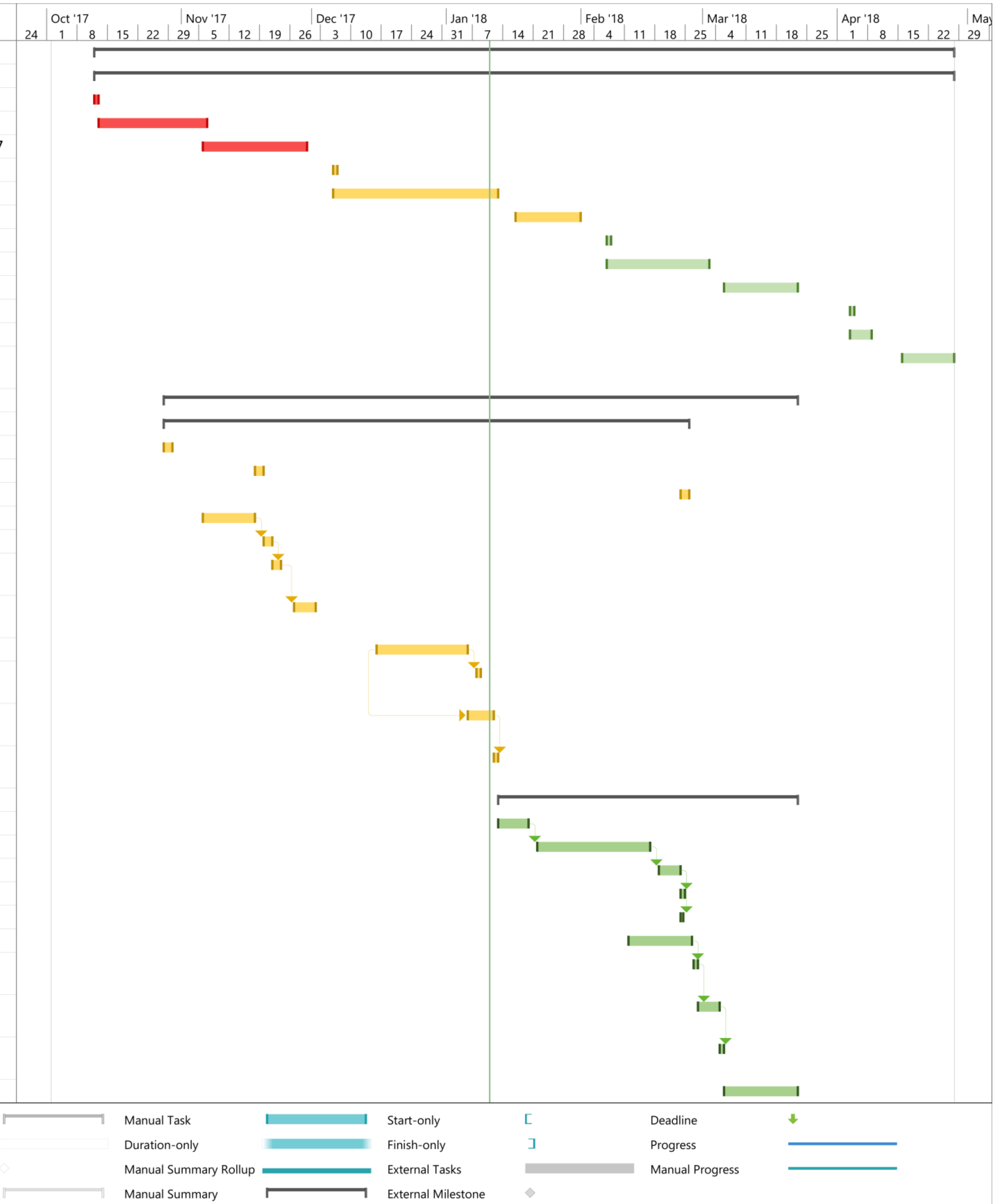
Tacho Lycos will be manning a booth for the 2018 Weatherstone Elementary School STEM Expo during which the team will help participants learn about Newton's Laws of Motion and build water bottle rockets. In addition, Tacho Lycos will be discussing its involvement in NASA SL and this year's design.

8.5.2.3 Science Olympiad Coaching

Tacho Lycos will be traveling to help coach Science Olympiad teams representing a local elementary and middle school. The team will be helping the students build and design their own water bottle rockets. In addition, the team will discuss our participation in NASA SL.

8.6 Timeline

ID	Task Name	Duration	Start	Finish
1	**2017-2018_Tacho_Lycos_HPRC_Schedule**	**143.25 days**	**Thu 10/12/17**	**Fri 4/27/18**
2	**NASA Student Launch Schedule**	**143.25 days**	**Thu 10/12/17**	**Fri 4/27/18**
3	Preliminary Design Review (PDR) Q&A	1 day	Thu 10/12/17	Thu 10/12/17
4	PDR	17 days	Fri 10/13/17	Mon 11/6/17
5	PDR Team Teleconference Window	18 days	Mon 11/6/17	Wed 11/29/17
6	Critical Design Review (CDR) Q&A	1 day	Wed 12/6/17	Wed 12/6/17
7	CDR	28 days	Wed 12/6/17	Fri 1/12/18
8	CDR Team Teleconference Window	11 days	Wed 1/17/18	Wed 1/31/18
9	Flight Readiness Review (FRR) Q&A	1 day	Wed 2/7/18	Wed 2/7/18
10	FRR	19 days	Wed 2/7/18	Fri 3/2/18
11	FRR Team Teleconference Window	13 days	Tue 3/6/18	Thu 3/22/18
12	Launch Readiness Review (LRR)	1 day	Wed 4/4/18	Wed 4/4/18
13	NASA Launch Week Events	4 days	Wed 4/4/18	Sun 4/8/18
14	Post-Launc Assessment Review (PLAR)	10 days	Mon 4/16/18	Fri 4/27/18
15	**Tacho Lycos Schedule**	**105.25 days**	**Sat 10/28/17**	**Thu 3/22/18**
16	**Subscale and CDR**	**86.25 days**	**Sat 10/28/17**	**Sun 2/25/18**
17	Subscale Flight Test Window 1	2 days	Sat 10/28/17	Sun 10/29/17
18	Subscale Flight Test Window 2	2 days	Sat 11/18/17	Sun 11/19/17
19	Full-Scale Flight Test Window	2 days	Sat 2/24/18	Sun 2/25/18
20	Subscale construction and testing	10 days	Mon 11/6/17	Fri 11/17/17
21	Subscale Flight Test	2 days	Mon 11/20/17	Tue 11/21/17
22	Review subscale data & and analyze results	2 days	Wed 11/22/17	Thu 11/23/17
23	Incorporate design changes to full scale, finalize motor selection	5 days	Mon 11/27/17	Fri 12/1/17
24	Write first draft of CDR	16 days	Sat 12/16/17	Fri 1/5/18
25	Submit CDR draft to advisors/mentors for review	1 day	Mon 1/8/18	Mon 1/8/18
26	Fine-tune CDR and incorporate changes	5 days	Sat 1/6/18	Thu 1/11/18
27	Post CDR to website and email NASA SL office	1 day	Fri 1/12/18	Fri 1/12/18
28	**Full-Scale and FRR**	**50.25 days**	**Sat 1/13/18**	**Thu 3/22/18**
29	Purchase orders for full-scale	6 days	Sat 1/13/18	Fri 1/19/18
30	Full-scale construction	20 days	Mon 1/22/18	Fri 2/16/18
31	Full-scale pre-flight-test testing	5 days	Mon 2/19/18	Fri 2/23/18
32	Full-scale flight test	1 day	Sat 2/24/18	Sat 2/24/18
33	Full-scale flight test (backup date)	1 day	Sat 2/24/18	Sat 2/24/18
34	Write first draft of FRR	12 days	Mon 2/12/18	Mon 2/26/18
35	Submit FRR draft to advisors/mentors for review	1 day	Tue 2/27/18	Tue 2/27/18
36	Fine-tune FRR and incorporate changes	4 days	Wed 2/28/18	Sun 3/4/18
37	Post FRR to website and email NASA SL office	1 day	Mon 3/5/18	Mon 3/5/18
38	FRR video conference TBD	13 days	Tue 3/6/18	Thu 3/22/18



Project: Tacho_Lycos_2017-201
Date: Thu 1/11/18

9. References and Resources

All material properties were sourced from OpenRocket and SolidWorks material libraries.

Figure 7-6 sourced from: www.ti.com/tool/MSP-EXP430G2#1

Figure 7-7 sourced from: www.sparkfun.com/products/12577

Figure 7-8 sourced from: www.pololu.com/product/2820

Figure 7-9 sourced from: www.vxb.com/

Figure 7-10 sourced from: www.vxb.com/

Figure 7-11 sourced from: www.southco.com/en-us/

Figure 7-12 sourced from: www.southco.com/en-us/

Figure 7-14 sourced from: www.amazon.com/LanLan-5Pcs-Battery-Holder-Black/dp/B00PRUKYBI

10. Appendix A – MATLAB Script

```
clear all
close all
clc

% NCSU Tacho Lycos PDR
%Propulsion and Recovery

%% Exit Velocity

%  Subscale
% d_inches = 12.9;
% R_inches = 72;
% T_Newton = 482;
% W_lbf = 9.69;
% theta_degrees = 85;
%
%  calculations
% d_feet = d_inches / 12
% R_feet = R_inches / 12
% Lin_feet = R_feet - d_feet
% T_lbf = T_Newton * 0.224809
% m_slugs = W_lbf / 32.174
% vExit_feet = sqrt((2 * Lin_feet * (T_lbf-W_lbf*sind(theta_degrees)))/m_slugs)
% vExit_inches = vExit_feet * 12

% Fullscale
% initial conditions
d_inches2 = 28.25;
R_inches2 = 96;
T_Newton2 = 2243;
W_lbf2 = 38.2;
theta_degrees2 = 85;

% calculations
d_feet2 = d_inches2 / 12
R_feet2 = R_inches2 / 12
Lin_feet2 = R_feet2 - d_feet2
T_lbf2 = T_Newton2 * 0.224809
m_slugs2 = W_lbf2 / 32.174
vExit_feet2 = sqrt((2 * Lin_feet2 * (T_lbf2-W_lbf2*sind(theta_degrees2)))/m_slugs2)
vExit_inches2 = vExit_feet2 * 12



%% Kinetic Energy

% fullscale KE
KE_f_lbf = 75 %75 ft-lbf (NASA SL Handbook Requirement)
W = 38.2;
m = W/32.174
syms V1
```

```
eqn = KE_f_lbf == 0.5 * m * V1^2;
answer = solve(eqn,V1) %I don't why this keeps happening :(

% subscale KE
% KE_f_lbf2 = 39 % 52% of 75 ft-lbf (NASA SL Handbook Requirement)
% W2 = 9.1;
% m2 = W2/32.174
% syms V2
% eqn2 = KE_f_lbf2 == 0.5 * m2 * V2^2;
% answer2 = solve(eqn2,V2)
%% Drogue and main

% Subscale Parachute sizing equations
%
% Vs = 51.33; %feet per second
% ms = .248; %slugs
% g = 32.174; %feetpersecond^2
% ps = .002378; %slugs/ft^3
% C_dds = 1.5; %average sphereical chute
% Ss = (2*ms*g)/((Vs^2)*C_dds*ps);
% Ds = (C_dds*Ss*ps*Vs^2)/2;
% C_dms = 2.2; %average value for iris ultra
% V_ms = 17.73; %ft/s
% S_ms = (2*ms*g)/((V_ms^2)*C_dms*ps);
%
% subscale drogue
% dia = [12 18 24 30 36 ];
% desc_vel = [76.64 51.10 38.34 30.66 25.67];
% ma = 60 ; % ft/s
%
% figure
% hold on
% xlim([12 36])
% title('Subscale Drogue Parachute Descent Velocities of Various Parachute Diameters')
% xlabel('Diameter of Parachute (in.)')
% ylabel('Expected Descent Velocity (ft/s)')
% plot(dia,desc_vel,'--k');
% plot(dia,ma,'-r')
% legend('Descent Velocity of Variable Diameters','Maximum Velocity of 50 ft/s')
% hold off
%
% Subscale main
% di = [36 42 48 54 60 66 72 ];
% desc_velo = [21.1 18.08 15.82 14.06 12.66 11.51 10.55];
% maxx = 15 ; % ft/s

% figure
% hold on
% xlim([36 72])
% title('Subscale Main Parachute Descent Velocities of Various Parachute Diameters')
% xlabel('Diameter of Parachute (in.)')
% ylabel('Expected Descent Velocity (ft/s)')
% plot(di,desc_velo,'--k');
% plot(di,maxx,'-b')
% legend('Descent Velocity of Variable Diameters','Maximum Velocity of 15 ft/s')
```

```
% hold off

% fullscale parachute
Vf = 180; %feet per second **** need this 5 sec after apogee from raven
mf = 1.19; %slugs
g = 32.174; %feetpersecond^2
pf = .002378; %slugs/ft^3
C_ddf = 1.5; %average elliptical chute
Sf = (2*mf*g)/((Vf^2)*C_ddf*pf)
Df = (C_ddf*Sf*pf*Vf^2)/2
C_dmf = 2.2 ;%average value for iris ultra
V_mf = 11.22; %ft/s ** comes from KE eqn
S_m = (2*mf*g)/((V_mf^2)*C_ddf*pf) % area of main in ft^2

% fullscale drogue
diam = [12 18 24 30 36 42 48 54 60];
desc_veloc = [168.47 112.31 84.24 67.39 56.16 48.14 42.12 37.17 32.19];
max = 75 ; % ft/s

figure
hold on
xlim([12 60])
title('Drogue Parachute Descent Velocities of Various Parachute Diameters')
xlabel('Diameter of Parachute (in.)')
ylabel('Expected Descent Velocity (ft/s)')
plot(diam,desc_veloc,'--k');
plot(diam,max,'-b')
legend('Descent Velocity of Variable Diameters','Maximum Velocity of 75 ft/s')
hold off
% fullscale main
diam2 = [96 102 108 114 120 126 132 138 144];
desc_veloc2 = [17.31 16.29 15.38 14.58 13.85 13.19 12.59 12.04 11.54];
max2 = 15.38 ; % ft/s

figure
hold on
xlim([96 144])
title('Main Parachute Descent Velocities of Various Parachute Diameters')
xlabel('Diameter of Parachute (in.)')
ylabel('Expected Descent Velocity (ft/s)')
plot(diam2,desc_veloc2,'--k');
plot(diam2,max2,'-b')
legend('Descent Velocity of Variable Diameters','Maximum Velocity of 15.38 ft/s')
hold off

%% black powder
%L_d = length drogue section (in)
%D_d = diam drogue sect (in^2)
% 0.006 is the constant that converts in^3 to grams

%SUBSCALE drogue
% L_ds = 14.5;
% D_ds = 3.776;
% m_ds = 0.006*L_ds*(D_ds^2);
%
```

```
% % SUBSCALE main
% L_ms = 14.5;
% D_ms = 3.776;
% m_ms = 0.006*L_ms*(D_ms^2);

%fullscale drogue
L_df = 19;
D_df = 7.34;
m_df = 0.006*L_df*(D_df^2);

%fullscale main
L_mf = 20.25;
D_mf = 7.34;
m_mf = 0.006*L_mf*(D_mf^2);

%% wind drift

%0
%alt
y0= 5467; %ft
y00 = 0:y0;
x0= 7.33;%ft
x_0 = 0:x0;
%drift line eqn
m0 = y0/(-x0);
b0 = y0 - (y0/(-x0));
y_0 = m0*(x_0)+b0;
zero = 0;
%5
%alt
y5=5461;
y55= 0:y5;% ft
x5= 589.1; %ft
x_5=0:x5;
%drift
b5 = y5 - (y5/(-x5));
m5 = y5/(-x5);
y_5 = m5*(x_5)+b5 ;

%10
%alt
y10=5351;
y1010= 0:5351;%ft
x10= 1321.5; %ft
x_10 = 0:x10;
%drift
b10 = y10 - (y10/(-x10));
m10 = y10/(-x10);
y_10= m10*(x_10)+b10;

%15
%alt
y15= 5426;
y1515= 0:5426;%ft
x15= 1851.7;%ft
```

```
x_15=0:x15;
%drift
b15 = y15 - (y15/(-x15));
m15 = y15/(-x15);
y_15 = m15*(x_15) + b15 ;

%20
%alt
y20 = 5400;
y2020= 0:5400;%ft
x20= 2500.4;%ft
x_20 = 0:x20;

%drift
b20 = y20 - (y20/(-x20));
m20 = y20/(-x20);
y_20 = m20*(x_20) + b20 ;

% plots
figure
hold on
title('Effect of Wind on Altitude (ft) and Drift (ft)')
xlabel('Drift From Launch Pad (ft)')
ylabel('Altitude (ft)')

%plot(zero,y1515)
%plot(zero, y2020)
xlim([-500 3000])
plot([0,7.7],[0,5500],'-k')
plot(x_5,y_5,'-b')
plot(x_10,y_10,'-g')
plot(x_15, y_15,'-y')
plot(x_20, y_20,'-r')
legend('0 mph, 5467 ft AGL','5 mph, 5461 ft AGL','10 mph, 5351 ft AGL', '15 mph, 5426 ft AGL', '20 mph, 5400 ft AGL')

%% thrust to weight
```

11. Appendix B – FMECA Table

The FMECA table below uses the following hazard level classification:

1) Rocket mission failure; rocket is not recoverable; payload is not recoverable; rover mission failure
2) Rocket mission failure; rocket is recoverable; payload may be recoverable; rover mission may be complete
3) Rocket mission complete; rocket is recoverable; payload is not recoverable; rover mission failure
4) Rocket mission complete; rocket is recoverable; payload is recoverable; rover mission failure

Table 11-1: Failure Modes, Effects, and Criticality Analysis

System	Subsystem/ Component	Failure Mode	Causal Factors	Failure Effects		Hazard	Recommendations
				Subsystem	System		
Launch Vehicle	Nosecone	Cracks or breaks	Object in flight path	Loss of nose cone recoverability	Loss of controlled and stabilized flight	2	Ensure that skies are clear of any foreign objects per NAR operations, HPRC will follow the directions of the RSO and no premature launches
			Damaged during handling or assembly			2	Inspect for cracks, chips, or other damage during assembly directly prior to the launch
			Nosecone collides with other rocket component during recovery		N/A	2	Ensure that shock cord is appropriate length to space the nosecone during descent.
			Ground impact			2	Metal nose tip is appropriate to minimize the damage to vehicle upon impact
		Premature separation from midsection	Damaged during handling or assembly	Potential for permanent structural damage	Loss of controlled and stabilized flight	2	Inspect for cracks, chips, or other damage during assembly directly prior to the launch

Launch Vehicle			Shear pins not installed correctly			2	Follow design specifications for sizing, inspecting, and installing shear pins during assembly see Section 4.3.5
			Epoxy not cured properly			2	Follow proper procedures for mixing, applying, and curing epoxy
	Blue Tube Airframe	Cracks or breaks	Manufacturing defect	Loss of structural integrity or usability of Blue Tube body Sections or components	Premature separation of launch vehicle Sections during flight	1	Senior Design Team will perform a visual inspection after shipping and before assembly
			Loads experienced beyond design specifications			1	Ensure body tube components can hold flight forces in accordance with design specifications by not exceeding design limitations as described by the part manufacturer, further reducing the risk of upper limit loads ensure that all components can maintain a factor of safety of at least 1.5 during all regimes of flight by not exceeding design limitations as described by the part manufacturer

Launch Vehicle			Damaged during handling or assembly			1	Senior Design Team will inspect each body tube component for cracks, bends, warping, or other damage during assembly
			Improper storage			1	Store Blue Tube in a dry space and avoid any liquid spills and Blue Tube will not be stored with items on top
	Fins	Severe weather-cocking	Fin dimensions are not cut according to design	N/A	Decreased flight stability, unpredictable flightpath, and possible damage to other components	2	Laser cut fins to ensure manufacturing precision as well as ensure that excessive material is not removed during sanding by having a secondary team member monitor the sanding process
			Fins not installed at even increments around fin can (90 degrees to each other)			2	Use laser-cut jig with slots for fins exactly 90 degrees from each other

Launch Vehicle			Assembled rocket CG is too far forward (Stability Margin >> 2.0)			2	Ensure components and masses are installed according to design specifications
		Fin separation	Loads experienced beyond design specifications	N/A	Any one failure of a fin could lead to additional fin failures which will decrease flight stability and will likely cause a catastrophic failure	1	Analyze flight data and simulations to confirm that factor of safety is sufficient
			Damaged during handling or assembly			1	Inspect for cracks, chips, or other damage during assembly Replace any damaged components
			Fin flutter			2	Rocket will not exceed velocity necessary to induce significant flutter
			Ground impact			2	Implement a recover system design that ensures a low-speed surface impact

Launch Vehicle	Motor	Motor fails to ignite	Igniter not installed correctly	Failure of vehicle to start launch	Team member and RSO must insert new igniter and restart launch sequence	4	Follow launch checklist and use mentor/RSO supervision to install igniter correctly
			Faulty igniter used			4	Test batch of igniters prior to launch day to ensure quality
			Motor assembled incorrectly			4	Follow launch checklist and use mentor/RSO supervision to install motor correctly
		Catastrophic motor failure	Damaged during handling or assembly	Possible destruction of launch vehicle	Complete mission failure and additional hazard to ground crew and spectators	1	Carefully inspect for cracks, chips, or other damage during assembly
			Motor assembled incorrectly			1	Follow launch checklist and use mentor/RSO supervision to install motor correctly

Launch Vehicle			Motor casing dislodged during motor burn			1	Ensure all connection points between motor tube, centering rings, and fins are joined properly using epoxy Perform careful inspection of joints prior to launch
		Damage to motor casing	Superficial damage	Motor casing cannot be used	Rocket is not safe to launch if damage is major	4	Carefully inspect for cracks, chips, or other damage during assembly; step 2 on launch checklist under Motor Assembly heading
		Propellant contamination	Rocket fails to launch	Reduced performance of rocket motor	Rocket does not launch or perform as expected	2	Store and maintain motor fuel properly and in isolation/ order from reputable source
			Over-oxidized reaction			2	
			Reduced fuel efficiency			3	
	Bulkheads	Bulkhead separation from airframe during motor burn	Manufacturing defect			1	Visual inspection after shipping and before assembly

Launch Vehicle			Loads experienced beyond design specifications			1	Ensure body tube components can hold flight forces in accordance with design specifications Ensure that all components can maintain a factor of safety of at least 1.5 during all regimes of flight
			Damaged during handling or assembly			1	Inspect each bulkhead for cracks, warping, chips, or other damage during assembly Replace any damaged bulkheads
			Epoxy not cured properly			1	Follow proper procedures for mixing, applying, and curing epoxy

Launch Vehicle		U-bolt separation from bulkhead during recovery	Loads experienced beyond design specifications	Launch vehicle components not tethered to a parachute will continue accelerating during descent	Loss of safe and effective recovery system	1	Ensure body tube components can hold flight forces in accordance with design specifications Ensure U-bolt fasteners can handle near-instantaneous loading from parachute deployment
			Epoxy not cured properly			1	Follow proper procedures for mixing, applying, and curing epoxy
	Rail Buttons/ Launch Rail	Vehicle does not leave launch rail as intended	Rail button(s) separate from launch vehicle	Vehicle leaves rail at unpredictable orientation and velocity	Possible mission failure and additional hazard to ground crew and spectators	1	Epoxy rail buttons into body tube to mitigate risk of separation; step 5 on launch checklist under Launch Pad Procedures heading
			Damaged during handling or assembly			1	Inspect each pin for cracks, bends, chips, or other damage during assembly Replace any damaged components; step 5 on launch checklist under Launch Pad Procedures heading
			Launch rail breaks			2	Ensure that the rail is assembled correctly prior to launch; step 2 on launch checklist under Launch Pad Procedures heading

Launch Vehicle		Vehicle does not leave launch rail at all	Rail button(s) becomes stuck in launch rail	N/A	Mission failure as flight does not take place	2	Ensure that rail buttons match size of launch rail slot Lubricate the launch rail and rail buttons prior to launch Ensure that the vehicle moves smoothly on the launch rail during assembly and launch rail erection; steps 3 and 4 on launch checklist under Launch Pad Procedures heading
	Shear Pins	Pins break before charge detonation	Manufacturing defect	Loose assembly of compartment	Premature rocket separation and recovery system deployment	2	Team members inspected shear pins individually once delivered to ensure quality. Team members inspected shear pins again prior to launch to confirm functionality.
			Damaged during handling or assembly			2	Team members inspect each pin for cracks, bends, chips, warping, or other damage during assembly. Damaged components are discarded and replaced.
			Pins fall out of respective holes			2	Members ensure diameter of holes drilled in body tube match diameter of shear pins

Launch Vehicle			Loads beyond design specifications			2	Ensure pins can hold flight forces in accordance with design specifications
		Pins don't break at charge detonation	Manufacturing defect	Failure to separate compartment	Loss of safe and effective recovery system	1	Team members inspect each pin for cracks, bends, chips, warping, or other damage during assembly. Damaged components are discarded and replaced.
			Pins too tight in body tube holes			1	Members ensure diameter of holes drilled in body tube match diameter of shear pins
			Improper quantity of pins			1	Team members used calculations to ensure that pins will break from forces of detonation

Launch Vehicle	Shock Cord	Incorrect or partial deployment of shock cord	Snags, tears, or rips during ejection	Parachute no longer tethered to entirety of launch vehicle airframe	Loss of safe and effective recovery system	1	Inspected shock cord for damage prior to launch Ensured high-strength shock cord is used with a maximum loading greater than 1,500 lb Ensured shock cord is folded and stowed properly in launch vehicle Team members test shock cord tensile and compression strength prior to flight Design reduces/eliminates sharp edges to mitigate risk of snagging shock cord and parachutes
			Shock cord disconnects from airframe or parachutes			1	Ensure that connections between the shock cord, airframe, and parachutes are tight and secure

Launch Vehicle			Shock cord stuck within launch vehicle airframe	Parachute not entirely deployed		1	Ensure that the shock cord and parachutes are folded and stowed properly in launch vehicle Design reduces/eliminates sharp edges to mitigate risk of snagging shock cord and parachutes
	Parachute Deployment	Drogue parachute fails to deploy correctly	Drogue shock cord tangling	Parachute does not deploy correctly	Rocket is recoverable	2	Team members confirm that shock cords and parachutes are folded and positioned in the correct orientation
			Shock cord connections come loose			2	Team members test shock cord connections prior to flight, make sure secured properly before insertion
			Parachute bag does not fully open			2	Deployment bag is folded correctly and in accordance with proper technique Members ensure deployment bag is inserted correctly so that nothing can snag bags prior to, or during flight
		Parachute does not perform as expected	Tears/holes	Parachute deploys but does not perform as expected	Rocket is recoverable	2	Team members inspect parachute for rips, tears, worn fabric, tangled lines, and worn lines before folding and packing into rocket body

Launch Vehicle		Main parachute fails to deploy correctly	Charge is inadequate	Parachute does not deploy correctly	Separation 2 is not successful, rocket is not recovered safely	1	Ejection charge measurements for both parachutes are tested properly before flight day
			Payload blocks parachute		Separation 2 is not successful, rocket is not recovered safely	1	Team members designed payload compartment to ensure payload ejection hardware does not impede parachute release path
			Shock cords tangled		Rocket is recoverable	2	Prior to flight, team members ensure shock cords and parachutes are folded correctly
			Shock cord connections loose		Rocket is not recovered safely	1	Team members test shock cord connections prior to flight, make sure secured properly before insertion
		LARD	Shock cord and shroud lines tangled	Parachute does not deploy correctly	Payload is not recovered safely	3	Fold the parachute to ensure the proper deployment as well as securing shroud lines and attaching the parachute to the shock cord
			Jolly Logic fails to deploy	Parachute does not deploy		3	Test the jolly logic during full scale test flight to evaluate the release occurs at the correct altitude.
	Black Powder Charges	Single detonation failure	E-match doesn't light	Failure of one or more black powder charges	Will result in loss of safe and effective recovery system if redundant black powder	2	The Safety Officer, club advisors, and members experienced with the avionics will ensure that the connections are correct and that a valid E-match is inserted.

Launch Vehicle			Altimeter Malfunction		charge(s) do not detonate	2	The Avionics Lead, and members experienced with the avionics will test the altimeters prior to launch and periodically to maintain an accurate evaluation of integrity.
		Redundant detonation failure	E-match doesn't light	Failure of both ejection charges	Rocket fails to separate and deploy parachutes	1	The Safety Officer, club advisors, and members experienced with the avionics will ensure that the connections are correct and that a valid E-match is inserted.
			Altimeter Malfunction			1	The Avionics Lead, and members experienced with the avionics will test the altimeters prior to launch and periodically to maintain an accurate evaluation of integrity.
		Charge causes damage to any component other than shear pins	Charge is too big	Causes violent separation and/or damage to surrounding area	Potential to cause permanent damage to bulkheads or shock cord, resulting in a possible failure of parachute deployment	2	The Safety Officer with supervision of the Club Advisors will insert the correct amount of black powder that was confirmed in the ejection tests on November 16, 2017. Following, will be a physical and visual check of the rocket interior for accuracy.

Launch Vehicle		Charge ignites but fails to cause separation	Charge is too small	No ejection	Failure of parachute deployment	1	The Safety Officer with supervision of the Club Advisors will insert the correct amount of black powder that was confirmed in the ejection tests on November 16, 2017. Following, will be a physical and visual check of the rocket interior for accuracy.
	Altimeters	No power to altimeters	Uncharged or insufficiently charged batteries	Loss of real-time altitude data, failure to ignite e-match	Failure of parachute deployment	1	Categorically the batteries for any launch must be fresh and unused. Prior to installation, the voltage will be measured with a voltmeter to confirm the constitution of the battery.
	Black Powder Charges	Single detonation failure	Battery becomes disconnected from altimeter	Failure of one or more black powder charges	Will result in loss of safe and effective recovery system if redundant black powder charge(s) do not detonate	1	The Avionics Lead will connect the leads from the power source to the altimeters. An evaluation of the physical security of the connections will be made. The electronic viability is evaluated through the audio cues of each altimeter.

Launch Vehicle			Wiring short			1	The Avionics Lead will connect the leads from the power source to the altimeters. An evaluation of the physical security of the connections will be made. The electronic viability is evaluated through the audio cues of each altimeter.
		No launch detected False apogee detected	Manufacturing defect	Lack of flight data Premature/late ejection of drogue parachutes	Failure of parachute deployment Increased load on drogue recovery hardware and bulkheads	1	The altimeters will be tested by the avionics team in a vacuum chamber to simulate a flight. The audio cues will be used to continue monitoring immediately before launch.
			Manufacturing defect			2	The altimeters will be tested by the avionics team in a vacuum chamber to simulate a flight. The audio cues will be used to continue monitoring immediately before launch.

Launch Vehicle		Charge causes damage to any component other than shear pins	Incorrect altimeter readings	Causes violent separation and/or damage to surrounding area	Potential to cause permanent damage to bulkheads or shock cord, resulting in a possible failure of parachute deployment	2	The pressure ports will be checked for having adequate size and the audio cues will be used to continue monitoring immediately before launch.
		Main parachute deploys at wrong altitude	Incorrect pressure readings or improper programming	Main deployment between apogee and 1,200 ft	Excessive drift, but surface impact will remain below required maximums	2	The altimeters will be tested by the Avionics Team in a vacuum chamber to simulate a flight. The pressure ports will be checked for having adequate size and the audio cues will be used to continue monitoring immediately before launch.
	Altimeters GPS Avionics Sled	No power to altimeters Ground system failure Loss of signal	Uncharged or insufficiently charged batteries	Main deployment lower than 800 ft Inability to receive data from the GPS	Kinetic energy at surface impact will likely exceed 75 ft-lb parachute Inability to track and recover the rocket in less than an hour	1	Categorically the batteries for any launch must be fresh and unused. Prior to installation, the voltage will be measured with a voltmeter to confirm the constitution of the battery.

Launch Vehicle			Loss of power to ground receiver or the laptop			3	The Avionics Team will check that the club laptop and GPS receiver will be charging before the launch and must be fully charged prior to launch.
			Environment or rocket materials blocking signal			3	The club led by the Avionics Lead at least one week prior to launch will perform a range test to evaluate the adequacy of the GPS system. The system is expected to meet standards as it is the same system used from previous years.
		Radio interference	Multiple radio devices on the same local frequency and channel	Lack of flight data	Failure of parachute deployment	3	Club leadership will communicate with NASA SLI staff and other club representatives to alleviate the radio interference produced by any other systems as much as possible
		Loss of power Detaches from secure position	Flight forces cause GPS to disconnect from power supply	Premature/late ejection of drogue parachutes Damage to/loose wiring of avionics components	Increased load on drogue recovery hardware and bulkheads Loss of recovery system initiation	3	The Avionics Team will be sure to charge the GPS unit so that when the GPS is mounted in the rocket it will be fully charged. Launch simulations will be done to confirm mounting methods will be sufficient.

Launch Vehicle			Loads beyond design specifications			1	Simulated load tests will be carried out on the avionics sled design, with the final design meeting requirements with an included safety factor.
		Main parachute deploys at wrong altitude	Damage during handling Improper maintenance	Main deployment between apogee and 1,200 ft	Excessive drift, but surface impact will remain below required maximums	1	Avionics team members practiced wiring and inserting the sled, and will be handling and installing the sled using sufficient care and detail. Avionics team members will be briefed on the proper functioning of the sled so that detailed inspections can be carried out before and after each launch.
				Main deployment lower than 800 ft	Kinetic energy at surface impact will likely exceed 75 ft-lb parachute	1	
	Payload Exterior	Acrylic Tube Door Fails to Open Door Pin System Breaks Door Hinges Come Off	Manufacturing defects	Rover Systems at Risk Prevents Rover Deployment Prevents Rover Deployment	Electronics and rover can be damaged Rover will not complete its task	3	Before construction begins, the length of tubing will be inspected closely by the Payload Integration team.

Launch Vehicle		Loss of signal	Servo fails	Prevents Rover Deployment	Rover will not complete its task Possible structural damage to the payload	3	Payload Integration team will test servo to ensure door opens correctly before construction and before leaving for a launch day.
		Radio interference	Blocked by dirt after landing			3	During the design and testing phase of the full-scale, Payload Integration team will ensure the body will land angled upwards slightly to ensure proper deployment.
		Loss of power	Blocked by centering ring			3	The rover door will be designed with a fair margin from the centering ring so that a significant shift still won't block the door.
		Detaches from secure position	Fracture from Force	Unable to transfer loads Door may Detach	Increased loads on other structural members Rover will not complete its task	3	Materials and design of the payload will be run through simulated load tests by the Payload Integration team in conjunction with the Structures team.

Launch Vehicle			Improper Attachment			3	Payload Integration team will inspect door hinge screws and ensure a secure fastening before each launch.
			Improper maintenance			1	Avionics team members will be briefed on the proper functioning of the sled so that detailed inspections can be carried out before and after each launch.
Payload	Payload Bulkhead	Bulkhead Separation from payload Separation of Rover from platform	Poor Design	Load Transfer Failure	Unintended Structures Bear the Load	2	Stress Analysis testing on fixed support will be conducted by the Structures team to ensure bulkhead can take the loads.
			Manufacturing Defect	Prevents Rover Deployment	Rover will not complete its task	2	All construction materials will be closely inspected for damage and defects before and after construction.
			Loads Greater than Designed	Prevents Rover Deployment	Rover will not complete its task	2	Construction team will ensure strict adherence to design documents so that loads will remain within safety margins.
			Damaged During Handling	Prevents Rover Deployment	Possible structural damage to the payload	2	Proper care will be taken whenever transporting or handling to prevent damage, as well as inspections before and after each launch.
			Improper Attachment	Unable to transfer loads	Increased loads on other structural members	2	Payload Integration and Structures teams will inspect each bulkhead to ensure proper attachment before and after each launch

Payload	Rover Bay		Improper attachment	Rocket weight imbalance during flight Rover fails to rest at bottom of the tube	Rocket flight disrupted Prevents proper deployment	3 3	Team members will test the attachment of the weight and ensure it is secured properly
	Payload Bulkhead Rover Tracks	Electronics Fail Malfunction Rail button sheared off upon payload jettison Cracks or Breaks Premature detonation	Circuitry becomes damaged	Payload hardware experiences catastrophic failure Rover cannot move forward Rover performance hindered Rover performance hindered	Rover fails to deploy Prevents rover from deploying at the correct orientation Possible damage to other components Payload drifts farther than planned	3	Team members will test the electronics on the rover to ensure they are operating and defect free
			Unable to gain traction			4	Prior to launch, rover will be tested on all expected terrains
			Cannot traverse obstruction			4	Prior to launch, rover will be tested on all expected terrains and a structural analysis will be run to ensure that parts can withstand loads applied during flight
			Damage during flight			4	Proper care will be taken whenever transporting or handling to prevent damage, as well as inspections before and after each launch.
			Manufacturing defect			4	Team members will follow proper additive manufacturing techniques Prior to launch, rover will be tested on all expected terrains
	Rover Bay Hardware	Separation of Rover from platform	Damage during rover operation	Rocket weight imbalance during flight	Rocket flight disrupted	4	Team members will test the attachment of the weight

Payload		Break	Damage during flight	Rover cannot complete mission	Prevents rover from deploying at the correct orientation	4	and ensure it is secured properly Team members will test the structural integrity and run structural analysis of the parts to ensure that parts do not contain defects and can withstand loads applied during flight
		Rail button sheared off upon payload jettison	Manufacturing defect	Rover cannot complete mission	Possible damage to other components	4	Team members will follow proper additive manufacturing techniques and will test parts to ensure that they do not contain defects
	Rover Body Rover Gears/ Motor System	Cracks or Breaks Jammed Do not operate	Damage during rover operation	Rover cannot complete mission	N/A N/A N/A N/A	4	Run tests to determine rover capabilities
			Foreign objects get stuck in the gears/motor	Rover performance hindered		4	Run tests in similar conditions to landing site Ensure proper battery charging and handling techniques are followed
			Dead battery	Rover cannot complete mission		4	
		Break Do not deploy	Signal is not sent properly	Rover cannot complete mission	Payload drifts farther than planned	4	Extensively test transceiver in all conditions Run tests on Arduino to ensure high performance
			Programming bug	Rover cannot complete mission		4	
	Rover Body	Cracks or Breaks Jammed Do not operate Jammed Do not operate Low Charge	Signal is not sent properly	Design challenge is not completed	N/A	4	Extensively test transceiver in all conditions

Payload		Rail button sheared off upon payload jettison	Foreign objects get stuck in solar panel housing	Design challenge is not completed	Possible damage to other components	4	Test solar panels in conditions similar to landing site
	Rover Body/ Rover Gears/ Motor System/ Rover Gears/ Motor System/ Solar Panels/ Rover Battery/	Cracks or Breaks Jammed Do not operate Break Do not deploy Fire	Dead battery	Design challenge is not completed	Damage to payload	4	Ensure proper battery charging and handling techniques are followed
			Improper charging techniques	Rover performance hindered		4	Adhere to proper charging technique
			Improper storage	Rover performance hindered		4	Adhere to proper storage technique
		Break Do not deploy Deployment Failure	Not following proper safety protocol	Rover cannot complete mission		3	Maintain a high level of safety
			Mechanical Damage	Panels cannot meet competition requirements		4	Before the launch the rover's panels will be handled carefully top preserve their integrity. In regard to the launch the payload recovery system will be evaluated as to allow to the rover to be undamaged.
	Rover Body	Cracks or Breaks Jammed Do not operate Jammed Do not operate Low Charge	Servo Malfunction	Panels cannot meet competition requirements	N/A	4	The rover's connections will be made prior to launch and the rover team will have lead time to ensure accuracy.
			Software Malfunction	Potential hinderance to overall Rover performance		4	The code for the rover will be written in advance and tests can confirm the software viability.