NC STATE UNIVERSITY

Tacho Lycos
2021 NASA Student Launch
Critical Design Review

High-Powered Rocketry Club at NC State University
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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
FMEA	=	failure modes and effects 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)
LCO	=	Launch Control Officer
LOPSIDED	=	Lander for Observation of Planetary Surface Inclination, Details, and Environment Data
LRR	=	Launch Readiness Review
MAE	=	Mechanical & Aerospace Engineering Department
MSDS	=	Material Safety Data Sheet
MSFC	=	Marshall Space Flight Center
NAR	=	National Association of Rocketry
NCSU	=	North Carolina State University
NFPA	=	National Fire Protection Association
PDF	=	Payload Demonstration Flight
PDR	=	Preliminary Design Review
PLAR	=	Post-Launch Assessment Review
POS	=	Planetary Observation System
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
VDF	=	Vehicle Demonstration Flight

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1.1 Team Summary

1.1.1 Team Name and Mailing Address

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1.1.2 Mentor Information

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1.1.3 Time Spent on CDR Milestone

The team spent a total of 120 hours working towards completion of the CDR milestone.

1.2 Launch Vehicle Summary

1.2.1 Official Target Altitude

The team's official target altitude is 4473 feet. See section 3.5.1 for justification.

1.2.2 Final Motor Choice

The team's final motor selection is the Aerotech L1520T. See section 3.5.2 for justification.

1.2.3 Launch Vehicle Size and Mass

The final design calls for a 106.25-inch-long launch vehicle with a diameter of 6 inches. The fully loaded mass of the launch vehicle with the final motor onboard is 45.4 lbs. See section 3.1.3 for additional launch vehicle size discussion.

1.2.4 Recovery System

The recovery system design is a dual-deployment system controlled by two independent PerfectFlite Stratologger CF altimeters. An 18-inch drogue parachute will be deployed at apogee, and a 120-inch main parachute will be deployed at 700 feet AGL. See section 3.4.1 for discussion of the recovery system.

1.3 Payload Summary

The lander has been designated the Lander for Observation of Planetary Surface Inclination, Details, and Environment Data, abbreviated to LOPSIDED. The imaging system contained within LOPSIDED is designated the Planetary Observation System, abbreviated as POS. During the descent of the launch vehicle, the LOPSIDED-POS system will be removed from the payload bay by the main parachute recovery harness. The LOPSIDED-POS will then detach itself from the recovery harness by means of an Advanced Retention Release Device (ARRD). The LOPSIDED-POS will descend under its own parachute. After landing, LOPSIDED will record its angle relative to vertical, then disengage four solenoid latches, allowing gravity to rotate two concentric rings such that LOPSIDED is oriented vertically with respect to gravity. LOPSIDED will then record its final orientation. The POS will then capture an image from each of the four onboard cameras. The POS will then transmit these images over slow-scan television to a laptop located in the team's prep area. The laptop will then be used to combine these separate images into a single 360-degree panoramic image.

2. Changes Made Since PDR

2.1 Changes Made to Launch Vehicle

Table 2-1 below lists all changes made to the launch vehicle since PDR, along with justification of these changes.

Table 2-1 Changes to Launch Vehicle Since PDR

Description of Change	Justification of Change
The main parachute deployment altitude has changed from 675 ft. to 700 ft.	Increased launch vehicle mass decreased maximum wind drift. The team prefers to deploy the main parachute as early as possible to allow LOPSIDED as much time as possible to vacate the payload bay before releasing itself from the main parachute recovery harness.
The main parachute deployment system has changed to incorporate use of a piston ejection system.	The payload bay is located adjacent to the main parachute bay. Sensitive electronics onboard the LOPSIDED-POS must be shielded from hot ejection gasses while remaining accessible from outside the airframe to facilitate arming avionics. Using a piston to contain the ejection gasses and separate the body sections is an effective means of shielding the LOPSIDED-POS.
The nose cone bulkhead is now ¾-inch thick, and the engine block and aft centering ring are now each ½-inch thick.	The team determined that thinner bulkheads can sufficiently handle expected loading while reducing weight and material costs.

2.2 Changes Made to Payload

Table 2-2 below lists all changes made to the payload since PDR, along with justification of these changes.

Table 2-2 Changes to Payload Since PDR

Description of Change	Justification of Change
The payload parachute will be fully deployed at 500 ft. instead of being constrained by a Jolly Logic ChuteRelease until 200 ft.	Action item from PDR. Descent velocity under a furled payload parachute was deemed excessive.
A single Raspberry Pi is now the sole controller for LOPSIDED-POS electronics.	Use of a single controller is simpler to implement than communication between two controllers.

2.3 Changes Made to Project Plan

Table 2-3 below lists all changes made to the project plan since CDR, along with justification of these changes.

Table 2-3 Changes to Project Plan Since PDR

Description of Change	Justification of Change
TDR 1.1-1.4 added to team-derived requirements.	The team deemed it necessary to impose general team-derived requirements regarding lab and launch day safety.
TDR 2.1 updated to require a factor of safety of 2, increased from the previous requirement of a factor of safety of 1.5.	The team determined that a higher factor of safety was desirable and attainable without the addition of excess weight.
TDR 2.4 added to team-derived requirements.	The team determined that it was necessary to further limit the velocity of the launch vehicle below the NASA requirement of subsonic flight to reduce the risk of fin flutter.
TDR 4.1 changed from "The POS SHALL consist of multiple camera modules" to "The POS SHALL capture two separate 360-degree images, offset by 90 degrees."	This updated verbiage better reflects the intent of the team-derived requirement to make the POS imaging system redundant.
TDR 4.14-4.16 added to team-derived requirements.	The team deemed it necessary to impose specific design requirements on the image transmission system, payload electronics, and payload parachute.

3. Vehicle Criteria

3.1 Design and Verification of Launch Vehicle

3.1.1 Launch Vehicle Mission Statement

The mission of this launch vehicle is to reach the target apogee and return safely to the ground in a reusable condition. Additionally, the launch vehicle will support the payload mission by safely ejecting the payload at main parachute deployment.

3.1.2 Launch Vehicle Success Criteria

Mission success is defined by compliance with NASA SL requirements in Table 6-16 as well as the team-derived requirements in Table 6-17. Levels of success are defined in more detail in Table 3-1 below.

Table 3-1 Launch Vehicle Mission Success Criteria

Level of Success	Definition
Complete Success	– Launch vehicle recoverable – Nominal launch vehicle takeoff and descent – Lander is undamaged during deployment and after landing – Launch operations can be repeated the same day – Achieved apogee is between 3000 and 6000 feet
Partial Success	– Launch vehicle repairable – Successful launch vehicle takeoff and descent – Lander repairable following landing – Achieved apogee is between 3000 and 6000 feet
Partial Failure	– Launch vehicle repairable – Successful launch vehicle takeoff and unsuccessful descent – Lander repairable following landing – Achieved apogee is below 3000 feet or above 6000 feet
Complete Failure	– Launch vehicle unrecoverable – Lander unrecoverable

3.1.3 Overall Design

When fully assembled, the launch vehicle will be 106.25 inches long with a launch weight of 45.4 lbs and empty weight of 41.3 lbs.

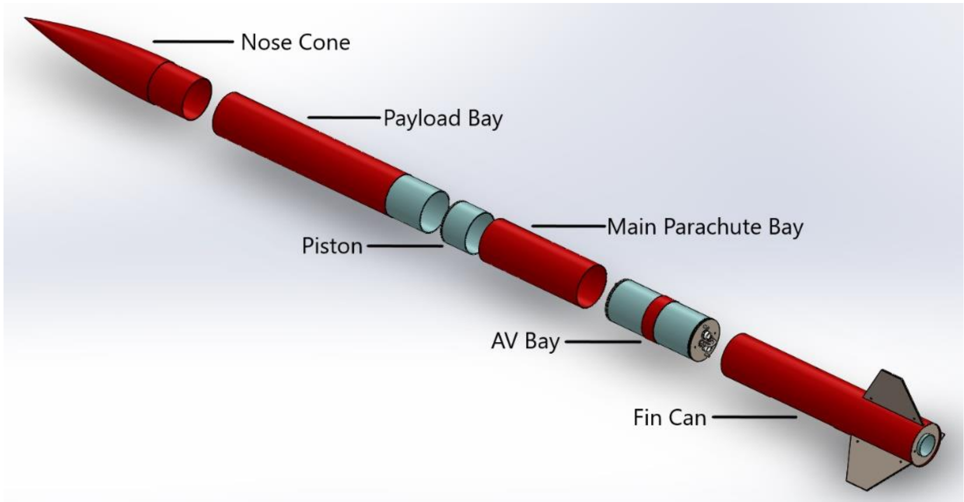


Figure 3-1 Launch Vehicle Sections

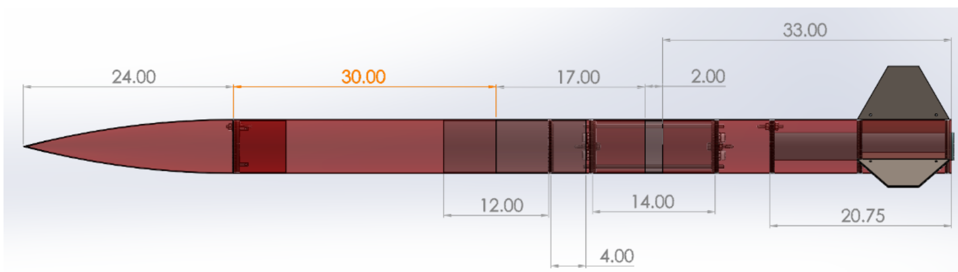


Figure 3-2 Launch Vehicle Dimensions

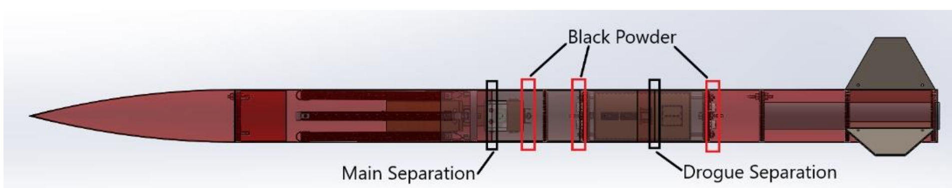


Figure 3-3 Launch Vehicle Points of Separation and Energetic Materials

3.1.4 Material Selection

G12 fiberglass has been selected as the material to use for both the airframe and the nose cone of the launch vehicle. G12 fiberglass is a popular choice in rocketry due to its durability and strength and it will easily resist the expected compressive loading along with any unexpected impact forces. Additionally, fiberglass is water resistant, which is an important property when considering launch vehicle reusability.

The fins and bulkheads will be manufactured from layers of 0.125-inch aircraft grade birch plywood. This material is lightweight and strong, particularly as the thickness is increased.

Two layers will be used per fin, so each will be 0.25 inches thick. Bulkheads will range in thickness from 0.5 inches to 0.75 inches depending on the loading they experience.

U-bolts and other hardware will be made of stainless steel. While this material is dense, the hardware amounts for only a small portion of the overall launch vehicle and will only slightly affect the weight. The use of a sturdy material like steel ensures that the U-bolts and other important hardware will not fail, as their failure could compromise the flight.

3.1.5 Nose Cone

To ensure aerodynamic similarity between the full scale and the subscale launch vehicle, the team decided to limit nose cone designs to those which would be commercially viable for both designs. The team limited design to commercially viable nosecones as the added cost and complexity of manufacturing a custom nose was undesirable. This constraint limited nose cone designs to Ogive nose cones. A 4:1 Ogive Nosecone was chosen as it offered the most desired stability margin for the vehicle.

The nosecone, bulkhead, and payload electronics, excluding any ballast, are expected to weigh 3.34 lbs.

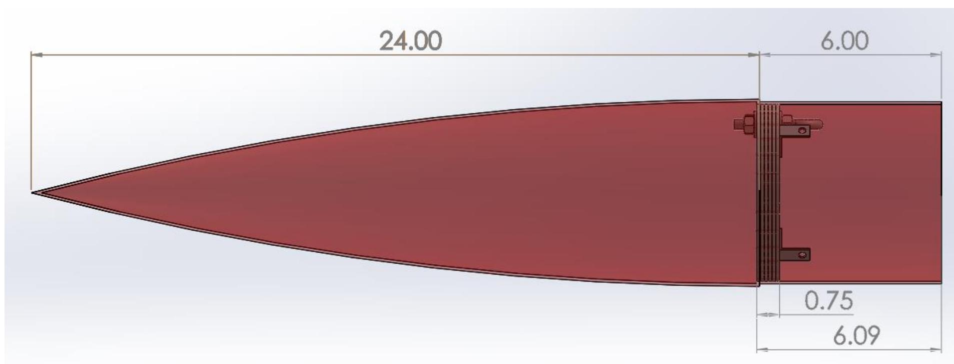


Figure 3-4 Nose Cone Dimensions

3.1.6 Nose Cone Bulkhead

The nose cone bulkhead will be made to be removable using L-brackets and bolts. It was deemed necessary that the bulkhead be removable to utilize the space of its forward side. This side of the bulkhead will be used to house payload integration electronics as well as ballast as needed to adjust stability.

Four L-brackets will be evenly spaced around the circumference of the bulkhead, as shown in Figure 3-5. These brackets and the attached bolts will be made of stainless steel. To ensure these attachments points reach the desired factor of safety, testing will be done as described in Section 6.1.1.1.

The nose cone bulkhead, including hardware, will weigh 0.75 lbs.

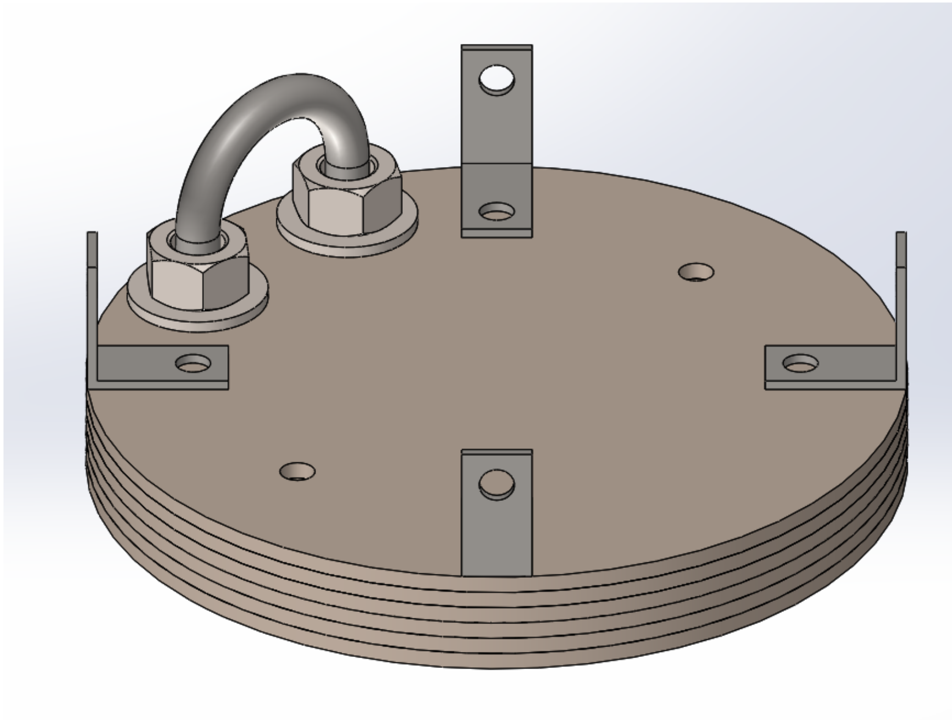


Figure 3-5 Nose Cone Bulkhead

3.1.7 Payload Bay

The 30-inch payload bay will be located between the nosecone and main parachute bay. A 12-inch coupler will be epoxied into the aft end of the body section with 6 inches exposed to connect to the main parachute bay. This connection will be secured with #4-40 nylon shear pins. The nosecone will be secured to the payload bay with a bolted connection. Additional shear pin holes will be added to the payload bay to hold the payload in place during flight while still allowing it to deploy with the main parachute.

Excluding the lander, the payload bay and coupler are expected to weigh 4.51 lbs.

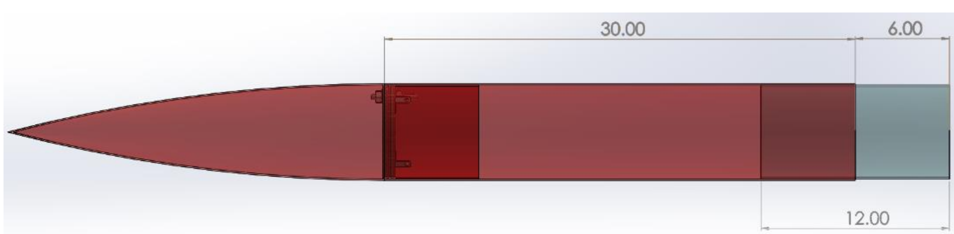


Figure 3-6 Payload Bay Dimensions

3.1.8 Main Parachute Bay

The main parachute bay will be located between the payload bay and the AV bay. The forward end of the main parachute bay will be secured to the payload bay coupler with shear pins. The aft end of the main parachute bay will be secured to the forward end of the AV coupler with a bolted connection. The body portion of the main parachute bay will be 17 inches long. The main parachute has a packed volume of 5 inches D x 7 inches L. As the main parachute bay holds most of the shock cord making up the main recovery harness, the recovery harness and parachutes can be estimated as taking up 10 inches of the main parachute bay. The remainder of the length is left open to allow a sufficient volume for the black powder ejection charge to expand into. Making this open volume will allow for a smoother pressure curve over the course of the detonation event, reducing wear and stress on the airframe.

As the payload bay is situated adjacent to the main parachute bay, it is critical to prevent exposure of sensitive payload electronics to the hot ejection gasses originating from the forward AV bulkhead. This payload protection problem is compounded by the need to access payload electronics from outside the launch vehicle while the launch vehicle is assembled on the launch pad. To correct this, a piston is situated in the main parachute bay and is tied into the main parachute recovery harness. The piston is composed of a section of G12 fiberglass of the same diameter as the coupler sections and measuring 4 inches long. The coupler tube section is capped by a 0.5-inch-thick bulkhead made from layered 0.125-inch aircraft grade birch plywood bonded to the piston coupler using West Systems marine epoxy. A slot is cut in the bulkhead to allow passage of the main parachute recovery harness through the piston cap securing the piston to the recovery harness. During section separation, the ejection gasses will be contained behind the piston and the force will be transferred to the coupler, breaking the shear pins.

Excluding the main parachute, the main parachute bay and piston are expected to weigh 2.54 lbs.

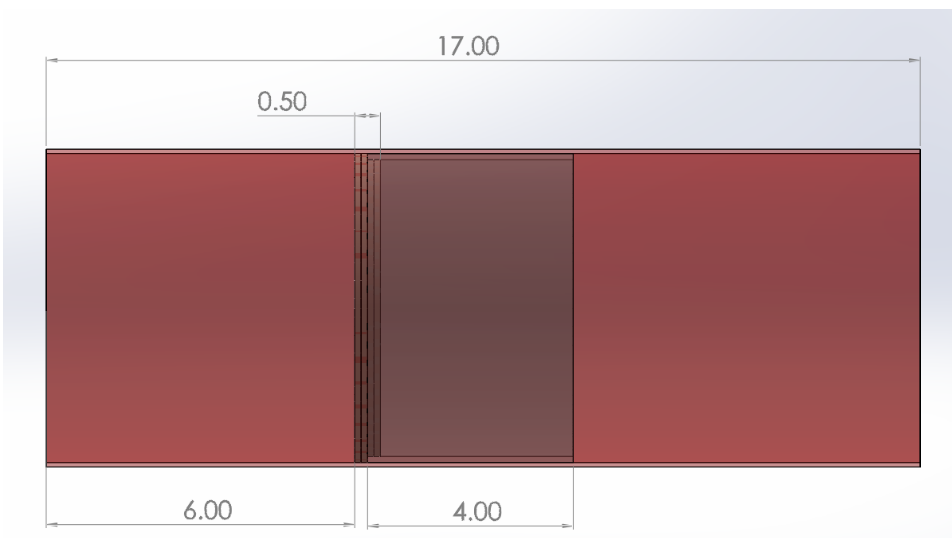


Figure 3-7 Main Parachute Bay Dimensions

3.1.9 AV Bay

The AV bay will be located between the main parachute bay and fin can. It will be a modular design, able to fully separate from the rest of the launch vehicle, allowing for a simple construction process and an easily accessible AV sled. This also allows for easy loading of black powder and allows the AV bay to be worked on and assembled separately from the rest of the launch vehicle.

The AV bay consists of a 14-inch-long coupler section with a 2-inch-thick band of body tube centered on the outside. The forward end is connected to the main parachute bay with a bolted connection and the aft end is secured to the fin can with shear pins. Each AV bay bulkhead will have a U-bolt for use in main and drogue parachute deployment. The bulkheads also each have two blast caps mounted on the outside to house the primary and secondary black powder charges for main and drogue parachute deployment. The AV sled is mounted inside the coupler on threaded rods that run between the two bulkheads.

Excluding the AV sled and black powder charges, the AV bay is expected to weigh 4.43 lbs.

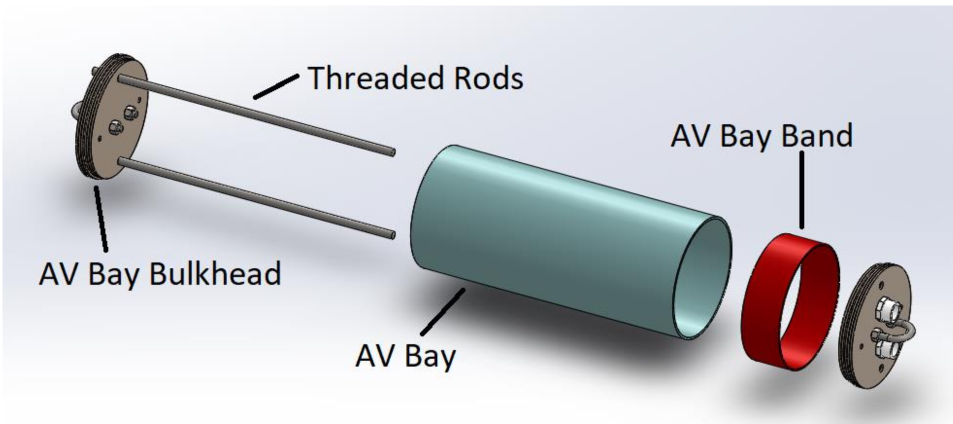


Figure 3-8 AV Bay Exploded View

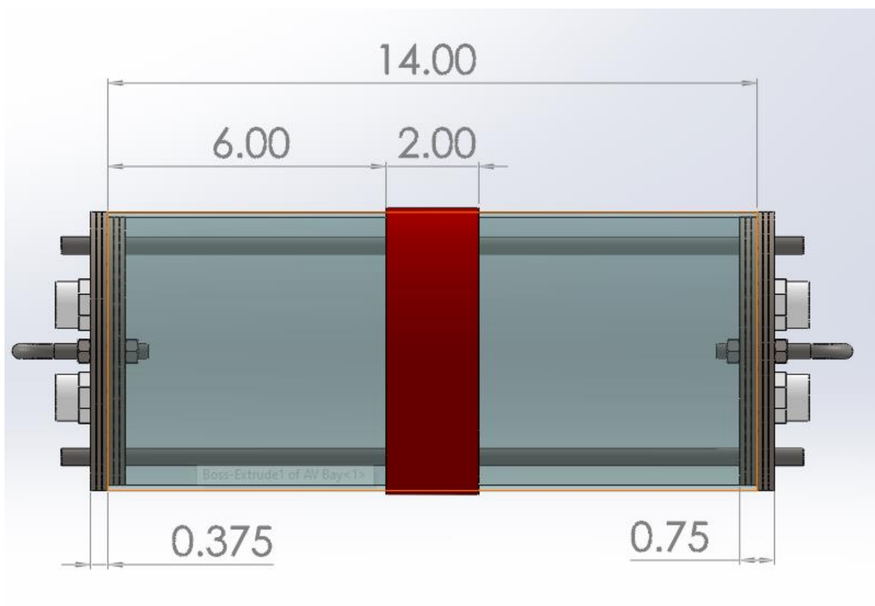


Figure 3-9 AV Bay Dimensions

3.1.10 Fin Can

The 33-inch-long fin can assembly houses the motor tube and the fins. The assembly consists of an engine block, two centering rings, the motor tube, and fins. The engine block and the aft centering ring will support most of the load from the motor while the middle centering ring is used primarily for motor tube and fin alignment. The fins will be designed with a fin slot that fits between the two centering rings for additional support. Half of the layers used in the engine block are centering ring layers so the engine block can also assist with motor tube alignment. Additionally, a U-bolt will be attached to the engine block to be used for drogue parachute deployment. The drogue parachute is housed in the additional space in front of the engine block. The motor will be retained by a motor retainer installed on the aft end of the motor tube using epoxy.

Excluding the motor, the fin can assembly and motor retainer are expected to weigh 6.63 lbs.

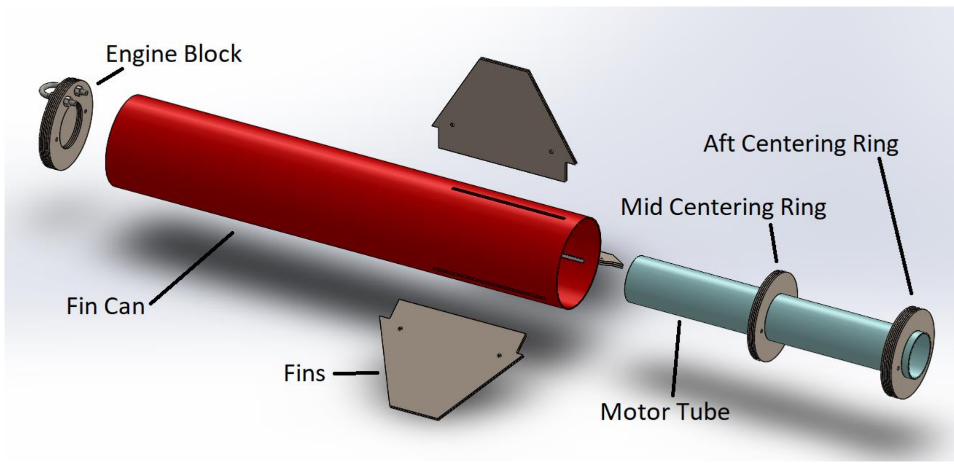


Figure 3-10 Fin Can Exploded View

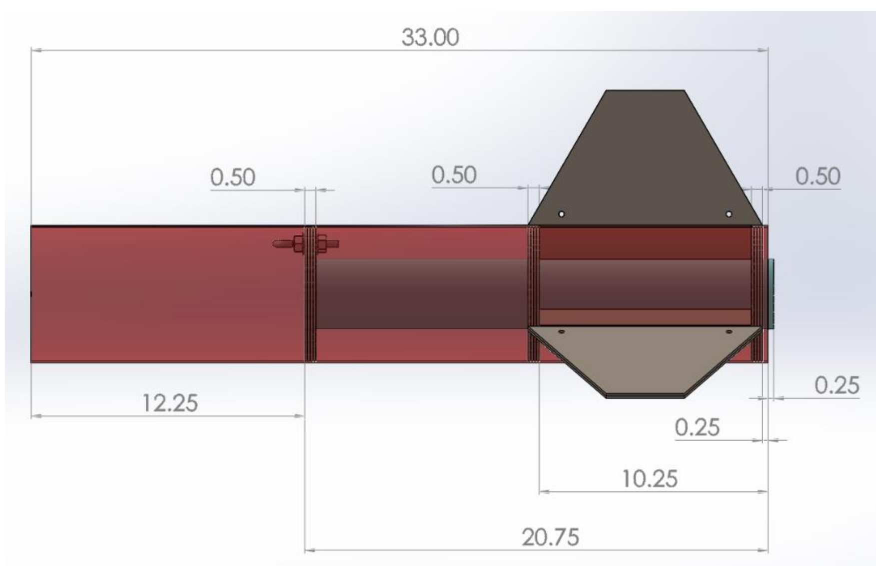


Figure 3-11 Fin Can Dimensions

3.1.11 Fin Configuration and Shape

The team has chosen a three-fin configuration which will be incorporated into the fin can. This configuration was chosen as it offers less weight, less drag, as well as the potential to reduce the chance of weathercocking when compared to a four-fin configuration. The fins are symmetrical about their center when divided by a line running perpendicular to the longitudinal axis of the launch vehicle and are placed one inch from the aft of the launch vehicle. The fins feature both a leading edge and trailing edge sweep to reduce drag and help prevent damage to the fins should the launch vehicle land fins first. The fins are also designed with fin tabs which will be used to slot into the fin can; the end of the fin tabs will attach to the motor tube inside the launch vehicle with an epoxy resin which will secure them in place. The fins will be 0.25 inches thick and will be constructed of two 0.125-inch plywood cutouts which will be attached to one another using an epoxy resin.

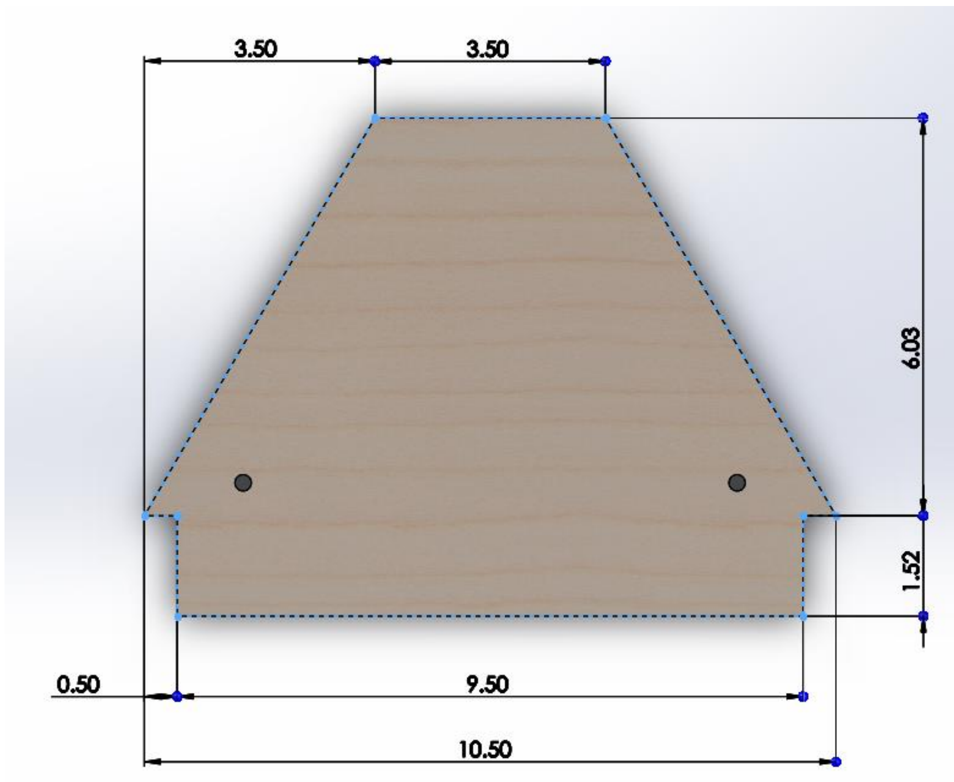


Figure 3-12 Fin Dimensions

3.1.12 Finite Element Analysis

FEA is a valuable resource for determining the amount of stress a part experiences under loading. To assist with bulkhead design, each load-bearing bulkhead was put through a structural simulation in ANSYS Workbench to find the factor of safety of the part under the expected loading.

The parts were created in Solidworks and saved as .STEP files before importing them into ANSYS. All bulkhead hardware such as U-bolts, nuts, and threaded rods were assigned stainless steel as their material. Stainless steel has a yield strength of about 30000 psi, which is far higher than the stress experienced in these simulations, so the focus will be on the plywood portions of the bulkheads. ANSYS does not come with plywood as a default material, so a custom material had to be made. Figure 3-13 shows the material properties used to approximate plywood. While these properties and behavior may not be entirely correct, they will work fine for these simulations.

Properties of Outline Row 4: Plywood

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	500	kg m^-3		
4	Isotropic Secant Coefficient of Thermal Expansion				
5	Coefficient of Thermal Expansion	3.39E-06	F^-1		
6	Isotropic Elasticity				
7	Derive from	Young's Mod...			
8	Young's Modulus	1.125E+06	psi		
9	Poisson's Ratio	0.3			
10	Bulk Modulus	6.4638E+09	Pa		
11	Shear Modulus	2.9833E+09	Pa		
12	Tensile Ultimate Strength	4500	psi		
13	Compressive Ultimate Strength	5250	psi		

Figure 3-13 Plywood Properties Used in ANSYS

To ensure the solution was as accurate as possible, the mesh on each part was checked for element quality and skewness. These metrics are used to assess the overall quality of the mesh and help lead to a better solution. Using advice from learning forums and online FEA courses, it was found that values greater than 0.3 are considered good for element quality and values between 0-0.5 are considered good for skewness. The mesh on each part was refined until these conditions were met.

Multiple thicknesses were tested for each bulkhead to compare the resulting factor of safety under the expected loading. It was found that if all bulkheads were made to be 0.5 inches thick, they would all have a factor of safety greater than 2 which meets TDR 2.2. However, the factor of safety for the 0.5-inch-thick AV Bay and Nose Cone bulkheads is only slightly greater than 2. If this simulation were perfect, these values would be acceptable, but since approximations had to be made it is hard to know whether the actual factor of safety will be higher or lower than these expected values. To account for this, the thicknesses of these parts were increased to 0.75 inches to ensure both their expected and actual factor of safety will be sufficiently high. The other bulkheads located in the fin can have sufficiently high factors of safety at their current 0.5-inch thickness. These bulkhead designs are discussed in more detail in the sections below.

3.1.12.1 Nose Cone Bulkhead FEA

Based on estimated deployment forces, it is expected that 172 lbf will be applied to the nose cone bulkhead. This loading was applied to the upper faces of the U-bolt. The bulkhead was constrained using fixed supports on the inside of the L-bracket holes to simulate the bolts holding the brackets in place. Frictionless supports were added to the circumference of the bulkhead to simulate the bulkhead inside the nose cone. It is expected that stress concentrations will be located around the U-bolt holes and the two closest L-brackets, so the mesh was refined in these locations.

The maximum and minimum principal stresses shown in the legends are not entirely correct. Stress singularities were created in areas of highest stress, particularly where the washers contact the plywood. These singularities would continue to increase in value as the mesh was refined instead of levelling off. To account for these singularities, the probe tool was used to find the approximate max and min values excluding the singularities. Respectively, they are 1400 psi and –1200 psi for only the plywood portion of the bulkhead. This results in a factor of safety of about 3.21. Since this simulation only addresses the stress in the plywood and some of the mounting hardware, shear testing will need to be done on the selected bolts.

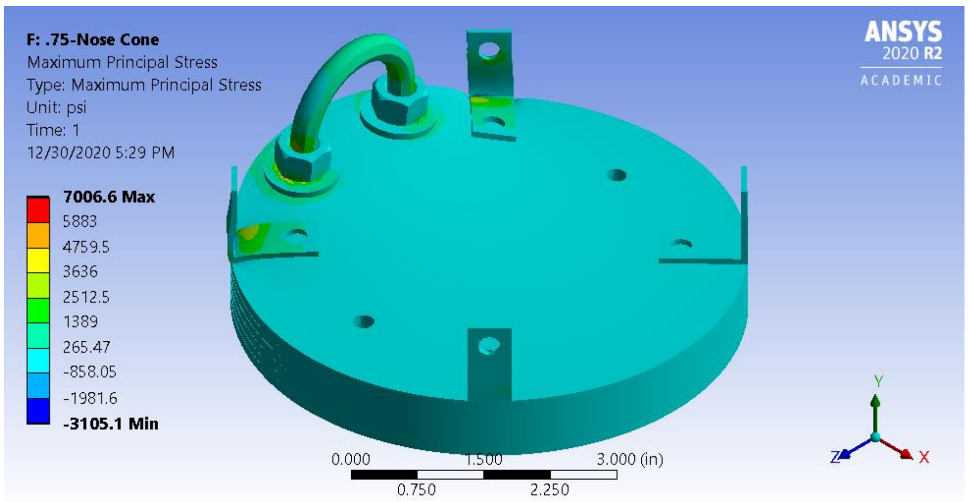


Figure 3-14 Maximum Principal Stress in Nose Cone Bulkhead

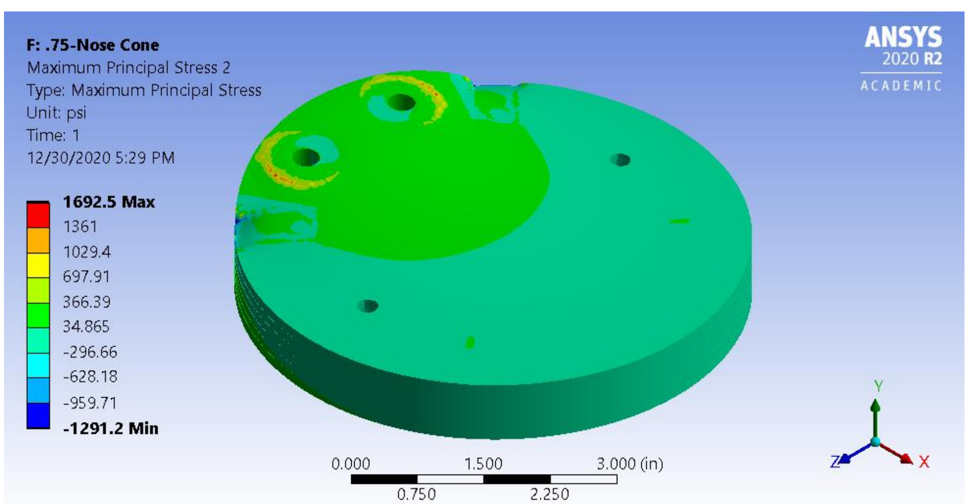


Figure 3-15 Maximum Principal Stress in Nose Cone Bulkhead Plywood

3.1.12.2 AV Bay Bulkhead FEA

Based on estimated deployment forces, it is expected that 172 lbf will be applied to the forward AV bulkhead and 200 lbf will be applied to the aft AV bulkhead. Both bulkheads will be identical, so the simulation was done with the higher loading. This loading was applied to the upper faces of the U-bolt. The bulkhead was constrained using fixed supports on the ends of the threaded rods to simulate the rods being held in place by the opposite bulkhead. Frictionless supports were added to the circumference of the bulkhead to simulate the bulkhead inside the body tube and coupler sections. It is expected that stress concentrations will be located around the U-bolt and threaded rod holes, so the mesh was refined in these locations.

The AV bulkhead experienced the same issue with stress singularities, so the probe tool was used again to find approximate max and min stress values. Respectively, they are 1350 psi and –125 psi. This results in a factor of safety of about 3.33, which is sufficiently high enough to conclude that this bulkhead design will work well.

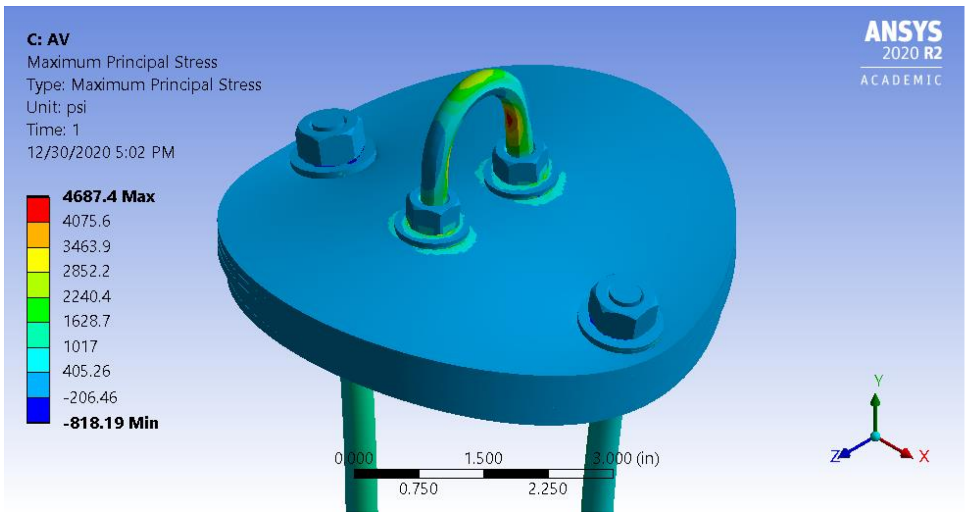


Figure 3-16 Maximum Principal Stress in AV Bulkhead

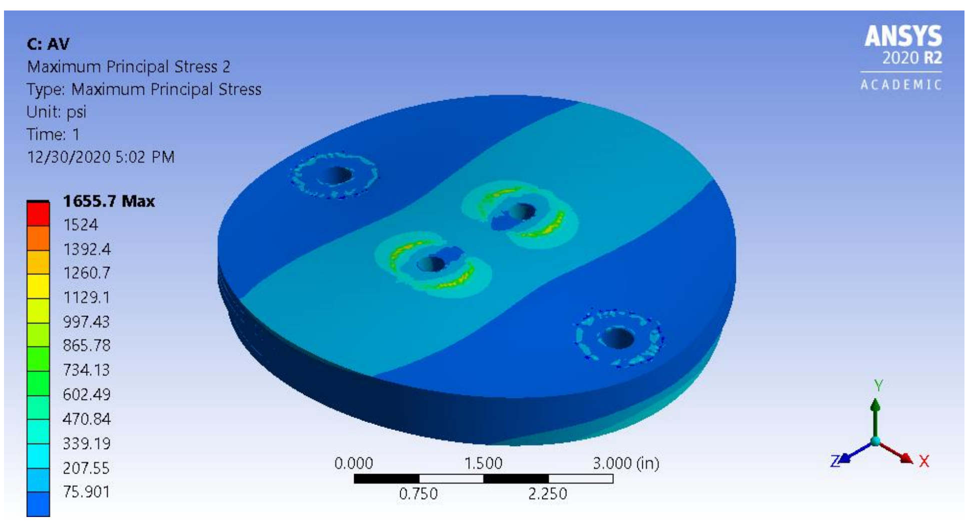


Figure 3-17 Maximum Principal Stress in AV Bulkhead Plywood, Top Face

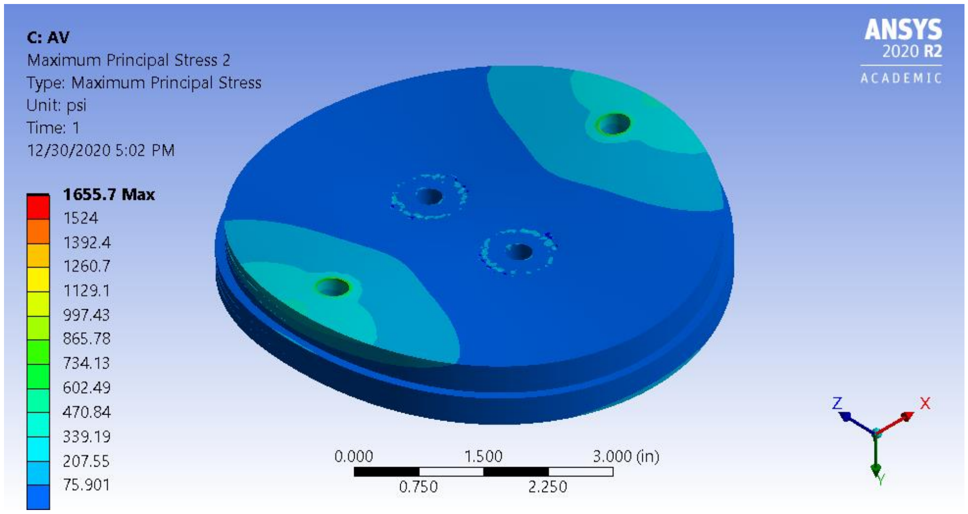


Figure 3-18 Maximum Principal Stress in AV Bulkhead Plywood, Bottom Face

3.1.12.3 Engine Block FEA

Based on estimated deployment forces, it is expected that 200 lbf will be applied to the engine block. This loading was applied to the upper faces of the U-bolt. The bulkhead was constrained using fixed supports on the outer circumference of the bulkhead and the inner circumference of the centering ring layers to simulate the epoxy bond to the body tube and the motor tube. It is expected that stress concentrations will be located around the U-bolt holes, so the mesh was refined in these locations.

Under this loading, the plywood in the engine block has a factor of safety of about 4.49, which is higher than required, but the thickness will make the bulkhead easier to work with and will make it easier to align the motor tube.

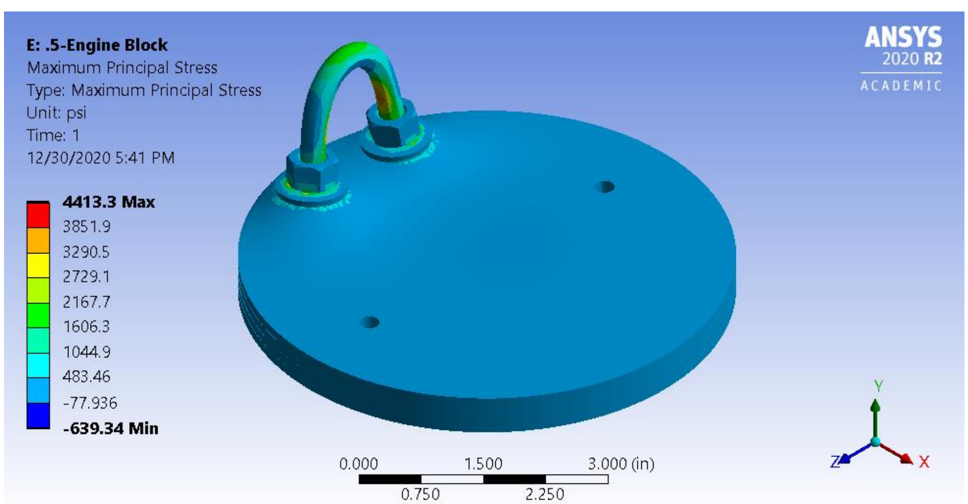


Figure 3-19 Maximum Principal Stress in Engine Block

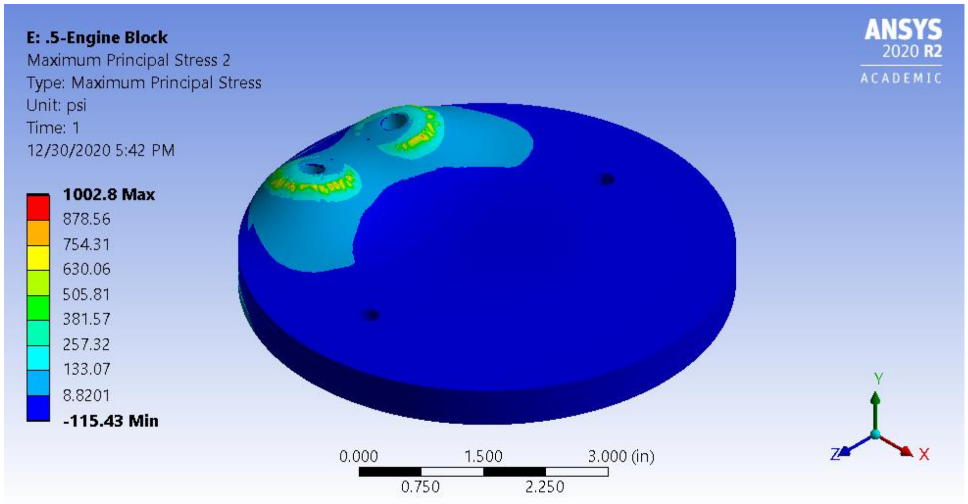


Figure 3-20 Maximum Principal Stress in Engine Block Plywood, Top Face

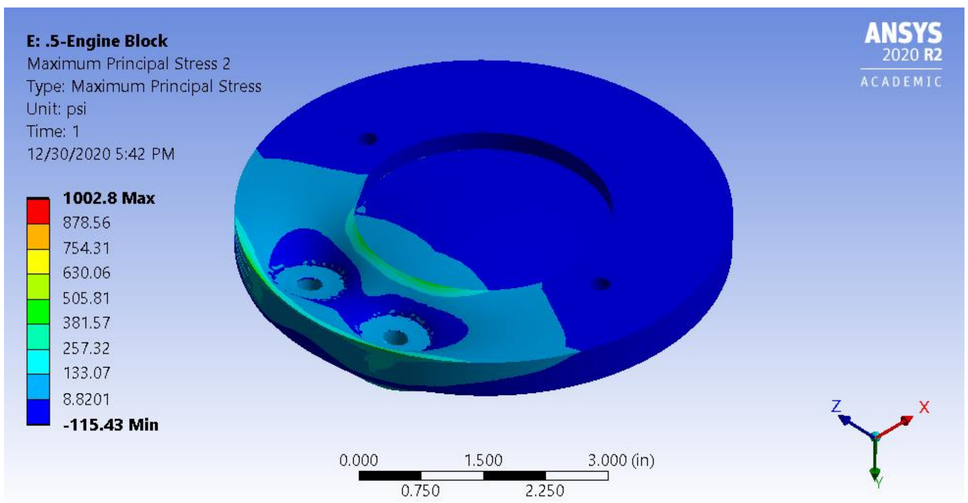


Figure 3-21 Maximum Principal Stress in Engine Block Plywood, Bottom Face

3.1.12.4 Fin Can FEA

A simulation was run on the fin can to determine how well the assembly withstood the thrust from the motor. The average thrust of 1766 N or 397 lbf was applied to the aft end of the motor tube to simulate the force from the motor and motor retainer. The outer edges of all the bulkheads were treated as fixed supports to simulate the epoxy bond. The connection between the bulkheads and motor tube is of most interest, so the mesh was refined there.

Under this loading the aft centering ring experiences the most stress compared to the engine block and mid centering ring. The aft centering ring has a factor of safety of about 10.5 under the motor thrust.

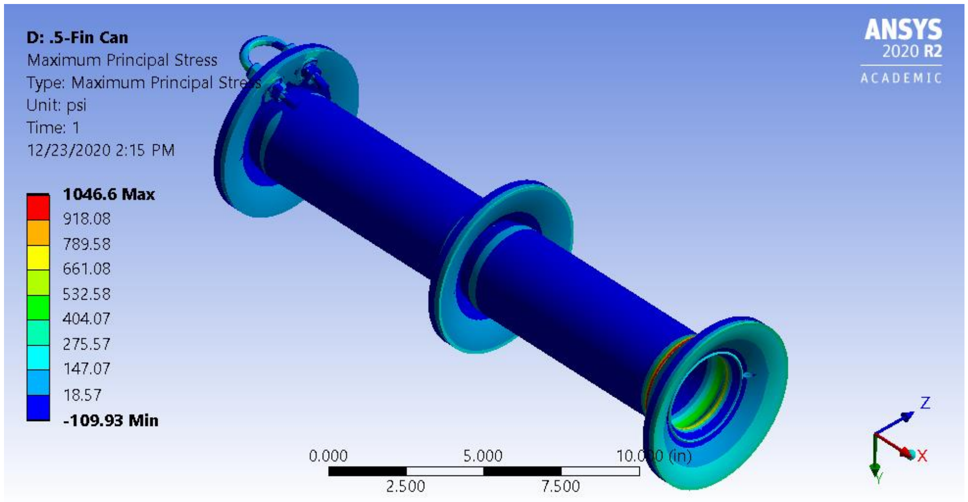


Figure 3-22 Maximum Principal Stress in Fin Can

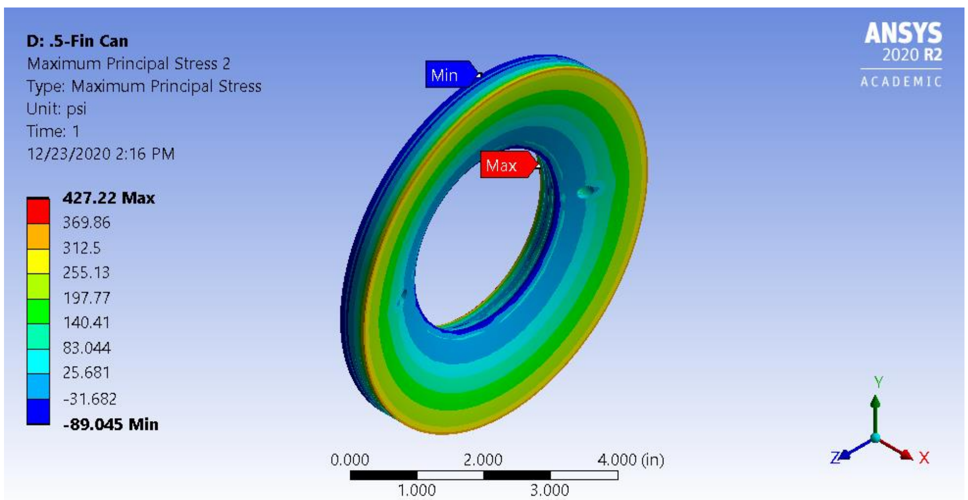


Figure 3-23 Maximum Principal Stress in Aft Centering Ring

3.2 Construction Methods

3.2.1 Bulkhead Fabrication

Each bulkhead in the launch vehicle is made from layers of 0.125-inch aircraft grade birch plywood epoxied together. These layers are drafted in Solidworks, each with two 0.25-inch holes. These holes will later be used for alignment during assembly. Once the CAD file is ready, the layers are manufactured using a laser cutter.

Once the layers are cut, each one is sanded on both sides to prepare for epoxy. The bottom layer is placed down on a vinyl sheet with dowel rods cut to match bulkhead thickness being placed in the 0.25-inch holes. Two-part epoxy is spread on the top face of the first layer and the bottom face of the second layer. The second layer is stacked on the first using the rods for alignment. This process is repeated until the bulkhead is complete. Each bulkhead is wrapped in peel-ply, then breather material and a second layer of vinyl is placed over top. Plumber's putty is used to seal the vinyl and a vacuum line is added. The setup is then left to cure for 24 hours.

To add the bulkheads to the body tube, a layer of epoxy is added to the edge of the bulkhead which is then slid into the body in the required location. After this bond has cured for 24 hours, silica filler is mixed with two-part epoxy and used to add fillets where the bulkhead meets the body tube. This fillet is then left to cure for another 24 hours.

3.2.2 Cutting Body Tubes

The team was able to get help from university machine shop personnel in cutting body tubes with a drop bandsaw for the subscale rocket and plans to do the same with full scale body tubes. However, the machine shop has recently had a change in staffing, and it is uncertain whether the team will have access at the start of the new semester. As a possible alternative, the merchant the team plans to purchase airframe tubing from offers to cut tubes to length for extra cost. While this would be the more expensive option, it would allow the team to begin manufacturing the launch vehicle as soon as parts are received.

3.2.3 Adhering Couplers to Body Tubes

For each coupler, the extent of the contact areas on both the coupler and the inside of the body tube sections is first measured and marked. These areas are then sanded to promote a better surface bond. Two-part epoxy is then be prepared and applied to both the coupler and the body tube within the contact areas. The coupler is then carefully inserted into the body tube up to the marked length. The completed coupler section is then set aside to cure for 24 hours before it is handled again.

3.2.4 Fin Can Assembly

To begin, the forward fin can bulkhead, also known as the engine block, is inserted and epoxied into place. Fillets are added between the bulkhead and body tube for extra strength. While this setup cures, the middle centering ring can be epoxied onto the motor tube in the correct location and fillets applied where the centering ring contacts the motor tube. Once all epoxy has cured, more epoxy is added to the forward fin can bulkhead where the motor tube is to be fitted and to the outer edge of the mid centering ring. The motor tube with centering ring can then be inserted in the aft end of the fin can.

Once the motor tube is in and the epoxy has cured, the fins can be inserted through their slots. The fins are typically laser-cut beforehand using the same method as the bulkhead layers. Epoxy is added to the motor tube and the middle centering ring where the fins contact. Before the aft centering ring is placed, more fillets are added where the fins touch the motor tube and on the inside and outside of the body tube around the fin slots. The aft centering ring is then epoxied into place and fillets added where it contacts the body tube. As a last step, the motor retainer is epoxied to the end of the motor tube.

3.2.5 Bolted Connections

The launch vehicle requires bolted connections in the nose cone to allow for a removable bulkhead and between the Main Parachute Bay and AV Bay. However, because the nuts would be difficult to reach inside the tubing, it is necessary to secure the nuts in place so bolts can be screwed in from outside the launch vehicle without needed access to the inside.

To start, holes are drilled through both the body tube and coupler sections to ensure they remain aligned. Then, using epoxy, nuts can be bonded to the inside coupler surface centered over each hole. In the case of the removable bulkhead, the nuts would be bonded to the L-brackets. Once the epoxy has cured, bolts can be threaded into the nuts to hold the bulkhead in place and the body and coupler sections together.

3.2.6 Ballast Installation

Should the launch vehicle's stability margin need to be adjusted, the team has the option of adding ballast to the nosecone bulkhead. Ballast would consist of lead blocks or lead pellets epoxied into a custom 3D-printed casing. The ballast could then be secured to the bulkhead using two-part epoxy.

3.2.7 Safety Standards

During construction, team members will follow the safety procedures put forth by the team's safety officer, including:

a) Training for the safe operation of power tools and machining equipment before use.

b) Proper usage of PPE while operating power tools and machining equipment. This includes safety glasses and disposable respirators.

c) Proper usage of PPE while handling epoxy. This includes safety glasses and disposable nitrile gloves.

d) Proper usage and storage of epoxy and other commonly used hazardous materials. These standards are discussed in more detail in Section 5.

3.3 Subscale Flight Performance

The team designed and built a subscale launch vehicle, named *Chicken Tendy*, to validate the design of the full scale launch vehicle. The launch was conducted on November 21, 2020 at the team's launch field in Bayboro, NC under the supervision of the TRA mentors listed in Section 1.1.2. The temperature was approximately 60 degrees Fahrenheit, skies were completely clear, and wind was calm, remaining under 5 mph. *Chicken Tendy* carried a dual-deploy recovery system consisting of an 18-inch drogue parachute deployed at apogee, and a 60-inch main parachute deployed at 500 ft AGL. Recovery was controlled by redundant Stratologger CF altimeters.

3.3.1 Flight Predictions

Simulations for the subscale flight were based on a 5^{o} launch rail angle, a 12-foot launch rail, and wind conditions ranging from 0 to 6 mph due to gusts of up to 6 mph being recorded on the ground on launch day. The expected apogee was 2700 feet, with the full predicted flight shown in red in the figure below. The subscale launch vehicle had a simulated static stability margin of 2.25.

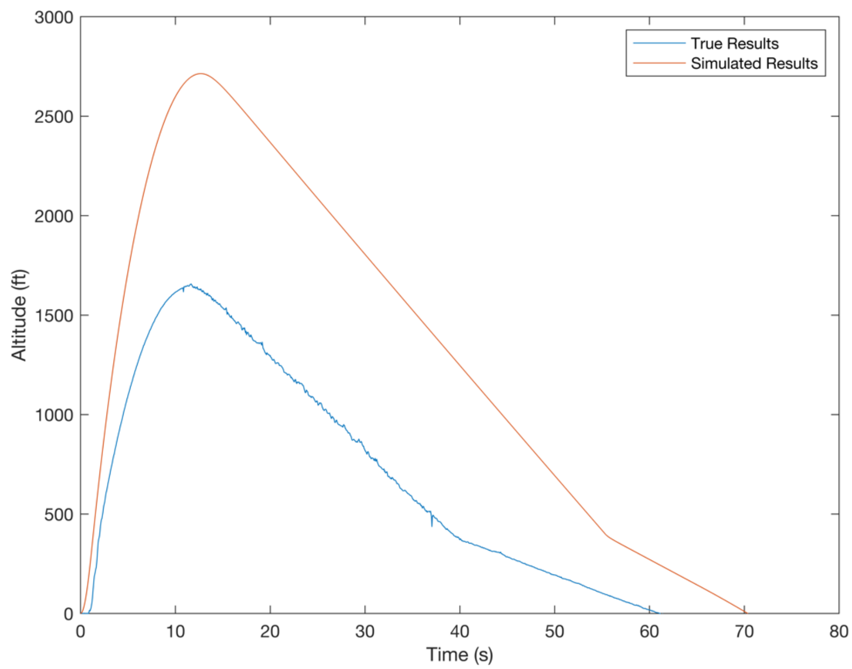


Figure 3-24 Subscale Launch Vehicle Flight Profile

3.3.2 Flight Data and Results

The recorded stability margin on launch day was 1.7 and the recorded apogee on launch day was 1657 feet, only 61% of the predicted apogee. This dramatic reduction in both expected launch height and stability is primarily attributed to an underestimation of the weight of components of the subscale launch vehicle. A table below shows the expected and recorded weight of each section. Every section besides the payload bay had a lower expected weight than the actual recorded weight. This increase in weight reduced the apogee of the launch vehicle; seeing as how the payload bay did not experience an increase in weight it also moved the center of gravity toward the aft of the launch vehicle.

Table 3-2 Subscale Comparison of Expected and Actual Section Weights

	Expected Weight (lbs)	Actual Weight (lbs)
Nose Cone	0.37	0.64
Payload Bay	2.6	1.6
Main Parachute Bay	0.90	2.19
Avionics Bay	1.21	1.63
Fin Can	2.82	3.875

Despite these issues, the flight was a success. The vehicle was successfully launched and recovered in a reusable condition. Figure 3-25 and Figure 3-26 below show the subscale launch vehicle during launch and descending under both deployed parachutes.

Figure 3-25 Subscale Launch Vehicle Departing Launch Rail

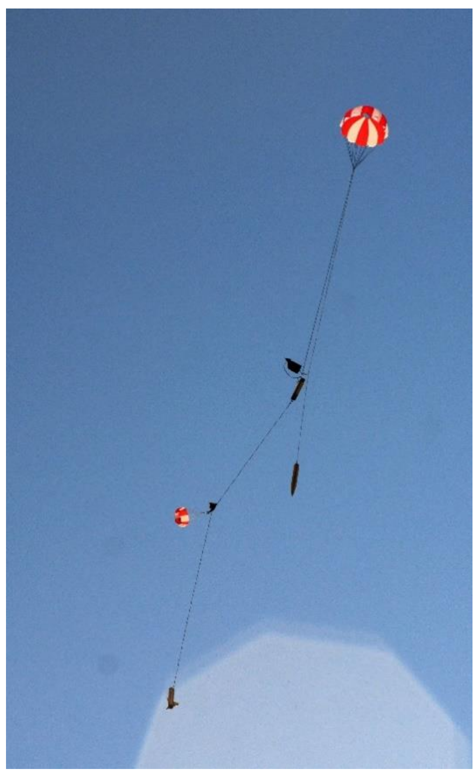


Figure 3-26 Subscale Launch Vehicle Descending Under Main and Drogue Parachutes

3.3.3 Scaling Factors

The team chose a scaling factor of 2/3 or 66%. This decision was primarily driven by the availability of 4-inch diameter blue tube, something the team has historically used for subscale construction. Using a true 2/3 scaling factor for each part of subscale construction proved to be unrealistic due to many measurements becoming irrational numbers, so while a 66% scaling factor was the goal, there was a tolerance of ±5%. A table of measurements along with their respective scaling factors is presented below. It should be noted that the design of the full-scale payload has been changed since the design of the subscale launch vehicle and the measurements in the table below are not representative of those changes.

Table 3-3 Subscale Scaling Factors

	Full-Scale	Subscale	Scaling Factor
Length (in)	109.36	76.74	70.17 %
CG (in)	64	46	71.88 %
CP (in)	77	55.35	71.88 %
d (in)	6.17	4.124	66.84 %
span (in)	17.37	11.59	66.72 %
Stability	2.11	2.25	

3.3.4 Subscale Influence on Full-Scale Design

The greatest takeaway from the subscale test was that the weight of both major and minor components was not being taken into account thoroughly enough. After realizing the error of the subscale simulations, the full-scale simulations were updated to include every object that would be on the launch vehicle during launch. The team also began weighing individual parts rather than relying on estimations from RockSim. A better accounting of weight, along with a 7% increase in fin size that occurred between proposal and PDR, should solve both the stability and performance issues experienced during the subscale launch.

3.4 Recovery Subsystem

3.4.1 Final Recovery Subsystem Design

The recovery and avionics subsystem comprises all aspects of the launch vehicle involved in ensuring a safe and controlled descent from apogee to touchdown. Launch Vehicle recovery system events will be controlled by two PerfectFlite StratoLogger CF altimeters. Each altimeter system has separate batteries, screw arming switches, and black powder charges constituting two independent and redundant systems. Both altimeters and the launch vehicle tracking system will be mounted on the avionics sled, which will be made from laser-cut 1/8 inch aircraft grade birch plywood. The AV sled is housed in the modular AV bay assembly, which in addition to the AV sled contains the black powder ejection charges in blast caps on the bulkhead. The design of this assembly is discussed in detail in Section 3.1.9. Two further PerfectFlite StratoLogger CF altimeters will be used in the LOPSIDED-POS recovery. One will be mounted to the nosecone bulkhead and provides a signal to release the payload electronic latch that secures the payload during ascent. The other is mounted to the LOPSIDED electronics board and serves to activate the ARRD at 500 ft to release the LOPSIDED-POS from the main parachute recovery harness. All four altimeter systems will be armed once the launch vehicle is in the vertical position on the launch rail before igniter insertion and flight. The arming process consists of engaging independent rotary screw switches through access ports in the airframe large enough to fit a screwdriver. At apogee, the primary altimeter will send current to the drogue primary e-match and detonate the drogue primary black powder charge separating the midsection and the fin can. One second after apogee the secondary altimeter will fire the larger drogue secondary black powder charge to ensure separation in the event of a failure of the primary altimeter system. The delay of the secondary charge guards against over-pressurization of the launch vehicle. The fin can and forward section will separate and descend to 700 ft under a Fruity Chutes 18" Classic Elliptical drogue parachute. The body sections will be tethered to the parachute by a 40 ft length of 5/8 inch tubular Kevlar shock cord. Loops on the ends of the shock cords will be connected to U-bolts on the aft AV bulkhead and the engine block by ¼ inch thick quick links. Once the descending launch vehicle reaches an altitude of 700 ft, the primary altimeter will fire the main primary e-match detonating the main primary black powder charge, separating the main parachute bay from the payload bay. A piston ejection system attached to the shock cord at a fixed distance will be used to protect the LOPSIDED-POS and parachute during ejection. At 650 ft, the secondary altimeter will fire the main secondary ejection charges. The main parachute and corresponding recovery harness are connected to the forward AV bulkhead and removable nosecone bulkhead using a 40 ft length of 5/8 tubular Kevlar shock cord, ¼ inch quick links, and U-bolts secured to launch vehicle bulkheads. This removable nosecone bulkhead is forward of the LOPSIDED-POS, and the main parachute deployment will be used to remove the LOPSIDED-POS from the payload bay, breaking the 3 4-40 nylon shear pins retaining the LOPSIDED during descent. The main parachute will be a Fruity Chutes 120" Iris UltraCompact parachute, protected by a Fruity Chutes 6 inch deployment bag. The LOPSIDED-POS will be secured to the main parachute recovery harness by the ARRD, and the payload parachute in a Fruity Chutes 4 inch Nomex deployment bag will be attached to the main parachute recovery harness between the main parachute and nosecone by a ¼ inch quick link. At 500 ft the ARRD altimeter will fire the ARRD retention/release system, allowing the LOPSIDED-POS to fall and pull the payload parachute free of the 4 inch deployment bag, which will be secured by the top loop on the deployment bag to the main parachute recovery harness. The selected payload parachute will be a Fruity Chutes 60" Classic Elliptical parachute. Warding against premature deployment of the payload parachute during main parachute ejection are two Jolly Logic parachute retention devices. These are tied together to provide a redundant release system for the payload parachute that will be programmed to unlatch at 600 ft before the LOPSIDED-POS deploys. The payload parachute will be secured to the LOPSIDED-POS by a 15 foot length of 5/8 inch tubular Kevlar shock cord connected to two electronic latches using ¼ inch quick links. The payload parachute will be secured to the opposite end of this shock cord also using a ¼ inch quick link.

3.4.1.1 Avionics Sled

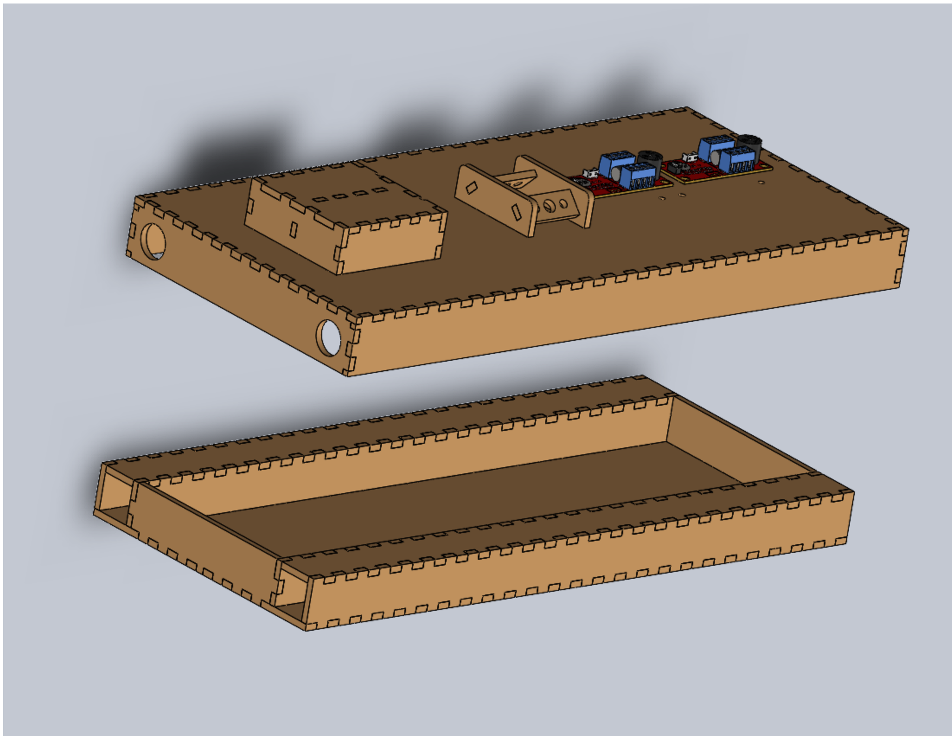


Figure 3-27 Avionics Sled Rendering

Pictured above is the assembled avionics sled. The AV sled will be manufactured from 1/8 inch thick aircraft grade birch plywood. Both halves of the AV sled will be aligned together and then secured laterally by two threaded rods passed through the holes seen in the figure above. Spacers on these threaded rods will prevent axial movement of the AV sled. This allows for the internal volume of the AV sled to be used for running wires in a manner that protects the wiring harness from snags and other potential hazards during assembly. The tilted plates on the AV sled provide mounting locations for screw switches used to arm the altimeters from outside the launch vehicle. Screw switches will be mounted on standoffs and positioned to ensure 90 degree radial alignment to each other for the altimeter screw switches. The enclosed box houses the two 9V altimeter batteries. The battery box lid will be secured using 4 #4-40 machine screws passed through the AV sled and bolted in place. The launch vehicle tracker and two StratoLogger CF altimeters will be secured to the AV sled on ¼ inch tall standoffs passed through laser cut mounting holes as shown. Save for the bolted connections discussed above; the AV sled will be assembled by bonding all wooden segments together along the jigsaw using wood glue. This method of construction has proved durable for the team in past projects for constructing electronics sleds. All wiring on the AV sled will be color coded as set out in Table 3-4 below. Four-pin connectors will be used to run the four signal wires to each bulkhead. Using one connector per bulkhead instead of two reduces the potential for mixing of the primary and secondary signal wires on launch day.

Table 3-4 AV Sled Wiring Code

Wire	Color
Power	Red
Ground	Black
Screw Switch	Green
Main Primary Signal	Blue
Main Secondary Signal	Orange
Drogue Primary Signal	Purple
Drogue Secondary Signal	Yellow

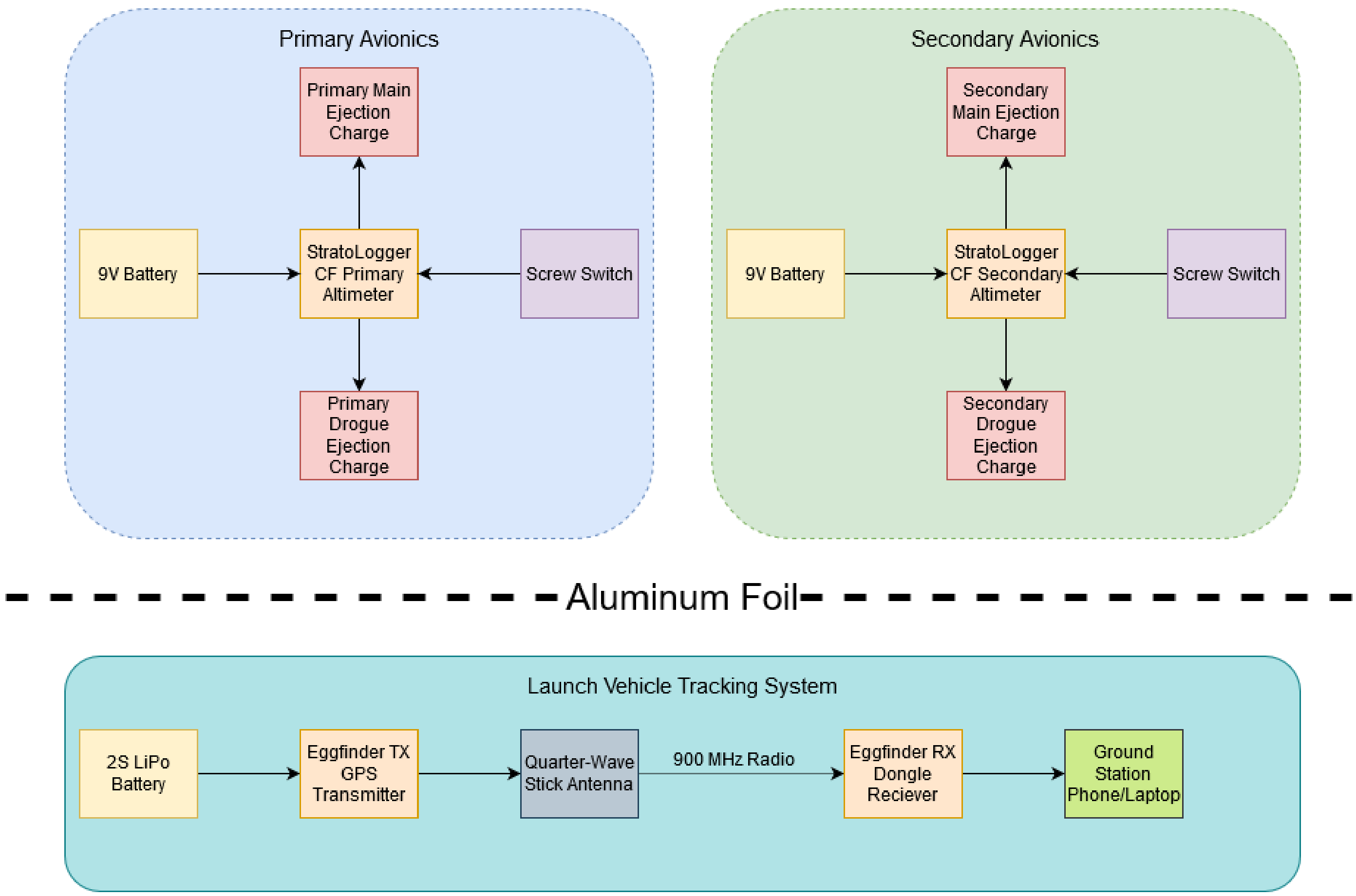


Figure 3-28 AV Sled Electronics Block Diagram

The block diagram above illustrates the components housed within the AV bay and how all of them will interact. The dashed blue box contains all components of the primary altimeter system. This system contains the competition altimeter which will record the team's official apogee, as well as all components needed to complete the required recovery events. The altimeter has four pairs of terminal screws which are connected to a 9V battery, a screw switch, and 2 E-matches. One E-match is inserted into the drogue primary blast cap and triggered at apogee, while the other E-match is inserted into the main primary blast cap and triggered at 700 ft. A fresh, tested battery is installed at each flight to ensure sufficient power is available for triggering both charges and recording flight data while meeting the pad time requirements set forth by requirement NASA 2.7.

The dashed green box contains the secondary altimeter system, which is quite like the primary altimeter system save for increased black powder charge masses and later ejection charge timing. The drogue charge is set to be triggered one second after apogee while the main charge is set to be triggered at 650 ft. Both the primary and secondary altimeter systems are capable of safely recovering the launch vehicle on their own. As there is no connection between the two altimeter systems, this creates a system redundancy. Should any one component fail, the other system will activate in its place to ensure a safe recovery of the launch vehicle and LOPSIDED-POS.

Housed on the opposite side of the AV sled is the Eggfinder TX transmitter, a 2S LiPo battery, and a ¼ wave stick antenna. Installed between these components and the sled is a sheet of aluminum foil, which will shield the recovery electronics from radio interference. This system is discussed in more detail in Section 4.3.4.

3.4.1.1(a) LOPSIDED-POS Recovery Electronics

Two PerfectFlite StratoLogger CF altimeters will be used during deployment of the LOPSIDED-POS. One StratoLogger CF will be mounted to the nosecone bulkhead, and the drogue signal will be used to release a latch mounted on the payload bay side of the nosecone bulkhead. This latch holds the payload in place during ascent and resists the acceleration of launch. At apogee this latch will release, and the LOPSIDED-POS will be secured in the payload bay by 3 #4-40 Nylon shear pins. Once the main parachute deployment has removed the LOPSIDED-POS from the payload bay, the LOPSIDED-POS will be tethered to the main recovery harness through the ARRD. An altimeter onboard the LOPSIDED-POS will be used to fire the ARRD from the main signal circuit. This will fully release the LOPSIDED-POS from the launch vehicle and start the payload parachute deployment.

3.4.1.2 Altimeters

All recovery events will be controlled using PerfectFlite StratoLogger CF altimeters. This altimeter was selected for its reliability, ease of wiring, programmability, and precision. Previous flights using multiple StratoLogger CF altimeters have recorded apogee altitudes within ten feet of each other. A quantity of StratoLogger CF altimeters are already owned by the team. The StratoLogger CF is a dual-deployment altimeter satisfying NASA 3.1. Using identical altimeters prevents mix-ups between the different protocols associated with using altimeters of dissimilar makes and models. The wiring layout of the StratoLogger CF is the cleanest out of the considered alternatives with clear labeling on the altimeter board and a dedicated switch terminal. As such, a StratoLogger CF will be used for both recovery altimeters, the LOPSIDED-POS ARRD altimeter, and the latch altimeter. With four onboard altimeters of the same manufacture, the beep pitch setting will be set to a different pitch for each altimeter. By changing the pitch, it is easier for the launch pad and field recovery teams to distinguish between the different altimeters and accurately complete the beep sheets.

3.4.1.3 Locating Trackers

Two independent tracking devices will be used for each untethered section of the launch vehicle, these being the launch vehicle and the LOPSIDED-POS. The LOPSIDED-POS will be tracked using a BigRedBee BRB900 tracker selected for its small size and simple, all-in-one setup. The BRB900 transmits GPS data on 900 MHz to a dedicated handheld receiver. An Eggfinder GPS TX/RX system will be used to track the launch vehicle. The Eggfinder RX receiver will be connected to an Android phone over Bluetooth in order to display launch vehicle location data on a map overlay for the field recovery team. The Eggfinder system will transmit on 921 MHz using the device ID #8 to minimize the chance of interference with other transmitters at the launch site. Both transmitters meet the requirements NASA 3.12 and NASA 2.22.8 of possessing a range greater than 5000 ft and an output power under 250 mW. No licensure is required to operate these transmitters in the 900 MHz ISM band.

3.4.1.4 Parachutes

The launch vehicle will descend from apogee to 700 ft under a Fruity Chutes 18” Classic Elliptical drogue parachute. This parachute was selected for its high descent velocity and ownership by the team. Under drogue, the launch vehicle will have a burnout mass of 1.285 slugs. This corresponds to a drogue descent velocity of 117.4 ft/s as calculated in Section 3.5.7. Once the main parachute deploys at 700 ft, the launch vehicle will descend under the selected main parachute, a Fruity Chutes 120” Iris UltraCompact parachute. This main parachute was selected as the only considered design alternative that met wind drift, descent time, and kinetic energy requirements for all three considered descent scenarios. With the LOPSIDED-POS attached to the launch vehicle, the assembly will descend from 700 ft to 500 ft at a descent velocity of 14.5 ft/s. Once the LOPSIDED-POS separates from the launch vehicle, the terminal velocity will decrease to 12.8 ft/s. Should the LOPSIDED-POS fail to exit the payload bay, the maximum section kinetic energy at landing will be 60.7 ft-lbs., meeting the requirement set forth by NASA 3.3. Should the LOPSIDED-POS exit the payload bay but fail to detach from the main parachute recovery harness, it may be treated as a separate tethered section for the purposes of kinetic energy requirements. In this scenario, the maximum section kinetic energy would be

38.8 ft-lbs at the fin can on landing. For the expected nominal deployment of the LOPSIDED-POS, the maximum kinetic energy at landing would correspond to the fin can at 30.3 ft-lbs. This scenario would also correspond to the maximum projected launch vehicle wind drift, as detailed in Section 3.5.8, of 2490.9 ft from the launch site. The kinetic energy requirements have sufficient margins to allow for a uniform increase in both launch vehicle and LOPSIDED-POS mass of up to 25% during construction while still meeting all descent requirements.

Once separated from the launch vehicle recovery harness, the LOPSIDED-POS will descend under a Fruity Chutes 60" Classic Elliptical parachute referred to as the payload parachute. This parachute was selected over a slightly larger parachute to give the LOPSIDED-POS as low of an impact force as possible while remaining within wind drift requirements and not running the risk of updrafts or similar phenomenon significantly impacting the descent of the LOPSIDED-POS. Under the payload parachute, the LOPSIDED-POS will have a descent velocity of 13.6 ft/s with a projected kinetic energy at landing of 25 ft-lbs. The total wind drift of the LOPSIDED-POS will be 2445.2 ft as calculated from apogee. This is well within the wind drift limits required by the competition and provides a safe landing scenario for the LOPSIDED-POS focusing on minimizing kinetic energy at landing.

3.4.1.5 Recovery Harnesses and Attachment Points

The launch vehicle recovery harnesses are made from two 40 ft lengths of 5/8 inch tubular Kevlar shock cord, tethering the nosecone/payload bay assembly to the midsection and the midsection to the fin can. A 15 ft length is used to attach the LOPSIDED-POS to the payload parachute. This material is rated for loads upwards of 6000 lbf, well in excess of the maximum predicted deceleration force of 388 lbf. The drogue shock cord will have a loop tied 160 inches down the shock cord from the aft AV bay to which the drogue parachute and its protective Nomex sheet will be secured using a ¼ inch quick link. The main shock cord will have a loop tied 160 inches forward of the forward AV bulkhead, to which the main parachute will be attached. The shock cord will be threaded through the piston, with a double overhand stopper knot tied on each side to secure it in place. Just forward of the piston a second loop will be tied to which the deployment bag will be secured with a ¼ inch quick link to rapidly remove the parachute from the deployment bag during main parachute deployment. A third and fourth loop will be tied between the main parachute and the payload bay to tether the LOPSIDED-POS and the payload parachute deployment bag to the main shock cord. This will serve to make use of the main parachute opening shock to remove the LOPSIDED-POS from the payload bay during main parachute deployment. The 15 ft length of shock cord used to tether the payload parachute to the LOPSIDED-POS will allow the LOPSIDED-POS time to build sufficient velocity to cleanly remove the payload parachute from its deployment bag. All recovery harness connection points will be secured using ¼ inch quick links. The main recovery harness layout is shown in Figure 3-29 below.

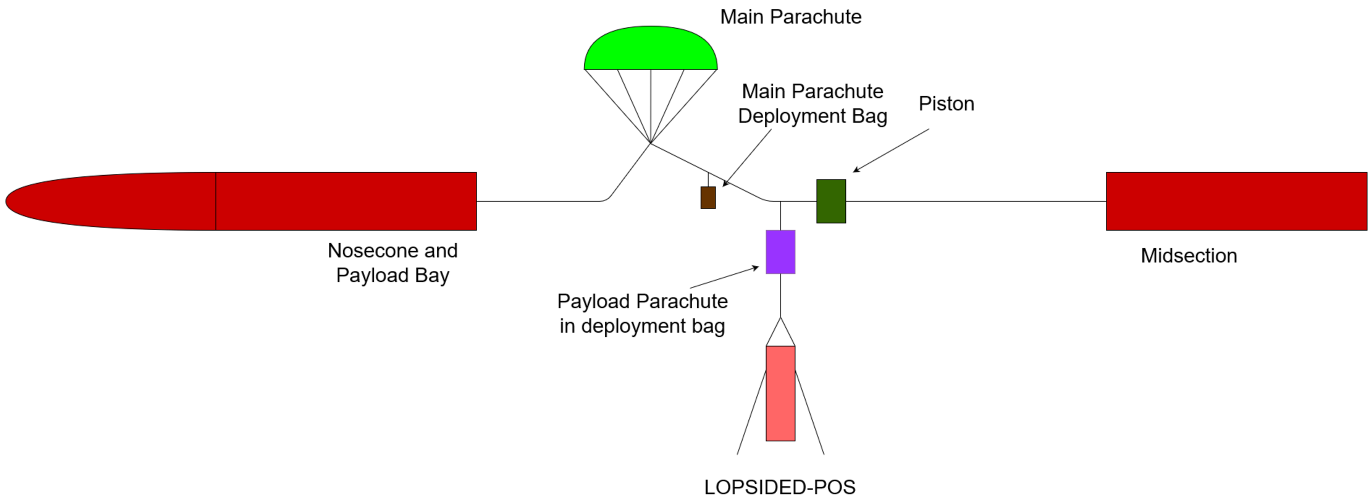


Figure 3-29 Main Parachute Recovery Harness

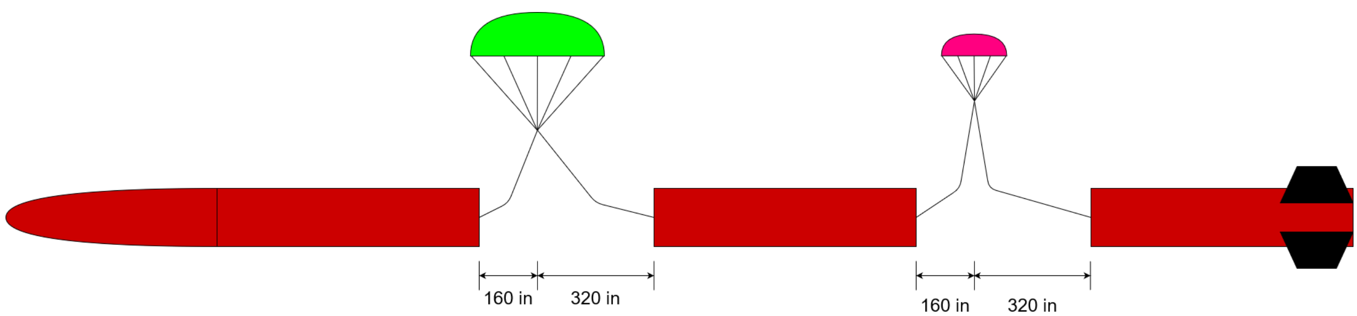


Figure 3-30 Parachute Attachment Locations

3.4.1.6 Main Parachute Piston Ejection System

The LOPSIDED-POS contains sensitive electronics, some of which are altimeters that must be armed once the launch vehicle is fully assembled on the launch pad. This necessitates a method of arming the altimeters from outside of the launch vehicle while still shielding the interior of the LOPSIDED-POS from hot ejection gasses produced during the main parachute ejection. To this end, a piston ejection system will be used. The piston design is described in Section 3.1.8 and the piston will be assembled in the main parachute bay capping the volume the black powder can expand into. When the ejection charge is fired, the expanding gasses will pressurize the volume behind the piston. This will in turn impart a force on the coupler epoxied into the payload bay, which will be secured to the main parachute bay using #4-40 nylon shear pins. A pressure rise of 15 psi will be used to overcome both the shear pins and the friction between the piston and airframe. To counteract this friction the piston will be lubricated during launch vehicle assembly before insertion into the main parachute bay. The piston will be attached to the main parachute shock cord two feet aft of the deployment bag, allowing much of the shock cord to be stored on the pressurized side of the piston to make full use of the limited space in the main parachute bay. Two stopper knots on either side of the piston will affix the piston to the shock cord such that it will not slide and potentially impact either the midsection or the main parachute.

3.4.1.7 Black Powder Ejection Charges

Energetic materials will be used for 3 separate ejection events. The energetic material used for all ejection events is 4F black powder. Four of these ejection charges will be housed on the avionics bulkheads in blast caps in order to deploy the main and drogue parachutes. The fifth ejection charge will be housed in the ARRD attached to the LOPSIDED-POS during flight. This ejection charge will separate the LOPSIDED-POS from the main parachute recovery harness.

Black powder ejection charge sizing is determined by finding the force necessary to overcome both the resistance of the shear pins and the friction of the body sections fit together. Subscale ejection tests suggest that accounting for the mass fraction of the black powder converted into gaseous products, a target pressure rise of 10 psi is sufficient to provide a good separation with a moderately tight fit of the recovery components. Both drogue and main sections have an inner diameter of 6 inches and the piston cavity is 4.25 inches long while the drogue parachute cavity is 5.75 inches long. The volume of the main parachute cavity will be 120.2 in^3 while the drogue parachute cavity will have a volume of 162.6 in^3. Black powder charges are calculated as discussed in Section 3.5.9 with a target pressure rise of 10 psi for the drogue ejection and 15 psi for the main ejection to overcome friction between the piston and launch vehicle body tubes.

To ensure body section separation and provide redundancy in the recovery system, a secondary black powder charge is provided for both main and drogue ejection. This redundant ejection charge will be 0.5 grams larger than the primary to ensure separation should the primary charge detonate successfully but fail to fully separate the body sections. Should the primary charge fail to detonate, the secondary charge is not so much larger than the primary that over pressurization of the body section would occur. Thus, four black powder ejection charges will be installed for each flight: a 2.6 gram drogue primary charge, a 3.1 gram drogue secondary charge, a 2.9 gram main primary charge, and a 3.4 gram main secondary charge.

3.5 Mission Performance Predictions

3.5.1 Launch Day Target Altitude

Based on simulations performed in RockSim, the team has determined the target apogee for the launch vehicle to be 4473 feet.

3.5.2 Updated Flight Profile Simulations

The team determined the official target apogee based on flight simulation data from RockSim using the leading design available while writing the Preliminary Design Review. Changes since PDR can be seen in section 2 and new simulations have been performed based on these changes, as well as including more accurate predictions regarding the weight of components. Simulations were based on a 5° launch rail angle, a 12-foot launch rail, and wind conditions ranging from 3 to 14.9 mph. Twenty simulations were run and their apogees averaged to calculate the updated apogee prediction of 4293 feet. Figure 3-31 shows one of the simulated flight profiles. The launch vehicle's rail exit velocity is 72.70 ft/s. The launch vehicle reaches a maximum Mach number of 0.471 during flight, well under the Mach 1 limit imposed by requirement NASA 2.22.6 and the Mach 0.7 limit imposed by TDR 2.4.

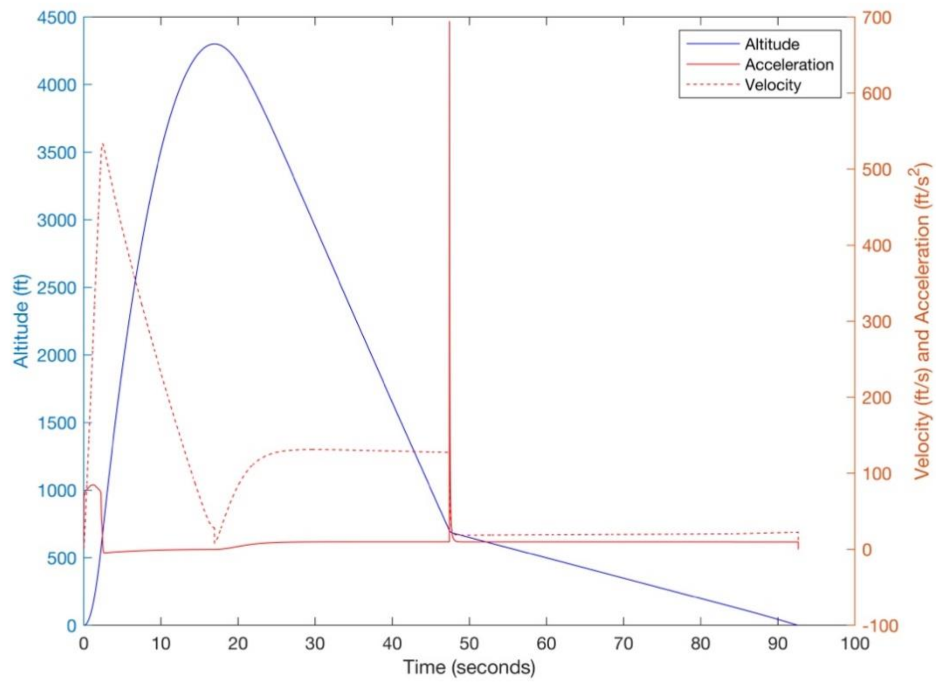


Figure 3-31 Predicted Launch Vehicle Flight Profile

Given the inherent uncertainty in both the wind speeds on launch day and the final weight of the constructed payload, a tolerance study was conducted in RockSim. All simulated launches used a 5° launch rail angle and a 12-foot launch rail. The figure below shows the predicted apogee of the launch vehicle given different potential weights of LOPSIDED and different varying windspeeds on launch day. Any final LOPSIDED weight within 7.5% of the predicted weight will result in an apogee within 400 feet of the declared apogee.

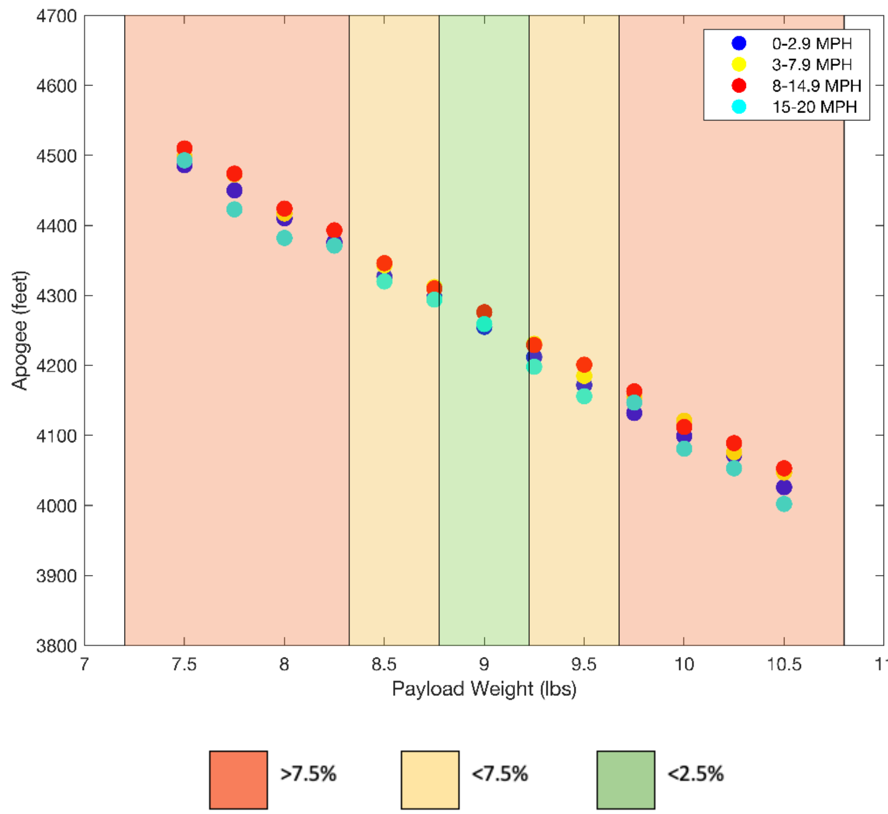


Figure 3-32 Effects of Payload Weight on Apogee

3.5.3 Altitude Verification

Several measurements from the rockets are necessary to perform hand calculations to calculate the apogee of launch vehicle and can be found in Table 3-5. The first step to altitude verification is to calculate the wind resistance coefficient, *k*, using the density of air, ρ, the reference area of the launch vehicle, *A*, and the C_D of the launch of vehicle. Additionally, in order to simplify the final equation, the variables q and x are solved using average thrust, *T*, mass of the rocket, M, and gravity, *g*.

Table 3-5 Variable Definition for Altitude Verification

Quantity	Variable	Value	Units
Density	ρ	1.225	Kg/m^3
Radius	R	0.078	m
Coefficient of Drag	C_D	0.292	N/A
Average Thrust	T	1,567.8	Newtons
Mass	M	20.57	Kg

Gravity	g	9.81	m/s^2
Burn Time	t	2.4	s

$$A = \pi R^2 = 19.113 * 10^{-3}\ m^2$$

$$k = 0.5\rho C_D\ A = 3.418 * 10^{-3}\frac{kg}{m}$$

$$q = \sqrt{\frac{T - Mg}{k}} = 632.187\frac{m^2}{s^2}$$

$$x = \frac{2kq}{M} = 0.210\frac{m}{s^2}$$

With x and q calculated, the maximum velocity of the launch vehicle, v_{max}, can be calculated:

$$v_{max} = q\frac{1 - e^{-xt}}{1 + e^{-xt}} = 156.11\frac{m}{s}$$

Using v_{max}, the height upon motor burnout can be calculated:

$$h_{burnout} = -\frac{M}{2k}ln\left(\frac{T - Mg - kv_{max}{}^2}{T - Mg}\right) = 189.29m$$

The height gained during coast was calculated next:

$$h_{coast} = \frac{M}{2k}ln\left(\frac{Mg + kv_{max}{}^2}{Mg}\right) = 1040.693\text{m}$$

The maximum height can be calculated by adding together the two previous values:

$$h_{max} = h_{burnout} + h_{coast} = 1229.983m = 4035.5\ feet$$

Table 3-6 Altitude Prediction Results

Method	Result
RockSim	4292 feet
Algebraic	4035 feet

The algebraic method yields a result within 6% of the RockSim calculations and, given how simple the method this, the team has decided that this is within an acceptable margin of error.

3.5.4 Stability Margin Simulation

According to RockSim, the final design of the launch vehicle has an initial stability margin of 2.07 calipers and a stability margin of 2.1 upon rail departure of the launch vehicle. The stability margin of the launch vehicle over the entirety of its flight can be seen in the figure below.

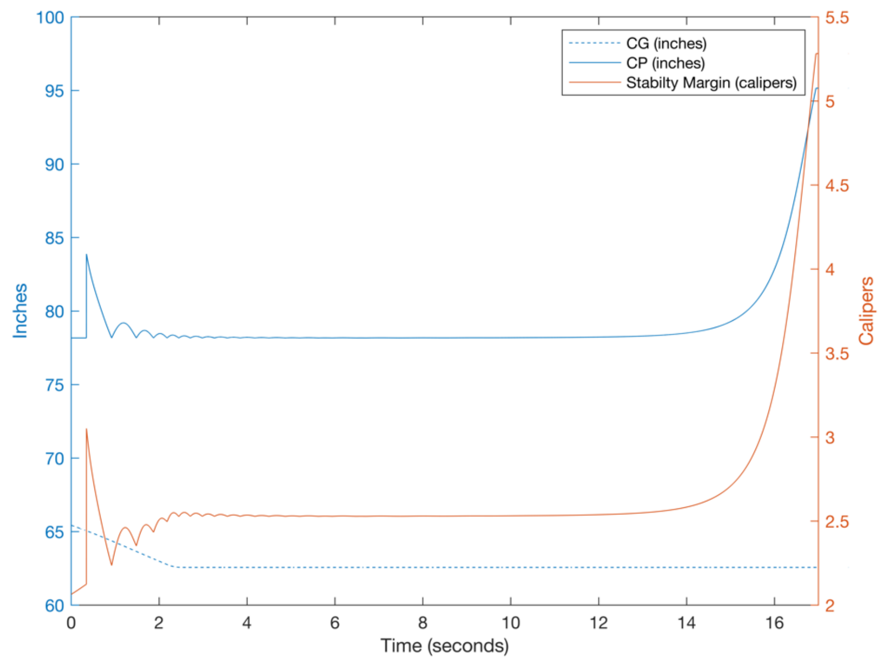


Figure 3-33 Stability Margin Simulation Results

Additionally, the Barrowman's method was used to calculate the initial stability margin in order to verify the results the team received from RockSim simulations. Barrowman's method is a simple series of algebraic equations that is popular in rocketry and is used to identify the center of pressure of the launch vehicle.

The first value that must be found is the arm length of the nose cone, X_N, which for an ogive nose cone has a linear relationship with the length of the nose cone, L_N. The final design for the nosecone of the launch vehicle is 24 inches, which gives:

$$X_N = 0.466 \cdot L_N = 11.184 \; inches$$

The next value to be calculated is the sweep angle. The sweep angle is a simple trigonometric relationship between the fin semi-span, S, and the fin sweep length when measured parallel to the launch vehicle body, X_N. The final design has S=6.00 inches and X_R=3.5 inches.

$$\theta = 90° - \tan^{-1}\frac{S}{X_R} = 30.256°$$

The sweep angle allows for the calculation of the fin mid-chord line length, L_F. Other values which are needed to calculate L_F are chord tip length, C_T, and chord root length, C_R. The final design has C_T = 3.5 inches and C_R = 10.5 inches.

$$L_F = \sqrt{S^2 + \left(\frac{1}{2}C_T - \frac{1}{2}C_R + \frac{S}{\tan\theta}\right)} = 6.541\ inches$$

With L_F calculated, the coefficient for the fins, C_F, can be calculated using the radius of the launch vehicle, *R,* and the number of fins, *N.* The final design has *R* = 3 inches and *N* = 3.

$$C_F = \left(1 + \frac{R}{S+R}\right)\left(\frac{4N\left(\frac{S}{2*R}\right)^2}{1 + \sqrt{1 + \left(\frac{2L_F}{C_R + C_T}\right)^2}}\right) = 6.755$$

In order for the arm length of the fins to be calculated, the distance from the tip of the nose cone to the fin root chord leading edge, X_B, must be used. The final design has an X_B = 95.25 inches.

$$X_F = X_B + \frac{X_R}{3}\frac{C_R + 2C_T}{C_R + C_T} + \frac{1}{6}\left(C_R + C_T - \frac{C_R C_T}{C_R + C_T}\right) = 98.604\ inches$$

Given that $C_N = 2$, with these values, the center of pressure is calculated:

$$X_{CP} = \frac{C_N X_N + C_F X_F}{C_N + C_F} = 78.634\ inches$$

Using the center of gravity from Rocksim, X_{CG} = 65.42 inches, the stability margin can be calculated. The stability margin from both the Barrowman method and RockSim simulations can be found in the table below. There is a 6.38% difference between the two calculation methods, but both remain above the NASA requirement of 2.0 calipers at launch.

Table 3-7 Stability Margin Calculation Results

Computation Method	Result (calipers)
Barrowman	$S_{M,B} = \frac{X_{CP} - X_{CG}}{R}$ =2.202
RockSim	2.07

A summary of the variables, and the values of those variables, used in the Barrowman method can also be found below.

Table 3-8 Stability Margin Variable Definition

L_F – Mid-chord line length	X_F – Fin arm length	X_R – Fin sweep length measured parallel to launch vehicle body	X_B – nose cone tip to fin root chord leading edge
L_N – Length of nose cone	C_N – Nose cone coefficient	X_N – Nose cone arm length	θ – Sweep angle
R – Radius of launch vehicle	C_R – Root chord length	C_T – Tip chord length	
S – Fin semi-span	N – Number of fins	C_F – Fin coefficient	

Table 3-9 Measured Stability Variable Values

Variable	Input Value	Units
C_N	2	N/A
L_N	24	Inches
R	3	Inches
S	6	Inches
N	3	N/A
C_R	10.5	Inches
C_T	3.5	Inches
X_B	95.25	Inches
X_R	3.5	Inches
CG	64.42	Inches

Table 3-10 Calculated Stability Variable Values

Variable	Output Value	Units
X_N	11.184	Inches
θ	30.256°	Degrees
L_F	6.541	Inches

C_F	6.755	N/A
X_F	98.604	Inches
X_{CP}	78.634	Inches
$S_{M,B}$	2.369	Calipers

3.5.5 Stability Margin Tolerance Study

Due to uncertainties in the final manufactured weight and CG of the payload, the team determined it would be necessary to conduct a tolerance study on how these uncertainties would affect the stability margin of the launch vehicle.

In order to perform this study, data was taken from RockSim manually while the weight and CG of the payload were varied. The weight was varied in 0.25lb increments up to a threshold of ±1.5lb, which is 16.7% of the projected design weight of the payload. The CG of the payload, as measured from the front of the payload bay, was varied in 0.5 inch increments up to a threshold of ±2 inches. The results of the tolerance study can be seen in the figure below.

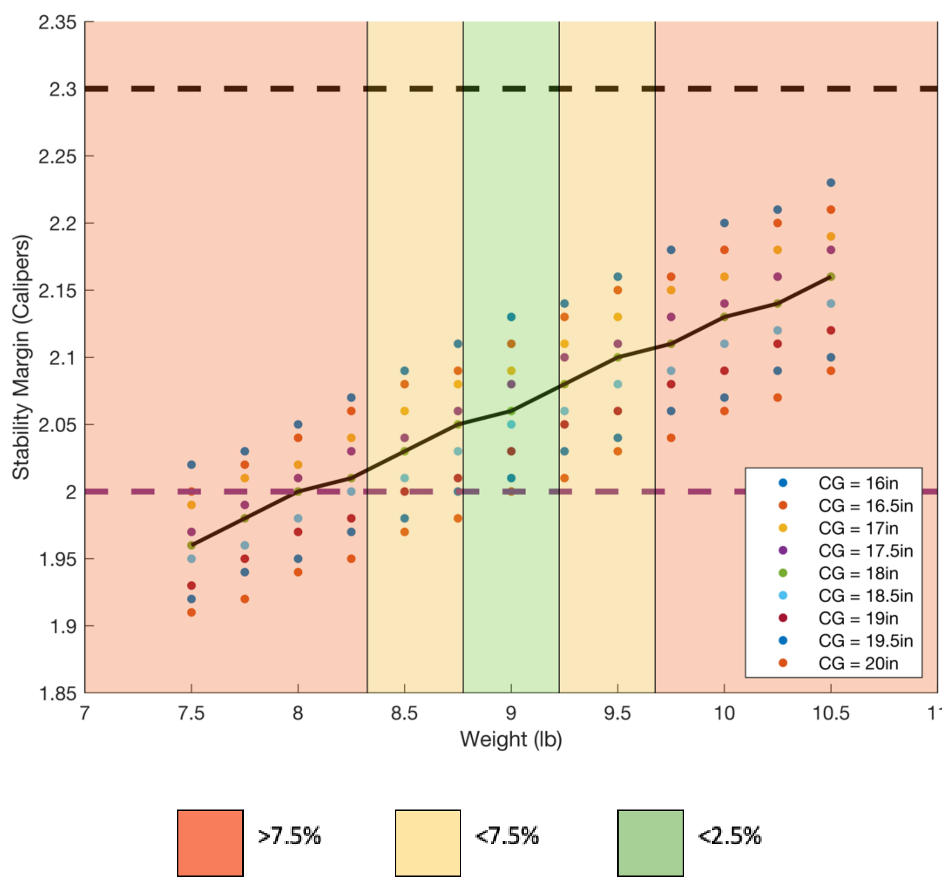


Figure 3-34 Stability Tolerance Study

The lower bound of a stability margin of 2.0 calipers is defined by NASA and the upper bound of 2.3 calipers is defined to reduce the chances of weathercocking after departure from the launch rail. The projected design CG of the payload is indicated by the black line, making it easy to tell which data points are above or below the projected design. What the tolerance study reveals is that the payload is skewing towards the lighter end of the acceptable stability margin envelope; there is more room to increase the weight of the payload than there is to decrease it. The tolerance study also reveals that while the CG of the payload does affect stability, the weight of the payload has a much greater effect. Both of these insights will be helpful when further iterating on the design of the payload and the launch vehicle itself. This study lastly reassures the team that the projected CG of the payload will still lead to a static margin of greater than 2.0 calipers as long as the final manufactured design is within ±7.5% of the final design.

3.5.6 Kinetic Energy at Landing

Kinetic energy can be calculated using the below equation, where E is the kinetic energy of the object, m is its mass, and V is its velocity.

$$E = \frac{1}{2} m V^2 \tag{1}$$

For each body section, the velocity of the body section for which it would have 75 ft-lbf of kinetic energy at landing has been tabulated below. The smallest of these velocities can be identified and serves to constrain the selection of a main parachute.

Table 3-11 Body Section Maximum Allowable Descent Velocity

Launch Vehicle Section	Section Mass	Maximum Allowable Descent Velocity
Nosecone with LOPSIDED-POS	.5704 slugs	16.2 ft/s
Nosecone	.2907 slugs	22.7 ft/s
LOPSIDED-POS	.2797 slugs	23.2 ft/s
Midsection	.3457 slugs	20.8 ft/s
Fin Can	.3686 slugs	20.2 ft/s

Using this data, the Fruity Chutes 120” Iris UltraCompact parachute has been selected as the main parachute as described in section 3.4.1.4. The descent velocity of this parachute is calculated for the vehicle mass both with and without the LOPSIDED-POS attached to the launch vehicle as detailed in section 3.4.1.4. The kinetic energy of each body section at landing has been calculated and tabulated below.

Table 3-12 Body Section Kinetic Energy at Landing

Section	Mass	Kinetic Energy w/ LOPSIDED-POS	Main Velocity w/ LOPSIDED-POS	Kinetic Energy w/o LOPSIDED-POS	Main Velocity w/o LOPSIDED-POS
Nosecone w/ LOPSIDED-POS	.5704 slugs	60.7 ft-lbf	14.5 ft/s	46.9 ft-lbf	12.8 ft/s
Nosecone	.2907 slugs	30.6 ft-lbf	14.5 ft/s	23.9 ft-lbf	12.8 ft/s
LOPSIDED-POS	.2797 slugs	29.4 ft-lbf	14.5 ft/s	23. ft-lbf	12.8 ft/s
Midsection	.3457 slugs	36.4 ft-lbf	14.5 ft/s	28.4 ft-lbf	12.8 ft/s
Fin Can	.3686 slugs	38.8 ft-lbf	14.5 ft/s	30.3 ft-lbf	12.8 ft/s

With a successful separation of the LOPSIDED-POS, the heaviest section of the launch vehicle will descend with a kinetic energy of 44.2 ft-lbf. If the LOPSIDED-POS successfully exits the payload bay but remains attached to the recovery harness, the descent velocity will increase with landing mass and the maximum body section kinetic energy becomes 56.4 ft-lbf. Should the LOPSIDED-POS remain in the payload bay all the way to descent, the maximum section kinetic energy becomes 60.7 ft-lbf. All three of the maximum body section kinetic energy predictions calculated for the main parachute are within the kinetic energy requirements set forth by NASA 3.3, therefore the 120” Iris UltraCompact is an effective selection for the main parachute.

By squaring the terminal velocity equation given in section 3.5.6, it can be shown that the velocity squared term in the kinetic energy equation scales linearly with mass. Should all body section masses be increased proportionally, kinetic energy will scale quadratically with mass. To this end, the total mass of the launch vehicle could increase by 22.5% and still meet kinetic energy requirements. This buffer accounts for any increases in mass due to manufacturing, changing mission or payload requirements, or model inaccuracies.

3.5.6.1 Alternative Calculation Method

To verify the validity of results calculated using the above method, the kinetic energy at landing was determined using RockSim. A test case was run using the worst-case scenario configuration wherein the LOPSIDED-POS fails to exit the payload bay. RockSim does not consider the configuration of the launch vehicle during descent, and as such cannot directly output section kinetic energy. The descent velocity at landing as computed in RockSim is therefore used to compute the kinetic energy at landing for each body section as below.

Table 3-13 RockSim Body Section Kinetic Energy at Landing

Section	Mass	Descent Velocity	Kinetic Energy
Nosecone w/ Payload	0.5704 slugs	14.95 ft/s	63.7 ft-lbf
Midsection	0.3457 slugs	14.95 ft/s	38.6 ft-lbf
Fin can	0.3686 slugs	14.95 ft/s	41.2 ft-lbf

The table above shows the kinetic energy of each body section at landing has only a mild increase of approximately 3 ft-lbf over the hand calculations. This difference arises from the numerical approximations performed by RockSim to determine the launch vehicle descent velocity under parachute. This approach accounts for the parachute spill hole but not the full parachute geometry, while the hand calculations make use of experimental data provided in the form of manufacturer ratings to calculate the drag coefficient.

3.5.7 Descent Time

Launch vehicle descent times from apogee are calculated as a necessary step during the wind drift calculations and are detailed in the following section.

3.5.8 Wind Drift

Wind drift calculations rely on several key assumptions. First, it is assumed that the rocket travels vertically to the predicted apogee, deploys the drogue parachute and immediately begins descending at the drogue parachute's terminal velocity. The same assumption is applied to the main parachute, where it is assumed that the launch vehicle immediately decelerates to the main parachute terminal velocity at 700ft, and to the payload deployment where it is assumed that when the LOPSIDED-POS separates from the main parachute recovery harness the launch vehicle assembly immediately decelerates with the reduction in weight. From apogee to landing, the launch vehicle and separated LOPSIDED-POS are assumed to travel in a single direction at a constant speed equal to the wind condition.

Although this calculation approach is not wholly accurate to the actual wind drift performance, it is a reasonable worst-case approximation. The assumption of the launch vehicle instantly reaching terminal velocity after parachute deployment means that the modeled vehicle descent time will be a few seconds shorter than the actual vehicle descent time.

The distances between apogee, main deployment, and landing are known as is the descent velocity of the launch vehicle during each stage of the recovery process. The descent time can therefore be easily calculated as below where t is the total descent time, z_d is the drogue deployment altitude, z_{m-} is the main deployment altitude, z_p is the LOPSIDED-POS deployment altitude, v_d is the descent velocity under drogue, v_{m1} is the descent velocity under main with the LOPSIDED-POS attached, and v_{m2} is the descent rate under main following separation of the LOPSIDED-POS.

$$t = \frac{z_d - z_m}{v_d} + \frac{z_m - z_p}{v_{m1}} + \frac{z_p}{v_{m2}} \quad (2)$$

Using the target apogee of 4473 ft gives a descent time of 85.0 seconds per the equation above. Multiplying this descent time by a given wind speed gives the distance traveled across the ground by the launch vehicle constantly sustaining these wind speeds, as shown in the table below.

Table 3-14 Wind Drift and Descent Time

Wind Speed	Apogee	Descent Time	Drift Distance
0 mph	4473 ft	85 s	0 ft
5 mph	4473 ft	85 s	622.7 ft
10 mph	4473 ft	85 s	1245.5 ft
15 mph	4473 ft	85 s	1868.2 ft
20 mph	4473 ft	85 s	2490.9 ft

At the maximum permissible wind speed for launch of 20 mph, the launch vehicle's estimated drift distance is 2490.9 ft, within the maximum allowable drift distance of 2500 ft set forth by requirement NASA 3.10. Since this model constitutes the worst-case scenario for wind drift, this proximity to the limit is deemed acceptable. While this does not allow any margin of error for reductions in launch vehicle weight, ballast may be added as detailed in section 3.2.6 without exceeding recovery system kinetic energy limits to increase descent speed and reduce wind drift.

3.5.8.1 Alternative Calculation Method

To confirm the validity of the above wind drift calculations, the wind drift was modeled in RockSim at the same wind speeds used for the hand calculation cases. The launch vehicle is assumed to be launched into the wind at a 5° launch rail angle. Wind drift distance is calculated by finding the difference between the range at apogee and the range at landing data points provided in the RockSim output. Descent time is calculated in a similar manner, taking the difference between the time at apogee and time at landing data points. Thus, the descent time and wind drift are determined as if the launch vehicle begins to descend directly above the launch pad.

Table 3-15 RockSim Wind Drift and Descent Time

Wind Speed	Apogee	Descent Time	Drift Distance
0 mph	4275 ft	76 s	0 ft
5 mph	4300 ft	76 s	557.7 ft
10 mph	4308 ft	76 s	1110.9 ft
15 mph	4292 ft	76 s	1669.6 ft
20 mph	4277 ft	76 s	2231.6 ft

It was found that the descent time was consistently 5 s less than the hand calculations. The wind drift was found to be decrease in comparison to hand calculated results as wind speed increases. These differences most likely result from the aforementioned differences in handling parachute drag coefficients between the two methodologies. Further, RockSim does not allow for controlled variable wind speed, hence the wind affects not only the descent but the ascent of the launch vehicle. This is more realistic but fails to capture the worst-case scenario considered by the hand calculations. As RockSim does not provide for the consideration of independent launch vehicle sections during flight, this method assumes that the payload stays within the launch vehicle to touchdown. This will reduce the wind drift distance; however sufficient margin of error exists even at the highest considered winds for the landing of both the launch vehicle and LOPSIDED-POS within the limits set forth by requirement NASA 3.10.

3.5.9 Black Powder Ejection Charge Mass

Several online calculators exist for calculating the mass of black powder required to form an effective ejection charge for a launch vehicle cavity volume and shear pin strength. Many of these calculators assume that black powder is converted into hot gasses at a 1:1 mass ratio. Examining even the simplest reaction models for black powder combustion shows that this is not the case, and inspection of launch vehicle body sections exposed to ejection charges shows solid particulate residue remaining after the detonation. The model below in Equation 3 therefore is used to determine the amount of black powder converted to ejection gasses for a given mass of black powder.

$$10\,KNO_3 + 3S + 8C \rightarrow 2K_2CO_3 + 3K_2SO_4 + 6CO_2 + 5N_2 \quad (3)$$

To determine the correct mass of black powder, the mass of the gaseous products is calculated as a fraction of a given mass of black powder, about 33.5% for the reaction model used here. The pressurized section is assumed to be at the ambient pressure for the altitude at parachute deployment. A target pressure rise is specified, and the ejection gasses are assumed to be at the manufacturer specified combustion temperature for the black powder. The mixing problem is then solved for the mass of hot gases needed to deliver the desired pressure rise. It is then trivial to back out the mass of black powder required to provide the needed mass of gas for a successful ejection under specified conditions.

Table 3-16 Ejection Charge Masses

Ejection Event	Black Powder Mass
Main Parachute Primary	2.9 g
Main Parachute Secondary	3.4 g
Drogue Parachute Primary	2.6 g
Drogue Parachute Secondary	3.1 g

The above table gives the calculated black powder masses for the main and drogue ejection charges. Secondary charges for both deployment events are sized 0.5 g larger than calculated to correct for circumstances preventing a successful ejection with the primary ejection charge. For the main parachute piston ejection system, the target pressure rise is 15 psi to compensate for friction forces between the piston coupler tube and the airframe.

3.5.10 Parachute Opening Shock

To model the stresses that will be applied to the shock cords and recovery harness attachment points, it is important to approximate the deceleration of the launch vehicle and the time it takes the parachute to inflate. A rule of thumb for parachute inflation time is that it takes a time approximately equal to the time it takes air to travel from the edge to the center of the furled parachute. This is given in the equation below, where t_i is the inflation time of the parachute, r is the parachute radius, and V is the descent velocity prior to parachute deployment. The coefficient of 8 is taken from Ludtke for a cloth parachute.

$$t_i = 8dV \quad (4)$$

From this and the difference in terminal velocities between the main and drogue parachutes, the equation below gives the deceleration of the launch vehicle at main parachute deployment where a is the deceleration, v_d is the drogue descent velocity, v_m is the main descent velocity, and t_i is the parachute inflation time.

$$a = \frac{v_d - v_m}{t_i} \quad (5)$$

For a total launch vehicle mass with the LOPSIDED-POS included of 1.395 slugs, the main parachute opening shock is computed to be 388 lbf using the deceleration value as computed above. The individual loading experienced by each section is given in the table below.

Table 3-17 Body Section Opening Shock

Launch Vehicle Body Section	Body Section Mass	Parachute Opening Time	Main Parachute Opening Shock
Nosecone w/ LOPSIDED-POS	.5704 slugs	.3 s	172 lbf
Full Launch Vehicle	1.2847 slugs	.3 s	388 lbf
Midsection and Fin Can	.7143 slugs	.3 s	303.4 lbf

4. Payload Criteria

4.1 Payload Mission Statement

The objective of the payload mission is to design, construct, and launch a planetary lander within a high-powered launch vehicle. This lander will achieve an upright orientation and be able to self-level within five degrees of horizontal. The initial and final angles relative to horizontal will be recorded. After leveling is complete, the payload will capture a 360-degree panoramic photo of the landing site and transmit this photograph back to the team's ground station.

4.2 Payload Success Criteria

The payload team has established the following criteria for categorizing the payload success levels based on the ability if LOPSIDED-POS to fulfil its goal.

Table 4-1 Payload Success Criteria

Success Level	Payload Aspect	Safety Aspect
Complete Success	LOPSIDED successfully lands in its upright configuration; the self-leveling procedure is completed within 5 degrees of horizontal; the POS captures and transmits at least one 360-degree image of the landing site, which is received by the team.	No injuries are inflicted on individuals present during the execution of mission requirements.
Partial Success	LOPSIDED successfully lands in its upright configuration; the self-leveling procedure fails to level the vehicle within 5 degrees of horizontal, or the leveling system is impeded in some way; the POS captures and transmits at least one 360-degree image of the landing site, which is received by the team.	One or more close calls involving individuals present during the execution of mission requirements, but no injuries occur.

Partial Failure	LOPSIDED fails to land upright; self-leveling cannot be attempted; the POS is still able to capture and transmit photos, but the images do not properly encapsulate the landing site; damage to LOPSIDED's landing gear/leveling system can be repaired.	Minor injuries inflicted on individuals present during the execution of mission requirements.
Complete Failure	LOPSIDED's deployment system fails, leading to an unrecoverable payload; no images are captured or transmitted.	Major injuries inflicted on individuals present during the execution of mission requirements.

4.3 LOPSIDED-POS Final Design

4.3.1 Overall Design

The final payload design consists of an upright rectangular body of varying thickness, with four equally spaced legs for support. The legs are attached to the lander's two-axis, gyroscopic leveling system. The leveling system consists of two concentric rings that will allow the body of the lander to rotate about two axes. Landing will be driven by gravitational force acting on the body of the lander. The combined payload body and leveling system are designated LOPSIDED, or Lander for Observation of Planetary Surface Inclination, Details, and Environment Data. In addition to the components related to payload leveling and recovery, LOPSIDED will also house the Planetary Observation System (POS). The POS is responsible for capturing a 360-degree image of LOPSIDED's landing site and transmitting this photo to the team's ground station on the launch field.

The figure below depicts an overview of the payload mission, and the major events that occur during operation. When the launch vehicle reaches apogee, the rotary latch attached to the payload bulkhead opens, which will allow the payload to be removed from the payload bay. This removal occurs at 700 feet, when the main parachute deploys and pulls the LOPSIDED-POS from the payload bay. The LOPSIDED-POS will descend with the main parachute until 500 feet, when an Advanced Retention Release Device (ARRD) separates the LOPSIDED-POS from the main parachute shock cord. This event also releases the LOPSIDED-POS parachute from its parachute bag and allows the payload to descend under its own parachute. Once the LOPSIDED-POS lands, two electronic latches will open to release the parachute, and the initial surface inclination of the landing site will be recorded. Then, the solenoid latches will open to release the gravity-assisted leveling system, and the final angle post-leveling will be recorded. After this, the POS will initiate the image capture sequence, the images will be processed and compressed as necessary, and the images will be transmitted to the team's ground station for further processing. The details of each of these events are elaborated on in the following sections.

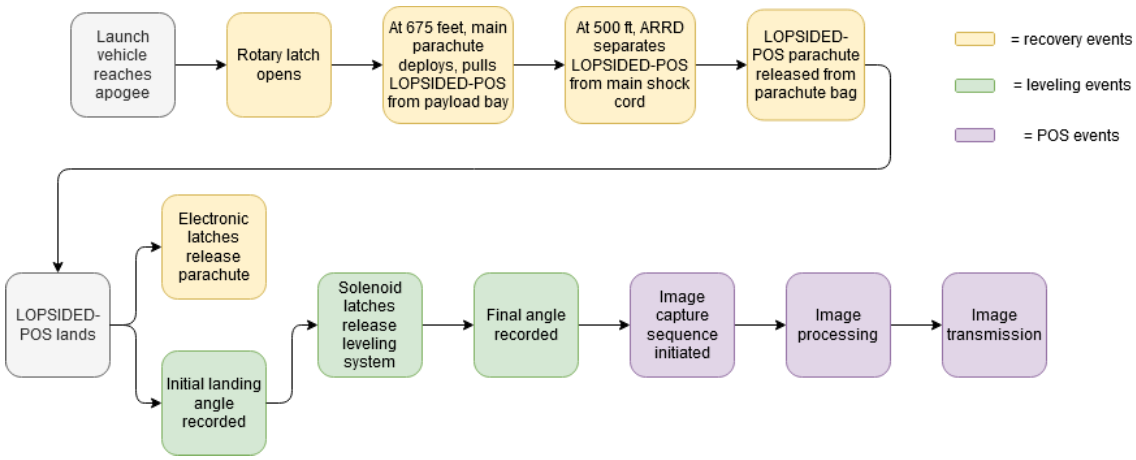


Figure 4-1 LOPSIDED-POS Mission Overview

4.3.2 LOPSIDED Vehicle

LOPSIDED is divided into 3 main sections: The first is the upper section that will house both the imaging and integration equipment. The second is a thinner section that the leveling system will attach to. The third is the lower section that will house the electronics.

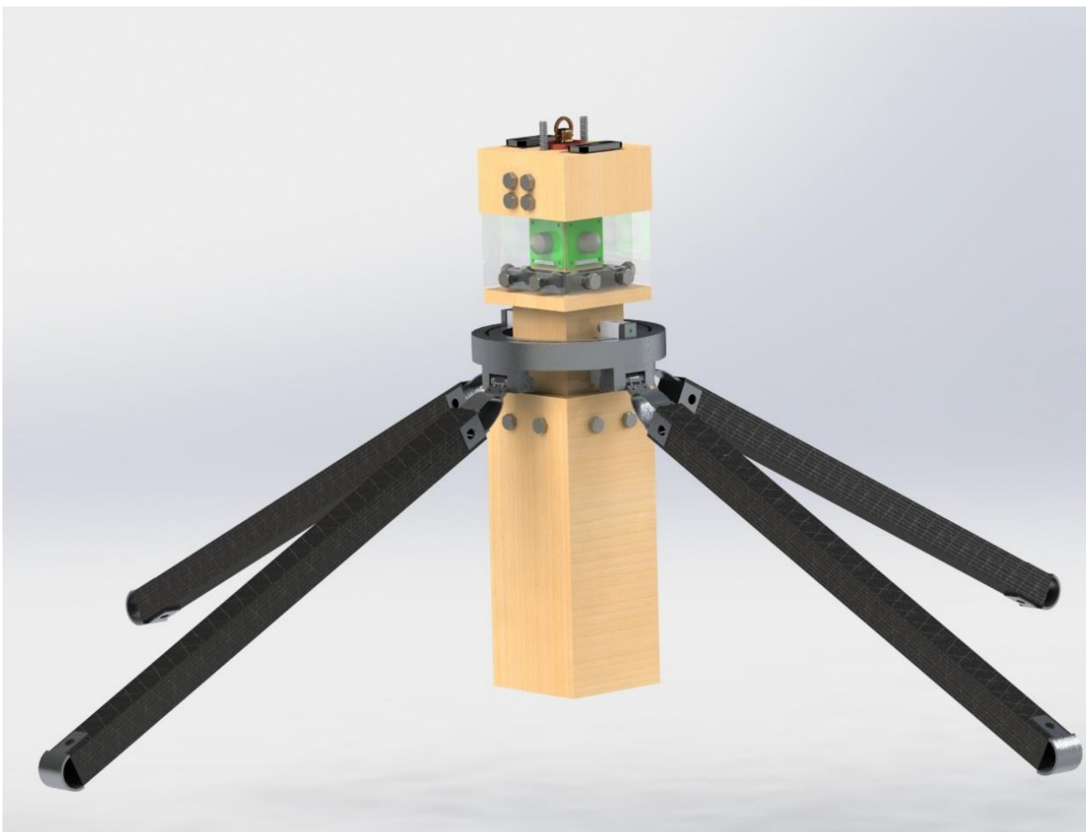


Figure 4-2 LOPSIDED-POS Exterior Overview

4.3.2.1 Structural frame

The ARRD at the top of the payload threads onto a threaded rod. This rod will run through the POS mounting block and will attach to an aluminum frame that fits the interior of the chassis. The purpose of this frame is to absorb most of the opening parachute shock forces as well as redistribute them throughout the body.

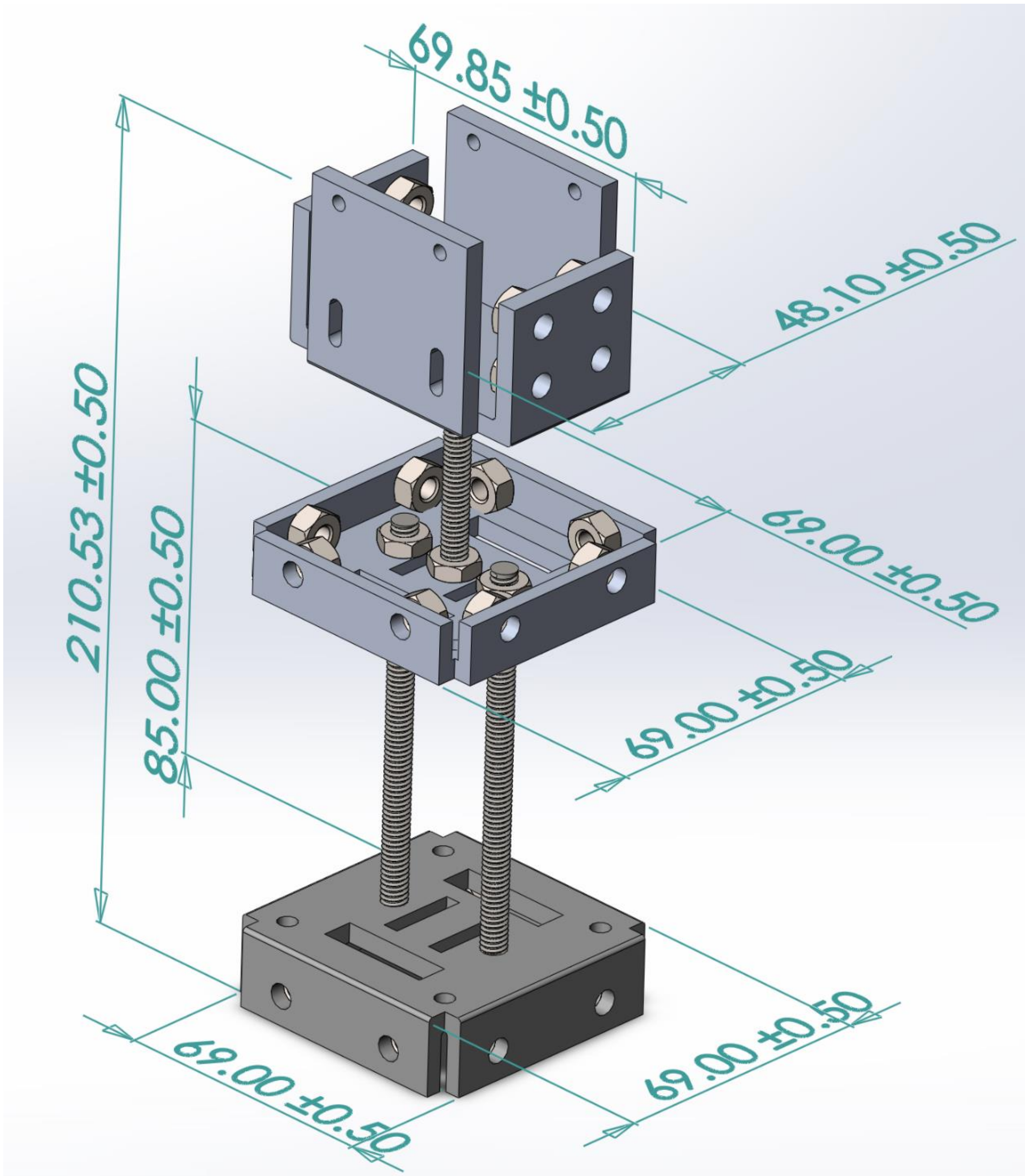


Figure 4-3 LOPSIDED Structural Frame Dimensions

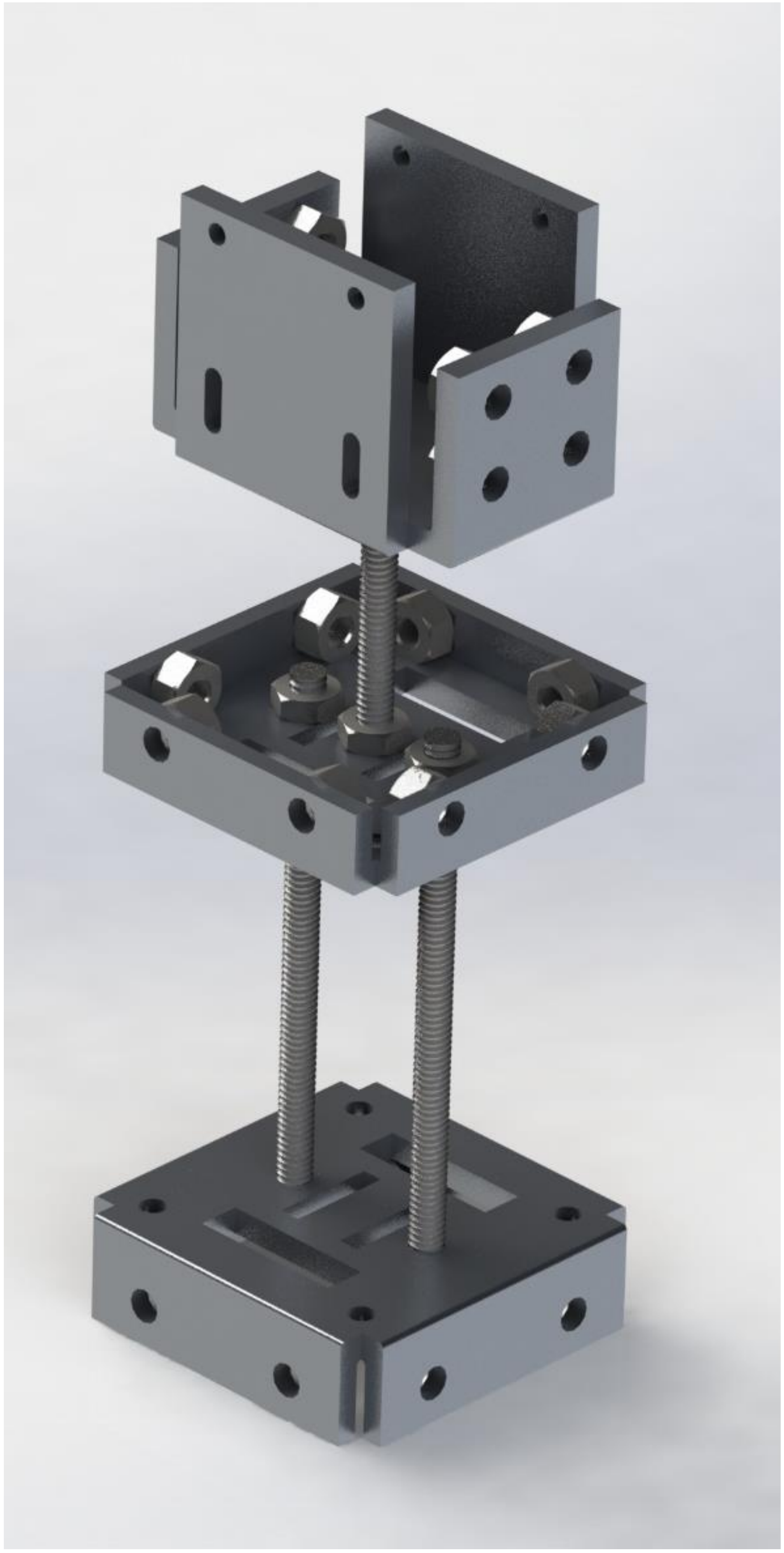


Figure 4-4 Rendered LOPSIDED Structural Frame

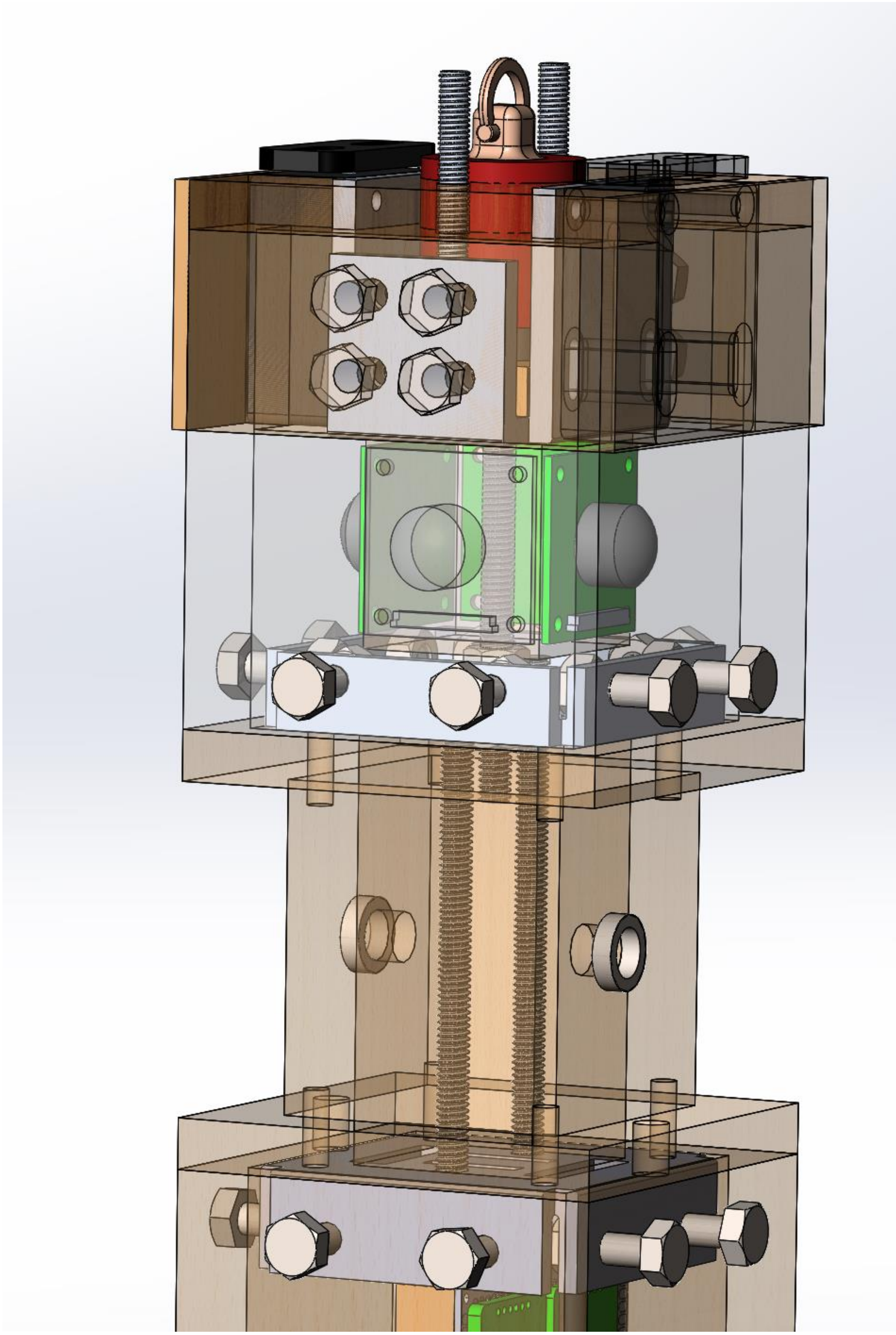


Figure 4-5 Structural Frame Within LOPSIDED Body

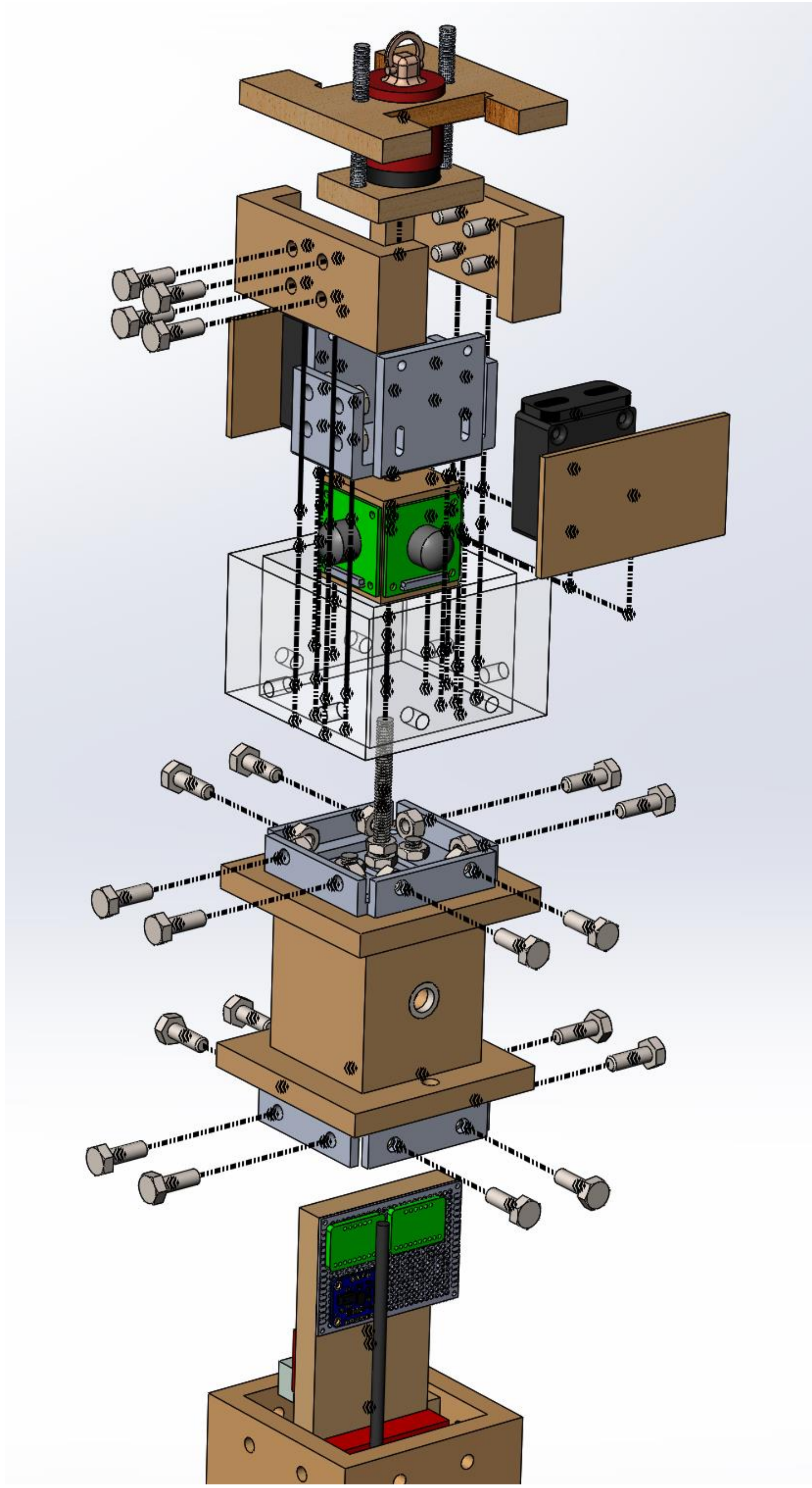


Figure 4-6 LOPSIDED Exploded View

The frame will also serve as an assembly structure that the three main chassis pieces can attach to. The threaded rod will screw into a plate just beneath the POS mounting block. This plate will have brackets so that the upper section can be mounted. The plate will be attached to a lower bracket that follows the interior of the chassis through the middle section along the walls adjacent to the through-axis that connects to the leveling system. These brackets will extend into the lower section, allowing it to be mounted to the frame.

4.3.2.2 Upper Section

The upper section will house the main parts of the integration and POS systems. It will consist of the ARRD, the electronic latches, and a mounting block with the four POS cameras.

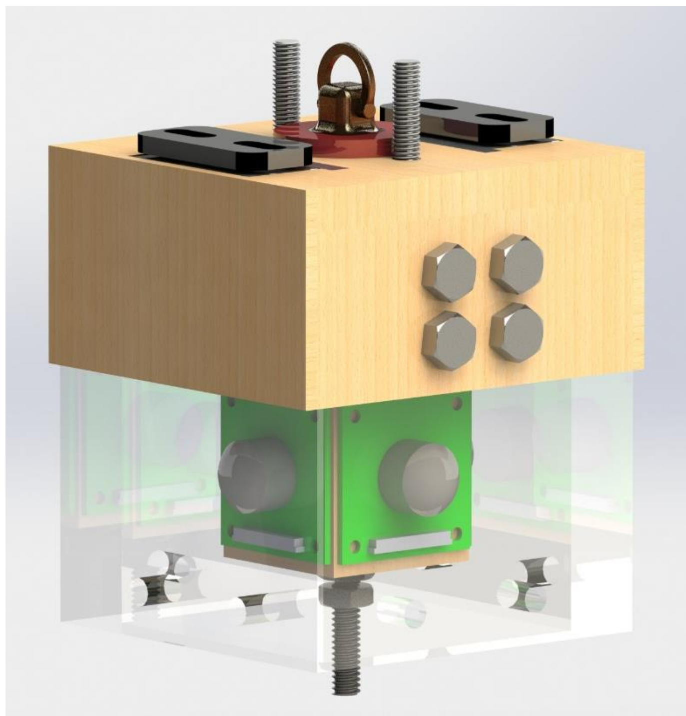


Figure 4-7 LOPSIDED Upper Section

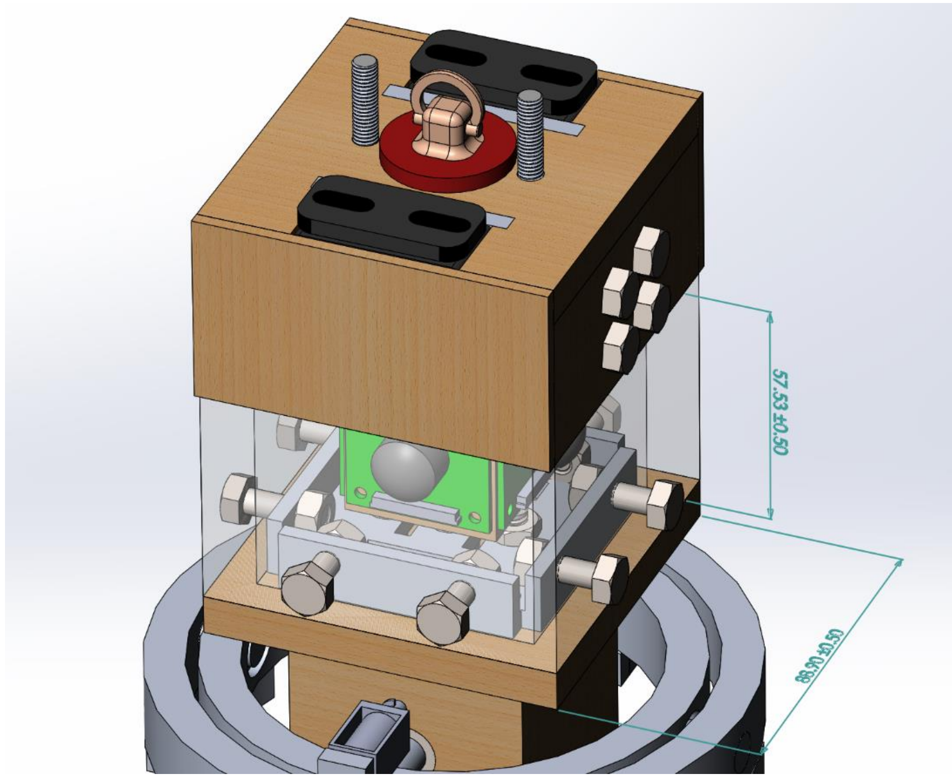


Figure 4-8 Polycarbonate Window Dimensions

A section of clear polycarbonate material will allow the POS cameras to capture the environment without any visual occlusions.

4.3.2.3 Middle Section

The middle is thinner than the upper and lower sections to allow for the leveling system to have a larger tilt range. Ball bearings will be press fitted into the outside walls of middle section, which will allow for the solenoid locking mechanism to be placed within the chassis for the inner ring. More detail is provided in section 4.3.2.5

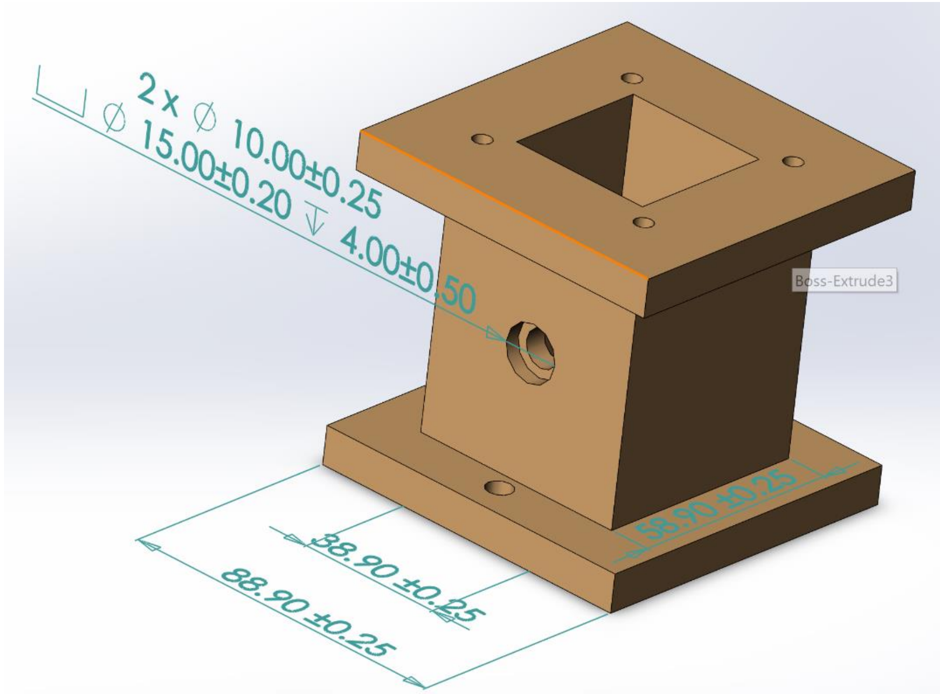


Figure 4-9 LOPSIDED Middle Section

The middle section, along with the structural frame will serve as a point of attachment for the other two sections.

4.3.2.4 Lower Section

The lower section is dedicated to electronics. A sled will be slotted into the lower section where the LOPSIDED, POS, and integration subsystem electronics will be mounted as shown in Figure 4-10. The structural frame mentioned previously will have sections cut out so that the POS ribbon cables, solenoid wires, and other wires can be routed into the lower section.

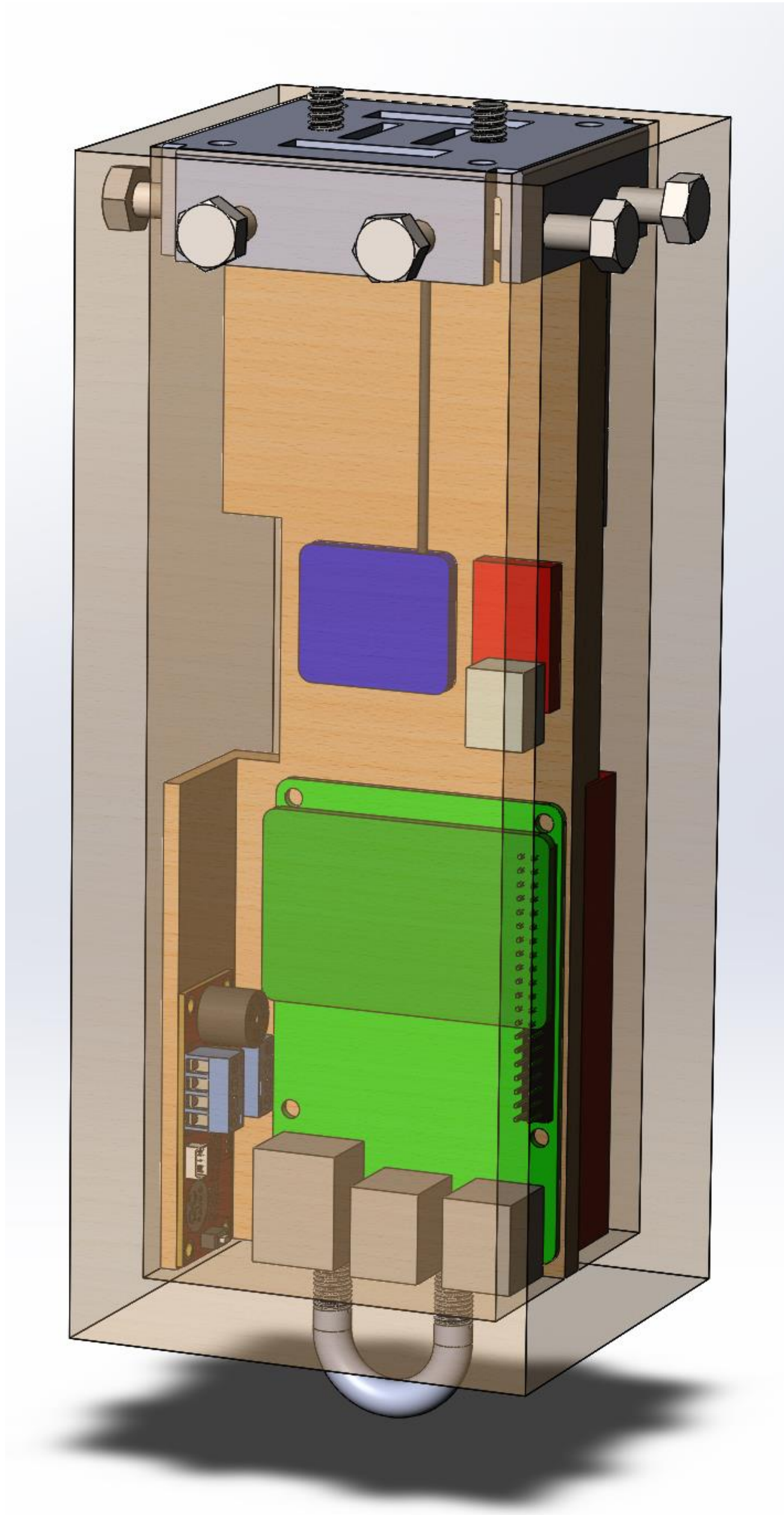


Figure 4-10 LOPSIDED Lower Section

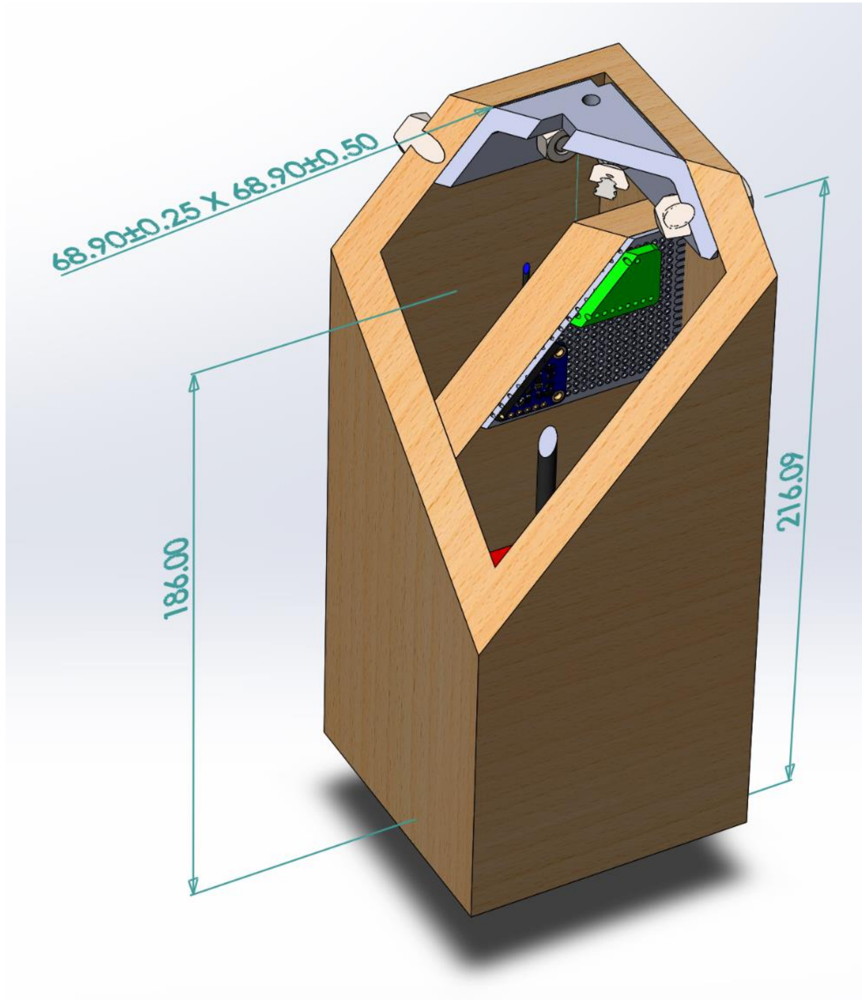


Figure 4-11 LOPSIDED Electronics Led Size Restrictions

Alongside the electronics, a ballast will be placed at the bottom of the lower section. This will help to lower LOPSIDED's CG and help with stability.

4.3.2.5 Leveling System

The levelling system and chassis design will feature a 2-axis, both of which are horizontal, gyroscopic ring design that will utilize the force due to gravity to actuate its rotation. For this to work a ballast will be placed at the bottom of the payload such that the CG lies beneath the 2 axes to improve stability. The chassis will have a cut-out design where a thinner middle section allows the rings to rotate further, increasing its tilt range. The payload is designed to have a minimum tilt of 15° off its neutral axis, meaning it can handle a 20° grade and still be within the 5° tolerance.

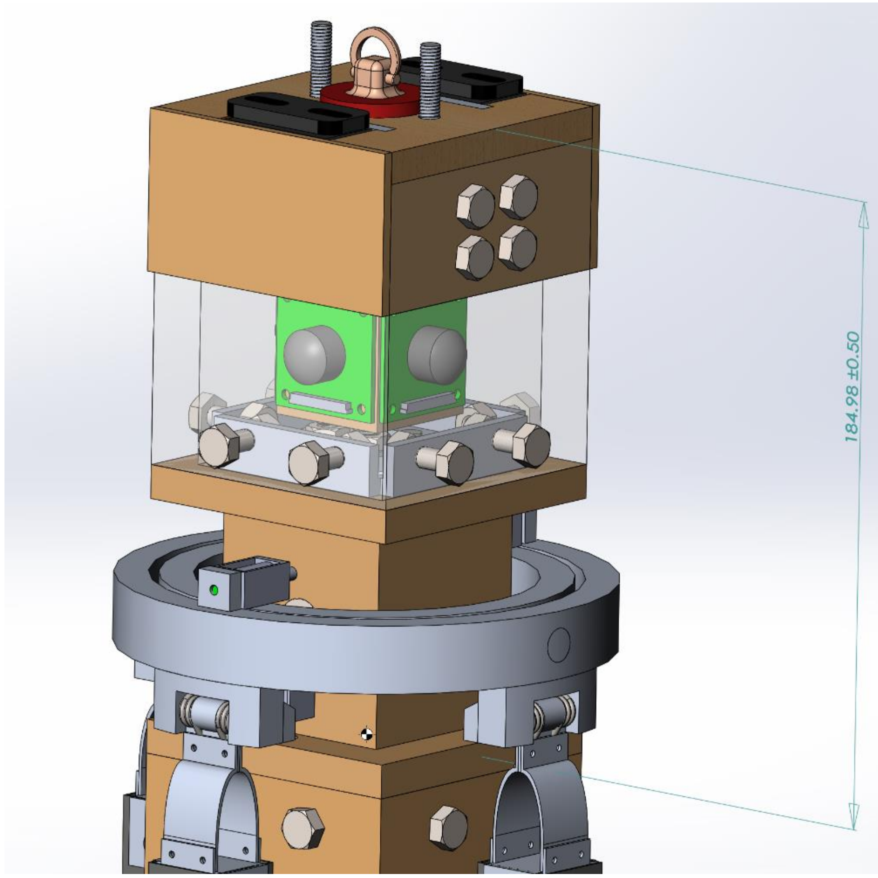


Figure 4-12 LOPSIDED Center of Gravity

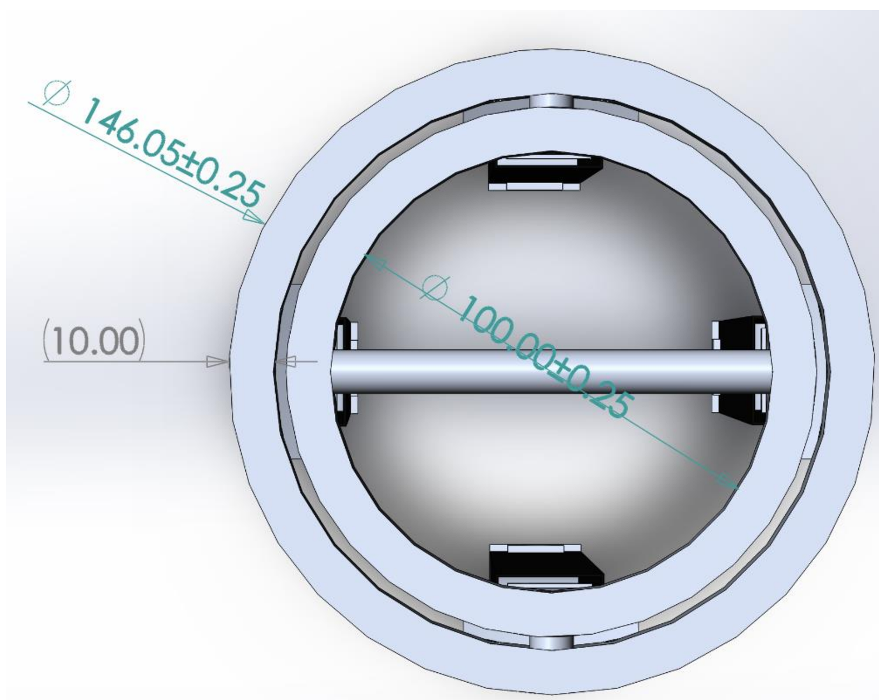


Figure 4-13 LOPSIDED Ring Dimensions

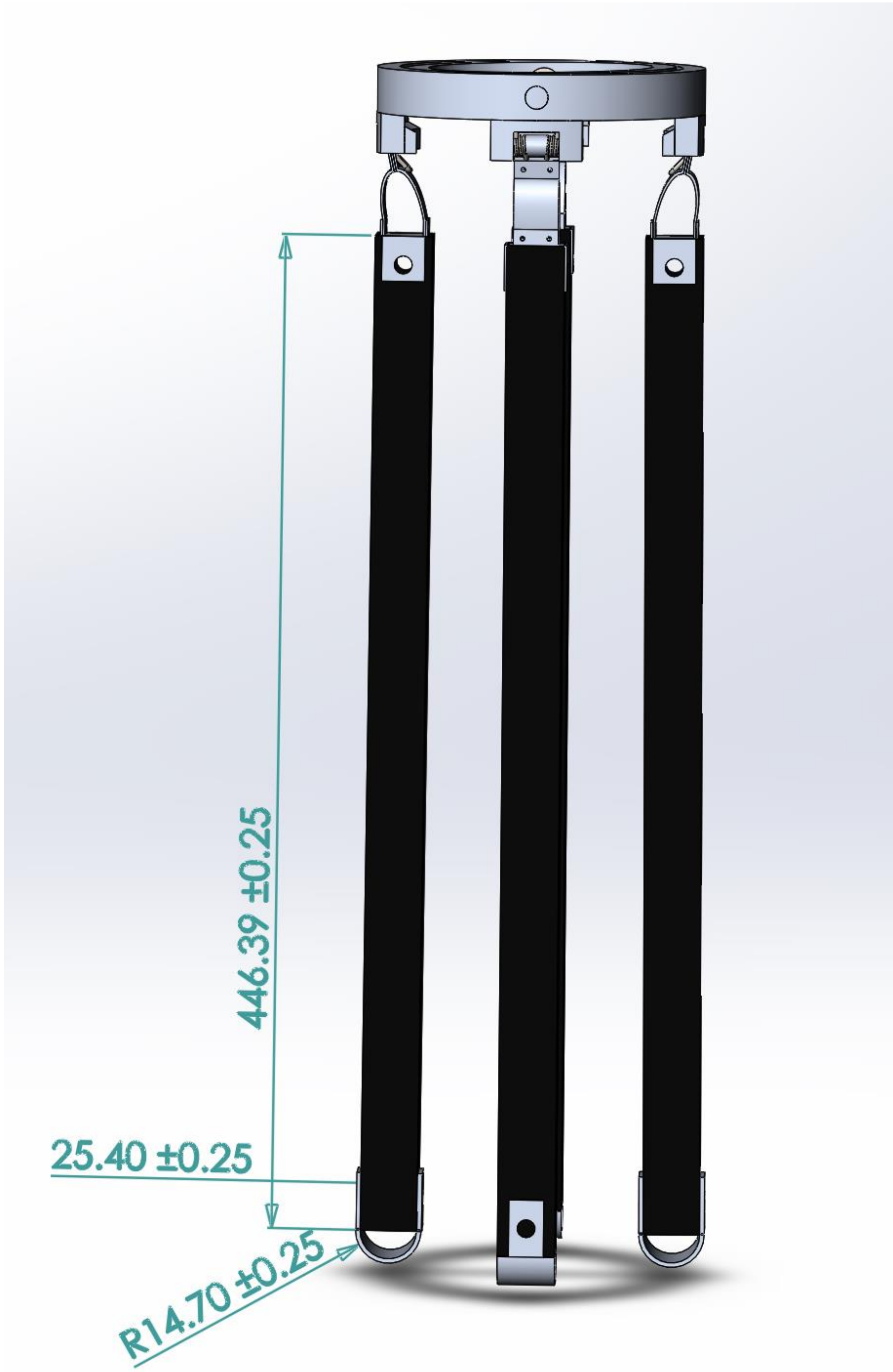


Figure 4-14 LOPSIDED Leg Dimensions

The design features two rings. The inner ring will have a rod running across its diameter that the body can rotate about. The outer ring will have two smaller rods connecting to the inner ring. Ball bearings will be press fitted at the connection points to allow for smooth rotation. The outer ring will also have mounting brackets for the legs to attach to. The rings will be made from CNC'ed aluminum and the legs will be made from a shelled-out rectangular bar of carbon fiber. The parts joining the legs to the outer ring, as well as feet, will be made from bent aluminum sheet metal.

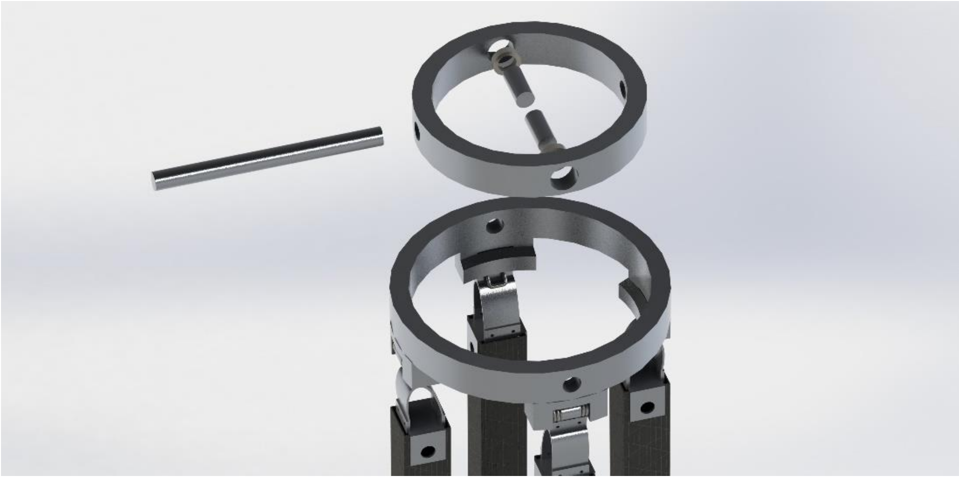


Figure 4-15 LOPSIDED Supports Exploded View

The legs will be stowed flat against the body while inside the payload bay. Once removed from the payload bay, the legs will rotate out to an angle determined by a cable, this process will be driven by a torsional spring. The cable will run through the outer ring into the inside and be attached to legs. The torsional spring will rotate until the cable becomes taught. As the cable is strong in tension, it will be strong enough to counter the moment generated upon landing.

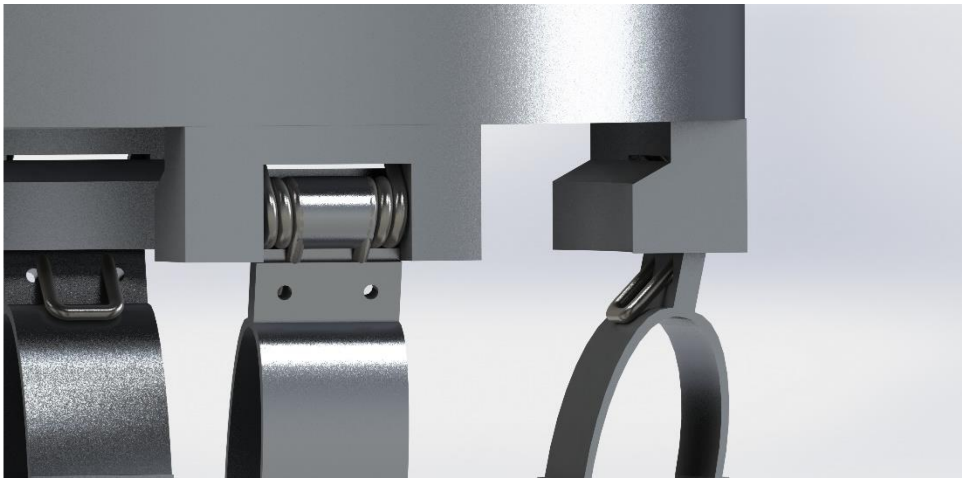


Figure 4-16 Landing Leg Spring Mechanism

4.3.2.6 Range of Motion

Using the CAD model to make tilt range approximations across all orientations. The maximum tilt range was recorded as follows. LOPSIDED appears to have the smallest maximum tilt at the orientation shown with a tilt of 15 degrees. It's largest maximum tilt at a more preferred orientation was measured to be just under 20 degrees. With the 5-degree tolerance, the current design can handle a landing site slope grade of 20-25 degrees depending on the landing orientation.

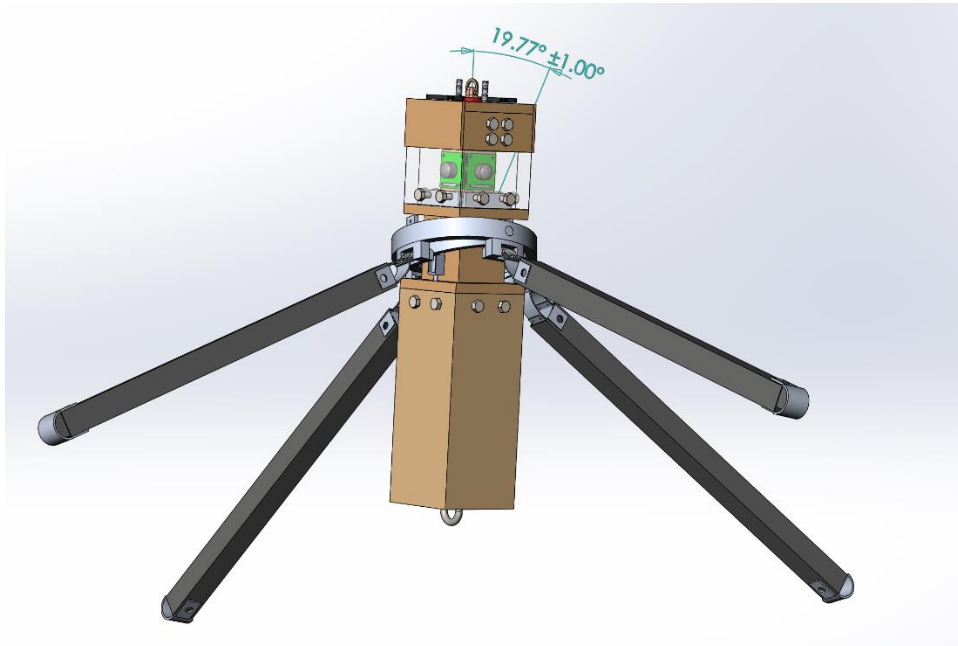


Figure 4-17 LOPSIDED Tilt Example

4.3.2.7 Actuation

Two sets of solenoid locks will be implemented, one set to lock the outer ring, and one to lock the inner. There are two solenoids for locking each ring for redundant reasons. The solenoids will experience some forces from the launch vehicle, opening shock, and landing. They must lock the orientation for safety and mission completion reasons, therefore there are two in order to ensure they complete their job should one fail.

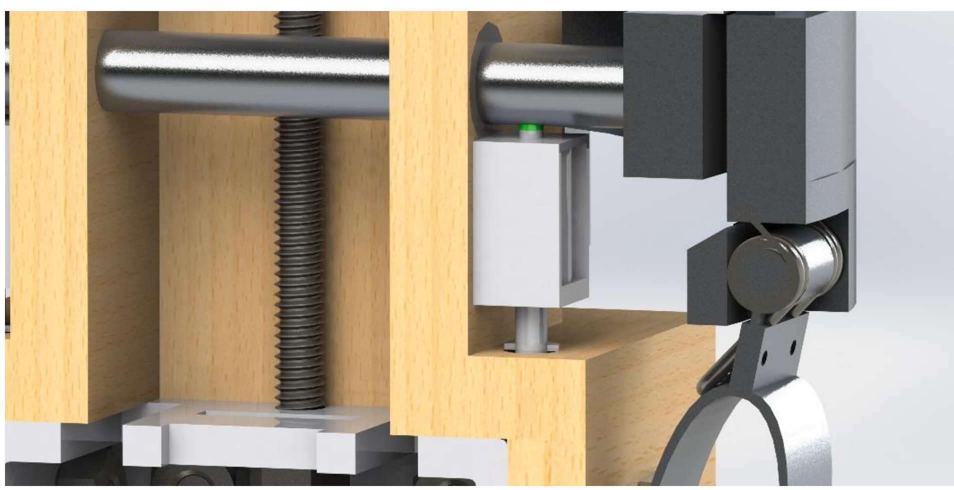


Figure 4-18 Inner Ring Locking Mechanism

The inner ring solenoid locks will be mounted on the outside of the middle chassis section as shown in Figure 4-18. They will be placed beneath the through-axle and will interface with it. When extended, they will prevent the chassis from rotating about that axle.

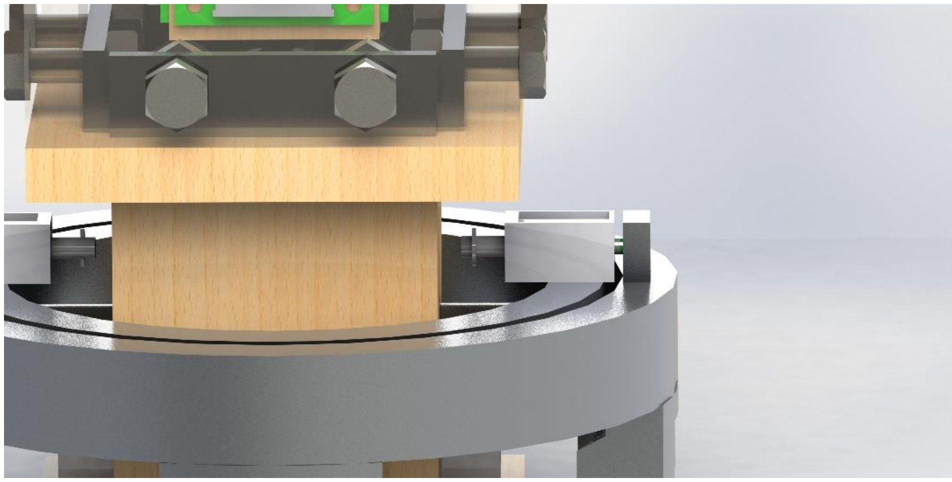


Figure 4-19 Outer Ring Locking Mechanism

The outer ring solenoid locks will be mounted on the upper surface of the inner ring, above the through-axle as seen in Figure 4-19. They will extend into a gate mounted on the outer bracket, preventing it from rotating.

4.3.3 Final POS Design

The Planetary Observation System (POS) will be used to capture and transmit 360-degree images of the payload landing site, to fulfill NASA requirements 4.2 and 4.3.4.1-4.3.4.4. The major components of POS design consist of the imaging components responsible for capturing the 360-degree photographs, a transmitter for sending the photographs, and the on-board computer for controlling these components.

Of the designs presented in the Preliminary Design Review, the final POS design consists of four Arducam Fisheye Raspberry Pi camera modules. This design was selected for its simplicity and versatility compared to other alternatives. The camera modules will be oriented 90 degrees from each other and mounted to a wooden fixture in the upper section of LOPSIDED. Each module has four mounting holes designed for M3 screws.

Figure 4-20 POS Camera Module and Mounting Fixture Located Within LOPSIDED Upper Section

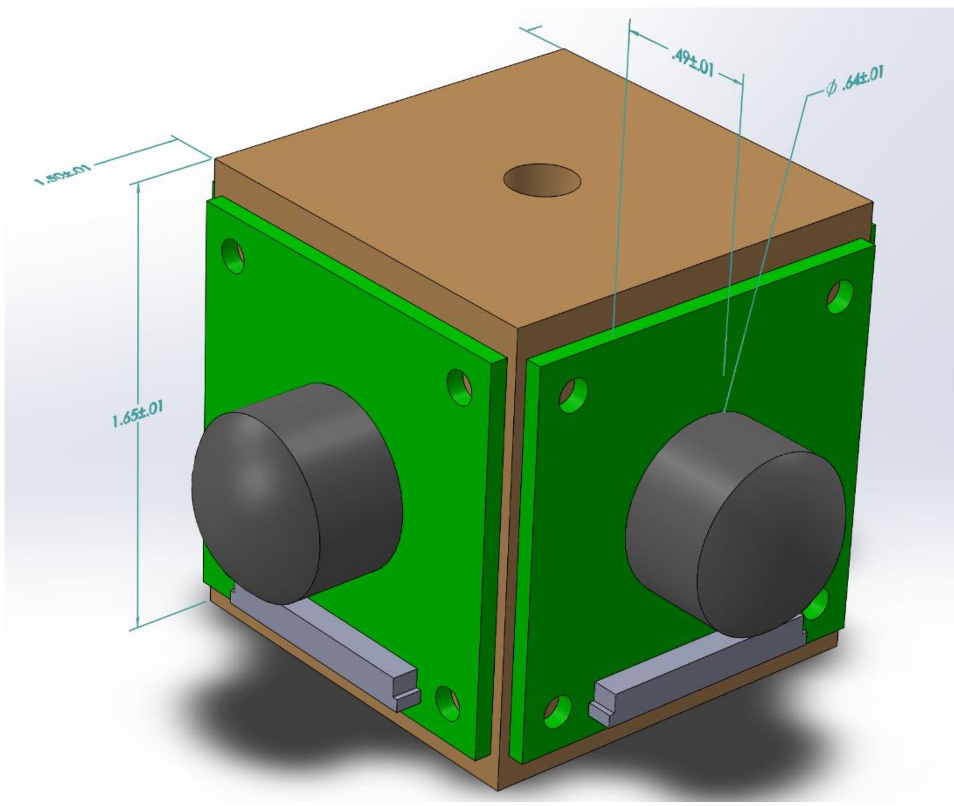


Figure 4-21 POS Camera Module and Mounting Fixture Dimensions

Each camera module has a horizontal field of view (HFOV) of 194 degrees, which allows two cameras to capture a full 360-degree image. The POS utilizes four camera modules, which allows it to capture two separate panoramic images, offset by 90 degrees. This provides redundancy in the event that one module fails, or two opposite-facing modules fail. Even if two adjacent modules were to fail, the captured field-of-view of the two operational cameras would be 284 degrees – almost 79 percent of the surveyable area. Before the camera modules are installed, their field of view will be measured to ensure they can cover at least 180 degrees in the horizontal direction. This will be done to verify Requirement TDR 4.1, as having proper coverage from each camera is crucial to capturing a complete 360-degree image.

These cameras will interface with a Raspberry Pi 3B+. Standard Raspberry Pi boards are equipped with only one Camera Serial Interface (CSI), which allows only one camera module to be attached and utilized at once. For this reason, an Arducam Multi-Camera Adapter Board will be used. The Multi-Camera Adapter allows for four individual camera modules to be attached to one Raspberry Pi. The details of these electronic components will be discussed in Section 4.3.4.

4.3.4 LOPSIDED-POS Electronics

The electronic components required for the leveling system, the POS, and the recovery system are integrated with each other. These systems will be powered by the same battery and will be controlled by the same on-board computer. This is to reduce volume, since the lower LOPSIDED section is only a 69 x 69 x 189 mm volume. This also reduces weight and cost of the LOPSIDED-POS. Most of these components will be mounted on an aircraft-grade plywood sled, which will slide into the Lower LOPSIDED section. A mock-up of this sled is shown in the figures below. The sled is 186 mm (7.32 in) and 68.9 mm (2.71 in) wide.

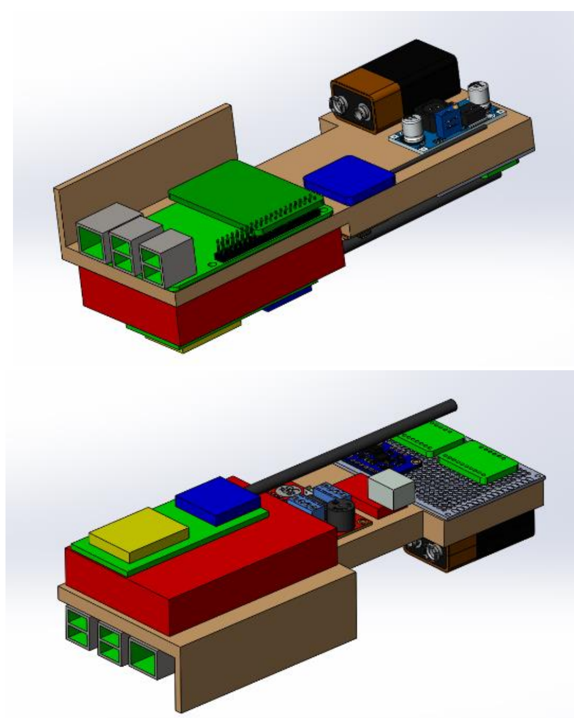


Figure 4-22 LOPSIDED-POS Electronics Sled

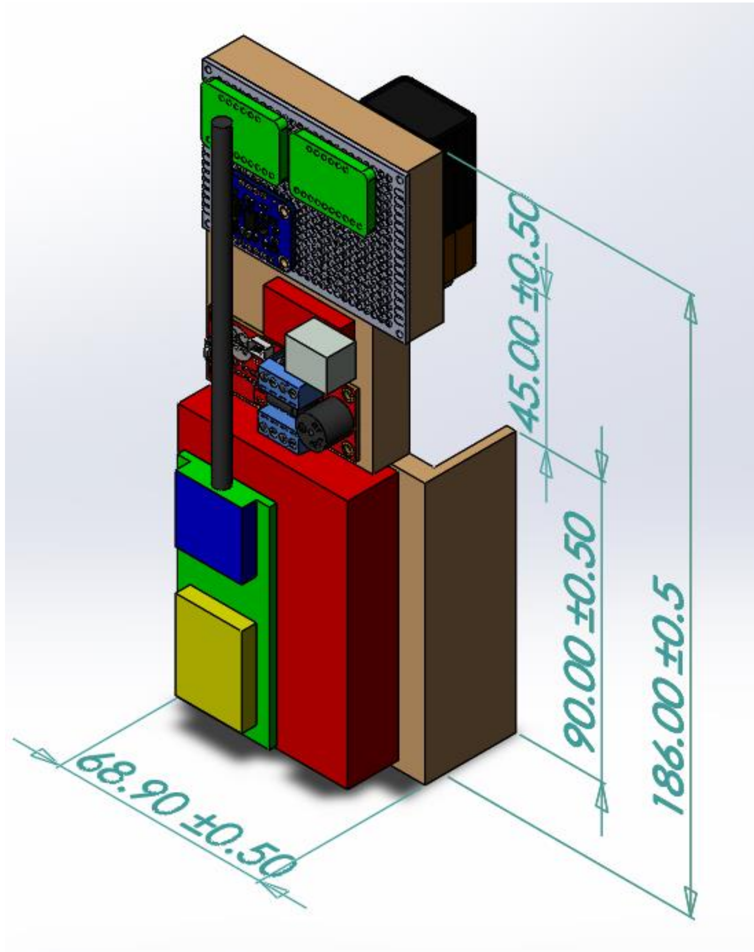


Figure 4-23 LOPSIDED-POS Electronics Sled Dimensions

POS electronics consist of four Arducam Fisheye camera modules and an Adafruit RFM69HCW 433 MHz transmitter, which will transmit to an RTL 2832 SDR receiver located at the team's ground station. The SDR receiver will be connected to a laptop computer to receive the transmitted POS images. Electronics for the leveling system consist of four 5V solenoid latches, two for each gimbal ring, a LM2596 step-down voltage regulator, and an Adafruit BNO055 orientation sensor. Electronics for the recovery system consist of two Dormakaba 3510LM 12V electromechanical locks, a StratologgerCF altimeter, a 9V battery, and a BRB900 GPS tracker. The GPS transmitter will communicate with the BRB900 receiver, which will be located with the team at the ground station. The altimeter will communicate with the ARRD, which will be activated using e-matches. The details of the ARRD are provided in section 4.3.7. It is important to clarify that the altimeters will be protected from the transmitter's frequency with the use of aluminum foil to prevent interference that can cause a failed ARRD ignition. A failed ARRD ignition means that the ARRD ignites too early or too late in which cases the payload could either not exit the launch vehicle at all as it will remain locked by the shear pins, or the payload could be falling too fast as it deploys its parachute at a lower altitude than intended. The testing setup for RF interference for the StratoLoggerCF onboard LOPSIDED-POS is shown in

Figure 4-24, where the BRB 900 tracker and the altimeter are fixed to the sled as intended to place for launch and the altimeter is tested to activate at a given pressure inside a sealed bucket with a vacuum connected to it.

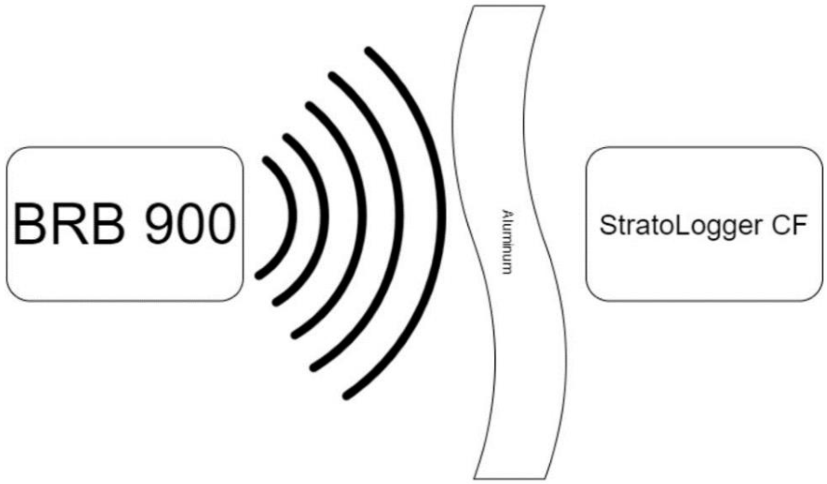


Figure 4-24 Tracker-Altimeter Shielding

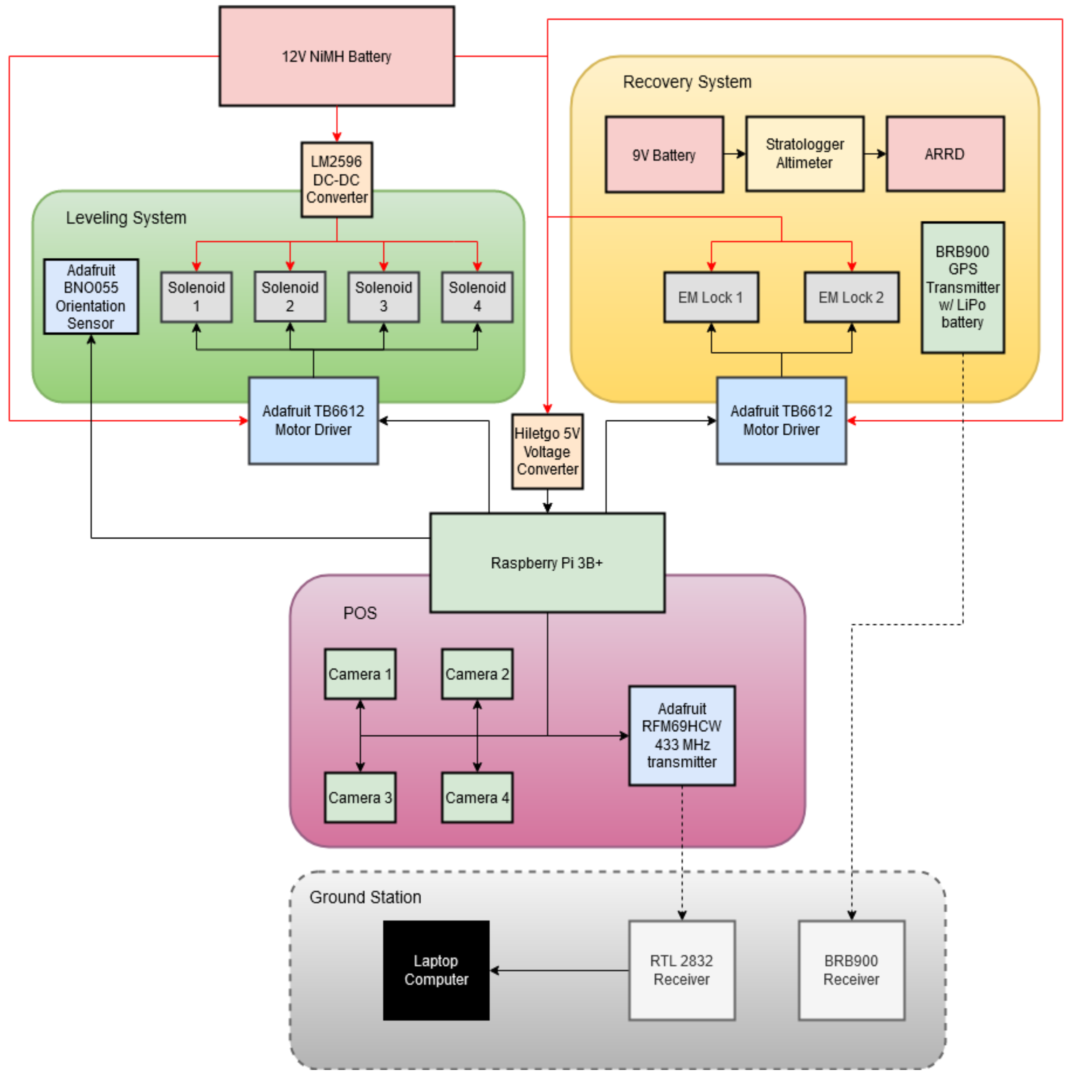


Figure 4-25 LOPSIDED-POS Electronics Flow Chart

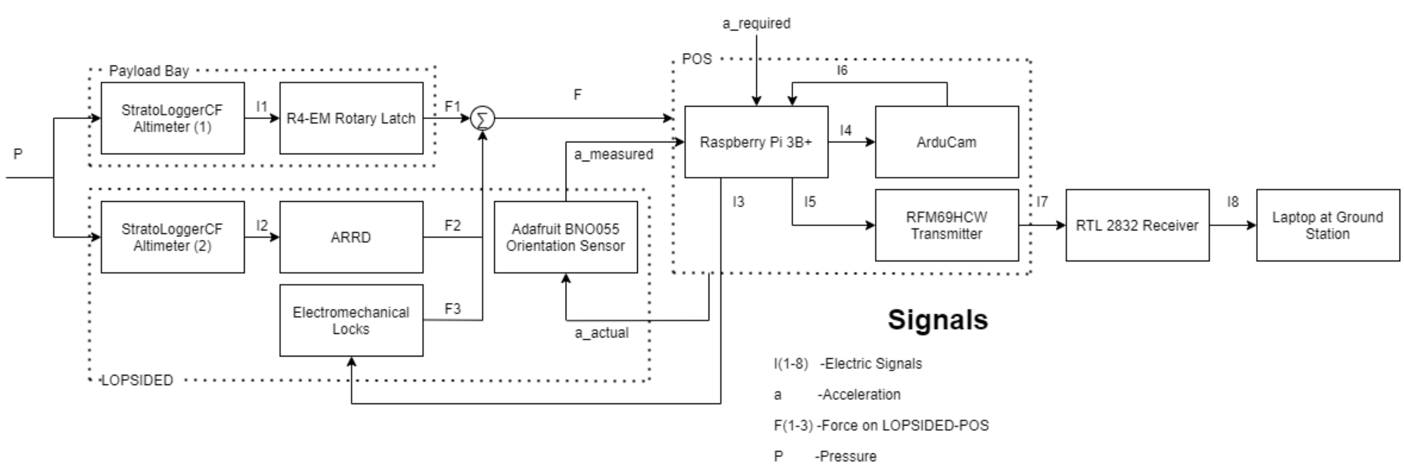


Figure 4-26 LOPSIDED-POS Signal Block Diagram

The majority of LOPSIDED-POS processes will be controlled by a Raspberry Pi 3B+. The computing power of the Pi, as well as its versatile GPIO pins, allow it to command a variety of components. Two Adafruit TB6612 motor drivers will be used to operate the solenoid latches and the electromechanical locks, respectively. These drivers allow the Raspberry Pi to send commands to these devices despite the voltage discrepancy. A 12V 1600 mAh NiMH battery will be used to provide power to most of the LOPSIDED-POS electronics. The altimeter, as per requirement NASA 3.6, will be powered by its own 9V battery. The 12V battery will provide power directly to the electromechanical locks and the motor drivers. Two different DC-DC voltage converters will be used, one to provide power to the solenoid latches, and one to provide power to the Raspberry Pi. The step converter for the Pi is equipped with a USB port, which will allow the Pi to receive power via microUSB. This is the safest way to power the Pi, as opposed to using the 5V pins. The POS cameras, transmitter, and the leveling system's orientation sensor will be powered from the Raspberry Pi. A wiring schematic for the Raspberry Pi is shown in the figure below. Additionally, the table below shows the power consumption of each LOPSIDED-POS component.

Table 4-2 LOPSIDED-POS Component Power Consumption

Component	Voltage (V)	Current (mA)	Active Time (s)	Capacity (mAh)
BRB900 Tracker	4.2	315	7200	630
3510LM EM Lock (x2)	12	500	4	1.11
StratoLogger Altimeter	9	1.5	7200	3.00
BNO055 Accelerometer	3.6	12.3	7200	24.6
Raspberry Pi	5	500	7200	1,000
Arducam Camera	5	250	15	1.75
RFM69HCW Transmitter	5	150	1200	50
Open Frame Solenoid SK-F0420 (x4)	12	250	4	1.11
Total	-	-	-	1,710

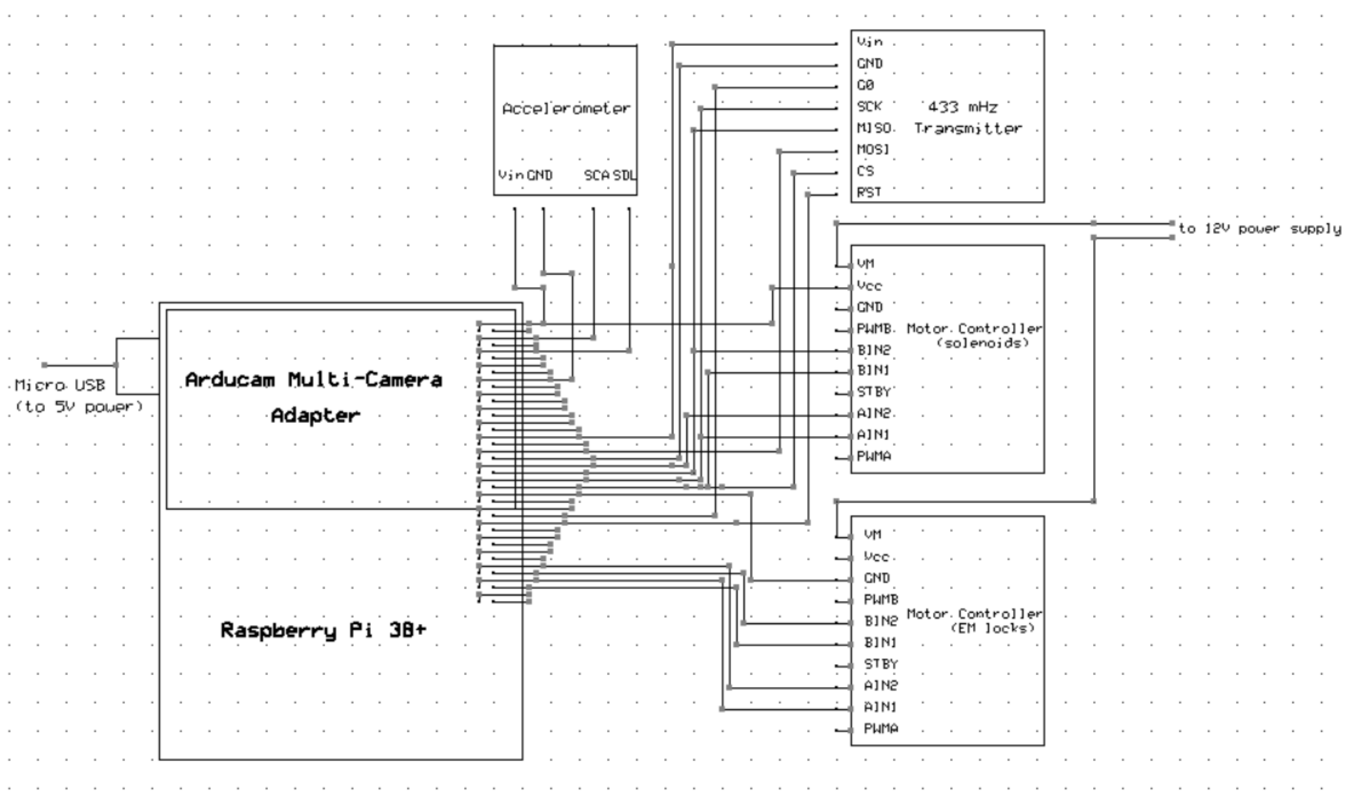


Figure 4-27 Raspberry Pi Wiring Diagram

In addition to the four camera modules, Figure 4-27 details the components which will wire directly with the Raspberry Pi. Since these devices will not all be operating synchronously, a single GPIO pin can have more than one component connected to it.

To protect from inductive flyback generated by inductive DC devices, flyback diodes will be used for each solenoid and electromechanical lock. These diodes are wired across the leads of the inductive device and prevent any voltage spikes that occur when power is disconnected. This is especially crucial in order to protect the Raspberry Pi, which could be permanently damaged as a result of flyback. Figure 4-28 below depicts a representation of the implementation of this diode. In the LOPSIDED-POS, perfboard will be used to wire the diodes across the appropriate terminals.

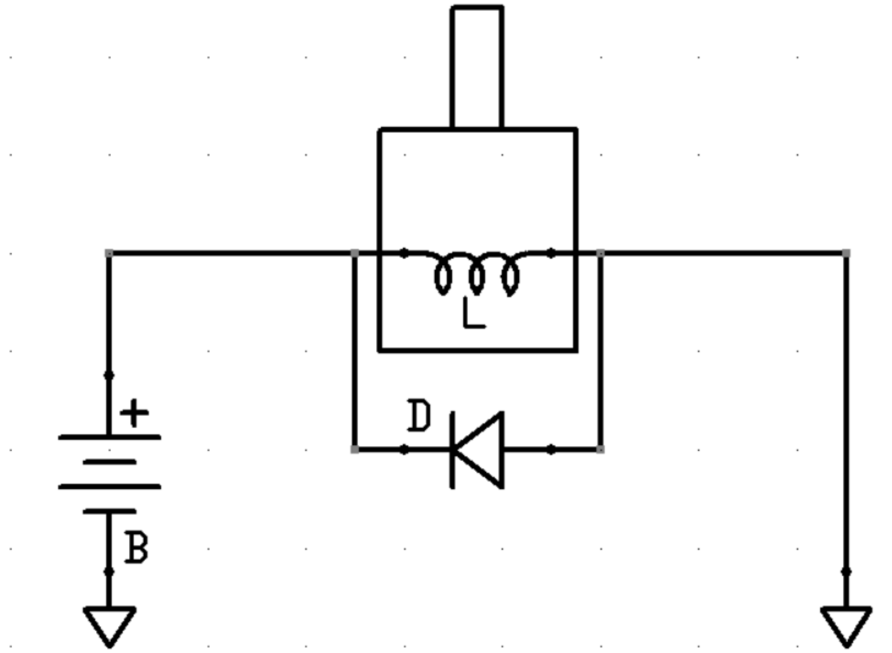


Figure 4-28 Flyback Diode Wiring Schematic

The LOPSIDED-POS has two on-board transmitters; the BRB900 is a GPS tracker, which will transmit location information for the payload at a frequency of 900 MHz. The BRB900 is equipped with its own single cell LiPo battery, and thus is separate from the rest of LOPSIDED-POS's power system. The RFM69HCW is used for POS image transmission, at a frequency of 433 MHz.

4.3.5 POS Image Transmission

The POS will utilize digital Slow-Scan Television (DSSTV) as the method of image transmission. This is a communication method common in amateur HAM radio, which allows static images to be transmitted via radio waves over long distances. This is achieved by converting images into WAV audio files and transmitting this audio data over HF, VHF, or UHF radio frequencies. On the receiving end, a personal computer equipped with SSTV software can be used to demodulate the incoming signals. With SSTV software, a PC’s sound card can be used as a modem to achieve this.

Standard SSTV is an analog signal, but DSSTV allows images to be received with less drop in quality due to transmission – image quality can still suffer as a result of compression, but this is a controllable variable. The details of DSSTV are documented by Michael Bruchanov in chapter nine of “Image Communication on Short Waves,” an SSTV handbook[1].

[1] http://www.sstv-handbook.com/download/sstv_09.pdf

To receive POS transmissions, a team member's personal laptop will be equipped with an Adafruit SDR Radio USB Stick. This device consists of a tunable antenna and RTL dongle connected to a USB port which can be plugged into a laptop. This model is tunable between 24 and 1850 MHz, allowing it to receive 433 MHz transmissions easily. The laptop will utilize DSSTV software called Easypal in order to receive and download image transmissions.

The POS transmitter will be equipped with a quarter-wavelength whip, or monopole antenna. The total length of the antenna can be calculated with the formula

$$\lambda = c/f$$

$$L = \lambda/2$$

$$E = L/2$$

Where λ is the wavelength, c is the wave speed, f is the wave frequency, L is the total antenna length, and E is the dipole length. The total length of a quarter-wave antenna is equal to a quarter of the wavelength at the antenna's target frequency[2]. At 433 MHz, the total antenna length is 0.173 meters, or 6.8 inches. Space within the LOPSIDED-POS is limited, so this length can be decreased by introducing loading coils. Coiling section of the antenna wire allows a shorter overall length to be "electrically" equivalent to the full quarter-wavelength antenna[3]. This will allow the antenna to fit within the limits of the lower LOPSIDED section.

A quarter wavelength antenna inductance calculator can be used to determine the matching impedance of a loaded antenna[4]. The online calculator shown below uses a formula for calculating loading coil inductance from the paper "Off-center loaded dipole antennas," written by Jack Ponton in 1974. Inputs for this formula include frequency, antenna length, coil position, and wire diameter. A coil inductance calculator, such as Coil64, can be used to determine the physical dimensions of the coils itself, such as the number of turns, the length of winding, etc[5].

[2] "The Half-Wave Dipole Antenna," 2009-2011. http://www.antenna-theory.com/antennas/halfwave.php
[3] Jollet, Claude. "The Short Dipole." https://www.hamradiosecrets.com/short-dipole.html
[4] https://m0ukd.com/calculators/loaded-quarter-wave-antenna-inductance-calculator/
[5] https://coil32.net/download-coil64-for-windows.html

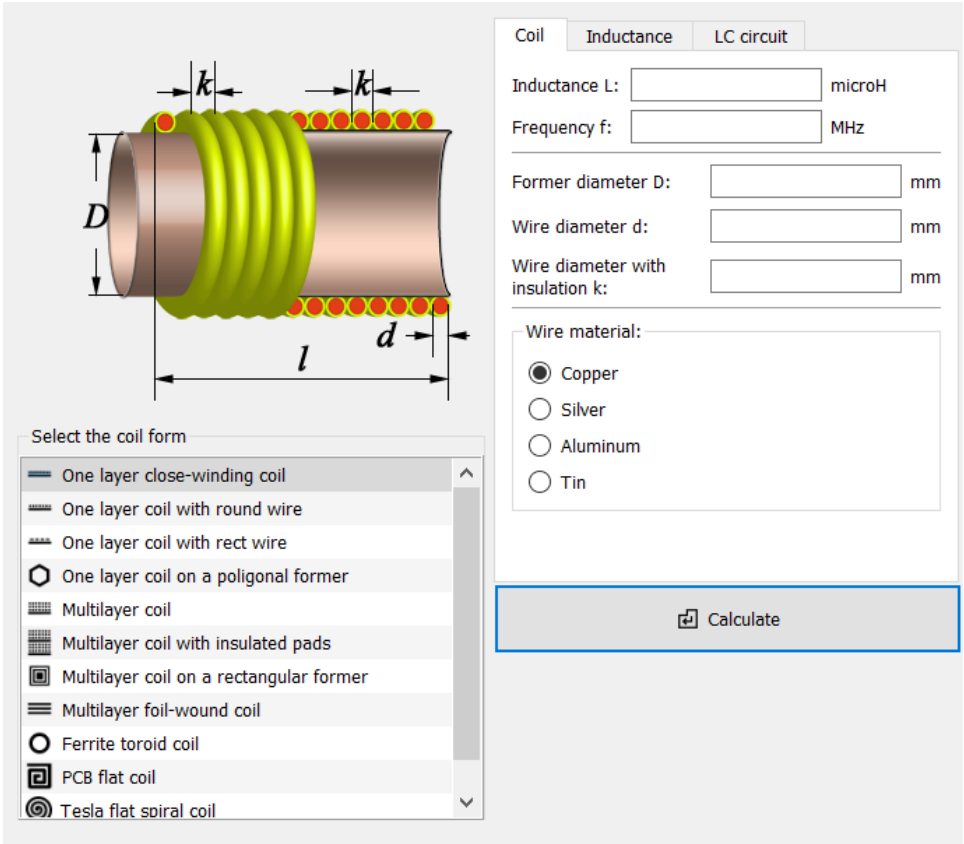


Figure 4-29 Coil64 Software for Loading Coil Determination

An RF range calculator from Silicon Labs was used to calculate the estimated POS transmission range[6].

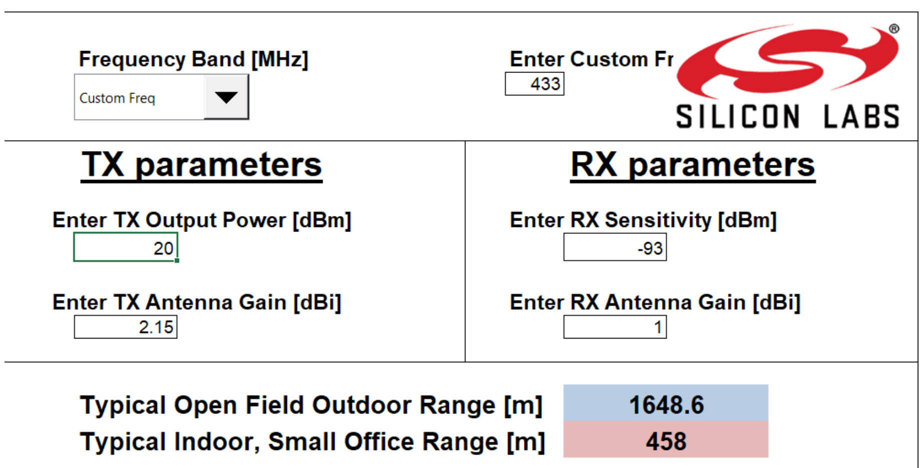


Figure 4-30 POS Transmission Range Calculation

[6] Silicon Labs. "RF Range Calculator." 2017. https://www.silabs.com/community/wireless/proprietary/knowledge-base.entry.html/2017/12/07/rf_range_factors-fnT1

The maximum output power of the RFM69HCW is 100 mW, which is equivalent to 20 dBm. The transmitter power can be adjusted between 13 and 20 dBm. The gain of a half-wave dipole antenna is 2.15 dBi[1]. The sensitivity and gain of the SDR module are currently unknown, so the receiver sensitivity and gain were estimated to be –93 dBm and 1 dBi, respectively, as this is a standard for a large number of receiver models. Transmitter and receiver antenna gain were assumed to be 1 dBi. For 433 MHz, the transmission range is calculated to be 1649 meters, or 5410 feet. This is well above what would be required of the POS. This calculator does utilize a few assumptions, such as an antenna height of 1 m, so these values will not be entirely accurate. Testing of the POS transmitter and ground station receiver will be conducted to determine the actual transmission range.

4.3.6 Subscale Payload Results

Some components of the POS were tested within the subscale launch vehicle during flight. This included a Raspberry Pi 3B+, an Arducam Fisheye camera, an accelerometer, and a 5V battery. The camera was mounted to the inner surface of the payload bay with a 3D printed housing, and the other components were attached to a plywood sled secured within the payload bay with two threaded rods. A Python script on the Pi would collect data from the accelerometer, averaged over ten second intervals. Once the change in acceleration due to launch was detected, the camera module would take images in increments of 10 seconds for 300 seconds. The goals of this payload were to confirm the ability of the Arducam Fisheye camera modules to withstand flight forces, assess the quality of images taken during and after flight, and to gain experience working with Python and communication between different electronic components, such as the Pi and the accelerometer.

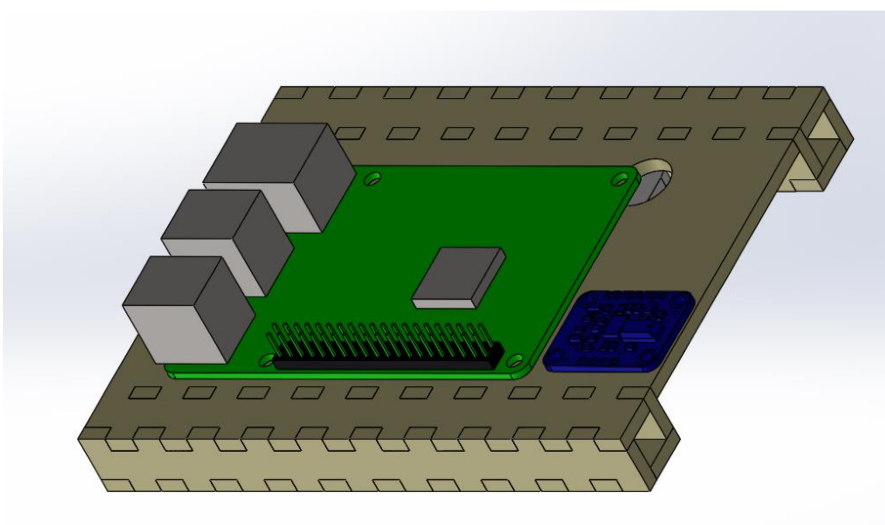


Figure 4-31 Subscale Payload Sled

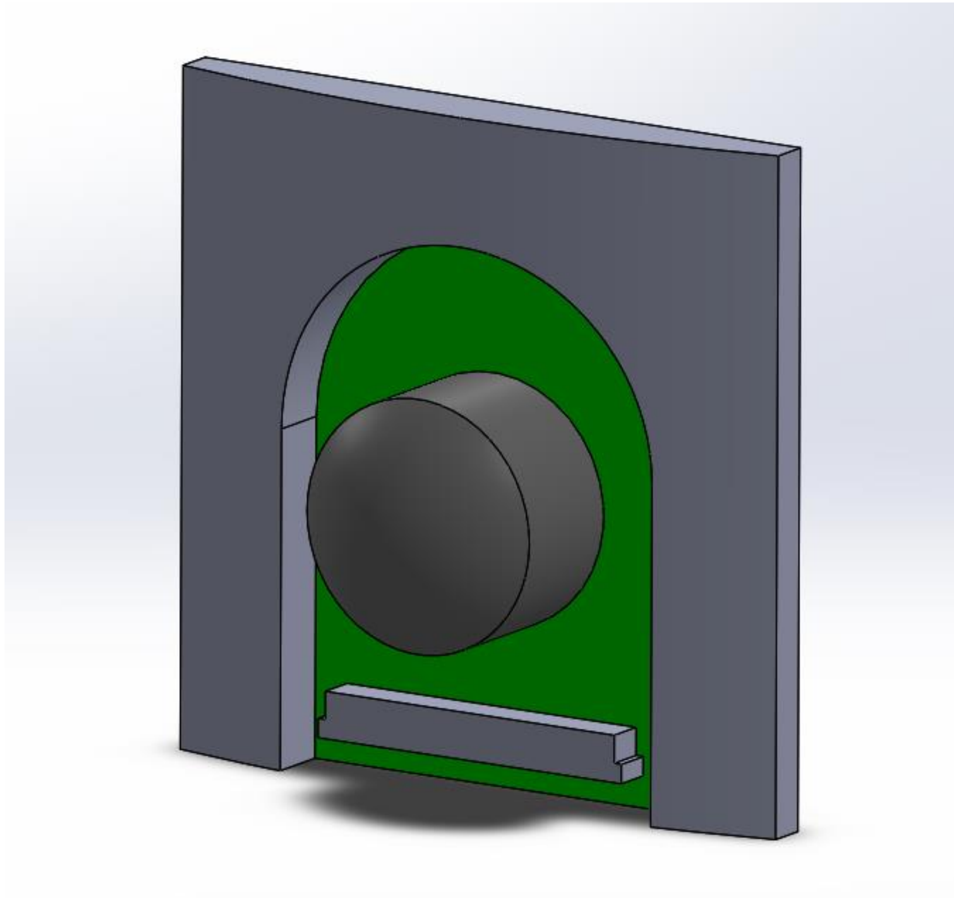


Figure 4-32 Subscale Payload Camera Mount

Unfortunately, during launch, the Raspberry Pi detected the camera CSI port as being disabled. This prevented the script from running properly at the start of the launch, meaning no images were captured. It is believed that the act of disconnecting and re-connecting the power supply to the Pi can affect the enabled/disabled state of the Pi's peripherals, although the exact scenario that caused the failure has yet to be replicated. Moving forward, extra care will be taken to confirm the configuration state of the Raspberry Pi to ensure it is properly communication with all connected components. Despite the failure to collect in-flight images, the camera module has been confirmed to be functional post-flight, meaning the camera is capable of withstanding flight forces. Other information learned about the Raspberry Pi, the camera module, and the accelerometer - such as relevant Python libraries, proper wiring, etc. - have been documented and will be beneficial to the development of the LOPSIDED-POS.

4.3.7 Final Payload Integration Design

The two main objectives for payload integration are to retain LOPSIDED-POS within the launch vehicle and to jettison LOPSIDED-POS such that it can land and complete the survey of the landing site. These objectives result from NASA requirement 4.2. In order to retain LOPSIDED-POS inside the launch vehicle, the payload integration design limits the payload's movement in three directions: along the body tube, towards the body tube walls, and rotation about the central axis of the launch vehicle. Minimizing the movement minimizes the chances of LOPSIDED-POS impacting anywhere inside the payload bay and damaging electronics or mechanical components essential for the success of the mission. The selected design is simple and maximizes the space inside the payload bay for LOPSIDED-POS.

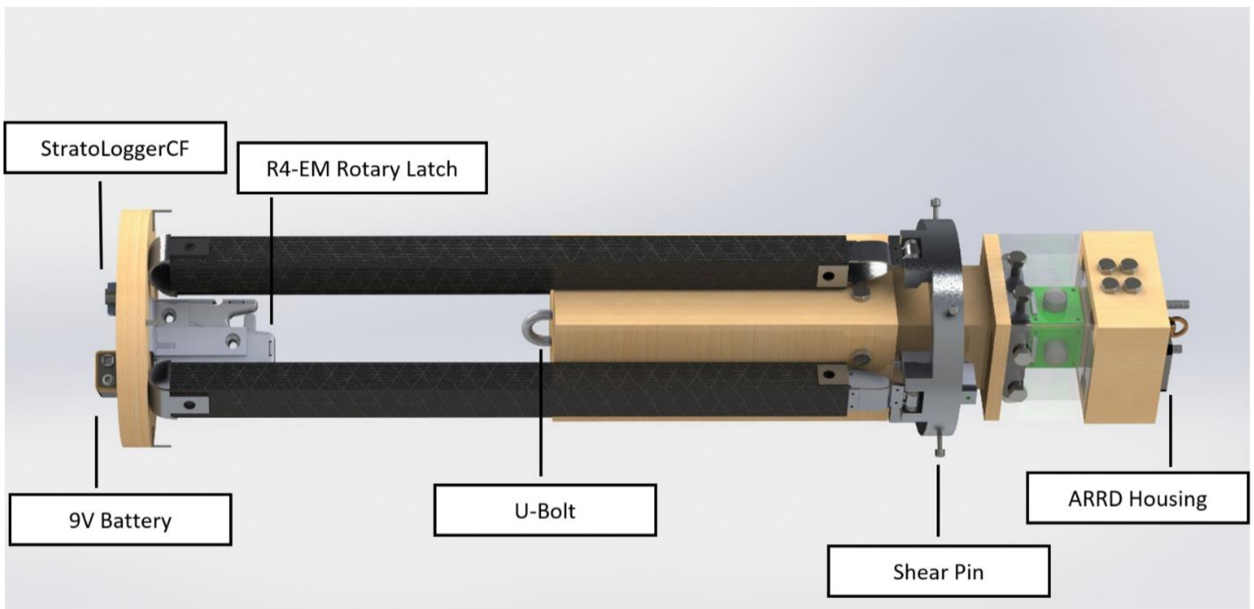


Figure 4-33 Payload Integration Design

Figure 4-33 shows the components used for the selected payload integration design; these include a StratoLoggerCF altimeter with a 9V battery, a small 12V A23 Alkaline battery for the R4-EM Rotary Latch, a U-bolt, three shear pins, and an ARRD (Advanced Retention Release Device) housing at the top. The system is set so that LOPSIDED-POS is placed upside-down inside the launch vehicle when placed on the launch rail. LOPSIDED-POS will hang from the rotary latch as it will be attached to it using a shock cord like those described in the recovery section in order to sustain the load at launch. The rotary latch prevents LOPSIDED-POS from moving down the payload bay during ascent; in addition, the shear pins prevent LOPSIDED-POS from rotating and moving towards the payload bay walls. Moreover, the gimble ring on LOPSIDED-POS makes a tight enough fit inside the payload bay in order to minimize unnecessary movement. Once the launch vehicle reaches apogee, the StratoLoggerCF altimeter, which has its own dedicated battery and has an accessible arming switch through a small hole on the payload bay, sends a signal to the R4-EM Rotary Latch to open and release the cord to which the payload is attached to. After that point, the payload is only supported by the shear pins that go in through the payload bay walls to screw into the LOPSIDED-POS ring. The shear pins used are 3 #4-40 nylon shear pins rated for 35 lbf breaking load as detailed in the recovery section 3.4.1. Figure 4-34 shows the distances between the bottom of the bulkhead and the location of the shear pins, which is 21.5 inches. The length of the cord that attaches the rotary latch and the U-bolt is 7.60 inches.

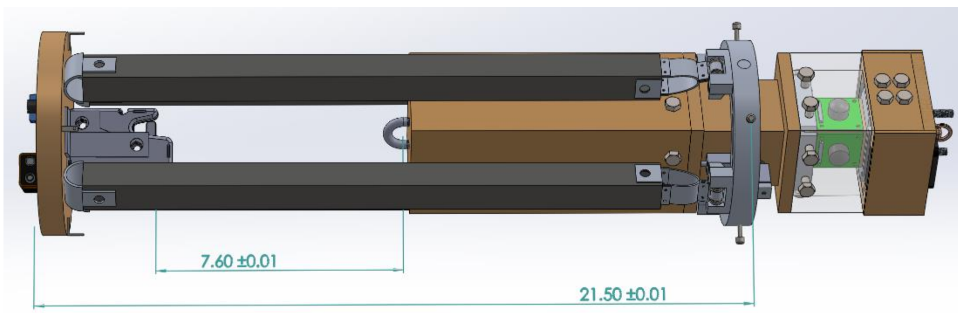


Figure 4-34 Payload Integration System Dimensions

The ARRD housing is positioned at the top of LOPSIDED-POS as displayed in Figure 4-35. The ARRD housing consists of the ARRD, two 3510LM Electromechanical Locks from Dormakaba, two screws at the top next to the ARRD, and one screw going through a wooden block at the bottom of the ARRD. The ARRD is a device that contains 0.1g of black powder that ignites to separate the top pin from the bottom red body. The ARRD is rated to resist up to 2,000 lbs. The two top screws serve the purpose of holding the ARRD and the bottom wooden block to LOPSIDED-POS. The bottom attachment screw connects the ARRD to the metal frame discussed in section 4.3.2.1. The two EM locks are attached to two metal plates on the side of the ARRD. The ARRD is rated to resist up to 2000 lbf loading where the shock from the main parachute can reach up to 175 lbf (as detailed in the recovery section 3.5.10). The EM locks were selected due to their size as they can fit inside the top section of LOPSIDED-POS in addition to having a holding force rating of 250 lbf when the maximum estimated load would be much less than the main parachute shock of 175 lbf (since main is a bigger parachute). Using the main parachute shock as an overestimate, the factor of safety would be near 3 for the locks since the two locks add up to 500 lbf. The EM locks were also selected due to the easy detachment where the accelerometer (BNO055) onboard would activate them to release the parachute upon touching the ground. This process will be tested as described in the testing section 6.1.3.5.

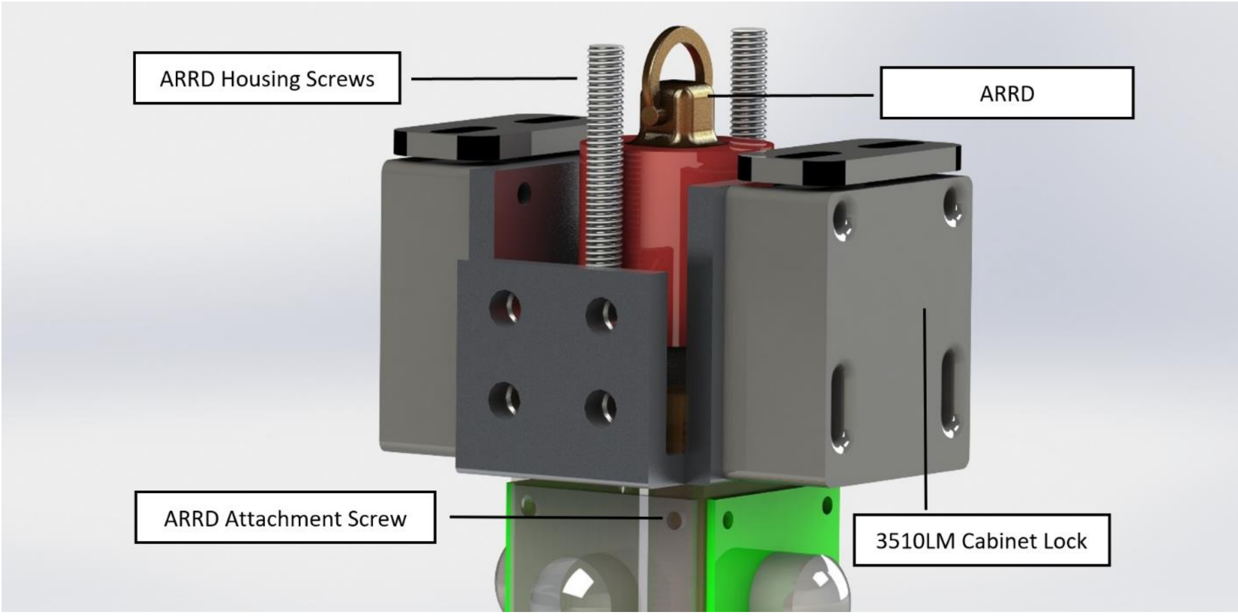


Figure 4-35 ARRD Housing and Electromechanical Locks

4.3.8 Final Payload Deployment System

The final payload deployment system is composed of mechanical as well as electronic components such as a pulling force on the ARRD by the main parachute recovery harness at main parachute deployment, and the detachment of LOPSIDED-POS's parachute at landing. It is important to mention that LOPSIDED-POS will always remain attached to a parachute being either the main parachute (attached at the ARRD) or the payload parachute (which is easily pulled out by LOPSIDED-POS's weight once the payload exits the launch vehicle). As detailed in Figure 4-36, the first step describes how LOPSIDED-POS will remain within the payload bay until the deployment of the main parachute at 700ft AGL (which is the point of main parachute deployment). On step two, LOPSIDED-POS will exit the payload bay and the ARRD device will ignite at 500ft AGL, releasing LOPSIDED-POS from the main vehicle. The main parachute (in red) will still be attached to the main vehicle while the parachute for LOPSIDED-POS (in blue) will be inside a deployment bag that is attached to the main parachute shock chord. LOPSIDED-POS will pull the parachute out of the bag and proceed to land, as depicted on step three. On step four, LOPSIDED-POS will land. The change in velocity will indicate the onboard sensors to send a signal to the post-landing parachute release devices to release the parachute. Figure 4-26 displays the block diagram for LOPSIDED-POS, and it is noticed how the rotary latch, ARRD, and the payload parachute apply a force to LOPSIDED-POS resulting in a new acceleration reading by the accelerometer (BNO055). There will be a set acceleration reading that can only be achieved after the payload is falling with the parachute and the payload suddenly decelerates due to contact with the ground. At that point, the Raspberry Pi will signal the EM locks to disengage the payload parachute.

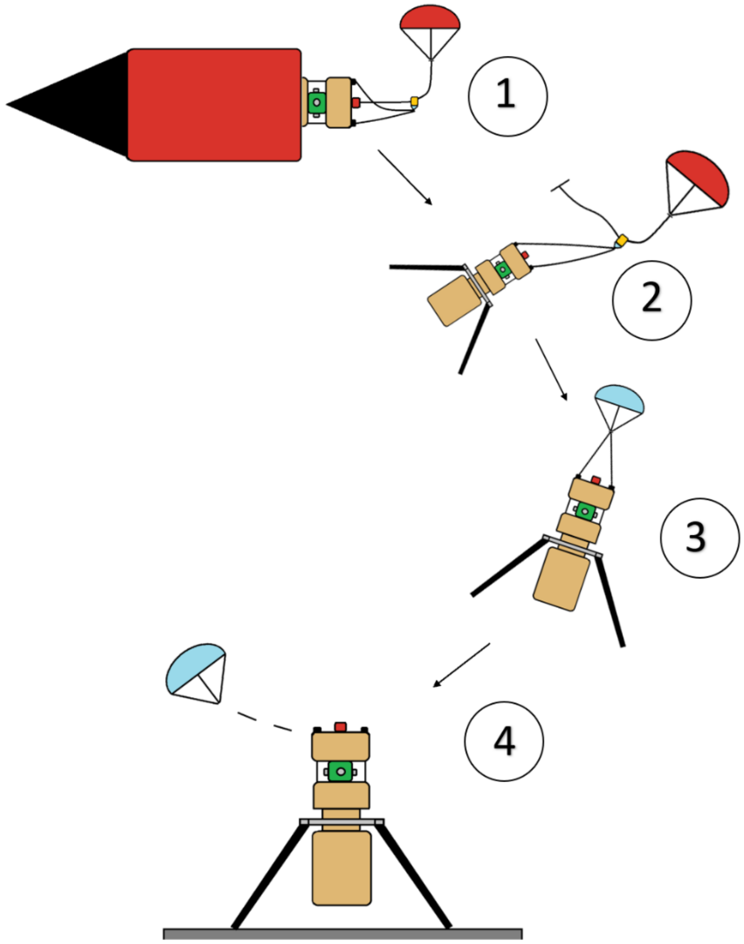


Figure 4-36 LOPSIDED-POS Deployment Sequence

5. Safety

5.1 Safety Officer Identification

The team safety officer for the 2021 Student Launch competition is Emma McDonald, who is replacing previous safety officer Frances McBride who will be on a co-op rotation. As safety officer, Emma is responsible for ensuring an overall level of safety within the project. This includes collaborating with design teams to ensure safety of all subsystems and develop hazard mitigations, being present for all fabrication activities, being present for launch day activities, and fostering a safety culture within the team. Emma is also responsible for meeting all requirements detailed in handbook requirement NASA 5.3.

5.2 Launch Concerns and Operation Procedures

The team is in the process of creating launch day checklists and procedures for the full scale launch vehicle. The procedures and checklists developed for the subscale launch are used as a template and first draft of full scale launch procedures, as many of these procedures are similar or identical between the two launch vehicles. These completed checklists are presented below.

Chicken Tendy

Launch Day Checklists

This checklist completed by: Evan Waldron

On: 11 / 21 / 20

1. E-MATCH INSTALLATION

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	√
Safety Officer	Frances McBride	√
E-Match Personnel 1	Alex Thomas	√
E-Match Personnel 2	~~Daniel Jaramillo~~ Evan Patterson	√

Required Materials			
Item	Quantity	Location	Completion
Bulkhead #4 (Fwd AV)	1	AV Bulkhead Box	√
Bulkhead #5 (Aft AV)	1	AV Bulkhead Box	√
Blue tape	1	LD Toolbox (Top Drawer)	√
E-Match	4	LD Toolbox (Top Drawer)	√
Scissors	1	LD Toolbox (Top Drawer)	√
Wire cutters	1	LD Toolbox (Middle Drawer)	√
Wire strippers	1	LD Toolbox (Middle Drawer)	√
Terminal block screwdriver	1	LD Toolbox (Middle Drawer)	√

Note: This checklist is to be executed on bulkheads 4 and 5 simultaneously

Bulkhead 4 uses labels **MP** and **MS**, Bulkhead 5 uses labels **DP** and **DS**

Number	Task	Completion
1.1	Unscrew all *UNOCCUPIED* terminal blocks on bulkheads 4 and 5	√
1.2	Take one e-match (each) and trim the e-match to approximately 6.5 inches in length using wire cutters	√
1.3	Remove red plastic protective e-match cover by sliding it down the e-match wire	√
1.4	Feed the e-match through the **MP** (Bulkhead 4) or **DP** (Bulkhead 5) wire hole, with the e-match head on the side with the blast caps	√
1.5	Use a fingernail to separate the two e-match wires	√
1.6	Use wire strippers to strip 1 inch of insulation from end of each e-match wire	√
1.7	Bend each exposed e-match wire section into a loop	√

1.8	Place the exposed e-match wires into the **MP** or **DP** terminal block, one into each unoccupied block	✓
1.9	Tighten the screws on the **MP** or **DP** terminal block	✓
1.10	Verify e-match security by lightly tugging on the wires coming out of the **MP** or **DP** terminal block	Safety Officer: Safety Officer High-Powered Ro NC State
1.11	Place the e-match head into the **MP** or **DP** blast cap	✓
1.12	Bend the e-match wire such that the head lies flat against the bottom of the blast cap	✓
1.13	Bend the e-match wire such that it is flush to the inner and outer walls of the blast cap	✓
1.14	Using blue tape, tape the e-match wire to the outside wall of the blast cap	✓
1.15	Using blue tape, tape the e-match wire to the bulkhead surface	✓
1.16	Confirm the e-match in the **MP** or **DP** blast cap is connected to the **MP** or **DP** terminal block, respectively	Safety Officer: Safety Officer High-Powered
1.17	Confirm that all bulkhead and wiring labels are still visible	✓
1.18	Take one e-match (each) and trim the e-match to approximately 6.5 inches in length using wire cutters	✓
1.19	Remove red plastic protective e-match cover by sliding it down the e-match wire	✓
1.20	Feed the e-match through the **MS** (Bulkhead 4) or **DS** (Bulkhead 5) wire hole, with the e-match head on the side with the blast caps	✓
1.21	Use a fingernail to separate the two e-match wires	✓
1.22	Use wire strippers to strip 1 inch of insulation from end of each e-match wire	✓
1.23	Bend each exposed e-match wire section into a loop	✓
1.24	Place the exposed e-match wires into the **MS** or **DS** terminal block, one into each unoccupied block	✓
1.25	Tighten the screws on the **MS** or **DS** terminal block	✓
1.26	Verify e-match security by lightly tugging on the wires coming out of the **MS** or **DS** terminal block	Safety Officer: Safety Officer High-Powered Rocketry NC State
1.27	Place the e-match head into the **MS** or **DS** blast cap	✓
1.28	Bend the e-match wire such that the head lies flat against the bottom of the blast cap	✓
1.29	Bend the e-match wire such that it is flush to the inner and outer walls of the blast cap	✓
1.30	Using blue tape, tape the w-match wire to the outside wall of the blast cap	✓

1.31	Using blue tape, tape the e-match wire to the bulkhead surface	✓
1.32	Confirm the e-match in the **MS** or **DS** blast cap is connected to the **MS** or **DS** terminal block, respectively	Safety Officer: Safety Officer High-Powered Rocke NC State
1.33	Confirm that all bulkhead and wiring labels are still visible	✓

2. MAIN BLACK POWDER

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	
Safety Officer	Frances McBride	
Black Powder Personnel 1	Alex Thomas	
Black Powder Personnel 2	Trent Couse	

Required Materials			
Item	Quantity	Location	Completion
Bulkhead #4 (Fwd AV)	1	AV Bulkhead Box	√
8.5x11 copy paper	2	Recovery Tupperware	√
Paper Towel Roll	1	Recovery Tupperware	√
Blue Tape	1	LD Toolbox (Top Drawer)	√
Plumbers Putty	1	LD Toolbox (Top Compartment)	√
Scissors	1	LD Toolbox (Top Drawer)	√
Anti-static bag	1	-	√
Safety Glasses	4	PPE Toolbox	√
Nitrile Gloves	4	PPE Toolbox	√
Heavy Duty Gloves	1	PPE Toolbox	√
Main Primary Charge (2.2 g)	2	AV HDX Box	√
Main Secondary Charge (2.4 g)	2	AV HDX Box	√

Number	Task	Completion
2.1	Confirm that all members within the assembly tent are wearing safety glasses	Safety Officer: Safety Officer High-Powered Rocketry NC State
2.2	Confirm that members handling black powder are wearing nitrile gloves	Safety Officer: Safety Officer High-Powered Rocket NC State
2.3	Roll one sheet of copy paper into a funnel with a bottom diameter of about ½ inch; secure with strips of blue tape	√
2.4	Confirm the inside of the paper funnel is smooth with no edges	√

2.5	Place the bottom of the funnel into the **MP** blast cap and carefully pour the **Main Primary Charge** of black powder into the **MP** blast cap over the e-match head	√
2.6	Lift the e-match head so that it rests on top of the black powder	√
2.7	Fill the remaining space in the blast cap with fingertip sized pieces of paper towel. The paper towel should fill the space, but not be packed in tightly	√
2.8	Place small 2-3 inch strips of blue tape over the top of the **MP** blast cap to cover the blast cap completely. Do NOT have any overlaps greater than 1mm, but leave no gaps	√
2.9	Confirm all edges of the **MP** blast cap are covered with blue tape	Safety Officer: Safety Officer High-Powered Rocke NC State
2.10	Wrap blue tape around the outside wall of the blast cap to keep the top layers of tape tight and fold down the excess tape to be flush with the top of the blast cap	√
2.11	Place the bottom of the funnel into the **MS** blast cap and carefully pour the **Main Secondary Charge** of black powder into the **MS** blast cap over the e-match head	√
2.12	Lift the e-match head so that it rests on top of the black powder	√
2.13	Fill the remaining space in the blast cap with fingertip sized pieces of paper towel. The paper towel should fill the space, but not be packed in tightly	√
2.14	Place small 2-3 inch strips of blue tape over the top of the **MS** blast cap to cover the blast cap completely. Do NOT have any major overlaps, but leave no gaps	√
2.15	Confirm all edges of the **MS** blast cap are covered with blue tape	Safety Officer: NC State High-Powered Rocketry Safety Officer
2.16	Wrap blue tape around the outside wall of the blast cap to keep the top layers of tape tight and fold down the excess tape to be flush with the top of the blast cap	√
2.17	Place a sheet of white copy paper on the assembly table and turn the bulkhead over above the paper	√
2.18.1	Confirm that no black powder has leaked onto the copy paper	√
2.18.2	If black powder has leaked, wipe copy paper clean and repeat checklist items 2.5-2.10 or 2.11-2.16 depending on which charge leaked, then repeat checklist items 2.17-2.18.1	N/A
2.19	Use plumber's putty to seal any holes in the bulkhead	√
2.20	Wrap the entire bulkhead in an anti-static bag	√

3. DROGUE BLACK POWDER

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	✓
Safety Officer	Frances McBride	✓
Black Powder Personnel 1	Alex Thomas [illegible]	✓
Black Powder Personnel 2	Daniel Jaramillo	✓

Required Materials			
Item	Quantity	Location	Completion
Bulkhead #5 (Fwd AV)	1	-	✓
Paper funnel (see 3. Main Black Powder Required Materials)	1	-	
8.5x11 copy paper	2	Recovery Tupperware	✓
Paper Towel Roll	1	Recovery Tupperware	✓
Blue Tape	1	LD Toolbox (Top Drawer)	✓
Plumbers Putty	1	LD Toolbox (Top Compartment)	✓
Scissors	1	LD Toolbox (Top Drawer)	✓
Safety Glasses	4	PPE Toolbox	✓
Nitrile Gloves	4	PPE Toolbox	✓
Heavy Duty Gloves	1	PPE Toolbox	✓
Drogue Primary Charge (1.0 g)	2	AV HDX Box	✓
Drogue Secondary Charge (1.2 g)	2	AV HDX Box	✓
Anti-static bag	1	-	✓

Number	Task	Completion
3.1	Confirm that all members within the assembly tent are wearing safety glasses	Safety Officer: Safety Officer High-Powered Rocketry NC State
3.2	Confirm that members handling black powder are wearing nitrile gloves	Safety Officer: Safety Officer High-Powered Rocketry NC State
3.3	Place the bottom of the funnel into the **DP** blast cap and carefully pour the **Drogue Primary Charge** of black powder into the **BP** (DP) blast cap over the e-match head	✓

3.4	Lift the e-match head so that it rests on top of the black powder	√
3.5	Fill the remaining space in the blast cap with fingertip sized pieces of paper towel. The paper towel should fill the space, but not be packed in tightly	√
3.6	Place small 2-3 inch strips of blue tape over the top of the **DP** blast cap to cover the blast cap completely. Do NOT have any overlaps greater than 1mm, but leave no gaps	√
3.7	Confirm all edges of the **DP** blast cap are covered with blue tape	Safety Officer: Safety Officer High-Powered Rocketry NC State
3.8	Wrap blue tape around the outside wall of the blast cap to keep the top layers of tape tight and fold down the excess tape to be flush with the top of the blast cap	√
3.9	Place the bottom of the funnel into the **DS** blast cap and carefully pour the **Drogue Secondary Charge** of black powder into the **DS** blast cap over the e-match head	√
3.10	Lift the e-match head so that it rests on top of the black powder	√
3.11	Fill the remaining space in the blast cap with fingertip sized pieces of paper towel. The paper towel should fill the space, but not be packed in tightly	√
3.12	Place small 2-3 inch strips of blue tape over the top of the **DS** blast cap to cover the blast cap completely. Do NOT have any major overlaps, but leave no gaps	√
3.13	Confirm all edges of the **DS** blast cap are covered with blue tape	Safety Officer: Safety Officer High-Powered Rocketry NC State
3.14	Wrap blue tape around the outside wall of the blast cap to keep the top layers of tape tight and fold down the excess tape to be flush with the top of the blast cap	√
3.15	Place a sheet of white copy paper on the assembly table and turn the bulkhead over above the paper	√
3.16.1	Confirm that no black powder has leaked onto the copy paper	√
3.16.2	If black powder has leaked, wipe copy paper clean and repeat checklist items 3.3-3.8 or 3.9-3.14 depending on which charge leaked, then repeat checklist items 3.15-3.16.1	N/A
3.17	Use plumber's putty to seal any holes in the bulkhead	√
3.18	Wrap the entire bulkhead in an anti-static bag	√

4. AVIONICS BAY ASSEMBLY

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	✓
Safety Officer	Frances McBride	✓
Recovery Lead	Robert Kempin	✓
AV Personnel 1	Alex Forsgard	✓

Required Materials			
Item	Quantity	Location	Completion
Bulkhead #4	1	AV Bulkhead Box	✓
Bulkhead #5	1	AV Bulkhead Box	✓
AV Sled (assembled)	1	Recovery Tupperware	✓
Screw Switch	2	AV Sled	✓
Stratologger CF	2	AV Sled	✓
AV Bay	1	-	✓
9V Battery	2	AV HDX Box	✓
#4-40 screw	4	AV Sled	✓
#4-40 washer	4	AV Sled	✓
#4-40 nut	4	AV Sled	✓
¼-20 nut	4	Recovery Hardware	✓
¼-20 washer	2	Recovery Hardware	✓
7/16" Wrench	2 ~~1~~	LD Toolbox (Middle Drawer)	✓
Adjustable Wrench	1	LD Toolbox (Middle Drawer)	✓
Multimeter	1	LD Toolbox (Top Compartment)	✓
Remove Before Flight Tag	2	Recovery Tupperware	
~~#8 screw~~	4	Recovery Hardware	
Main Parachute bay	1		
Safety Glasses	4	PPE Toolbox	✓

screwdriver

Number	Task	Completion
4.1	Use multimeter to test voltage of the primary 9V battery	Note Voltage: 9.52 V
4.2	Use multimeter to test voltage of the secondary 9V battery	Note Voltage: 9.57 V
4.3	If either battery measures below 9V, replace with a fresh battery and repeat checklist item 4.1 or 4.2	N/A
4.4	Remove battery cover from avionics sled	✓
4.5	Connect each battery to its battery clip in the battery compartment	✓
4.6	Place primary and secondary batteries in the avionics sled battery compartment ~~with the tops of the batteries facing the battery~~ clips	✓
4.7	Place battery cover over the battery compartment and secure with four #4-40 machine screws and eight #4-40 hex nuts	✓
4.8.1	Turn the primary screw switch to the on position	✓
4.8.2	Verify primary altimeter beeps match the expected pattern detailed on the Primary Altimeter Beep Sheet	✓
4.9	Turn the primary screw switch to the off position	✓
4.10.1	Turn the secondary screw switch to the on position	✓
4.10.2	Verify secondary altimeter beeps match the expected pattern detailed on the Secondary Altimeter Beep Sheet	✓
4.11	Turn the secondary screw switch to the off position	✓
4.12	Insert the two "remove before flight tags" through the primary and secondary switch holes in the airframe	✓
4.13	Wrap the string from the primary remove before flight tag around the primary screw switch. Tighten the screw to hold the string in place	✓
4.14	Wrap the string from the secondary remove before flight tag around the secondary screw switch. Tighten the screw to hold the string in place **NOTE: ALTIMETERS MUST NOT BE POWERED ON PAST THIS POINT UNTIL CHECKLIST ITEM X.X** 10.15	✓
4.15	Confirm all members within the assembly tent are wearing safety glasses	Safety Officer: Safety Officer High-Powered Rocketry NC State
4.16	Remove Bulkhead #5 from its anti-static bag	✓
4.17	Lightly tug on the wires coming out of the **DP** and **DS** terminal blocks to verify security	Safety Officer: Safety Officer High-Powered Rocketry NC State

4.18	While pointing the blast caps away from personnel, connect the orange and purple wires on the avionics sled to the orange and purple wires on Bulkhead #5	√
4.19	Lightly tug on the wire connection between the avionics sled and Bulkhead #5 to verify security	Safety Officer: Safety Officer High-Powered Rocketry NC State
4.20	Slide Bulkhead #5 ~~onto~~ the threaded rods ~~on~~ the side of the avionics sled with the orange and purple wires	√
4.21	Secure Bulkhead #5 to the avionics sled using one ¼ washer and two ¼ inch hex nuts on each threaded rod	√
4.22	Confirm the avionics sled is ready to be inserted into the avionics bay	Recovery Lead:
4.23	Align the avionics bay coupler labeled 5 pointing towards Bulkhead #5. Slide the avionics bay over the avionics sled until Bulkhead #5 fits within the coupler section	√
4.24	Use the two black marks on the coupler and Bulkhead #5 to align the sled	√
4.25	Use a small screwdriver to probe the pressure ports on the avionics bay switch band to confirm they are clear	Safety Officer: Safety Officer High-Powered Rocketry NC State
4.26	Confirm that both screw switches are visible through the screw switch holes	√
4.27	Remove Bulkhead #4 from its anti-static bag	√
4.28	Lightly tug on the wires connected to the **MP** and **MS** terminal blocks to verify security	Safety Officer: Safety Officer High-Powered Rocketry NC State
4.29	While pointing the blast caps away from personnel, connect the blue and yellow wires on the avionics sled to the blue and yellow wires on Bulkhead #4	√
4.30	Lightly tug on the wire connection between the avionics sled and Bulkhead #4 to verify security	Safety Officer: Safety Officer High-Powered Rocketry NC State
4.31	Slide Bulkhead #4 onto the threaded rods coming out of the avionics bay coupler labeled 4 until the bulkhead fits within the coupler section	√
4.32	Secure Bulkhead #4 to the avionics bay using one ¼ inch washer and two ¼ hex nuts on each threaded rod, tighten until snug	√

4.33	Confirm all nuts are snug and avionics bay is properly aligned	Recovery Lead: Checked Safety Officer: Safety Officer High-Powered Rocketry NC State

5. PAYLOAD ASSEMBLY

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	√
Safety Officer	Frances McBride	√
Payload Imaging Lead	Emma Jaynes	√
Payload Personnel 1	Izabella Sciora	√

Required Materials			
Item	Quantity	Location	Completion
Payload Bay	1	-	√
Nose Cone	1	-	√
#10 Machine Screws	4	Nose Cone	√
Payload Sled (RPi and BNO attached)	1	Payload Tupperware	√
Arducam Fisheye camera module	1	Payload Tupperware	√
12" Camera Ribbon Cable	1	Payload Tupperware	√
¼-20 Nuts	4	Payload Tupperware	√
M3 Screws	4	Payload Tupperware	√
Blue Flathead Screwdriver	1	Payload Tupperware	√
Needle Nose Pliers	1	LD Toolbox (Middle Drawer)	√
Double-Sided Foam Tape	-	LD Toolbox (Top Drawer)	√
Electrical Tape	-	LD Toolbox (Top Drawer)	√

Number	Task	Completion
5.1	Confirm that Raspberry Pi is secured to payload sled with four M2.5 screws and nuts. Tighten if necessary.	√
5.2	Confirm that BNO jumper wires are secured to the Pi's GPIO pins	√
5.3	Confirm that BNO jumper wires are secured to bread board	√
5.4.1	Attach breadboard to payload sled with adhesive foam included with breadboard	√
5.4.2	Confirm that breadboard is securely attached to payload sled	√

5.5	Remove blue micro-USB plug from payload battery pack	√
5.6	Apply strip of adhesive foam to the front surface of the battery pack (reads "Koulomb")	√
5.7	Feed blue micro-USB through payload sled hole labeled "micro-USB"	√
5.8.1	Remove protective layer from foam adhesive and attach battery pack to the bottom of the payload sled	√
5.8.2	Confirm that payload battery pack is securely attached to payload sled	√
5.9	Attach Fisheye Camera Module to Pi's CSI port using 12" ribbon cable	√
5.10.1	Plug micro-USB into Raspberry Pi micro-USB port	√
5.10.2	Confirm that Raspberry Pi PWR LED is lit red (indicates that Pi is receiving power)	√
5.11	Slide payload sled onto threaded rods attached to payload bay bulkhead. The top of the payload sled (with Pi and BNO) should be facing the camera mount within the payload bay	√
5.12	Secure payload sled with four ¼-20 hex nuts, two nuts on each rod	Safety Officer: Safety Officer High-Powered Rocketry NC State
5.13.1	Attach camera module to camera mount with four M3 screws and blue flathead screwdriver	√
5.13.2	Confirm that camera module is secured to camera mount, and that the camera lens is centered in the payload bay port hole	√
5.14	If software startup performs automatically, proceed to item 5.21. Otherwise, continue the checklist with item 5.15	Payload Imaging Lead: N/A
5.15	Enable mobile hotspot on G8 ThinQ **Hotspot password: mac&cheese**	√
5.16	Confirm that the Raspberry Pi is connected to hotspot **RPi IP: 192.168.43.82**	√
5.17	Connect designated laptop to mobile hotspot	√
5.18	Open PuTTY and establish connection **Pi username: pi** **Pi password: blueberry**	√

5.19	In PuTTY session, enter 'subscale2020' directory **$ cd subscale2020**	✓
5.20	Run flightScript.py using python3 with nohup command **$ nohup python3 flightScript.py &**	✓
5.21	Remove the #10 screws from the nose cone	✓
5.22	Slide the nose cone shoulder into the payload bay, using the marks for alignment	✓
5.23	Secure the nose cone to the payload bay using four #10 machine screws	Safety Officer: NC State High-Powered Rocketry Safety Officer

6. DROGUE RECOVERY ASSEMBLY

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	✓
Safety Officer	Frances McBride	✓
Recovery Lead	Robert Kempin	✓
Drogue Personnel 1	Meredith Patterson	✓
Drogue Personnel 2	Emma McDonald	✓

Required Materials			
Item	**Quantity**	**Location**	**Completion**
Fin Can	1	-	✓
AV bay Assembly	1	-	✓
Safety Glasses	4	PPE Toolbox	✓
Drogue Parachute (18 in)	1	Recovery Tupperware	✓
Nomex Sheet	1	Recovery Tupperware	✓
Drogue Parachute Shock Cord	1	Recovery Tupperware	✓
Quicklink (#5-7)	~~4~~ 3	Recovery Hardware Box	✓
Shear Pin	3	Recovery Hardware Box	✓
Electrical Tape	1	LD Toolbox (Top Drawer)	✓
Scissors	1	LD Toolbox (Top Drawer)	✓
Plumbers Putty	1	LD Toolbox (Top Compartment)	✓

Number	Task	Completion
6.1	Confirm that all members within the assembly tent are wearing safety glasses	Safety Officer: Safety Officer High-Powered Rocketry NC State
6.2	Fold the length of shock cord between **Loops 5 and 6** accordion-style with 18-inch lengths	✓
6.3	Secure the length of shock cord between **Loops 5 and 6** with a single rubber band. Do not cover any part of a parachute. Two fingers should fit snugly under the rubber band	✓
6.4	Fold the length of shock cord between **Loops 6 and 7** accordion-style with 18-inch lengths	✓

6.5	Secure the length of shock cord between **Loops 6 and 7** with a single rubber band. Do not cover any part of a parachute. Two fingers should fit snugly under the rubber band	√
6.6	Confirm the shock cord is folded accordion-style	Recovery Lead: Checked
6.7	Attach **Quicklink 6** to **Drogue Parachute Quicklink 6.** Do not tighten	√
6.8	Attach the hole in the nomex sheet to **Quicklink 6**. Do not tighten	√
6.9	Attach **Quicklink 6** to shock cord **Loop 6** and tighten by hand until secure	Recovery Lead: Checked
6.10	Attach **Quicklink 7** to shock cord **Loop 7.** Do not tighten	√
6.11	Attach **Quicklink 7** to fin can Bulkhead #7 and tighten by hand until secure	√
6.12	Confirm the shock cord is secured to the fin can by visual inspection and pulling on shock cord	Recovery Lead: Checked
6.13	Attach **Quicklink 5** to shock cord **Loop 5**. Do not tighten	√
6.14	Attach **Quicklink 5** to aft avionics bay Bulkhead #5 and tighten by hand until secure	√
6.15	Confirm the shock cord is secured to the avionics bay by visual inspection and pulling on shock cord	Recovery Lead: Checked
6.16	Confirm the drogue parachute is properly folded	Recovery Lead: Checked
6.17	Firmly grasp the drogue parachute and remove the rubber band securing the drogue parachute	√
6.18	Confirm all rubber bands are removed from drogue parachute and shroud lines	√
6.19	Wrap the nomex cloth around the drogue parachute, like a burrito, continuing to firmly grasp the parachute	√
6.20	Carefully insert the shock cord between **Loops 6 and 7** into the fin can cavity	√
6.21	Carefully insert the drogue parachute into the fin can cavity with the ~~yellow tag~~ facing the aft end of the fin can	√

quick link

6.22	Carefully insert the shock cord between **Loops 5 and 6** into the fin can cavity	√
6.23	Slide the avionics bay coupler labeled 5 into the fin can, using the paint markings for alignment	√
6.24.1	Insert a #4-40, ½-inch long nylon shear pin into each of the three shear pin holes	√
6.24.2	If any shear pin is loose, place a small piece of electrical tape over the shear pin head. If the shear pin is still loose, place plumber's putty over the shear pin head.	√
6.25	Hold the avionics bay and let the fin can hang free and confirm fin can holds its own weight	Recovery Lead: Checked

7. MAIN RECOVERY ASSEMBLY

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	√
Safety Officer	Frances McBride	√
Recovery Lead	Robert Kempin	√
Drogue Personnel 1	Daniel Jaramillo	√
Drogue Personnel 2	Evan Patterson	√

Main Chute Bay →

Required Materials			
Item	**Number**	**Location**	**Confirmation**
Nosecone Assembly	1	-	√
Fin Can Assembly	1	-	√
Safety Glasses	5	PPE Toolbox	√
Main Parachute (48 in)	1	Recovery Tupperware	√
Deployment Bag (4 in)	1	Recovery Tupperware	√
~~Nomex Sheet~~	~~1~~	~~Recovery Tupperware~~	
Main Parachute Shock Cord	1	Recovery Tupperware	√
Quicklink (#1-4)	4	Recovery Hardware Box	√
Shear Pin	2	Recovery Hardware Box	√
Electrical Tape	1	AV HDX Box	√
Scissors	1	LD Toolbox (Top Drawer)	√
Plumbers Putty	1	LD Toolbox (Top Compartment)	√

Number	Task	Completion
7.1	Confirm that all members within the assembly tent are wearing safety glasses	Safety Officer: Safety Officer High-Powered Rocketry NC State
7.2	Fold the length of shock cord between **Loops 1 and 2** accordion-style with 18-inch lengths	√
7.3	Secure the length of shock cord between **Loops 1 and 2** with a single rubber band. Do not cover any part of a parachute. Two fingers should fit snugly under the rubber band	√
7.4	Fold the length of shock cord between **Loops 2 and 4** accordion-style with 18-inch lengths	√
7.5	Secure the length of shock cord between **Loops 2 and 4** with a single rubber band. Do not cover any part of a parachute. Two fingers should fit snugly under the rubber band	√

7.6	Confirm the shock cord is folded accordion-style	Recovery Lead: Checked
7.7	Attach **Quicklink 2** to main parachute **Eye-bolt 2**. Do not tighten	✓
7.8	Attach **Quicklink 2** to shock cord **Loop 2** and tighten by hand until secure	Recovery Lead: Checked
7.9	Attach **Quicklink 3** to deployment bag **Loop 3**. Do not tighten	✓
7.10	Attach **Quicklink 3** to shock cord **Loop 3** and tighten by hand until secure	Recovery Lead: Checked
7.11	Attach **Quicklink 4** to shock cord **Loop 4**. Do not tighten	✓
7.12	Pass the length of shock cord between **Loops 2 and 4** through the main parachute bay, with loop 4 pointing towards the aft end of the main parachute bay	✓
7.13	Attach **Quicklink 4** to forward avionics Bulkhead #4 and tighten by hand until secure	✓
7.14	Confirm the shock cord is secured to the avionics bay by visual inspection and pulling on shock cord	Recovery Lead: Checked
7.15	Slide the main parachute bay over the avionics bay coupler labeled 4, being careful not to pinch the shock cord, and using the paint marks to align the sections	✓
7.16	Use four #10 machine screws to fasten the main parachute bay to the avionics bay	✓
7.17	Confirm the deployment bag flap covers all parachute shroud lines	✓
7.18	Carefully insert the deployment bag completely into the main parachute bay with the deployment bag **Loop 3** pointed towards the nose cone	✓
7.19	Attach **Quicklink 1** to shock cord **Loop 1**. Do not tighten	✓
7.20	Attach **Quicklink 1** to payload bay Bulkhead #1 and tighten by hand until secure	✓
7.21	Confirm the shock cord is secured to the payload bay by visual inspection and pulling on shock cord	Recovery Lead Checked
7.22	Slide the payload bay over the main parachute bay coupler, being careful not to pinch the shock cord, and using the paint marks for alignment	✓
7.23.1	Insert a #4-40, ½-inch long nylon shear pin into each of the three shear pin holes	✓

remove rubber band

7.23.2	If any shear pin is loose, place a small piece of electrical tape over the shear pin head. If the shear pin is still loose, place plumber's putty over the shear pin head.	N/A
7.24	Hold the launch vehicle upright by the payload bay and verify the launch vehicle can hold its own weight from shear pins alone	Recovery Lead:

8. MOTOR ASSEMBLY

Required Personnel		Confirmation
Aerodynamics Lead	Justin Parkan	✓
Level 3 Mentor	Alan Whitmore	✓
Motor Personnel 1	Alex Forsgard	✓

Required Materials			
Item	Quantity	Location	Completion
Aerotech I435T Reload Kit	1	Motor Box	
Aerotech RMS 38/1080 motor casing	1	Motor Box	
Motor Igniter	1	LD Toolbox (Top Drawer)	
Vaseline	1	LD Toolbox (Top Compartment)	
Needle nose pliers	1	LD Toolbox (Middle Drawer)	
Baby Wipes	1	LD Toolbox (Top Compartment)	
Sharpie Marker	1	LD Toolbox (Top Compartment)	
Blue Tape	1	LD Toolbox (Top Drawer)	
Nitrile Gloves	2	PPE Toolbox	
Paper Towels	1	Recovery Tupperware	

NOTE: Follow all manufacturer procedures for assembling motor!

Number	Task	Completion
8.1	Use Vaseline to lightly grease all three included O-Rings	✓
8.2	Use Vaseline to lightly grease threads on motor casing	✓
8.3	Install smoke grain into smoke insulator until snug	✓
8.4	Use Vaseline to lightly grease one end of the smoke grain	✓
8.5	Install smoke grain into forward closure, greased side facing forward, until snug	✓
8.6	Install forward seal disk O-Ring on forward seal disk	✓
8.7	Install forward seal disk and O-Ring into one end of motor liner until snug	✓

8.8	Install three propellant grains into motor liner	✓
8.9	Install motor liner into motor casing, holding the liner centered within the casing	✓
8.10	Install forward O-Ring into forward end of motor casing. The O-Ring MUST be seated against the forward end of the forward seal disk assembly	✓
8.11	Install the forward closure with smoke grain assembly onto the forward end of the motor casing, on top of the forward O-Ring. Tighten until finger tight	✓
8.12	Install aft nozzle on the aft end of the motor casing	✓
8.13	Install aft O-Ring onto aft nozzle	✓
8.14	Install aft closure onto aft O-Ring	✓
8.15	Install aft closure assembly into aft end of motor casing. Tighten until finger tight. NOTE: There will be exposed threads when the aft closure is snug	✓
8.16	Install nozzle cap	✓
	Prepare motor ignitor	✓
8.17.1	Hold ignitor wire along the side of the motor casing	
8.17.2	Designate appropriate length by marking ignitor wire with Sharpie	
8.17.3	Separate ends of ignitor wire	
8.17.4	Strip ends of ignitor wire	
8.17.5	Coil ignitor wire back into original orientation	
8.17.6	Store ignitor in field recovery toolbox	
8.18	Return to launch vehicle assembly location with motor and prepared ignitor. Designate one person to hold the motor. **KEEP MOTOR AWAY FROM OTHER PERSONNEL UNTIL CHECKLIST ITEM 9.2**	

9. FINAL MEASUREMENTS

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	√
Safety Officer	Frances McBride	√
Measurements Personnel 1	Emma McDonald	√
Measurements Personnel 2	Izabella Sciora	√

Required Materials			
Item	Quantity	Location	Completion
Fish Scale	1	LD Toolbox (Bottom Drawer)	√
Calculator	1	Phone	√
Rope	1	LD Toolbox (Bottom Drawer)	√
Circle Stickers	2	LD Toolbox (Top Compartment)	√
Sharpie	1	LD Toolbox (Top Compartment)	√
Launch Vehicle (assembled)	1	-	√
Motor (assembled)	1	-	√

Tape Measer

Number	Task	Completion
9.1	Unscrew motor retainer	√
9.2	Slide motor casing into motor tube	√
9.3	Secure motor casing using motor retainer screw	Safety Officer: Safety Officer High-Powered Rocketry NC State
9.4	Measure the center of pressure of the launch vehicle. This point is *53.02 inches* from the tip of the nosecone. Ensure tape measure is straight	√
9.5	Use an orange circular sticker labelled "CP" to mark the center of pressure of the launch vehicle	√
9.6	Using the rope and fish scale, locate the center of gravity of the launch vehicle. Tie the rope around the launch vehicle and move the rope until the launch vehicle balances	√
9.7	Record the weight of the launch vehicle using the fish scale	Record weight here: 10.0 lb

9.8	Use a green circular sticker labelled "CG" to mark the center of gravity of the launch vehicle	✓
9.9	Measure the center of gravity's distance from the tip of the nose cone using the tape measure. Ensure the tape measure is straight	Record CG location here: 46.35 in
9.10	Calculate the stability margin using the formula (CP-CG)/D. This is (53.02 - CG)/4. The stability margin must exceed 2.0	Record stability margin here: 1.69 Team Lead: PASS!
9.11	Load the field recovery box with the items required by checklist 10	✓
9.12	Proceed to the launch pad	

10. LAUNCH PAD

Required Personnel		Confirmation
Student Team Lead	Evan Waldron	
Safety Officer	Frances McBride	
Launch Pad Personnel 1	Robert Kempin	
Launch Pad Personnel 2	Evan Patterson	

Required Materials			
Item	Quantity	Location	Completion
Launch Vehicle (assembled)	1	-	
Motor ignitor	1	Field Recovery Box	✓
Vaseline	1	LD Toolbox (Top Compartment)	✓
Nitrile Gloves	4	PPE Box	✓
Heavy Duty Gloves	2	PPE Box	✓
Safety Glasses	4	PPE Box	
Switch Screwdriver	1	LD Toolbox (Middle Drawer)	✓
TB Screwdriver	1	LD Toolbox (Middle Drawer)	
Adjustable Wrench	1	LD Toolbox (Middle Drawer)	✓
Rubber Bands	6	Recovery Hardware Box	✓
Phone	1	-	✓
Wire Snips	1	LD Toolbox (Middle Drawer)	✓
Wire Strippers	1	LD Toolbox (Middle Drawer)	✓
Blue Tape	1	LD Toolbox (Top Drawer)	✓
Fire extinguisher	1	Field Recovery Box	✓

Number	Task	Completion
10.1	Confirm with RSO that field conditions are safe for launch	✓
10.2	Submit flight card to RSO for review	✓
10.3	Proceed to launch pad	✓
10.4	Record coordinates of launch pad	

10.5	Confirm blast deflector is mounted on launch rail	Safety Officer:
10.6	Carefully slide the launch vehicle onto the launch rail	✓
10.7.1	Visually confirm the launch vehicle slides smoothly along the rail	Safety Officer:
10.7.2	If there is resistance in sliding along the rail, remove the launch vehicle, apply vaseline to the launch rail, then repeat items 10.6 and 10.7.1	✓
10.8	Rotate launch rail into the upright position and lock into place	✓
10.9	Orient the launch rail such that it is pointed 5 degrees away from spectators	✓
10.10	Confirm the launch rail is locked	Safety Officer:
10.11	Take team pictures as necessary	✓
10.12	All non-essential personnel leave the launch pad	✓
10.13	Confirm that all remaining individuals are wearing safety glasses	Safety Officer:
	Altimeter arming procedure:	
10.14	Slightly loosen primary screw switch and remove "remove before flight" tag	
10.15	Turn primary screw switch until tight	✓
10.16	Confirm primary altimeter is programmed correctly using Appendix A – Primary Beep Sheet	✓
10.17	Turn secondary screw switch until tight	✓
10.18	Confirm secondary altimeter is programmed correctly using Appendix B – Secondary Beep Sheet	✓
10.19	Confirm both altimeters are powered on with full continuity	Safety Officer:
	Ignitor installation procedure:	
10.20	Attach ignitor to wooden dowel	✓
10.21	Insert ignitor fully into the motor	✓
10.22	Tape ignitor into place at the bottom of the launch vehicle, using the mark made in item 8.17.2	N/A
10.23	Confirm that launch pad power is turned off	✓
10.24	Connect ignitor wires to launch pad power	

10.25	Confirm launch pad continuity, measurement should read between 1.5 and 3.5	3.2
10.26	All personnel navigate to safe location behind the launch table	✓
10.27	Pass the primary checklist and field recovery toolbox to the Safety Officer	✓
10.28	Inform the RSO the team is ready for launch	✓
10.29	Launch until golden brown and crisp	

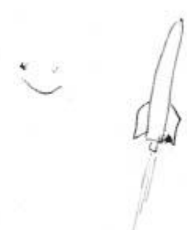
11. FIELD RECOVERY

Required Personnel		Confirmation
Recovery Lead	Robert Kempin	✓
Safety Officer	Frances McBride	✓
Field Recovery Personnel 1	Trent Couse	✓
Field Recovery Personnel 2	Sailor Koeplinger	✓

Required Materials			
Item	Quantity	Location	Completion
Nitrile Gloves	4	Field Recovery Box	
Heavy Duty Gloves	1	Field Recovery Box	
Safety Glasses	5	Field Recovery Box	
Switch Screwdriver	1	Field Recovery Box	
TB Screwdriver	1	Field Recovery Box	
Adjustable Wrench	1	Field Recovery Box	
Rubber Bands	6	Field Recovery Box	
Phone	1	Field Recovery Box	
Wire Snips	1	Field Recovery Box	
Wire Strippers	1	Field Recovery Box	
Blue Tape	1	Field Recovery Box	
Fire extinguisher	1	Field Recovery Box	

Number	Task	Completion
11.1	Confirm that all personnel are wearing safety glasses	Safety Officer:
11.2	Confirm that all personnel handling the launch vehicle are wearing nitrile gloves	Safety Officer:
11.3	Approach the launch vehicle on foot	✓
11.4	If a parachute is open and pulling the launch vehicle, follow items 11.5.1-11.5.3. Otherwise, proceed to item 11.6	✓
11.5.1	Approach the parachute from the billowed side	
11.5.2	Use hands and body to pull down the parachute by the CANOPY. **Do not grab the shroud lines or shock cord**	
11.5.3	Repeat for second parachute if necessary	
11.6	If the launch vehicle appears to be on fire or smoking, use the fire extinguisher to put out the flame	

11.7	Use a rubber band to secure the main parachute	✓
11.8	Use a rubber band to secure the drogue parachute	✓
11.9	Carefully pick up the forward end of the main parachute bay and inspect the forward AV bulkhead for un-blown black powder charges	✓
11.10	Inspect the aft AV bulkhead for un-blown black powder charges	✓
11.11	If there are un-blown charges, follow items 11.12.1-11.12.2. Otherwise, proceed to item 11.13	
11.12.1	Equip heavy duty gloves before handling the body tube	Safety Officer:
11.12.2	Use the switch screwdriver to turn off the primary AND secondary screw switches	✓
11.13	Listen to the altimeters and record flight data using Appendix C - Post-Flight Beep Sheet	✓
~~**11.14**~~	~~Power off both altimeters by turning off both screw switches~~	
11.15	Record the coordinates of the final resting position of the launch vehicle	✓
11.16	Record the coordinates of the initial ground impact point	✓
11.17	Take pictures of any damage to the launch vehicle	✓
11.18	Inspect for and collect non-biodegradable waste from the landing site	✓
11.19	Collect each launch vehicle section and return to the launch site	



APPENDIX A – PRIMARY BEEP SHEET

NOTE: There is a long beep between each row

The Beeps: What do they mean	Write Beeps Here	Expected Output
A siren and error code if an error was encountered during the last flight.	—	Ignore, currently not important
A one-digit number (range of 1 to 9) corresponding to the currently-selected program preset.	1	Should be 1
A two second pause, and then a three- or four-digit number corresponding to the main deploy altitude setting.	500	IMPORTANT: Should be 500
(optional) only if you have added an apogee delay to the currently selected preset: A two second pause, and then a ***five second continuous tone*** *to warn you that your apogee firing is set to be delayed.*	—	IMPORTANT: SHOULD NOT SOUND
A two second pause, and then a three to six-digit number representing the apogee altitude of the last flight.	—	Ignore, currently not important
A two second pause, and then a two- or three-digit number representing the battery voltage in tenths of a volt (e.g. 9.2 volts would report as 92).	9.5	IMPORTANT: Should be between 8.8 and 11.0
A two second pause, and then continuity beeps repeated every 0.8 seconds – a single beep means drogue e-match continuity is OK, two beeps means main e-match continuity is OK, three beeps means both drogue and main have good continuity.	3	IMPORTANT: Should be 3

APPENDIX B – SECONDARY BEEP SHEET

NOTE: There is a long beep between each row

The Beeps: What do they mean	Write Beeps Here	Expected Output
A siren and error code if an error was encountered during the last flight.	\	Ignore, currently not important
A one-digit number (range of 1 to 9) corresponding to the currently-selected program preset.	1	Should be 1
A two second pause, and then a three- or four-digit number corresponding to the main deploy altitude setting.	450	IMPORTANT: Should be 450
(optional) only if you have added an apogee delay to the currently selected preset: A two second pause, and then a ***five second continuous tone*** *to warn you that your apogee firing is set to be delayed.*	√	IMPORTANT: SHOULD SOUND
A two second pause, and then a three to six-digit number representing the apogee altitude of the last flight.	\	Ignore, currently not important
A two second pause, and then a two- or three-digit number representing the battery voltage in tenths of a volt (e.g. 9.2 volts would report as 92).	9.6	IMPORTANT: Should be between 8.8 and 11.0
A two second pause, and then continuity beeps repeated every 0.8 seconds – a single beep means drogue ematch continuity is OK, two beeps means main ematch continuity is OK, three beeps means both drogue and main have good continuity.	3	IMPORTANT: Should be 3

APPENDIX C – POST-FLIGHT BEEP SHEET

The Beeps: What do they mean	Primary Beeps	Secondary Beeps	Expected Output
An extra-long tone to indicate the start of the reporting sequence			Ignore, currently not important
A three to six-digit number representing the peak altitude in feet	1651	1652	Should be approximately 2600 ft. Record
A long separator tone followed by a two to five-digit number representing the maximum velocity during the flight in miles per hour	327		Record
If the "siren delay" number is set to a number greater than zero, the altimeter will wait for the specified siren delay time, and then emit a 10 second warbling siren tone.			Ignore, currently not important
After a 10 second period of silence, the sequence repeats until power is disconnected.			Ignore, currently not important

~~1651~~ 470

328 1652

94

5.3 Hazard Classification

In order to better classify risks and hazards associated with the project, the team has developed a likelihood-severity (LS) method of hazard classification. This classification system is detailed in Table 5-1 below.

Table 5-1 Likelihood-Severity (LS) Classifications

		Level of Severity			
		1 Low Risk	2 Medium Risk	3 High Risk	4 Severe Risk
Likelihood of Occurrence	A Very Unlikely	1A	2A	3A	4A
	B Unlikely	1B	2B	3B	4B
	C Likely	1C	2C	3C	4C
	D Very Likely	1D	2D	3D	4D

These LS classifications are used to determine the importance of mitigations of their associated hazards. Any hazard with a severity of at least 3 or likelihood of at least C must be mitigated. The definitions of each severity level are provided in Table 5-2 below.

Table 5-2 Severity Definitions

Hazard Type	1 (Low Risk)	2 (Medium Risk)	3 (High Risk)	4 (Severe Risk)
Personnel	No personnel injury.	Any personnel injury is treatable with first aid.	Moderate personnel injuries, manageable with launch field first aid.	Severe personnel injuries requiring hospitalization.
Launch Vehicle	Any damage to launch vehicle is reversible.	Any damage to launch vehicle is repairable.	Damage to launch vehicle is repairable, but not to original condition.	Damage to launch vehicle is irreparable.
Mission	Mission success.	Partial mission failure, successful flight.	Partial mission failure, partially successful flight.	Complete mission failure, unsuccessful flight

Each hazard is also given a label for unique identification. These labels follow the format "System.Hazard Category.Number." Systems are defined by one or two-letter codes, shown in Table 5-3 below. Hazard categories are listed as horizontal bars within the FMEA table separating different sections. Their abbreviations are different for each system. The number is used to differentiate hazards with the same system and category.

Table 5-3 Hazard Label System Codes

Code	System Represented
A	Aerodynamics
E	Environmental
P	Payload
Pe	Personnel
R	Recovery
S	Structures

5.4 Failure Modes and Effects Analysis (FMEA)

The FMEA tables include a hazard label, the hazard identified by the label, causes of the hazard, and effects of the hazard. Each cause has a mitigation and verification associated with it. These causes are also assigned an LS classification for before and after the mitigation is implemented. The FMEA tables begin on the following page.

Table 5-4 Structures Subsystem FMEA

Label	Hazard	Cause	Effect	Pre-LS	Post-LS	Mitigation	Verification
Fin Hazard							
S.F.1	Fin structural damage (cracks/shears)	Freestream velocity approaching transonic regime; fin flutter	(1) Flight path diverted (2) Failure to reach target apogee (3) Launch vehicle enters nose-over-tail spin	4B	4A	Flight velocity simulations have been performed in RockSim – no part of the launch vehicle nears transonic speeds	CDR Section 3.5.2
S.F.2	Fin delamination from airframe	Insufficient time for a complete fillet cure Gaps in fillet epoxy		4C	2A	Epoxy fillets are given at least 24 hours to fully cure before flight	TDR 1.1,
Airframe Hazard							
S.A.1	Airframe cracking/rupture	Fin loss; launch vehicle enters into nose-over-tail spin	(1) Premature black powder detonation due to rapid pressure change (2) Loss of inner components	4C	2A	See S.F.1 and S.F.2 Mitigation	See S.F.1 and S.F.2 Verification
		Loose inner payload components during flight		2D	2A	An electronic latch and nylon shear pins secure the payload in place prior to ejection	CDR Section 4.3.7

		Excessive internal stresses		2C	1B	(1) G12 Fiberglass, a strong and durable material, is chosen for the full scale airframe (2) Prior to launch, ejection tests shall be performed to confirm that the minimum necessary black powder amount is used	(1) CDR Section 3.1.4, TDR 2.1 (2) Full Scale Ejection Test scheduled to be performed on 2/6/2021
S.A.2	Shear pin failure to shear	Insufficient black powder charge	Ballistic launch vehicle descent	4B	4A	(1) Black powder mass is calculated using the ideal gas law and realistic reaction model (2) Ejection tests shall be performed prior to launch to confirm appropriate black powder mass	(1) CDR Section 3.5.9 (2) Full Scale Ejection Test scheduled to be performed on 2/6/2021
		Excessive shear pin diameter				(1) 4-40 shear pins are used (2) Shear pin stress tests shall be performed prior to launching the launch vehicle	(1) CDR Section 3.4.1 (2) Full Scale Ejection Test is scheduled to be performed on 2/6/2021; Checklist Section: Main Recovery Assembly (7.24)
S.A.3	Premature shear pin shear	Premature black powder detonation	(1) Potential airframe exposure to burning motor	3B	3A	Pressure ports are drilled into airframe	CDR 3.4.1

		Insufficient shear pin diameter	(2) Ballistic payload descent (3) Failure to reach target apogee			(1) 4-40 shear pins are used (2) Shear pin stress tests shall be performed immediately prior to launching the launch vehicle	(1) CDR 3.4.1 (2) Full Scale Ejection Test is scheduled to be performed on 2/6/2021; Checklist Section: Main Recovery Assembly (7.24)
S.A.4	Airframe exposure to burning motor	Premature section separation	(1) Inability of airframe to withstand flight forces; complete disintegration (2) Nosecone plastic melting	4A	3A	See S.A.3 Mitigations	See S.A.3 verifications
S.A.5	LV section collision	Excessive shock cord length Insufficient shock cord length	Airframe cracking/rupture	4C	2A	The launch vehicle descends under drogue with the midsection above the fin can	CDR Section 3.4.1.5
S.A.6	Elevated pressure inside LV	Insufficient pressure ports	(1) Airframe rupture (2) Inability of black powder to detonate	4B	4A	Pressure ports are drilled into airframe	CDR Section 3.4.1
Hazard to Bulkheads							

S.B.1	Bulkhead delamination	Gaps in epoxy layers Excessive forces from bolts	(1) Inner LV component structural damage (2) Airframe cracking/shear (3) Motor separation from airframe	3B	2A	Bulkheads shall be designed with a factor of safety of at least 2 such that they can withstand at least 2 times the nominal flight loading expected	(1) TDR 2.2 (2) Bulkhead Tensile Loading Tests are scheduled to be performed on 1/29/2021 – CDR Section 6.1.1
S.B.2	Bulkhead cracking/ripping	Excessive force from bolts	(1) Airframe cracking/shear (2) Parachute separation from LV	2A	1A	U-bolts are chosen over eyebolts for their superior load distribution	CDR Section 3.4.1.5
		Insufficient bulkhead thickness				Bulkheads and their U-bolts shall have a FOS greater than or equal to 2	CDR Section 3.1.12, TDR 2.2

Table 5-5 Payload Subsystem FMEA

Label	Hazard	Cause	Effect	Pre-LS	Post-LS	Mitigation	Verification
Payload Structure Hazard							
P.S.1	Pre-separation retention latch disengagement	Premature payload altimeter signal	LOPSIDED essential power/ communication cord disconnection LOPSIDED/POS cracks, chips, and breaks	2B	2A	(1) Payload wires shall be chosen such that their length allows some slack	(1) CDR Section 4.3.4
P.S.2	LV ground touchdown while retaining payload in payload bay	Retention latch failure to open	Cracks, chips, and breaks in payload structure from loads imparted to system by payload latch and airframe Damage to ARRD and ARRD housing	2B	2A	Payload wires shall be chosen such that their length allows some slack	CDR Section 4.3.4
P.S.3	Payload-parachute connection shear/break		Ballistic descent of payload	4C	2B	(1) The area connecting LOPSIDED and POS is	CDR Section 4.3.2.2, TDR 4.2

		Excessive load from payload parachute	Irreparable payload structural damage			made of strong polycarbonate material (2) LOPSIDED-POS can withstand the approximately 112 lbs of maximum load expected during nominal flight	
P.S.4	LOPSIDED leveling leg crack/break	Touchdown with excessive kinetic energy	Inability of LOPSIDED to orient POS parallel to the vertical direction; unclear picture obtained	2C	1B	Legs made out of hollow carbon fiber which sustains flight and landing forces	CDR Section 4.3.2.5, Payload Ground Test scheduled to be performed on 2/15/2021
	LOPSIDED hinge connection shear			3C	2A	The maximum possible angle of landing at which LOPSIDED is able to right itself, 27 degrees, exceeds the angle at which structural failure of the hinge connection will occur	CDR Section 4.3.2.6, Payload Ground Test scheduled to be performed on 2/15/2021
Payload Retention Hazard							
P.R.1	Retention latch failure to open	Retention latch power cord disconnection	Payload retention structural failure (see F.P.S.2)	2B	2A	Payload wires shall be chosen such that their length allows some slack	CDR Section 4.3.4
P.R.2	Payload angled such that frictional forces from payload bay prevent ejection	Payload ring of excessive diameter	Untimely/absent payload ejection	3B	3A	The ring surrounding LOPSIDED is 5.75 inches in diameter, small enough to generate negligible frictional forces against the body tube	CDR Section 4.3.2.5

P.R.3	Excess in-flight load imparted to payload-parachute connection	Parachute movement during flight	Structural failure (cracks, breaks) in payload-parachute connection	3C	3A	(1) The area connecting LOPSIDED and POS is made of strong polycarbonate material (2) LOPSIDED-POS can withstand the approximately 112 lbs of maximum load expected during nominal flight	CDR Section 4.3.2.1, TDR 4.2
P.R.4	Payload parachute attachment at landing	Payload ground impact with insufficient force	(1) Payload abrasion against ground from parachute drag (2) Inability of leveling system to right POS; no clear picture obtained	2B	2A	The payload parachute is a 60-inch iris ultra compact parachute; the payload accelerometer is calibrated to this parachute's drag	CDR Section 3.4.1.4
		Loss of power to accelerometer				The payload battery is tested with a multimeter to confirm its voltage meets or exceeds 12V	Checklist Section: Payload Assembly
Imaging System Hazard							
P.I.1	In-flight camera dislodgement	LV structural failure (F.S.A.1, F.S.B.1&2)	(1) Obstructed field of view (2) No clear picture obtained	4B	4A	A powered camera module shall fly on the sub-scale model to test its ability to withstand flight forces	CDR Section 4.3.6
		Inability of camera to withstand flight forces		3B	3A		
P.I.2	Abrasion to camera surface	LV structural failure (F.S.A.1, F.S.B.1&2)	No clear picture obtained	3B	2A	(1) Payload bay is confirmed to be clean prior to launch	(1) Checklist Section: Payload Assembly

		Parachute movement during flight (see F.P.R.3)				(2) LOPSIDED will right the payload such that no contact is made between the lenses and the ground (3) POS is surrounded by four clear polycarbonate sheets to protect it from launch field debris	(2) CDR Section 4.3.2.5 (3) CDR Section 4.3.2.2
P.I.3	LOPSIDED lopsided touchdown	Excessively steep landing area	POS camera obstruction; inability to take and transmit clear picture	3C	3A	LOPSIDED can right itself at angles ranging from 0 to 27 degrees, far beyond the expected grade of the launch field	TDR 4.8, CDR Section 4.3.2.6
P.I.4	In-flight camera cable disconnection In-flight Raspberry Pi USB power cord disconnection In-flight transmitter wire disconnection In-flight accelerometer wire disconnection	Pre-separation retention latch disengagement	Inability for POS to capture/transmit image	3B	3A	(1) Payload wires are chosen such that their length allows some slack (2) The final payload electronics circuit will be soldered using perfboard to avoid loose connections	(1) CDR Section 4.3.4, (2) CDR Section 4.3.4
P.I.5	Payload landing outside of transmitter range	Wind drift Recovery failure (See R.A.2 and R.BP.1)	Poor signal quality of photo transmission	2B	2A	See R.A.2 Mitigation	See R.A.2 Verification
	RF interference between POS transmitter and GPS transmitter	POS and GPS transmitters sharing a frequency		2A	1A	POS and GPS transmitters shall operate on different frequencies	NASA 2.22.9

P.I.6	Battery disconnection	Excessive loads from main parachute (see F.P.R.3)	Loss of power to POS	3B	3A	(1) A piece of electrical tape secures the lead to the battery (2) Wire lengths shall be chosen such that slack is present in each wire	(1) CDR Section 4.3.4 (2) CDR Section 4.3.4
	Insufficient battery capacity	Unanticipated in-flight current draw		3B	2A	All batteries used for launch are tested with a multimeter prior to launch	Checklist Section: Payload Assembly
P.I.7	Voltage higher than 5.25V is applied to Raspberry Pi	Inductive flyback	Irreparable damage to Raspberry Pi; loss of payload control	3B	3A	A step-down USB module will be used to power the Raspberry Pi, and a multimeter will be used to check that the provided voltage is between 4.75-5.25V	CDR Section 4.3.4, Checklist Section: Payload Assembly
P.I.8	Voltage lower than 4.75V is applied to Raspberry Pi	Insufficient power in step-down USB module	Raspberry Pi receives insufficient power to control payload	3B	2A		
P.I.9	Payload circuit inductive flyback	Abrupt power-off to the circuit	Damage to critical circuit components; loss of payload control	4B	3A	A flyback diode is used to provide a path in which excess damaging current can flow	CDR Section 4.3.4

Table 5-6 Aerodynamics Subsystem FMEA

Label	Hazard	Cause	Effect	Pre-LS	Post-LS	Mitigation	Verification
Stability Hazard							
A.S.1	Launch vehicle weather cock into wind gust	Overstability (Stability margin ≥ 2.5)	Diverted flight path; target apogee not reached	3C	1B	(1) CP, CG, and stability margin calculated through RockSim prior to flight (2) CG, weight, and stability margin observed manually directly prior to flight	(1) CDR Section 3.5.4 (2) Checklist Section: Final Measurements (9.4-9.10)
A.S.2	Launch vehicle diversion away from wind gust	Understability (Stability margin ≤ 2.0)		3C	2B		
A.S.3	Fin flutter	Transonic freestream velocity around fins	(1) Fin structural damage (2) Loss of fins (3) Launch vehicle enters nose-over-over-tail spin	4B	2A	Flight velocity simulations have been performed in RockSim – no part of the launch vehicle nears transonic speeds	CDR Section 3.5.2, TDR 2.4
Motor Hazard							
A.M.1	Motor retention ring ejection	Structural failure of retention ring	Catastrophe at Takeoff (CATO)	4B	4A	Aerotech motor casings and retention rings are chosen for their strength and durability	CDR Section 1.2.2
A.M.2	Uneven pressure buildup inside of motor	Gap/bubble in motor propellant grain Clogged nozzle Holes/cracks in motor casing		4B	4A	Aerotech APCP motors shall be chosen for their low likelihood of factory defects leading to CATO and motor failures	CDR Section 1.2.2, NASA 2.10, NAR High Power Rocket Safety Code Section 3

A.M.3	Rapid change in stability margin	Difference between in-flight and theoretical thrust curve of L1520T	Diverted flight path; target apogee not reached	2B	1A		
A.M.4	Absence of igniter ignition	High humidity	Absence of motor ignition; inability to fly	4C	4A	The team shall only launch in dry conditions	NAR High Power Rocket Safety Code Section 9
		Faulty igniters				Extra igniters are supplied by the team on launch day	Checklist Section: Launch Pad (Materials)
A.M.5	Motor cracks	Torsion applied to propellant grains in assembly	Catastrophe at takeoff	4C	2A	A NAR/Tripoli official shall monitor the assembly of the motor for all launches	NAR High Power Rocket Safety Code Section 1

Recovery/Avionics

Label	Hazard	Cause	Effect	Pre-LS	Post-LS	Mitigation	Verification
Hazard to/from Avionics							
R.A.1	Avionics exposure to ejection gases	Gap between AV bulkheads and body tube	(1) Electronics damage/ destruction (2) Failure of altimeter to detonate main charge; LV lands with excessive kinetic energy	3B	3A	Bulkhead-airframe contacts filleted on both sides; bulkheads confirmed to be flush with airframe	CDR Section 3.1.9
R.A.2	Dual deploy with main at apogee	Crossed main and drogue signal wires	Large wind drift; inability to recover rocket	4C	4A	AV Bay wiring will be confirmed by at least four	Checklist Section: Avionics Bay

R.A.3	No parachute deployment		(1) Ballistic descent (2) Personnel injury	4C	4A	team members prior to final assembly	Assembly (4.16-4.22 & 4.28-4.30)
Hazard to Parachutes/Shock Cord							
R.P.1	Shock cord disconnection	U-bolt shear U-bolt disconnection Bulkhead wood crack, shear Bulkhead delamination	(1) Ballistic descent of at least one launch vehicle section (2) Excessive kinetic energy upon landing	4B	3A	Bulkheads and their connecting pieces shall be designed with a factor of safety of 2 or greater	TDR 2.2, CDR Section 3.1.12
		Shock cord rip		4A	2A	Kevlar shock cord is chosen to withstand the maximum expected force on shock cord, 388 lbf	CDR Section 3.4.1.5
R.P.2	Parachute rip/hole/tear	Contact with explosive black powder	Partial parachute deployment	3D	2B	Fireproof Nomex cloth is wrapped around parachute to insulate it from ejection gases	CDR Section 3.4.1.4, Checklist Section: Main and Drogue Assembly
R.P.3	Partial parachute deployment	Parachute rip/hole/tear Recovery harness + parachute entanglement	(1) Excessive kinetic energy upon landing (2) Personnel injury	4B	4A		
		Impact of body section with parachute				The launch vehicle descends under drogue with the midsection above the fin can	CDR Section 3.4.1.5
R.P.4	Late parachute deployment	Delayed e-match burning	Structural damage due to	3B	3A	Strips of flammable paper towels are placed on top of	

		Delayed black powder detonation	excessive force on shock cords			black powder to force proper contact between e-match and black powder and to ensure sufficient packing density	Checklist Section: Main and Drogue Black Powder
R.P.5	Premature parachute deployment	Incorrect altimeter pressure readings	(1) Parachute deployment during ascent (2) Recovery harness/airframe structural damage	4B	3A	Pressure ports are drilled in airframe to allow for ambient pressure changes to be detected	CDR Section 3.4.1
		Excessive flight forces				(1) 4-40 Shear pins are used to secure body sections (2) Shear pin stress tests shall be performed prior to launch	(1) CDR Section 3.4.1 (2) Checklist Section: Final Measurements (9.4-9.10)
R.P.6	Premature payload parachute deployment	Deployment bag opening due to main black powder deployment	Payload parachute tangle in recovery harness Rips/holes/tears in payload parachute; semi-ballistic landing			Two Jolly Logic ChuteReleases are wrapped around the deployment bag; these altimeters will release only at 550 feet, after the secondary main BP detonation	CDR Section 3.4.1
Hazard to/from Black Powder							

R.BP.1	Lack of shear pin breakage	Shear pins of excessive diameter/strength	(1) Ballistic descent; excessive kinetic energy upon landing (2) Personnel injury	4C	4A	(1) 4-40 Shear pins are used to secure body sections (2) Shear pin stress tests shall be performed prior to launch	(1) CDR Section 3.4.1 (2) Checklist Section: Final Measurements (9.4-9.10)
		Insufficient black powder charges				(1) Black powder mass is calculated using the ideal gas law and realistic reaction model (2) Ejection tests shall be performed prior to launch to confirm appropriate black powder mass	(1) CDR Section 3.5.9, Equation 3 (2) Full Scale Ejection Test scheduled to be performed on 2/6/2021
R.BP.2	Premature section separation	Premature shear pin break during ascent	(1) Body tube zippering from shock cord (2) Diverted flight path resulting in low final apogee (3) Premature payload ejection	3B	3A	(1) 4-40 Shear pins are used to secure body sections (2) Shear pin stress tests shall be performed prior to launch	(1) CDR Section 3.4.1 (2) Checklist Section: Final Measurements (9.4-9.10)
R.BP.3	Premature shear pin break during ascent	Shear pins of insufficient diameter or strength	Premature section separation	3B	3A	(1) 4-40 Shear pins are used to secure body sections	(1) CDR Section 3.4.1

		Shear pin ejection				(2) Shear pin stress tests shall be performed prior to launch	(2) Checklist Section: Final Measurements (9.4-9.10)
R.BP.4	High wind drift	Premature section separation during descent	Inability to communicate with payload or launch vehicle GPS	4B	3A	(1) Pressure ports are drilled into airframe (2) The team shall launch only in winds of 20mph or less	(1) CDR Section 3.4.1 (2) CDR Section 3.5.8
R.BP.5	Excessive pressure in AV bay	Sympathetic detonation of primary and secondary black powder charges	(1) Hoop stress on body tube (2) Structural damage (See S.A.1)	4B	4A	Bulkheads separate primary and secondary black powder charges such that they fire away from one another	CDR Section 3.1.9

5.5 Personnel Hazard Analysis

Table 5-7 Personnel Hazard Analysis Matrix

Label	Hazard	Cause	Effect	Pre-LS	Post-LS	Mitigation	Verification
Hazard to Skin and Soft Tissue							
Pe.S.1	Slips, trips, and falls	Uneven launch field conditions	(1) Ligament sprain (2) Bruising (3) Skin abrasion	3C	1B	(1) Team members shall be instructed to maintain a walking pace on launch day (2) Those recovering launch vehicle are ONLY trained, experienced, pre-assigned personnel (3) Recovery personnel shall be instructed to wear closed toe walking shoes on launch day	(1) TDR 1.2 (2) Checklist Section: Recovery (Required Personnel) (3) Checklist Section: Recovery
Pe.S.2	Contact with large, airborne shrapnel	Catastrophe at takeoff	(1) Scrape (2) Deep scratch	2C	1A	Aerotech APCP motors shall be chosen for their low likelihood of factory defects leading to CATO	NASA 2.10, CDR Section 1.2.2, NAR High Power Rocket Safety Code Section 3

		On-ground explosion of motor/black power				(1) Personnel are required by the RSO to maintain a minimum distance away from the launch pad (2) Altimeters are armed and igniters are attached only when launch vehicle is on launch pad and ready for flight	(1) NAR High Power Rocket Safety Code Section 11 (2) Checklist Section: Launch Pad (10.15-10.19)
		Ballistic descent of payload or airframe shrapnel				See payload, recovery, and structures FMEAs for full mitigations	See payload, recovery, and structures FMEAs for full verifications
Pe.S.3	Contact with small, airborne particulates	Sanding, cutting, or drilling into brittle/granular materials				(1) Protective eye and face equipment shall be provided to personnel working with power tools (2) Dremel blades are inspected for defects prior to use	(1) TDR 1.3 (2) Lab Safety Handbook (to be included in FRR)
Pe.S.4	Exposure to uncured epoxy fluid	Working with liquid epoxy	(1) Skin irritation (2) Rash	2C	2A	Nitrile gloves shall be provided to personnel working with uncured epoxy or volatile organic compounds	TDR 1.4
Pe.S.5	Exposure to chemical fumes	Working with volatile organic compounds		3B	2A		
Hazard to Bones							
Pe.B.1	Personnel contact with large airborne shrapnel	Pre-flight motor/black powder ignition	Bone fracture requiring immediate medical attention	4B	4A	(1) Personnel are required by the RSO to maintain a minimum distance away from the launch pad	(1) NAR Nigh Power Rocket Safety Code Section 11

		Catastrophe at takeoff				(2) Aerotech APCP motors shall be chosen for their low likelihood of factory defects leading to CATO	(2) NASA 2.10, CDR Section 1.2.2, NAR High Power Rocket Safety Code Section 3
Pe.B.2	Slips, trips, and falls	Uneven ground conditions	(1) Bone bruise (2) Minor bone fracture (3) Ligament sprain	4B	3A	(1) Running shall be strictly forbidden on launch day (2) Those recovering launch vehicle are ONLY trained, experienced, pre-assigned personnel (3) Recovery personnel shall be instructed to wear closed toe walking shoes on launch day	(1) TDR 1.2 (2) Checklist Section: Recovery (Required Personnel) (3) Checklist Section: recovery
Hazard to Eyes							
P.E.1	Exposure to fumes	Working with uncured epoxy	Eye irritation	2B	1A	(1) Protective eye equipment shall be provided to personnel working with uncured epoxy (2) In the event of eye irritation, eye wash stations are accessible to all personnel	(1) TDR 1.4 (2) Lab Safety Handbook (to be included in FRR)
P.E.2	Eye contact with metallic, wood, or plastic shrapnel	Sanding Material failure while drilling	(1) Eye abrasion (2) Blindness	3C	2A	(1) Protective eye equipment shall be provided to personnel	(1) TDR 1.4

		Premature, on-ground black powder or motor ignition				working with potentially airborne material (2) Personnel shall be instructed in checklists to stand away from any potential explosives	(2) Checklist Section: Black Powder; Recovery
Hazard to Limbs							
Pe.L.1	Contact with explosive gases Contact with large, airborne shrapnel	On ground motor/black powder ignition	(1) Limb loss (2) Severe injury warranting amputation	4B	4A	(1) Personnel shall be instructed in checklists to stand away from any potential explosives (2) Altimeters shall remain disarmed until launch vehicle is on launch rail, ready for flight	(1) Checklist Section: Black Powder; Recovery (2) Checklist Section: Launch Pad (10.15-10.19)
Pe.L.2	Personnel contact with ballistic launch vehicle components	Ballistic descent (R.A.2)	(1) Limb loss (2) Severe injury warranting amputation	4B	4A	(1) See recovery FMEAs for mitigations through design (2) Personnel shall be instructed to remain still until launch vehicle components are confirmed by the RSO to have landed	(1) See recovery FMEAs for verifications (2) NAR High Power Rocket Safety Code Sections 8 and 9

Pe.L.3	Finger snag in bit of power tool	Wearing gloves while working with power tools	Finger loss	4B	2A	(1) Gloves are located at the far end of the lab from desktop power tools and in a separate cabinet from hand-held power tools (2) Safety presentations are conducted that detail proper procedure prior to use of a power tool	Lab Safety Handbook (to be included in FRR)
Hazard to Respiratory System							
Pe.R.1	Exposure to fumes	Working with uncured epoxy Working with uncovered paint Off-gassed chemicals stored in flame cabinet	(1) Lung irritation (2) Difficulty breathing	3D	2A	(1) Particulate masks shall be provided to personnel working with epoxy, paint, and chemicals from the flame cabinet (2) In cases where epoxy cannot be applied outside, an oxygen monitor is in use to prevent irritation/difficulty breathing (3) All painting occurs outdoors	(1) TDR 1.4 (2)(3) Lab Safety Handbook
Pe.R.2	Exposure to particulates	Sanding, drilling, and/or cutting brittle or granular materials		3D	2A	Particulate masks shall be provided to personnel working with power tools	TDR 1.3
Hazard to Head							

Pe.H.1	Impact with ballistic launch vehicle sections	Shock cord breakage or disconnection	(1) Concussion (2) Memory loss (3) Brain injury (4) Skull fracture	4B	3A	(1) Kevlar shock cord shall be used to withstand, at least, the maximum expected load (388 lbf) (2) Any bulkhead-shock cord systems shall have a factor of safety of at least 2	(1) CDR Section 3.4.1.5 (2) TDR 2.2
		No/late parachute deployment				(1) Adequately sized pressure ports are drilled during construction (2) 4-40 shear pins shall be used	(1) CDR Section 3.4.1 (2) CDR Section 3.4.1
	Impact with ballistic payload	Premature payload parachute ejection		4B	3A	(1) Payload and recovery altimeters shall be tested before flight (2) Personnel shall maintain a minimum distance away from the launch site as maintained by the RSO	(1) Altimeter Operational Test scheduled for 2/6/2021 (2) NAR High Power Rocket Safety Code Section 11
		Premature payload ejection from launch vehicle					
	Impact with large, airborne shrapnel (payload or launch vehicle components)	Catastrophe at takeoff		4B	3A	Aerotech APCP motors shall be chosen for their low likelihood of factory defects leading to CATO	NASA 2.10, CDR Section 1.2.2, NAR High Power Rocket Safety Handbook Section 3

		Premature on-ground motor/black powder ignition				(1) Personnel shall be instructed in checklists to stand away from any potential explosives (2) Altimeters shall remain disarmed until launch vehicle is on launch rail, ready for flight	(1) Checklist Section: Black Powder; Recovery (2) Checklist Section: Launch Pad (10.15-10.19)
		Shock cord shear; shock cord disconnection from bulkhead				(1) Kevlar shock cord shall be used to withstand, at least, the maximum expected load (388 lbf) (2) Any bulkhead-shock cord systems shall have a factor of safety of at least 2	(1) CDR Section 3.4.1.5 (2) TDR 2.2

5.6 Environmental Hazard Analysis

Table 5-8 Hazard Analysis for Hazards to the Environment

Label	Hazard	Cause	Effect	Pre-LS	Post-LS	Mitigation	Verification
Hazard to Land							
E.L.1	Catastrophe at takeoff	Cracks in motor casing	(1) Fire around launch field (2) Wildfire risk	4B	4A	(1) Aerotech APCP motors shall be chosen for their low likelihood	(1) CDR Section 1.2.2, NAR High Power Safety Code Section 3, NASA 2.10

		Holes/bubbles in propellant grain				of defects contributing to CATO (2) A fire extinguisher is made available to personnel by the RSO	(2) CDR Section 5.2
E.L.2	Explosion on touchdown	Late black powder charge detonation	(1) Fire at recovery site (2) Wildfire risk	3A	1A	A fire extinguisher, provided by the team, shall be brought to the recovery site	Checklist: Recovery (Materials)
E.L.3	Creation of launch field craters and ruts	Launch vehicle ballistic landing (see recovery FMEA table)	Difficulty using field for primary purpose: farming	3D	2A	The launch vehicle shall descend with a kinetic energy no greater than 75 ft-lbs	NASA 3.3
E.L.4	Wildfire on field	Catastrophe at takeoff	Significant damage to leftover crops that fertilize the next round of corn	4B	4A	Aerotech APCP motors shall be chosen for their low likelihood of defects contributing to CATO	(1) CDR Section 1.2.2, NAR High Power Safety Code Section 3, NASA 2.10 (2) CDR Section 5.2
		Explosion on touchdown		3A	1A	A fire extinguisher is made available to personnel by the RSO	
Hazard to Air and Water							
E.AW.1	Chemical off-gassing	Avionics/payload battery leak	Air pollution	1C	1A	Batteries are shielded from environmental hazards through protective casing	CDR Section 4.3.4
		Uncured epoxy remaining on launch vehicle		1D	1A	Epoxy shall be given at least 24 hours to fully cure before assembly, launch prep, or launch	TDR 1.1

		Production of combustion by-products		2D	1C	Aerotech APCP motors shall be used for their known reliability and relatively low environmental impact	CDR Section 1.2.2, NAR High Power Safety Code Section 3, NASA 2.10
						The full-scale launch vehicle shall use an L1520T motor, well within the acceptable limit for creation of by-product gases	CDR Section 1.2.2, NAR High Power Rocket Safety Code Section 8, NASA 2.12
E.AW.2	Creation of wildfire smoke	Catastrophic explosion at takeoff		4B	4A	Aerotech APCP motors shall be chosen for their low likelihood of defects contributing to CATO	CDR Section 1.2.2, NAR High Power Safety Code Section 3, NASA 2.10
							CDR Section 5.2
		Black powder explosion on landing		3A	1A	A fire extinguisher, provided by the team, is brought to the recovery site	Checklist Section: Recovery (Materials)
		Contact between exhaust flame and dry corn stalks		4C	2B	A blast plate, provided by the RSO protects the dry ground from launch flames	CDR Section 5.2
E.AW.3	Creation of hydrochloric acid from combustion by-product reaction with water	Excessive amount of by-product from APCP combustion	Pollution of surrounding irrigation ditches	3B	2A	The full-scale launch vehicle shall use an L1520T motor, well within the acceptable limit for creation of by-product gases	CDR Section 1.2.2, NAR High Power Rocket Safety Code Section 8, NASA 2.12
Hazard to Wildlife							
E.W.1	Payload/avionics battery leakage	Puncture during flight	Consumption of volatile chemicals by wildlife	4B	2A	Batteries are shielded from environmental	CDR Section 4.3.4

						hazards through protective casing	
E.W.2	Noise pollution	Launch in proximity to wildlife	Wildlife disruption and anxiety	2D	1A	Launches conducted in Bayboro, NC are at least one mile from the surrounding tree line	NAR High Power Rocket Safety Code Section 10
						One high-power launch is performed at a single time, reducing contributions to volume amplitude	CDR Section 5.2
E.W.3	Wildfire	Black powder explosion on touchdown	Loss of wildlife Significant tree damage Inability to use the land for farming	3A	1A	(1) A fire extinguisher, provided by the team, shall be brought to the recovery site (2) See recovery FMEA for black powder mitigations	(1) Checklist Section: Recovery (Materials) (2) See recovery FMEA for black powder verification
E.W.4	Abandonment of irretrievable launch vehicle shrapnel	Catastrophe at takeoff Catastrophic payload failure	Consumption of inedible materials by wildlife	4B	2A	As much shrapnel is collected as possible by members of the recovery team	Checklist Section: Recovery
E.W.5	LV touchdown in surrounding trees	Large wind gusts contributing to wind drift	Damage to trees and local wildlife	3B	3A	(1) The team shall exclusively launch in wind conditions below 20 mph (2) The team shall abandon launch vehicle components that are	(1) NAR High Power Rocket Safety Code Section 9 (2) NAR High Power Rocket Safety Code Section 13

						irretrievable without tree damage	
E.W.6	High-velocity contact between launch vehicle and avian wildlife	Launch into uncleared skies	Significant wildlife injury/loss of life	4B	3A	Working with the RSO, the team will wait to launch until skies are clear and will avoid all	NAR High Power Rocket Safety Code Section 9

Table 5-9 Hazard Analysis for Hazards from the Environment

Label	Hazard	Cause	Effect	Pre-LS	Post-LS	Mitigation	Verification
Hazard to Launch Vehicle Structure							
E.S.1	LV touchdown in surrounding trees	Large wind gusts contributing to wind drift	Launch vehicle structural damage Inability to recover launch vehicle	4C	3A	The team shall exclusively launch in wind conditions below 20 mph	NAR High Power Rocket Safety Code Section 9
E.S.2	Body tube water saturation	Launch vehicle touchdown in irrigation ditch	Inability to repair damaged components without significant effort	4C	1C	The launch vehicle shall be water resistant; G12 Fiberglass is used to construct the full scale	TDR 2.1, CDR Section 3.1.4
E.S.3	High-velocity contact between launch vehicle and avian wildlife	Launch into uncleared skies	Body tube crack, rupture, and irreparable damage	2B	1A	Working with the RSO, the team will wait to launch until skies are	NAR High Power Rocket Safety Code Section 9

			Diverted flight path leading to lower apogee	2B	1A	clear and will avoid all obstructions	
			Launch vehicle enters nose-over-tail spin	4B	4A		
Hazard to Payload							
E.PA.1	Waterlogged payload bay	Launch vehicle touchdown in irrigation ditch	Waterlogged payload electronics; insufficient power to complete mission	3C	3B	The launch vehicle shall be water resistant; G12 Fiberglass is used to construct the full scale	TDR 2.1, CDR Section 3.1.4
E.PA.2	Electronics rust	Launch during rain and high humidity	Loss of payload-controlling electronics			The team shall exclusively launch in dry conditions	NAR High Power Rocket Safety Code Section 9
	In-flight electronics short		No payload ignition or deployment				
E.PA.2	LOPSIDED lopsided touchdown	Launch field ruts, ditches, and dips	Inability of LOPSIDED to right the system; no clear picture obtained	3D	3A	LOPSIDED successfully rights the system at touchdown angles less than or equal to 15°	CDR Section 4.3.2.6, Payload Ground Test scheduled to be performed on 2/15/2021
E.PA.3	POS camera abrasion	Lens contact with launch field dust and debris	Clouded lens; inability to take a clear picture	3D	1A	Four cameras make up POS; if one or more cameras fails, at least one camera can take a partial picture	CDR Section 4.3.3
						The cameras of POS are housed in a protective casing in LOPSIDED	CDR Section 4.3.2.2

Hazard to Flight Success							
E.F.1	Wind drift	High wind conditions	Launch vehicle touchdown outside of GPS tracking range; inability to recover launch vehicle	4C	4A	The team shall exclusively launch in wind conditions below 20 mph	NAR High Power Rocket Safety Code Section 9
			Launch vehicle touchdown in trees; inability to recover launch vehicle				
E.F.2	Damp propellant grains	High humidity	Inability to ignite motor; failure to launch	4B	4A	The team shall exclusively launch in dry conditions	
E.F.3	High-velocity contact between launch vehicle and avian wildlife	Launch into uncleared skies	Diverted flight path	2B	1A	Working with the RSO, the team will wait to launch until skies are clear and will avoid all obstructions in the sky	NAR High Power Rocket Safety Code Section 9
			Launch vehicle nose-over-tail spin	4B	4A		
E.F.4	Live black powder charges on touchdown	High humidity	BP explosion prompted by personnel-generated pressure changes	4B	4A	(1) The team shall exclusively launch in dry conditions (2) Altimeters are disarmed in the event of un-detonated black	(1) NAR High Power Rocket Safety Code Section 9 (2) Checklist Section: Recovery (11.12.1-11.12.2)

						powder charges remaining	
Hazard to Personnel							
E.PE.1	Ballistic descent of launch vehicle	Waterlogged black powder from rain/high humidity	Head injury, broken bones, damage to soft tissue, and/or loss of life	4C	2A	Launch rails are directed by the RSO away from assembling and onlooking personnel	NAR High Power Rocket Safety Code Section 9
						The team shall exclusively launch in wind conditions below 20 mph	
						Team members are instructed by the RSO to maintain a minimum distance away from the launch pad	NAR High Power Rocket Safety Code Section 11
E.PE.2	Heat exhaustion and/or heat stroke	Exposure to temperature extremes	Organ failure, permanent or semipermanent brain damage	4B	2A	A tent is set up to provide shade	CDR Section 5.2
	Hypothermia			4A	2A	Cars used to transport team members and launch materials can be used to quickly balance bodily temperature	
E.PE.3	Slips, trips, and falls	Uneven launch field conditions	Sprains, broken bones, bruising, and/or head injury	3B	2A	Recovery team members are instructed to wear closed-toed shoes at all times	Checklist Section: Recovery
						Team members shall maintain a walking pace, especially during recovery events	TDR 1.2

6. Project Plan

6.1 Testing

6.1.1 Launch Vehicle Test Suite

6.1.1.1 Nose Cone Bulkhead Tensile Loading Test

Per TDR 2.2, all critical components of the launch vehicle shall be designed with a minimum factor of safety of 2. This test aims to validate the strength of the nose cone bulkhead and the bolted connection. Sufficient bulkhead strength is critical to the success of the launch vehicle. Should parachute deployment cause a bulkhead to fail, sections of the rocket may descend untethered to a parachute causing a safety hazard. Success criteria are shown in Table 6-1 below. Should any of the criteria not be met, the bulkheads will need to be redesigned.

Two ¾" bulkheads will be manufactured in the nose cone configuration and inserted into a 6" diameter body tube section. Each bulkhead will have an off-center U-bolt attached on the outward face. Both U-bolts will need to be aligned to ensure the part does not rotate in the testing machine. One bulkhead will be secured on one end with 2-part epoxy and the other using four L-brackets attached to the body tube with bolts. During testing in previous years, bolted connections have failed at lower loadings than epoxied connections, so the intention is that the epoxied bulkhead is used as an anchor while the bolted bulkhead is tested until failure. The piece will be tested to a tensile loading of 344 lbf using a universal testing machine, this value gives a factor of safety of 2 with the expected deployment force of 172 lbf.

Table 6-1 Nose Cone Bulkhead Tensile Loading Test Success Criteria

Success Criteria	Met? (Y/N)
The test sample withstands a load of over 344 lbf	TBD
The test sample shows no visible damage under 344 lbf loading	TBD

6.1.1.1(a) Controllable Variables

- Bulkhead material: aircraft-grade birch plywood
- Bulkhead thickness: 0.75 inches
- Applied loading: 344 lbf

6.1.1.1(b) Procedure

- Ensure everyone in attendance is wearing safety glasses
- Attach a quick link to each bulkhead U-bolt
- Insert the quick links into each end of the universal testing machine
- Begin increasing the force on the test piece in increments of 50 lbf
- Once the force passes 200 lbf, decrease the increment to 25 lbf
- Allow the test piece to settle for ~5 seconds between each increment
- Continue increasing the loading until one of the test pieces fails
- Record the failure point

6.1.1.2 AV Bay Bulkhead Tensile Loading Test

Per TDR 2.2, all critical components of the launch vehicle shall be designed with a minimum factor of safety of 2. This test aims to validate the strength of the AV Bay bulkheads and the bolted connection. Sufficient bulkhead strength is critical to the success of the launch vehicle. Should parachute deployment cause a bulkhead to fail, sections of the rocket may descend untethered to a parachute causing a safety hazard. Success criteria are shown in Table 6-2 below. Should any of the criteria not be met, the bulkheads will need to be redesigned.

A test AV Bay will be made using two 0.75-inch AV Bay bulkheads inserted into a 14-inch-long coupler section. Each bulkhead will have a U-bolt attached on the outward face and they will be secured with two threaded rods going through the coupler. The piece will be tested to a tensile loading of 400 lbf using a universal testing machine, this value gives a factor of safety of 2 with the highest expected deployment force of 200 lbf.

Table 6-2 AV Bay Bulkhead Tensile Loading Test Success Criteria

Success Criteria	Met? (Y/N)
The test sample withstands a load of over 400 lbf	TBD
The test sample shows no visible damage under 400 lbf loading	TBD

6.1.1.2(a) Controllable Variables

- Bulkhead material: aircraft-grade birch plywood
- Bulkhead thickness: 0.75 inches
- Applied loading: 400 lbf

6.1.1.2(b) Procedure

- Ensure everyone in attendance is wearing safety glasses
- Attach a quick link to each bulkhead U-bolt
- Insert the quick links into each end of the universal testing machine
- Begin increasing the force on the test piece in increments of 50 lbf
- Once the force passes 300 lbf, decrease the increment to 25 lbf
- Allow the test piece to settle for ~5 seconds between each increment
- Continue increasing the loading until one of the test pieces fails
- Record the failure point

6.1.1.3 Shear Pin Shear Loading Test

This test is used to ensure the accuracy of the shear strength specified by the shear pin manufacturers. Should the tested shear strength differ from manufacturer specifications, the test strength will be used for recovery calculations. Should the shear pin strength differ from expected values on launch day, the vehicle may fail to separate leading to a ballistic descent, proving the necessity of the test. Success criteria are detailed in Table 6-3 below. Should the criteria not be met the new tested shear strength will be used in calculations.

Two steel plates will be used in conjunction with a universal testing machine for shear testing. Each plate will have a 0.25-inch hole drilled at the end to allow for a quick link connection to the testing machine. Another hole matching the diameter of the shear pins will be drilled at the opposite end.

Table 6-3 Shear Pin Loading Test Success Criteria

Success Criteria	Met? (Y/N)
The shear pins fail within 1 lbf of manufacturer specifications	

6.1.1.3(a) Controllable Variables

- Chosen shear pin
- Applied loading: manufacturer specified

6.1.1.3(b) Procedure

- Attach a quick link through the 0.25-inch holes on each plate
- Align the two remaining holes and insert a shear pin
- Insert the quick links into each end of the universal testing machine
- Begin increasing the applied loading in increments of 5 lbf
- Once within 10 lbf of the expected failure, decrease the increment to 1 lbf
- Continue increasing the loading until the shear pin fails
- Record the failure point

6.1.1.4 Fastener Shear Loading Test

Per TDR 2.2, all critical components of the launch vehicle shall be designed with a minimum factor of safety of 2. This test aims to validate the strength of the chosen bolts for the nose cone bulkhead. Should parachute deployment cause the bolts to fail, sections of the rocket may descend untethered to a parachute causing a safety hazard. Success criteria are shown in Table 6-4 below. Should any of the criteria not be met, new bolts will need to be chosen.

Two steel plates will be used in conjunction with a universal testing machine for shear testing. Each plate will have a 0.25-inch hole drilled at the end to allow for a quick link connection to the testing machine. Another hole matching the diameter of the bolt will be drilled at the opposite end. Due to the off-center location of the U-bolt on the nose cone bulkhead, the bolts closest to the U-bolt will experience a higher loading of approximately 86 lbf based on FEA analysis. Accounting for a factor of safety of 2, the bolt will be tested to a tensile loading of 172 lbf.

Table 6-4 Fastener Shear Loading Test Success Criteria

Success Criteria	Met? (Y/N)
The fastener withstands a loading of 172 lbf	TBD

6.1.1.4(a) Controllable Variables

- Chosen fastener size
- Applied loading: 172 lbf

6.1.1.4(b) Procedure

- Attach a quick link through the 0.25-inch holes on each plate
- Align the two remaining holes and insert a bolt
- Insert the quick links into each end of the universal testing machine
- Begin increasing the applied loading in increments of 20 lbf
- Once the force passes 150 lbf, decrease the increment to 5 lbf
- Continue increasing the loading until the bolt fails
- Record the failure point

6.1.2 Recovery and Avionics Test Suite

6.1.2.1 Subscale Ejection Test

Per requirement NASA 3.2, a black powder ejection test will be performed prior to each launch using ejection charges of the same mass and assembly as the primary ejection charges used during flight. This test confirms that the ejection assembly will function as intended and section separation will occur. Should section separation fail to occur, the launch vehicle will enter a ballistic descent state leading to an increased risk to personnel and likely loss of the launch vehicle constituting mission failure. The success criteria for this test are given in Table 6-5 below. In the event that the success criteria are not met, the mass of the ejection charges will be altered. The below described procedure is a test of the deployment of recovery hardware which was performed on 11/20/2020. The test was successful on the second attempt following an increase in mass of the ejection charges, and the team proceeded with the subscale demonstration flight.

The drogue primary black powder charge of X grams will be assembled as for flight on the aft AV bulkhead. The main primary black powder charge of X grams will be assembled as for flight on the forward aft AV bulkhead. The AV bay will be assembled without the AV sled for the purpose of this test, and the launch vehicle assembled as for flight. Electrical leads will be passed from the terminal blocks on the inside of the AV bay through the switch holes for attaching the ejection testing trigger. Four #4-40 shear pins will be used to secure the payload bay to the main parachute bay as well as to secure the fin can to the AV bay. The assembled launch vehicle will be placed on foam mats and braced against a sturdy surface, protected by more foam mats. The test switch will be attached to the drogue primary ejection charge leads. Once all personnel are safely clear the drogue primary ejection charge will be fired. After the range is safe, the forward section of the launch vehicle will be reset, and the test repeated for the main primary ejection charge. This replicates the order of recovery events during flight.

Table 6-5 Subscale Ejection Test Success Criteria

Success Criteria	Met (Y/N)
Vigorous and complete separation at the main parachute bay	Yes
Vigorous and complete separation at the drogue parachute bay	Yes
No damage to recovery devices	Yes
No damage to launch vehicle	Yes

6.1.2.1(a) Controllable Variables

The controllable variables in this test are as follows:

- Black Powder Mass

6.1.2.1(b) Procedure

See Section 5.2 for the field assembly checklist used for launch. The following changes to the launch checklist for this test.

- The AV sled and electronics mounted thereon are not placed in the AV bay
- Long wires are connected to the terminal block input side
- Output wires are fed through screw switch holes in the AV bay to the launch vehicle exterior
- Motor assembly and launch pad procedures are not performed
- Once the launch vehicle is fully assembled, it is placed horizontal on a piece of foam
- The motor is backed against a wall with another piece of foam between the wall and the launch vehicle
- All team members retreat to a safe distance and out of the path of the launch vehicle
- One designated team member approaches the launch vehicle to attach the ejection switch to the drogue e-match wires using alligator clips
- The designated tram member retreats to a safe distance
- The battery is attached to the switch, and the switch is thrown to detonate the drogue ejection charge
- The fin can is placed out of the way and the remaining midsection is placed back against the wall and a piece of foam is again used for padding
- All team members retreat to a safe distance and out of the path of the launch vehicle
- One designated team member approaches the launch vehicle to attach the ejection switch to the main e-match wires using alligator clips
- The designated tram member retreats to a safe distance
- The battery is attached to the switch, and the switch is thrown to detonate the main ejection charge

6.1.2.2 Full Scale Ejection Test

Per requirement NASA 3.2, a black powder ejection test will be performed prior to each launch using ejection charges of the same mass and assembly as the primary ejection charges used during flight. This test confirms that the ejection assembly will function as intended and section separation will occur. Should section separation fail to occur, the launch vehicle will enter a ballistic descent state leading to an increased risk to personnel and likely loss of the launch vehicle and LOPSIDED-POS constituting mission failure. The below described procedure is a demonstration of the deployment of recovery hardware which will be performed on 2/6/2021. The success criteria for this test are given in Table 6-6 below. In the event that the success criteria are not met, the mass of the ejection charges will have to be increased.

The drogue primary black powder charge of X grams will be assembled as for flight on the aft AV bulkhead. The main primary black powder charge of X grams will be assembled as for flight on the forward aft AV bulkhead. The AV bay will be assembled without the AV sled for the purpose of this test, and the launch vehicle assembled as for flight. Electrical leads will be passed from the terminal blocks on the inside of the AV bay through the switch holes for attaching the ejection testing trigger. Four #4-40 shear pins will be used to secure the payload bay to the main parachute bay as well as to secure the fin can to the AV bay. For this test, the LOPSIDED-POS will be mounted in the payload bay in the expected state at main deployment. Hence it will be retained only by 4 4-40 shear pins. The assembled launch vehicle will be placed on foam mats and braced against a sturdy surface, protected by more foam mats. The test switch will be attached to the drogue primary ejection charge leads. Once all personnel are safely clear the drogue primary ejection charge will be fired. After the range is safe, the forward section of the launch vehicle will be reset, and the test repeated for the main primary ejection charge. This replicates the order of recovery events during flight.

Table 6-6 Full-Scale Ejection Test Success Criteria

Success Criteria	Met (Y/N)
Vigorous and complete separation at the main parachute bay	TBD
Vigorous and complete separation at the drogue parachute bay	TBD
No damage to recovery devices	TBD
No damage to launch vehicle	TBD
Vigorous and complete deployment of LOPSIDED-POS from payload bay	TBD

6.1.2.2(a) Controllable Variables

The controllable variables in this test are as follows:

- Black Powder Charge Mass

6.1.2.2(b) Procedure

See Section 5.2 for the field assembly checklist used for launch. The following changes to the launch checklist for this test.

- The AV sled and electronics mounted thereon are not placed in the AV bay
- The LOPSIDED-POS is secured in the launch vehicle using 4-40 nylon shear pins and tied into the main parachute recovery harness
  - The retaining latch is not engaged
- Long wires are connected to the terminal block input side
- Output wires are fed through screw switch holes in the AV bay to the launch vehicle exterior
- Motor assembly and launch pad procedures are not performed
- Once the launch vehicle is fully assembled, it is placed horizontal on a piece of foam
- The motor is backed against a wall with another piece of foam between the wall and the launch vehicle
- All team members retreat to a safe distance and out of the path of the launch vehicle
- One designated team member approaches the launch vehicle to attach the ejection switch to the drogue e-match wires using alligator clips
- The designated tram member retreats to a safe distance
- The battery is attached to the switch, and the switch is thrown to detonate the drogue ejection charge
- The fin can is placed out of the way and the remaining midsection is placed back against the wall and a piece of foam is again used for padding
- All team members retreat to a safe distance and out of the path of the launch vehicle
- One designated team member approaches the launch vehicle to attach the ejection switch to the main e-match wires using alligator clips
- The designated tram member retreats to a safe distance
- The battery is attached to the switch, and the switch is thrown to detonate the main ejection charge
- The launch vehicle body sections are placed out of the way
- The LOPSIDED-POS is positioned on the foam
- All team members retreat to a safe distance and out of the path of the LOPSIDED-POS
- One designated team member approaches the launch vehicle to attach the ejection switch to the ARRD e-match wires using alligator clips
- The designated tram member retreats to a safe distance
- The battery is attached to the switch, and the switch is thrown to detonate the ARRD ejection charge

6.1.2.3 Altimeter Operational Test

Altimeter functionality must be verified prior to flight usage. To accomplish this, the altimeter must both register pressure changes and signal the correct flight events in response to these pressure changes. Should an altimeter fault result in incorrect signaling or the lack of a signal, negative outcomes including a failure to deploy a parachute, or an incorrect parachute deployment could occur. Success criteria for this test are given below in Table 6-7. If the success criteria are not met, the altimeter will be checked for faults and replaced with an altimeter that meets the success criteria.

In order to test altimeter functionality, the pressure decrease as a function of altitude will be replicated using a vacuum chamber. The altimeters to be tested will be connected to a test circuit and powered. The pressure will then be decreased, and slowly increased to simulate first launch then recovery. Visual indicators of the firing signal will be observed through the viewing port of the pressure vessel.

Table 6-7 Altimeter Operation Test Success Criteria

Success Criteria	Met (Y/N)
LED #1 lights when the altimeter senses apogee	TBD
LED #2 lights when the altimeter senses the main deployment altitude	TBD
Pre- and post-flight beeps match what is recorded in the beep sheet. See section 5.2 for beep sheets.	TBD
Post-flight beeps do not contain any errors	TBD

6.1.2.3(a) Controllable Variables

The controllable variables in this test are as follows:

- Pressure
- Rate of Change of Pressure
- Altimeter Model

6.1.2.3(b) Procedure

The test procedure is as follows:

- Primary and secondary altimeters are wired to the test assembly
- Each altimeter is powered on with one 9 V battery
- The test assembly is placed in the vacuum chamber
- The vacuum chamber is sealed, making sure the lights are visible through the view port
- The vacuum pump is connected to the vacuum chamber fitting
- A vacuum is drawn down to simulate ascent
- The vacuum pressure is slowly decreased while the test assembly is observed
- Once the vacuum begins to be rolled off, the first light should turn on

- Shortly afterwards as the vacuum is rolled off, the second light should turn on
- Open the vacuum chamber and record the post-flight beep sheet
- Confirm the recorded altitudes are the same
- Download the post-flight data and confirm that the recorded altitude and event timings are as expected

6.1.2.4 Recovery Avionics Battery Life Test

Per requirement NASA 2.7, a demonstration of the launch vehicle's capacity to remain in a launch-ready state for extended duration is required. The Recovery Avionics Battery Life Demonstration will prove that the batteries powering the recovery avionics can last more than 2 hours once connected to the altimeters and powered on. The success criteria for this test are defined in Table 6-8 below. A failure to meet these success criteria will result in a change to the type of battery or altimeter until the success criteria are met.

For this test, all Recovery Avionics Systems will be assembled in a flight-ready configuration and powered on. Here, a timer will be started and the system monitored at a regular interval to confirm continued functionality. Once sufficient time has passed to demonstrate suitable battery life, the test will be concluded.

Table 6-8 Recovery Avionics Battery Life Test Success Criteria

Success Criteria	Met (Y/N)
Primary altimeter's battery life lasts longer than two hours	TBD
Secondary altimeter's battery life lasts longer than two hours	TBD
Eggfinder GPS tracking system's battery life lasts longer than two hours	TBD

6.1.2.4(a) Controllable Variables

The controllable variables in this test are as follows:

- Choice of 9V batteries
- Choice of LiPo batteries
- Choice of Altimeter
- Choice of Tracking Device

6.1.2.4(b) Procedure

The test procedure is as follows:

- Assemble the AV sled with altimeters, tracking device, and batteries
- Connect a 9V battery to each altimeter
- Connect a 2S LiPo to the tracking device
- Start the stopwatch
- Check every 15 minutes to confirm the altimeters and tracking device remain functional

- At 3 hours, conclude the test

6.1.2.5 Tracking Device Operational Test

Per requirement NASA 3.12, a tracking system is required for all independent sections of the launch vehicle and LOPSIDED-POS. The tracking device operational test serves to confirm that the GPS locator devices being placed in the launch vehicle and the LOPSIDED-POS function and are accurate in relaying the GPS location data. The success criteria for this test are defined in Table 6-9 below. If the GPS fails this test, the cause will be determined and repaired if possible or the tracker replaced.

To test the ability of the tracking device to accurately record location data, the device will be placed in the private vehicle of a team member and driven on a course of at least five miles, the route of which will be determined by the driver of the vehicle. The tracker will be set to record and store this data, and the resulting course will be compared to the actual course for accuracy.

Table 6-9 Tracking Device Operational Test Success Criteria

Success Criteria	Met (Y/N)
The recorded GPS tracker paths match that taken by the driving team member	TBD

6.1.2.5(a) Controllable Variables

The controllable variables in this test are as follows:

- Selected route
- Selected GPS tracker

6.1.2.5(b) Procedure

The procedure for carrying out this test is as follows:

- Power on the Eggfinder ground receiver dongle and transmitter
- Pair the Eggfinder ground receiver dongle to a club member's Android phone with Rocket Locator installed
- Power on the BRB900 handheld receiver
- Power on the BRB900 transmitter
- Establish connection between ground receivers and transmitters
- Make sure the location is properly displaying on Rocket Locator
- Have one team member carry the transmitters into their car
- Have another team member hold the receiver dongles and the Rocket Locator phone, while displaying Google Maps on the laptop
- While the team member with the transmitters is driving, the receiver member is comparing the track plotted on Rocket Locator to the course of the road

- After the transmitter member returns, compare the recorded tracks to the actual route taken by the transmitter team member

6.1.3 Payload Test Suite

Table 6-10 Payload Test Suite Summary

Test	Requirements Verified	Required Facilities/Location	Required Personnel	Scheduled Date
LOPSIDED-POS Battery Capacity Test	NASA 2.7; TDR 4.15	N/A	Payload Imaging Lead, Payload Integration Lead	1/29/2021
POS Transmission Range Test	NASA 4.2; TDR 4.14	Dorothea Dix Park	Payload Imaging Lead, at least two additional team personnel	1/25/2021
LOPSIDED-POS Ground Performance Test	NASA 4.2, 4.3.3, 4.3.3.1, 4.3.3.2, 4.3.4; TDR 4.6, 4.8, 4.14, 4.15	Dorothea Dix Park	Payload Imaging Team Lead, Payload Vehicle Lead, Payload Integration Lead	2/15/2021
LOPSIDED-POS Transmitter-Altimeter Interference Test	NASA 3.13, 3.13.2	Senior Design Lab	Payload Integration Lead, at least two additional team personnel	1/29/2021
LOPSIDED-POS Payload Parachute Release Test	NASA 4.2 and TDR 4.16	Dorothea Dix Park	Payload Integration Lead, Vehicle Lead, and one additional team personnel	2/16/2021

6.1.3.1 LOPSIDED-POS Battery Capacity Test

This demonstration test is designed to ensure the LOPSIDED-POS battery can provide sufficient power for all payload components and operations. This includes operating time after the payload lands, as well as the "stand-by" launch pad configuration. This test will verify Requirement NASA 2.7, which states that the payload must be able to maintain launch pad configuration for at least two hours. It will also verify TDR 4.15, which states that the LOPSIDED-POS must be powered from a single battery pack, with the exception of the payload altimeter, which will be powered with its own 9V battery. Failure to meet the success criteria for this test will require further analysis of the LOPSIDED-POS power system, including the current draw of individual components, the time they spend active, and the specifications of the selected battery pack. If the selected battery pack does not have the capacity required to cover the full operating range of the LOPSIDED-POS, a new battery will need to be used, which could lead to structural changes within LOPSIDED to accommodate the new battery.

6.1.3.1(a) Control Variables

Control variables for this test include battery make and model, LOPSIDED-POS electronic components, and the power on/off states of these components during payload operation.

6.1.3.1(b) Procedure

- Ensure LOPSIDED-POS battery is fully charged prior to testing.
- Check the battery voltage with a multimeter and ensure it matches battery specifications.
- Wire all LOPSIDED-POS electronics, according to procedures documented in LOPSIDED-POS assembly checklists.
- Supply power by connecting the payload battery.
- Run Battery Capacity Test Python script on Raspberry Pi.
- Leave set-up in launch pad configuration for two hours, using a timer. Check the functionality of components in 20-minute intervals
- After the two-hour stand-by window has passed, the Battery Capacity Test script will initiate all payload events which draw power from the payload battery, including:
    a. Release of parachute latches
    b. Release of leveling system solenoid latches
    c. Image capture
    d. Image transmission
- Verify that all payload events occur without loss of power.

6.1.3.1(c) Success Criteria

Table 6-11 LOPSIDED-POS Battery Capacity Test Success Criteria

Success Criteria	Met (Y/N)
The LOPSIDED-POS remains in stand-by mode for two hours without loss of power	TBD
The LOPSIDED-POS completes mission procedures after two hours on stand-by, without loss of power	TBD

6.1.3.2 POS Transmission Range Test

This experimental test is designed to determine the practical range of the POS image transmission components. Per Requirement TDR 4.14, the POS should be able to transmit images from up to 4500 feet away from the ground station, and the ground station should be able to receive these images within a reasonable time, and the quality of the received images should high enough such that the content of the photograph can be discerned. Transmission for a single image should not exceed 5 minutes. Failure to meet the success criteria for this test will result in further analysis of the POS transmission system. A transmitter capable of higher transmission power, or a modified transmission antenna may be necessary.

6.1.3.2(a) Control Variables

The control variables for this test include transmitter make and model, SDR receiver make and model, transmitter power, transmission frequency, receiver frequency

6.1.3.2(b) Procedure

- Save test image into proper directory on the Raspberry Pi prior to testing
- In a flat, open area, connect the Raspberry Pi, POS transmitter, and battery pack as per LOPSIDED-POS assembly checklists. With a laptop, establish SSH connection with Raspberry Pi.
- Assemble POS Ground Station as per LOPSIDED-POS assembly checklists.
- With POS transmitter assembly and laptop, have personnel walk 500 feet in a single direction away from the ground station.
- Once POS transmitter is in place, notify ground station personnel via cell phone. Initiate Transmission Range Test Python script with the Pi via SSH.
- Using a timer, have ground station personnel record time elapsed from image transmission to the beginning as well as the end of image transmission/reception
- Have ground station personnel save the received image in the designated folder on the ground station's laptop
- Repeat steps 4-7 eight times. The ninth transmission should take place at 4500 feet.
- Analyze results, including transmission times and resulting image quality.

6.1.3.2(c) Success Criteria

Table 6-12 POS Transmission Range Test Success Criteria

Success Criteria	Met (Y/N)
The POS is able to transmit and receive images from up to 4500 feet	TBD
Receiving time does not exceed 5 minutes for a single image	TBD

6.1.3.3 LOPSIDED-POS Ground Performance Test

The ground performance test will be conducted to demonstrate the operation of the LOPSIDED-POS in all post-landing procedures. This includes the completion of autonomous leveling, the recording of inclination data, the capture of images, and the transmission of images. This test will verify requirements NASA 4.2, 4.3.3, 4.3.3.1, 4.3.3.2, 4.3.4, and TDR 4.6, 4.8, 4.14, and 4.15. Since most LOPSIDED-POS operations are autonomous, this test will require little personnel input. Since the initiation of multiple LOPSIDED-POS events depend on specific in-flight data, such as changes in acceleration, a modified Python script will be written for this test. This script will have the LOPSIDED-POS in a "stand-by" state similar to that at the launch pad, and then will begin post-landing procedures with a computer input sent to the Raspberry Pi via SSH.

6.1.3.3(a) Control Variables

Control variables for this test include ground inclination and payload electronics.

6.1.3.3(b) Procedure

- Before the test, identify an outdoor location with a minimum 5 degrees of surface inclination
- Follow the procedure outlined in the LOPSIDED-POS Assembly checklist
- Set up ground station for receiving POS transmissions
- With the same laptop, connect the Raspberry Pi to a laptop via SSH
- Place the LOPSIDED-POS with legs extended on the inclined surface
- Send input to Pi via SSH to begin the leveling and POS procedures
- Analyze results, including images captured, and pre- and post- leveling angles recorded

6.1.3.3(c) Success Criteria

Table 6-13 LOPSIDED-POS Ground Performance Test Success Criteria

Success Criteria	Met (Y/N)
LOPSIDED is able to self-level within 5 degrees of vertical	TBD
LOPSIDED successfully records pre- and post- leveling angles for later access after leveling is complete	TBD
The POS successfully captures images from each of the four camera modules	TBD
The POS successfully transmits the images from the Pi to the ground station	TBD

6.1.3.4 LOPSIDED-POS Transmitter-Altimeter Interference Test

The altimeter and the tracker are planned to be tested to ensure that the tracker does not interfere the altimeter as this can result in an unsuccessful payload jettison, where the payload will either remain attached to the main-parachute shock chord or the payload may remain within the payload bay. This happens as the altimeter can either ignite the ARRD prematurely or not ignite it at all. Either way, the payload is set to remain attached to the main vehicle during recovery. This test shall verify NASA requirements 3.13 and 3.13.2.

6.1.3.4(a) Control Variables

Control variables for this test include the BRB 900, the StratoLoggerCF, and the pressure of activation.

6.1.3.4(b) Procedure

- Attach the tracker and altimeter to a test sled with an aluminum foil sheet in between, simulating actual placement for launch
- Place the assembled test sled inside a sealed space
- Vary the pressure inside the sealed space to increase altitude read by altimeter
- Observe LED lights to check if altimeter activates at desired pressure/altitude

6.1.3.4(c) Success Criteria

Table 6-14 LOPSIDED-POS Transmitter-Altimeter Interference Test Success Criteria

Success Criteria	Met (Y/N)
The altimeter activates noise signal at desired pressure	TBD
The tracker is still active	TBD
The altimeter activates visual signal at desired pressure	TBD
The tracker functions correctly throughout test	TBD

6.1.3.5 LOPSIDED-POS Payload Parachute Release Test

The payload parachute release test will demonstrate the operation of the LOPSIDED-POS parachute release system upon landing. The test will show how robust the system is in preventing the parachute from interfering in the leveling process after landing. This test will verify requirements NASA 4.2 and TDR 4.16. A code is required for this test due to the reliance on an accelerometer to detect the moment of landing; therefore, a modified Python script will be written for this test.

6.1.3.5(a) Control Variables

Control variables for this test include altitude for drop, the type of parachute, the EM locks used, and the accelerometer in use.

6.1.3.5(b) Procedure

- Before the test, identify an outdoor location with a minimum of 10 feet of altitude with a landing site on grass
- Follow the LOPSIDED-POS checklist for assembly

- Set the parachute attached to LOPSIDED-POS so that it inflates as soon as it is dropped
- Observe for any early parachute detachments while LOPSIDED-POS falls
- Observe parachute as LOPSIDED-POS touches the ground

6.1.3.5(c) Success Criteria

Table 6-15 LOPSIDED-POS Parachute Release Test Success Criteria

Success Criteria	Met (Y/N)
LOPSIDED is detached from the parachute	TBD
LOPSIDED successfully lands on all four of its legs	TBD
The parachute does not cover LOPSIDED-POS	TBD
The accelerometer collected correct acceleration data	TBD

6.2 Requirements Compliance

6.2.1 NASA Handbook Requirements

Table 6-16 below shows the verification plans and status for the NASA Handbook requirements.

Table 6-16 NASA Handbook Requirements Verification Matrix

Req No.	Shall Statement	Success Criteria	Verification Method	Subsystem Allocation	Status	Status Description
NASA 1.1	Students on the team SHALL do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor). Teams SHALL submit new work. Excessive use of past work will merit penalties.	The students of the High-Powered Rocketry Club at NC State design and construct a solution to the requirements as listed in the Student Launch Handbook using new and original work.	Inspection	Project Management	Not Verified	The team plans on using all original work from students to complete the project. This requirement will be verified at the FRR milestone following completion of nearly all of the project work.

NASA 1.2	The team SHALL provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations.	The project management team, including the team lead, vice president, treasurer, secretary, safety officer, webmaster, and social media lead manage the project planning tasks pertaining to this requirement.	Inspection	Project Management	Not Verified	See section 6.3 for current project plan. This requirement will be verified at the FRR milestone once the final version of the project plan is presented.
NASA 1.3	Foreign National (FN) team members SHALL be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during Launch Week due to security restrictions. In addition, FN's may be separated from their team during certain activities on site at Marshall Space Flight Center.	Foreign National (FN) team members are identified and reported in the PDR milestone document.	Inspection	Project Management	Verified	There are no Foreign National team members.
NASA 1.4	The team SHALL identify all team members who plan to attend Launch Week activities by the Critical Design Review (CDR).	All team members attending launch week activities are identified and reported in the CDR milestone document.	Inspection	Project Management	Not Verified	The deadline for verification of this requirement has been delayed by the Student Launch project management team. Additionally, the team does not plan on travelling to Launch Week.

NASA 1.4.1	Team members attending competition SHALL include students actively engaged in the project throughout the entire year.	The project management team identifies and selects members actively engaged in the project throughout the year to attend competition.	Inspection	Project Management	Not Verified	See results for NASA 1.4. If the team decides to attend Launch Week, only active team members will be selected.
NASA 1.4.2	Team members attending competition SHALL include one mentor (see requirement 1.13).	The project management team invites the mentors listed in section 1.1.2 to attend competition.	Inspection	Project Management	Not Verified	See results for NASA 1.4. If the team decides to attend Launch Week, at least one mentor will attend.
NASA 1.4.3	Team members attending competition SHALL include no more than two adult educators.	The project management team invites the adult educator listed in section 1.1.2 to attend competition.	Inspection	Project Management	Not Verified	See results for NASA 1.4. If the team decides to attend Launch Week, no more than two adult educators will attend.

NASA 1.5	The team SHALL engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities. These activities can be conducted in-person or virtually. To satisfy this requirement, all events must occur between project acceptance and the FRR due date. The STEM Engagement Activity Report SHALL be submitted via email within two weeks of the completion of each event.	The outreach lead implements STEM engagement plans with K-12 student groups throughout the project lifecycle. The outreach lead submits a STEM Engagement Activity Report via email within two weeks of the completion of each event.	Inspection	Project Management	Not Verified	The team is scheduled to engage in STEM outreach with more than 200 students between the CDR and FRR milestones. The team has currently reached 48 students, and has multiple events scheduled that will result in a total of at least 200 students reached. This requirement will be verified at the FRR milestone once all outreach activities are completed.
NASA 1.6	The team SHALL establish a social media presence to inform the public about team activities.	The webmaster and social media lead coordinate to develop an educational and engaging social media presence on platforms including, but not limited to: the club website, Facebook, Instagram, and Twitter	Inspection	Project Management	Verified	Team social media information has been sent to the NASA project management team. This presence is continuously maintained throughout the year.

NASA 1.7	The team SHALL email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient.	The team lead sends all deliverables to the NASA project management team prior to each specified deadline. In the event that the deliverable is too large, the webmaster posts the document on the team's website, and the team lead sends the NASA project management team a link to the file.	Inspection	Project Management	Not Verified	The team plans to email all deliverables to the NASA project management team by the deadline specified in the handbook. This requirement will be verified at the FRR milestone with submission of the last major deliverable, excluding PLAR.
NASA 1.8	All deliverables SHALL be in PDF format.	The team lead converts all deliverables to PDF format prior to submission to the NASA project management team.	Inspection	Project Management	Verified	This report is submitted in PDF format.
NASA 1.9	In every report, the team SHALL provide a table of contents including major sections and their respective sub-sections.	The team lead creates and manages a Table of Contents in each milestone report.	Inspection	Project Management	Verified	A Table of Contents is included on page ii**Error! Bookmark not defined.** of this document.
NASA 1.10	In every report, the team SHALL include the page number at the bottom of the page.	For each milestone report, the team uses a document template which includes page numbers at the bottom of each page.	Inspection	Project Management	Verified	Page numbers are listed at the bottom of each page of this document.

NASA 1.11	The team SHALL provide any computer equipment necessary to perform a video teleconference with the review panel.	Each team member participating in the video teleconference acquires the necessary equipment for them to perform a video teleconference with the review panel.	Inspection	Project Management	Not Verified	The team plans on providing their own computer equipment necessary to participate in video teleconferences with the review panel. The team has provided their own equipment in the past. This requirement will be verified at the FRR milestone once plans have been made to complete the FRR teleconference.
NASA 1.12	The team SHALL be required to use the launch pads provided by Student Launch's launch services provider.	The aerodynamics lead designs a launch vehicle to be launched from either an 8 foot 1010 rail or a 12 foot 1515 rail. The structures lead fabricates the launch vehicle according to this design.	Inspection	Aerodynamics; Structures	Not Verified	The launch vehicle is designed to be launched from a 12-foot 1515 rail. See section 3.5.2 for final launch rail interface design. This requirement will be verified at the VDF once the launch vehicle is inspected for successfully attaching to a 12-foot 1515 rail.
NASA 1.13	Each team SHALL identify a "mentor."	The team lead identifies qualified community members to mentor team members.	Inspection	Project Management	Verified	See section 1.1.2 for mentor listing and contact information.
NASA 1.14	Each team SHALL track and report the number of hours spent working on each milestone.	The team reports the number of hours spent on each milestone in the associated milestone report.	Inspection	Project Management	Verified	See section 1.1.3 for time spent on this milestone.

NASA 2.1	The vehicle SHALL deliver the payload to an apogee altitude between 3,500 and 5,500 feet above ground level (AGL).	The aerodynamics lead designs a launch vehicle to reach an apogee between 3,500 and 5,500 feet AGL. The team then constructs the vehicle as designed and the launch vehicle flies between 3,500 at 5,500 feet AGL.	Analysis; Demonstration	Aerodynamics	Not verified	The launch vehicle is predicted to deliver the payload to an apogee of 4,293 feet AGL. See section 3.5.2 for apogee predictions. This requirement will be verified based on the results of the VDF.
NASA 2.2	The team SHALL identify their target altitude goal at the PDR milestone.	The aerodynamics lead declares the team's target altitude goal in the PDR milestone report.	Inspection	Aerodynamics	Verified	The target altitude of 4,473 feet was identified in the PDR document. See section 1.2.1 for target altitude identification.
NASA 2.3	The vehicle SHALL carry one commercially available, barometric altimeter for recording the official altitude used in determining the Altitude Award winner.	The recovery lead designates one onboard altimeter to record the official altitude used in determining the Altitude Award winner.	Inspection	Recovery	Not verified	One of the recovery system's Stratologger CF altimeters will be designated as the official altimeter for competition purposes. See section 3.4.1.1 for final avionics system design. This requirement will be verified by inspection of the AV bay at the VDF.

NASA 2.4	The launch vehicle SHALL 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 structures and recovery leads design the launch vehicle such that it is capable of being recovered with minimal damage and launched again on the same day without repairs or modifications.	Inspection, Demonstration	Recovery; Structures	Not verified	The launch vehicle is designed to be recoverable and reusable. See section 3.4.1 for the final recovery design. This requirement will be verified by inspection of the launch vehicle following the VDF.
NASA 2.5	The launch vehicle SHALL have a maximum of four (4) independent sections.	The aerodynamics and recovery subsystem leads design a launch vehicle that has fewer than four (4) independent sections.	Inspection	Aerodynamics; Recovery	Verified	The launch vehicle has a total of three independent sections, excluding the payload lander. See section 3.1.3 for the final launch vehicle design.
NASA 2.5.1	Coupler/airframe shoulders which are located at in-flight separation points SHALL be at least 1 body diameter in length.	The aerodynamics lead designs the airframe such that couplers/shoulders at in-flight separation points are at least 1 body diameter in length	Inspection	Aerodynamics	Not verified	Coupler shoulders at in-flight separation points are 6 inches long. See section 3.1.3 for the final launch vehicle design. This requirement will be verified at the FRR milestone following fabrication of the launch vehicle.
NASA 2.5.2	Nosecone shoulders which are located at in-flight separation points SHALL be at least 1/2 body diameter in length.	The aerodynamics lead designs the airframe such that nosecone shoulders at in-flight separation points are at least 1/2 body diameter in length.	Inspection	Aerodynamics	Not verified	The nosecone shoulder is not located at an in-flight separation point. See section 3.1.5 for the final launch vehicle design. This requirement will be verified at the FRR milestone following fabrication of the launch vehicle.

NASA 2.6	The launch vehicle SHALL be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens.	The project management and safety teams develop launch day checklists that can be executed in less than two (2) hours.	Demonstration	Project Management; Safety	Not verified	The launch vehicle is designed to be prepared for launch within 2 hours. This requirement will be verified during vehicle assembly at the VDF.
NASA 2.7	The launch vehicle and payload SHALL be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components.	The project management and safety teams monitor the power consumption of each electrical launch vehicle and payload component and verify functionality of each component after two (2) hours.	Demonstration	Project Management; Safety	Not verified	The launch vehicle and payload are designed to remain fully function in a launch-ready configuration for at least 2 hours. See sections 6.1.2.4 and 6.1.3.1 for pad stay time test information. This requirement will be verified at the FRR milestone following completion of the Recovery Avionics Battery Life Test and the LOPSIDED-POS Battery Capacity Test.
NASA 2.8	The launch vehicle SHALL be capable of being launched by a standard 12-volt direct current firing system.	The project management and safety teams select a motor ignitor capable of being ignited from a 12-volt direct current firing system.	Demonstration	Project Management; Safety	Not verified	The launch vehicle is designed to use commercially available ignitors powered by a standard 12V DC firing system. This requirement will be verified following demonstration of a successful launch on a 12V DC firing system at the VDF.

NASA 2.9	The launch vehicle SHALL require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).	The project management and safety teams limit the launch vehicle such that no external circuitry or ground support equipment is required for launch.	Demonstration	Project Management; Safety	Not verified	The current launch vehicle design does not require external circuitry for launch. This requirement will be verified following demonstration of a successful launch without external circuitry at the VDF.
NASA 2.10	The launch vehicle SHALL 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 aerodynamics lead selects a commercially available solid motor propulsion system using APCP that is approved by NAR, TRA, and/or CAR for use in the launch vehicle.	Inspection	Aerodynamics	Verified	The team has selected the Aerotech L1520T as its final motor. See section 1.2.2 for final motor selection.
NASA 2.10.1	Final motor choices SHALL be declared by the Critical Design Review (CDR) milestone.	The aerodynamics lead declares the team's final motor choice in the CDR milestone report.	Inspection	Aerodynamics	Verified	The team has selected the Aerotech L1520T as its final motor. See section 1.2.2 for final motor selection.

NASA 2.10.2	Any motor change after CDR SHALL be approved by the NASA Range Safety Officer (RSO).	The project management team requests approval from the NASA RSO for motor changes following submission of the CDR milestone report.	Inspection	Project Management	Not verified	If the team wishes to change its motor selection, it will only do so with approval of the NASA RSO. This requirement will be verified at the FRR milestone following continued selection of the Aerotech L1520T or an approved request for a motor change.
NASA 2.11	The launch vehicle SHALL be limited to a single stage.	The aerodynamics lead designs the launch vehicle such that it only utilizes a single stage.	Inspection	Aerodynamics	Verified	The launch vehicle is a single stage. See section 3.1.3 for the final launch vehicle design.
NASA 2.12	The total impulse provided by a College or University launch vehicle SHALL not exceed 5,120 Newton-seconds (L-class).	The aerodynamics lead selects a motor that does not exceed 5,120 Newton-seconds of total impulse.	Inspection	Aerodynamics	Verified	The team has selected the Aerotech L1520T as its final motor. See section 1.2.2 for final motor selection.
NASA 2.13	Pressure vessels on the vehicle SHALL be approved by the RSO.	The structures lead provides the necessary data on any onboard pressure vessels to the NASA RSO and home field RSO.	Inspection	Structures	Verified	No pressure vessels are included in the final design.

NASA 2.13.1	The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) for pressure vessels on the vehicle SHALL be 4:1 with supporting design documentation included in all milestone reviews.	The structures lead includes design documentation supporting a factor of safety of 4:1 for any pressure vessel on the launch vehicle in each milestone report.	Analysis; Inspection	Structures	Verified	No pressure vessels are included in the final design.
NASA 2.13.2	Each pressure vessel SHALL include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank.	The structures lead selects any onboard pressure vessels such that they include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank.	Analysis; Inspection	Structures	Verified	No pressure vessels are included in the final design.

NASA 2.13.3	The full pedigree of any pressure vessel on the launch vehicle SHALL be described, including the application for which the tank was designed and the history of the tank. This SHALL include the number of pressure cycles put on the tank, the dates of pressurization/depressurization, and the name of the person or entity administering each pressure event.	The structures lead records the full history of each pressure vessel, including the number of pressure cycles, the dates of pressurization/depressurization, and the name of each person or entity administering the pressure events.	Inspection	Structures	Verified	No pressure vessels are included in the final design.
NASA 2.14	The launch vehicle SHALL have a minimum static stability margin of 2.0 at the point of rail exit.	The aerodynamics lead designs the launch vehicle such that it has a static stability margin of at least 2.0 at the point of rail exit.	Analysis	Aerodynamics	Verified	The launch vehicle will have a static stability margin of 2.1 at rail exit. See section 3.5.4 for stability calculations for the final launch vehicle design.

NASA 2.15	Any structural protuberance on the rocket SHALL be located aft of the burnout center of gravity. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the rocket's stability	The aerodynamics lead designs the launch vehicle such that there are no structural protuberances forward of the burnout center of gravity. If any camera housings are included, the aerodynamics lead shows that the housings cause minimal aerodynamic effects on launch vehicle stability.	Analysis; Inspection	Aerodynamics	Verified	The final launch vehicle design does not include structural protuberances forward of the burnout center of gravity. See section 3.1.3 for the final launch vehicle design.
NASA 2.16	The launch vehicle SHALL accelerate to a minimum velocity of 52 fps at rail exit.	The aerodynamics lead designs the launch vehicle such that a minimum velocity of 52 fps is achieved by rail exit.	Analysis	Aerodynamics	Verified	Rail exit velocity is 72.7 ft/s. See section 3.5.2 for performance calculations for the final launch vehicle design.
NASA 2.17	The team SHALL successfully launch and recover a subscale model of their rocket prior to CDR. Subscale flight data SHALL be reported at the CDR milestone.	The team launches and recovers a subscale model of the launch vehicle. The team reports subscale flight data in the CDR milestone report.	Demonstration	Project Management	Verified	The team completed a successful launch of the subscale model on November 21, 2020. See section 3.3 for flight results.

NASA 2.17.1	The subscale model SHALL resemble and perform as similarly as possible to the full-scale model, however, the full-scale SHALL not be used as the subscale model.	The aerodynamics lead designs a unique subscale launch vehicle which performs similarly to the full-scale launch vehicle.	Inspection	Aerodynamics	Verified	The subscale model was designed to resemble the full scale launch vehicle. See section 3.3.3 for subscale design details. The subscale is a different launch vehicle than the full scale launch vehicle.
NASA 2.17.2	The subscale model SHALL carry an altimeter capable of recording the model's apogee altitude.	The recovery lead installs an altimeter capable of recording the subscale launch vehicle's apogee altitude in the subscale launch vehicle.	Inspection	Recovery	Verified	Two Stratologger CF altimeters were carried by the subscale model. See section 3.3.2 for flight results.
NASA 2.17.3	The subscale rocket SHALL be a newly constructed rocket, designed and built specifically for this year's project.	The team constructs a new subscale launch vehicle, designed and built specifically for this year's project.	Inspection	Project Management	Verified	The team has constructed a new subscale rocket specifically built for this year's project.
NASA 2.17.4	Proof of a successful flight SHALL be supplied in the CDR report.	The team supplies proof of a successful subscale flight in the CDR milestone report.	Inspection	Project Management	Verified	See section 3.3 for details of the subscale flight results.
NASA 2.18.1	Vehicle Demonstration Flight - All teams SHALL successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration.	The team launches and recovers the full-scale launch vehicle in its final flight configuration prior to the FRR milestone.	Demonstration	Project Management	Not verified	See section 6.3.3 for the project plan timeline. A vehicle demonstration flight is scheduled for February 20, 2021. This requirement will be verified following completion of a successful VDF.

NASA 2.18.1.1	The vehicle and recovery system SHALL function as designed during the VDF.	No anomalies are detected in the performance of the launch vehicle and its recovery system during the VDF.	Demonstration	Project Management	Not verified	The launch vehicle and recovery system will be monitored during the VDF to ensure functionality as designed. This requirement will be verified following completion of the VDF.
NASA 2.18.1.2	The full-scale rocket SHALL be a newly constructed rocket, designed and built specifically for this year's project.	The team constructs a new full-scale launch vehicle, designed and build specifically for this year's project.	Inspection	Project Management	Not verified	The full scale rocket will be newly constructed and specifically designed for this year's project. This requirement will be verified following the end of construction of the full-scale rocket.
NASA 2.18.1.3.1	If the payload is not flown on the VDF, mass simulators SHALL be used to simulate the payload mass.	If the payload is not flown on the VDF, the structures lead installs mass simulators to simulate the payload mass.	Inspection	Structures	Not verified	The team plans to include the payload on the VDF. This requirement will be verified by inspection of the payload onboard the launch vehicle during the VDF.
NASA 2.18.1.3.2	Payload mass simulators SHALL be located in the same approximate location on the rocket as the missing payload mass.	If the payload is not flown on the VDF, the structures lead install mass simulators in the same approximate location of the missing payload mass.	Inspection	Structures	Not verified	The team does not anticipate the need for payload mass simulators, as the payload will be flown on the VDF. This requirement will be verified by inspection of the payload onboard the launch vehicle during the VDF.

NASA 2.18.1.4	If the payload changes the external surfaces of the rocket (such as camera housings or external probes) or manages the total energy of the vehicle, those systems SHALL be active during the full-scale Vehicle Demonstration Flight.	If the payload changes the external surfaces or manages the total energy of the launch vehicle, the project management team activates those systems during the VDF.	Inspection	Project Management	Verified	The payload does not change any external surfaces or manage the total energy of the vehicle. See section 4.3 for final payload design.
NASA 2.18.1.5	Teams SHALL fly the Launch Day motor for the Vehicle Demonstration Flight.	The aerodynamics lead installs the Launch Day motor for the VDF.	Inspection	Aerodynamics	Not verified	The team will fly the Launch Day motor on the VDF. This requirement will be verified by inspecting the motor installed during the VDF.
NASA 2.18.1.6	The vehicle SHALL be flown in its fully ballasted configuration during the full-scale test flight.	The structures lead installs all required ballast for the VDF.	Inspection	Structures	Not verified	The launch vehicle will be flown in its fully ballasted configuration during the VDF. This requirement will be verified by inspection of all onboard ballast during assembly for the VDF.
NASA 2.18.1.7	After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components SHALL not be modified without the concurrence of the NASA Range Safety Officer (RSO).	Following a successful VDF, the project management team does not allow modification of the launch vehicle or any of its components without approval from the NASA RSO.	Inspection	Project Management	Not verified	The team will not modify components of the launch vehicle without approval from the NASA RSO. This requirement will be verified at the FRR milestone once it is determined that no further modifications must be made.

NASA 2.18.1.8	Proof of a successful flight SHALL be supplied in the FRR report. Altimeter data output is required to meet this requirement.	The recovery lead includes altimeter data from the VDF in the FRR milestone report.	Inspection	Recovery	Not verified	Proof of a successful VDF will be included in the FRR report. This requirement will be verified in the FRR milestone.
NASA 2.18.1.9	Vehicle Demonstration flights SHALL be completed by the FRR submission deadline. Teams completing a required re-flight SHALL submit an FRR Addendum by the FRR Addendum deadline.	The team completes the VDF by the FRR milestone report submission deadline. If a re-flight is required, the team submits an FRR addendum by the FRR addendum deadline.	Inspection	Project Management	Not verified	The team plans on completing the VDF on February 20, 2021. If a VDF re-flight is required, the FRR Addendum will be completed by March 29, 2021. See section 6.3.3 for the current project plan. This requirement will be verified at the FRR milestone if a re-flight is not required, or at the FRR addendum if a re-flight is required.
NASA 2.18.2	Payload Demonstration Flight - All teams SHALL successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline. The rocket flown SHALL be the same rocket to be flown on Launch Day.	The team completes the PDF prior to the PDF deadline using the same rocket to be flown on Launch Day.	Inspection	Project Management	Not verified	The team plans on completing the PDF alongside the VDF on February 20, 2021. See section 6.3.3 for the current project plan. This requirement will be verified following successful completion of the PDF.

NASA 2.18.2.1	The payload SHALL be fully retained until the intended point of deployment (if applicable), all retention mechanisms SHALL function as designed, and the retention mechanism SHALL not sustain damage requiring repair.	The payload remains fully retained until the point of intended deployment with each retention mechanism functioning as designed and not sustaining damage requiring repair during the PDF.	Demonstration	Payload Integration	Not verified	During the PDF, the payload will be inspected to verify proper retention until the desired deployment point at 700 ft. AGL. The payload retention system will be inspected for damage. This requirement will be verified following demonstration of retention during the PDF.
NASA 2.18.2.2	The payload flown SHALL be the final, active version.	The payload flown on the PDF is the final, active version of the payload.	Inspection	Project Management	Not verified	The payload flown on the PDF will be the final, active version. This requirement will be verified by inspection of the payload installed during the PDF.
NASA 2.18.2.4	Payload Demonstration Flights SHALL be completed by the FRR Addendum deadline.	The PDF is completed by the FRR Addendum deadline.	Inspection	Project Management	Not verified	The team plans on completing the PDF alongside the VDF on February 20, 2021. See section 6.3.3 for the current project plan. This requirement will be verified following successful completion of the PDF.

NASA 2.19	An FRR Addendum SHALL be required for any team completing a Payload Demonstration Flight or NASA-required Vehicle Demonstration Re-flight after the submission of the FRR Report.	If the team is completing the PDF or a NASA-required VDF re-flight after the submission of the FRR Report, the team lead submits an FRR Addendum by the FRR Addendum deadline.	Inspection	Project Management	Not verified	The team does not plan on completing the PDF after submission of the FRR report. If a VDF re-flight is required, the FRR Addendum will be completed by March 29, 2021. This requirement will be verified at the FRR milestone if an addendum is not required, or at the FRR addendum if it is required.
NASA 2.19.1	If a re-flight is necessary, the team SHALL submit the FRR Addendum by the FRR Addendum deadline.	The team lead submits the FRR Addendum by the FRR Addendum deadline.	Inspection	Project Management	Not verified	If the team requires a re-flight, the team will submit the FRR Addendum by March 29, 2021. This requirement will be verified at the FRR milestone if an addendum is not required, or at the FRR addendum if it is required.
NASA 2.19.2	The team SHALL successfully execute a PDF to fly a final competition launch.	The project management team manages the schedule such that a PDF is successfully completed by the FRR Addendum deadline.	Demonstration	Project Management	Not verified	The team plans on completing the PDF alongside the VDF on February 20, 2021. See section 6.3.3 for the current project plan. This requirement will be verified following successful completion of the PDF.

NASA 2.20	The team's name and Launch Day contact information SHALL be in or on the rocket airframe as well as in or on any section of the vehicle that separates during flight and is not tethered to the main airframe. This information SHALL be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle.	The team lead places their contact information on the rocket airframe and any section of the vehicle that is not tethered to the main airframe in a manner that allows this information to be retrieved without opening or separating the vehicle.	Inspection	Project Management	Not verified	The team lead will place their contact information inside the rocket airframe and on the payload lander. This requirement will be verified by inspection of the contact information during the VDF. Any contact information will be displayed permanently, so the manner in which it is displayed at the VDF is the same manner in which it will be displayed on Launch Day.
NASA 2.21	All Lithium Polymer batteries SHALL be sufficiently protected from impact with the ground and SHALL be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other payload hardware.	The safety team ensures all Lithium Polymer batteries are sufficiently protected from ground impact and are marked appropriately.	Analysis; Inspection	Safety	Verified	The final launch vehicle and payload designs do not include Lithium Polymer batteries.
NASA 2.22.1	The launch vehicle SHALL not utilize forward firing motors.	The aerodynamics lead designs the launch vehicle such that it does not utilize forward firing motors.	Inspection	Aerodynamics	Verified	The final launch vehicle design does not include forward firing motors.
NASA 2.22.2	The launch vehicle SHALL not utilize motors that expel titanium sponges (Sparky, Skidmark, Metal-Storm, etc.)	The aerodynamics lead selects a motor that does not expel titanium sponges.	Analysis; Inspection	Aerodynamics	Verified	See section 1.2.2 for the final motor selection.

NASA 2.22.3	The launch vehicle SHALL not utilize hybrid motors.	The aerodynamics lead selects a motor which uses exclusively APCP.	Analysis; Inspection	Aerodynamics	Verified	See section 1.2.2 for the final motor selection.
NASA 2.22.4	The launch vehicle SHALL not utilize a cluster of motors.	The aerodynamics lead selects a single motor only for use in the launch vehicle.	Analysis; Inspection	Aerodynamics	Verified	See section 1.2.2 for the final motor selection.
NASA 2.22.5	The launch vehicle SHALL not utilize friction fitting for motors.	The structures lead installs a motor retention system that does not use friction fitting.	Inspection	Structures	Verified	See section 3.1.10 for the final launch vehicle motor retention design.
NASA 2.22.6	The launch vehicle SHALL not exceed Mach 1 at any point during flight.	The aerodynamics lead designs the launch vehicle such that it does not exceed Mach 1 at any point during flight.	Analysis	Aerodynamics	Verified	See section 3.5.2 for the final launch vehicle performance predictions.
NASA 2.22.7	Vehicle ballast SHALL not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad	The aerodynamics lead designs the launch vehicle such that it does not require ballast exceeding 10% of the total unballasted weight of the launch vehicle.	Analysis; Inspection	Aerodynamics	Not verified	See section 3.1.3 for the final launch vehicle design. This requirement will be verified at the FRR milestone following determination of the final required ballast based on the as-built launch vehicle weight distribution.

NASA 2.22.8	Transmissions from onboard transmitters, which are active at any point prior to landing, SHALL not exceed 250 mW of power (per transmitter).	The safety team verifies all transmitters activated prior to landing are not capable of transmissions exceeding 250 mW of power per transmitter.	Analysis	Safety	Verified	See the CDR Flysheet for transmitter identification. No transmitter exceeds 250mW of power.
NASA 2.22.9	Transmitters SHALL not create excessive interference. Teams SHALL utilize unique frequencies, hand-shake/passcode systems, or other means to mitigate interference caused to or received from other teams.	The safety team verifies no transmitter creates excessive interference. The safety team enforces the usage of unique frequencies to mitigate interference with other teams.	Analysis; Demonstration	Safety	Verified	See the CDR Flysheet for transmitter handshake and interference mitigation information.
NASA 2.22.10	Excessive and/or dense metal SHALL not be utilized in the construction of the vehicle.	The structures lead minimizes the amount of metal onboard the launch vehicle.	Inspection	Structures	Not verified	The final design includes metal only for threaded rods for the AV bay, and on the payload levelling system. This requirement will be verified at the FRR milestone by inspecting the launch vehicle and payload after final construction.

NASA 3.1	The full scale launch vehicle SHALL 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.	The recovery lead designs a dual-deployment recovery system.	Demonstration	Recovery	Not verified	See section 3.4.1 for final recovery system design. This requirement will be verified following successful performance of the recovery system during the VDF.
NASA 3.1.1	The main parachute SHALL be deployed no lower than 500 feet.	The recovery lead designs the recovery system such that the main parachute deploys no lower than 500 feet.	Demonstration	Recovery	Not verified	The main parachute is scheduled to be deployed at 700 feet. See section 3.4.1 for final recovery system design. This requirement will be verified following successful performance of the recovery system during the VDF.
NASA 3.1.2	The apogee event SHALL contain a delay of no more than 2 seconds.	The recovery lead designs the recovery system such that the apogee event has a delay of no more than 2 seconds.	Demonstration	Recovery	Not verified	No apogee delay is programmed for the primary altimeter. A one second apogee delay is programmed for the secondary altimeter. See section 3.4.1 for final recovery system design. This requirement will be verified following successful performance of the recovery system during the VDF.
NASA 3.1.3	Motor ejection SHALL not be used for primary or secondary deployment.	The recovery lead designs a recovery system that does not utilize motor ejection.	Inspection	Recovery	Verified	Motor ejection is not used for any recovery events. See section 3.4.1 for final recovery system design.

NASA 3.2	The team SHALL perform a successful ground ejection test for all electronically initiated recovery events prior to the initial flights of the subscale and full scale vehicles.	The recovery lead performs a ground ejection test for each electronically initiated recovery event prior to the initial flights of the subscale and full scale launch vehicles.	Demonstration	Recovery	Not verified	The team plans on completing ground ejection testing prior to the full scale launches. Ejection testing was completed on November 13, 2020 for the subscale launch vehicle. This requirement will be verified following a successful ground ejection demonstration for the full scale vehicle.
NASA 3.3	Each independent section of the launch vehicle SHALL have a maximum kinetic energy of 75 ft-lbf at landing.	The recovery lead designs a recovery system that results in no launch vehicle section having a kinetic energy greater than 75 ft-lbf at landing.	Analysis	Recovery	Verified	The maximum section kinetic energy at landing is 60.7 ft-lbf in a worst-case scenario. See section 3.5.6 for final recovery system calculations.
NASA 3.4	The recovery system SHALL contain redundant, commercially available altimeters.	The recovery lead includes at least two independent commercially available altimeters in the recovery system.	Inspection	Recovery	Verified	The recovery system contains two redundant Stratologger CF altimeters. See section 3.4.1.2 for final altimeter selection.

NASA 3.5	Each altimeter SHALL have a dedicated power supply, and all recovery electronics SHALL be powered by commercially available batteries.	The recovery lead designs the recovery system such that each altimeter has a dedicated power supply of commercially available batteries.	Inspection	Recovery	Verified	Each altimeter is powered by a dedicated off-the-shelf 9V battery. See section 3.4.1.1 for final avionics system design.
NASA 3.6	Each altimeter SHALL be armed by a dedicated mechanical arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.	The recovery lead installs dedicated mechanical arming switches accessible from the exterior of the launch vehicle airframe for each altimeter.	Inspection	Recovery	Verified	Each altimeter is capable of being armed by a screw switch accessible through a hole in the avionics bay airframe. See section 3.4.1.1 for final avionics system design.
NASA 3.7	Each arming switch SHALL be capable of being locked in the ON position for launch.	The recovery lead selects mechanical arming switches capable of being locked in the ON position.	Inspection	Recovery	Verified	Each altimeter is armed by a screw switch, which once tightened, is locked in the on position. See section 3.4.1.1 for final avionics system design.
NASA 3.8	The recovery system electrical circuits SHALL be completely independent of any payload electrical circuits.	The recovery lead designs the recovery system so that its electrical circuits are completely independent of any payload electrical circuits.	Inspection	Recovery	Verified	The recovery system electrical circuits are completely independent and located separately from all payload electrical circuits. See section 3.4.1.1 for final avionics system design.

NASA 3.9	Removable shear pins SHALL be used for both the main parachute compartment and the drogue parachute compartment.	The recovery lead designs the recovery system to use removable shear pins for the main parachute compartment and drogue parachute compartment.	Inspection	Recovery	Verified	#4-40 Nylon shear pins are used on the main and drogue parachute compartments. See section 3.4.1 for final recovery system design.
NASA 3.10	The recovery area SHALL be limited to a 2,500 ft. radius from the launch pads.	The recovery lead selects parachutes that prevent the launch vehicle from drifting more than 2,500 ft. from the launch pads.	Analysis; Demonstration	Recovery	Not verified	The maximum predicted wind drift is 2490.9 feet. See section 3.5.8 for final recovery system performance calculations. This requirement will be verified based on wind drift encountered during the VDF.
NASA 3.11	Descent time of the launch vehicle SHALL be limited to 90 seconds (apogee to touch down).	The recovery lead selects parachutes that allow the launch vehicle to touch down within 90 seconds of reaching apogee.	Analysis; Demonstration	Recovery	Not verified	The maximum predicted descent time is 85 seconds. See section 3.5.7 for final recovery system performance calculations. This requirement will be verified based on descent time recorded during the VDF.

NASA 3.12	An electronic tracking device SHALL be installed in the launch vehicle and SHALL transmit the position of the tethered vehicle or any independent section to a ground receiver.	The recovery lead selects and installs an electronic tracking device capable of transmitting the position of the launch vehicle or any independent section to a ground receiver.	Inspection; Demonstration	Recovery	Not verified	An EggFinder TX/RX system is used for launch vehicle tracking. A BigRedBee BRB 900 is used for payload tracking. Both of these systems transmit to ground receivers. See section 3.4.1.3 for final tracking device selection. This requirement will be verified after the VDF by inspection of the tracking devices installed in the launch vehicle and payload, and demonstration of their capability to transmit their location.
NASA 3.12.1	Any rocket section or payload component, which lands untethered to the launch vehicle, SHALL contain an active electronic tracking device.	The recovery lead installs an electronic tracking device in any launch vehicle section or payload component which lands untethered to the launch vehicle.	Inspection	Recovery	Verified	The payload is the only untethered component of the launch vehicle. It contains its own tracking device. See section 3.4.1.3 for final tracking device selection.
NASA 3.13	The recovery system electronics SHALL not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	The recovery lead designs the recovery system such that it is not affected by other on-board electronic devices.	Demonstration	Recovery	Not verified	See section 3.4.1.1 for final avionics system design. This requirement will be verified by demonstration of no interference during the VDF.

NASA 3.13.1	The recovery system altimeters SHALL 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 lead designs an avionics bay which houses the recovery system altimeters in a physically separate compartment within the launch vehicle.	Inspection	Recovery	Verified	All recovery system altimeters are located in the avionics bay, which is physically separate from the rest of the launch vehicle. See section 3.4.1.1 for final avionics system design.
NASA 3.13.2	The recovery system electronics SHALL be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.	The recovery lead designs and installs shielding for the recovery system electronics from all onboard transmitting devices.	Inspection	Recovery	Not verified	The recovery electronics will be shielded from onboard transmitters with aluminum foil. See section 3.4.1.1 for final avionics system design. This requirement will be verified by inspection of the installed aluminum foil shielding following full scale construction.
NASA 3.13.3	The recovery system electronics SHALL 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 recovery lead designs and installs shielding for the recovery system electronics from all devices which may generate magnetic waves.	Inspection	Recovery	Not verified	The recovery electronics will be shielded from the payload solenoid latches with aluminum foil. See section 3.4.1.1 for final avionics system design. This requirement will be verified by inspection of the installed aluminum foil shielding following full scale construction.

NASA 3.13.4	The recovery system electronics SHALL be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.	The recovery lead designs and installs shielding for the recovery system electronics from all devices which may adversely affect the proper operation of the recovery system electronics.	Inspection	Recovery	Not verified	The recovery electronics will be shielded with aluminum foil. See section 3.4.1.1 for final avionics system design. This requirement will be verified by inspection of the installed aluminum foil shielding following full scale construction.
NASA 4.2	The team SHALL design a planetary landing system to be launched in a high-power rocket. The lander system SHALL be capable of being jettisoned from the rocket during descent, landing in an upright configuration or autonomously uprighting after landing. The system SHALL self-level within a five-degree tolerance from vertical. After autonomously uprighting and self-leveling, it SHALL take a 360-degree panoramic photo of the landing site and transmit the photo to the team.	The payload team designs a planetary landing system to be launched in a high-powered rocket. The payload is capable of being jettisoned from the launch vehicle during descent, landing in an upright configuration or autonomously uprighting after landing, self-levelling within a five-degree tolerance from vertical, and taking a 360-degree panoramic photo of the landing site and transmitting the photo to the team.	Demonstration	Payload vehicle; Payload integration; Payload imaging	Not verified	See section 4.3 for final payload design. This requirement will be verified by successful demonstration of payload capabilities during the PDF.

NASA 4.3.1	The landing system SHALL be completely jettisoned from the rocket at an altitude between 500 and 1,000 ft. AGL. The landing system SHALL land within the external borders of the launch field. The landing system SHALL not be tethered to the launch vehicle upon landing.	The payload integration lead designs the payload such that it jettisons from the launch vehicle between 500 and 1,000 AGL, lands within the external border of the launch field, and is not tethered to the launch vehicle.	Demonstration	Payload integration	Not verified	The payload will be removed from the payload bay at 700 ft. AGL. The payload will release itself from the launch vehicle at 500 ft. AGL. See section 4.3.8 for final payload jettison design. This requirement will be verified by demonstration of payload deployment during the PDF.
NASA 4.3.2	The landing system SHALL land in an upright orientation or SHALL be capable of reorienting itself to an upright configuration after landing. Any system designed to reorient the lander SHALL be completely autonomous.	The payload vehicle lead designs the payload such that it lands in an upright position or reorients itself to an upright configuration after landing using a completely autonomous system.	Demonstration	Payload vehicle	Not verified	The lander is designed to land in an upright orientation. See section 4.3.2 for final payload lander design. This requirement will be verified by successful levelling system performance during ground demonstrations or during the PDF.
NASA 4.3.3	The landing system SHALL self-level to within a five-degree tolerance from vertical.	The payload vehicle lead designs the payload such that it is capable of self-leveling within a five-degree tolerance from vertical.	Demonstration	Payload vehicle	Not verified	The leveling system is designed to self-level to within 5 degrees of vertical. See section 4.3.2.5 for final payload leveling system design. This requirement will be verified by successful levelling system performance during ground demonstrations or during the PDF.

NASA 4.3.3.1	Any system designed to level the lander SHALL be completely autonomous.	The payload vehicle lead designs a payload leveling system that is completely autonomous.	Demonstration	Payload vehicle	Not verified	The leveling system is completely autonomous. See section 4.3.2.5 for final payload leveling system design. This requirement will be verified by autonomous levelling system operation during the PDF.
NASA 4.3.3.2	The landing system SHALL record the initial angle after landing, relative to vertical, as well as the final angle, after reorientation and self-levelling. This data SHALL be reported in the Post Launch Assessment Report (PLAR).	The payload vehicle lead designs a payload leveling system which records the initial angle after landing as well as the final angle relative to vertical. The payload vehicle lead reports this data in the PLAR.	Demonstration	Payload vehicle	Not verified	The lander will record the initial and final angles relative to vertical. See section 4.3.2.5 for final payload leveling system design. This requirement will be verified by demonstrating the recorded angles during the PDF.
NASA 4.3.4	Upon completion of reorientation and self-levelling, the lander SHALL produce a 360-degree panoramic image of the landing site and transmit it to the team.	The payload imaging lead designs an imaging system capable of producing a 360-degree panoramic image and transmitting it to the team following self-levelling of the payload vehicle.	Demonstration	Payload imaging	Not verified	Four cameras allow the lander to capture a 360-degree panoramic image. Slow-scan television will be used to transmit the image to the team. See section 4.3.3 for final imaging system design. This requirement will be verified by demonstrating imaging system performance during the PDF.

NASA 4.3.4.1	The hardware receiving the image SHALL be located within the team's assigned prep area or the designated viewing area.	The payload imaging lead selects a ground station capable of receiving the image and being located within the team's prep area or designated viewing area.	Inspection	Payload imaging	Not verified	The laptop used to receive the lander's image will be located within either the team's assigned prep area or the designated viewing area. See section 4.3.5 for final imaging system design. This requirement will be verified by inspecting the location of the team's laptop during the PDF.
NASA 4.3.4.2	Only transmitters that were onboard the vehicle during launch SHALL be permitted to operate outside of the viewing or prep areas.	The team does not operate transmitters outside the viewing or prep areas that were not onboard the vehicle during launch.	Demonstration	Payload imaging	Verified	No transmitters will be used that were not onboard the launch vehicle at launch. See the CDR Flysheet for transmitter information.
NASA 4.3.4.3	Onboard payload transmitters SHALL be limited to 250 mW of RF power while onboard the launch vehicle but may operate at a higher RF power after landing on the planetary surface. Transmitters operating at higher power SHALL be approved by NASA during the design process.	The payload imaging lead selects onboard transmitters limited to 250 mW of RF power while onboard the launch vehicle. The payload imaging lead receives approval from NASA for operating transmitters outside of the launch vehicle at higher power.	Inspection	Payload imaging	Verified	No transmitter will be operated at power levels exceeding 250 mW. See section 4.3.5 for final image transmitter system design. See the CDR Flysheet for transmitter information.

NASA 4.3.4.4	The image SHALL be included in the team's PLAR.	The payload imaging lead includes the captured image in the PLAR.	Inspection	Payload imaging	Not verified	The team will include the lander's image in the PLAR. This requirement will be verified at the PLAR milestone.
NASA 4.4.1	Black powder and/or similar energetics SHALL only be used for deployment of in-flight recovery systems.	The payload integration lead designs the payload recovery system such that any energetics are only utilized in-flight.	Inspection	Payload integration	Verified	Black powder is only used in-flight with the ARRD to separate the payload vehicle from the main parachute recovery harness and deploy the payload parachute. See section 4.3.7 for final payload deployment design.
NASA 4.4.2	Teams SHALL abide by all FAA and NAR rules and regulations.	The safety team verifies payload compliance with all FAA and NAR rules and regulations.	Demonstration	Safety	Not verified	The final payload design complies with all FAA and NAR rules and regulations. This requirement will be verified following demonstration of adherence to FAA and NAR rules and regulations at the VDF and PDF.
NASA 4.4.3	Any experiment element that is jettisoned, except for planetary lander experiments, during the recovery phase SHALL receive real-time RSO permission prior to initiating the jettison event.	The payload integration lead receives real-time RSO permission prior to initiating the jettison of any experiment element except for the planetary lander.	Demonstration	Payload integration	Verified	The team is not including a secondary payload experiment.

NASA 4.4.4	Unmanned aircraft system (UAS) payloads, if designed to be deployed during descent, SHALL be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAS.	The payload integration lead designs any UAS payload to be tethered to the launch vehicle with a remotely controlled release mechanism until the RSO gives permission to release the UAS.	Demonstration	Payload integration	Verified	The final payload design is not a UAS.
NASA 4.4.5	Teams flying UASs SHALL abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112-95 Section 336).	The safety team verifies any UAS payload's compliance with all applicable FAA regulations.	Demonstration	Safety	Verified	The final payload design is not a UAS.
NASA 4.4.6	Any UAS weighing more than .55 lbs. SHALL be registered with the FAA and the registration number marked on the vehicle.	The payload vehicle lead registers any UAS weighing more than .55 lbs with the FAA and marks the registration number of the vehicle.	Demonstration	Payload vehicle	Verified	The final payload design is not a UAS.

NASA 5.1	The team SHALL use a launch and safety checklist. The final checklists SHALL be included in the FRR report and used during the Launch Readiness Review (LRR) and any Launch Day operations.	The safety team creates a launch and safety checklist. The safety team includes these checklists in the FRR milestone report and verifies their use during LRR and Launch Day operations.	Inspection; Demonstration	Safety	Not verified	Launch and safety checklists have been developed for the subscale launch vehicle and are attached in Section 5.2. Launch and safety checklists for the full scale launch vehicle will be included in the FRR report. This requirement will be verified at the FRR milestone.
NASA 5.2	Each team SHALL identify a student safety officer who will be responsible for all items in requirements section 5.3.	A safety officer is identified in each milestone report.	Inspection	Project management	Verified	See section 5.1 for safety officer identification.
NASA 5.3.1.1	The safety officer SHALL monitor team activities with an emphasis on safety during the design of the launch vehicle and payload.	The safety officer is present for and engages in at least half of all launch vehicle and payload design meetings.	Inspection	Safety	Not verified	The safety officer has been present for more than half of all design meetings as of the CDR milestone. This requirement will be verified by a statement from the safety officer at the FRR milestone.
NASA 5.3.1.2	The safety officer SHALL monitor team activities with an emphasis on safety during the construction of the launch vehicle and payload components.	The safety officer is present and engaged for all launch vehicle and payload construction meetings.	Inspection	Safety	Not verified	The safety officer has been present for all construction activities as of the CDR milestone. This requirement will be verified by a statement from the safety officer at the FRR milestone.

NASA 5.3.1.3	The safety officer SHALL monitor team activities with an emphasis on safety during the assembly of the launch vehicle and payload.	The safety officer is present and engaged during the assembly of the launch vehicle and payload.	Inspection	Safety	Not verified	The safety officer will be monitoring assembly of the subscale and full scale launch vehicle and payload. This requirement will be verified by a statement from the safety officer at the FRR milestone.
NASA 5.3.1.4	The safety officer SHALL monitor team activities with an emphasis on safety during the ground testing of the launch vehicle and payload.	The safety officer is present and engaged for all ground tests of the launch vehicle and payload.	Inspection	Safety	Not verified	The safety officer has been present all ground testing as of the CDR milestone. This requirement will be verified by a statement from the safety officer at the FRR milestone.
NASA 5.3.1.5	The safety officer SHALL monitor team activities with an emphasis on safety during the subscale launch test(s).	The safety officer is present and engaged at any subscale launch test.	Inspection	Safety	Verified	The safety officer attended the subscale launch test and supervised all steps of the assembly, launch, and recovery procedure. See Section 5.2 for safety officer sign-offs on subscale launch checklists.
NASA 5.3.1.6	The safety officer SHALL monitor team activities with an emphasis on safety during the full-scale launch test(s).	The safety officer is present and engaged at any full-scale launch test.	Inspection	Safety	Not verified	The safety officer plans to attend the full scale launch test. This requirement will be verified by safety officer sign-offs on the VDF checklists.
NASA 5.3.1.7	The safety officer SHALL monitor team activities with an emphasis on safety during Launch Day.	The safety officer is present and engaged at Launch Day.	Inspection	Safety	Not verified	The safety officer plans to attend Launch Day. This requirement will be verified by safety officer sign-offs on the Launch Day checklists.

NASA 5.3.1.8	The safety officer SHALL monitor team activities with an emphasis on safety during recovery activities.	The safety officer is present and engaged for all recovery activities.	Inspection	Safety	Not verified	The safety officer will be assigned to the field recovery team. This requirement will be verified by safety officer sign-offs on the checklists included in the FRR milestone.
NASA 5.3.1.9	The safety officer SHALL monitor team activities with an emphasis on safety during STEM engagement activities.	The safety officer is present and engaged for at least half of all STEM engagement activities.	Inspection	Safety	Not verified	The team has only completed one STEM engagement activity as of the CDR milestone. This requirement will be verified by a statement from the safety officer at the FRR milestone.
NASA 5.3.2	The safety officer SHALL implement procedures developed by the team for construction, assembly, launch, and recovery activities.	The safety officer develops a safety plan for construction, assembly, launch, and recovery activities, and verifies team adherence to this plan.	Demonstration	Safety	Not verified	The safety officer has implemented procedures for construction, assembly, launch, and recovery activities. See Section 5.2 for subscale assembly, launch, and recovery checklists. This requirement will be verified by demonstration of adherence to these procedures at the VDF and PDF in the FRR milestone.

NASA 5.3.3	The safety officer SHALL manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	The safety officer manages and maintains current revisions of all hazard analyses, procedures, and MSDS/chemical inventory data.	Demonstration	Safety	Not verified	The safety officer is responsible for maintaining hazard analyses, procedures, and MSDS/chemical inventory data. This requirement will be verified at the FRR milestone by demonstration of the safety officer's involvement in maintaining hazard analysis, FMEA, procedures, and MSDS/chemical data.
NASA 5.3.4	The safety officer SHALL assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	The safety officer leads in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	Demonstration	Safety	Not verified	The safety officer has written the team's hazard analysis and failure mode analysis in Section 5.4. This requirement will be verified at the FRR milestone by demonstration of the safety officer's involvement in writing and developing hazard analysis, FMEA, and procedures.

NASA 5.4	During test flights, the team SHALL abide by the rules and guidance of the local rocketry club's RSO. Teams SHALL communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.	The safety officer communicates the team's intentions to the local club's President or Prefect and RSO prior to attending any NAR or TRA launch. The safety officer verifies team adherence to the rules and guidance of the local club's RSO.	Demonstration	Safety	Not verified	The team will abide by rules and guidance of the local rocketry club's RSO. The team has communicated our intentions to the local club's Prefect. This requirement will be verified by demonstration of adherence to local RSO guidance at the VDF and PDF.
NASA 5.5	Teams SHALL abide by all rules set forth by the FAA.	The safety officer verifies the team adheres to all rules set forth by the FAA.	Demonstration	Safety	Not verified	The team currently complies with all FAA regulations. This requirement will be verified at the FRR milestone by demonstration of adherence to FAA rules at the VDF and PDF.

6.2.2 Team-Derived Requirements

Table 6-17 below lists Team-Derived requirements along with their verification plan and status.

Table 6-17 Team-Derived Requirements Verification Matrix

Req No.	Shall Statement	Justification	Success Criteria	Verification Method	Subsystem Allocation	Status	Status Description
TDR 1.1	Epoxy SHALL be left to cure for at least 24 hours prior to use	Uncured epoxy weakens the overall system, making components vulnerable to structural failure	Epoxied components are unmoved from their position until the date and time indicated on their respective label.	Inspection	Safety	Not verified	Current construction procedures specify a 24-hour cure period for all epoxied components. This requirement will be verified at the FRR milestone following completion of all construction.
TDR 1.2	Launch day attendees SHALL be instructed to maintain a walking pace at all times, including during assembly, launch, and recovery	Maintaining a walking pace at all times will decrease the likelihood of slips, trips, and falls contributing to personnel injury	Team members have one foot on the ground at all times.	Inspection	Safety	Not verified	All launch day procedures explicitly prohibit running. Launch day safety briefings include instructions to walk at all times. This requirement will be verified at the FRR milestone by inspection of launch day checklists.

TDR 1.3	Safety glasses SHALL be provided to personnel working with power tools	The use of personal protective equipment will reduce the likelihood of skin and eye injury from large and small debris due to working with power tools	The number of safety glasses in the PPE cabinet matches or exceeds the number of personnel working with power tools.	Inspection	Safety	Verified	Safety glasses are provided in the lab space and all team members are instructed to use safety glasses when operating power tools. See section 5.5 for safety procedure details.
TDR 1.4	Nitrile gloves, safety glasses, and particulate masks SHALL be provided to personnel working with volatile liquid and powder chemicals	The use of PPE will reduce the likelihood of skin, eye, and lung irritation due to working with volatile liquids or powders	The number of glove pairs, safety glasses, and particulate masks in the PPE cabinet matches or exceeds the number of personnel working with volatile liquids and/or powders (max 3).	Inspection	Safety	Verified	Nitrile gloves, safety glasses, and particulate masks are provided in the lab space and all team members are instructed to use appropriate PPE when working with volatile liquid and powder chemicals. See section 5.5 for safety procedure details.

TDR 2.1	The launch vehicle airframe SHALL be water resistant.	The team's home launch field in Bayboro, NC has several large irrigation ditches that are typically filled with water. Should the launch vehicle land in the water, a water resistant airframe will help reduce potential damage.	The airframe is not damaged or deformed upon exposure to water.	Inspection, Analysis	Structures	Verified	G12 Fiberglass has been selected as a water resistant material for the launch vehicle airframe. See section 3.1.4 for details on material selection.
TDR 2.2	All critical components of the launch vehicle SHALL be designed with a minimum factor of safety of 2.	This will ensure that assumptions made in analysis or higher than expected loading will not cause unpredicted failure during flight. A factor of safety of 2 has been deemed sufficient to account for unexpected loading, while allowing components to remain lightweight.	The factor of safety of each critical component is reported in documentation and proven by structural testing.	Analysis, Test	Structures	Not verified	Factor of safety is determined through simulations and through testing. See section 3.1.12 for details on simulations. This requirement will be completed at the FRR milestone following the completion of the tests detailed in section 6.1.1.

TDR 2.3	The launch vehicle SHALL be no larger than 6 inches in diameter.	Limiting the size of the launch vehicle makes it safer and easier to manipulate on the field.	The diameter of the airframe is not larger than 6 inches.	Inspection	Aerodynamics, Structures	Verified	The final launch vehicle airframe selection is 6 inches in diameter. See section 3.1.3 for launch vehicle design.
TDR 2.4	The launch vehicle SHALL maintain speeds below transonic (M<=0.7)	Transonic speeds leave the launch vehicle vulnerable to fin flutter and delamination that can cause irreparable structural failure and total flight failure	Simulations in RockSim are performed to confirm the launch vehicle's maximum velocity.	Analysis	Safety	Verified	The maximum flight velocity of the launch vehicle is Mach 0.471. See section 3.5.2 for mission performance predictions.
TDR 3.1	The secondary black powder charges SHALL be of greater mass than the primary black powder charges.	In the event the primary black powder charge fails to cause section separation, a larger charge will have a better chance of successful separation.	The secondary black powder charges when weighed are of greater mass than the primary black powder charges.	Inspection	Recovery	Not verified	The secondary black powder charges are 0.5g larger than the primary black powder charges. See section 3.5.9 for black powder charge sizing calculations. This requirement will be verified at the FRR milestone following final black powder charge selection based on the results of the full scale ground ejection demonstration.

TDR 3.2	The launch vehicles blast caps SHALL be exposed and accessible.	Accessible energetic materials containers allow for safer loading of energetic materials.	The designed Avionics Bay has easily accessible blast caps.	Inspection	Structures; Recovery	Not verified	The avionics bay is designed to leave all blast caps exposed and accessible. See section 3.1.9 for Avionics Bay design. This requirement will be verified at the FRR milestone following assembly of the launch vehicle.
TDR 3.3	Drogue descent velocity SHALL be less than 125 fps.	This speed will minimize main parachute opening shock.	Calculations for launch vehicle velocity under drogue parachute are less than 125 fps.	Analysis	Recovery	Verified	Drogue descent velocity is 117 fps. See section 3.5.10 for descent velocity calculations.
TDR 3.4	The black powder ejection charges SHALL produce at least 10 psi.	This 10 psi target will produce sufficient force in most cases to shear a reasonable number of shear pins.	Black powder ejection charge calculations indicate a pressure of 10 psi will be reached.	Analysis	Recovery	Verified	The black powder charges will produce 15 psi. See section 3.5.9 for black powder charge sizing calculations.
TDR 3.5	The launch vehicle SHALL use U-bolts for all recovery harness attachment points.	U-bolts reduce the chance of a single point of failure and distribute the opening shock across the bulkhead.	The load bearing bulkheads have recovery attachment points that use U-bolts.	Inspection	Recovery	Verified	U-Bolts are used for all recovery harness attachment points. See section 3.4.1.5 for bulkhead design.

TDR 3.6	The launch vehicle SHALL use threaded quick-links for all recovery harness attachment points.	Thread quick-links reduce the likelihood of recovery harness detachment due to flight forces.	The recovery harness will be attached at all points by threaded quick-links.	Inspection	Recovery	Verified	Threaded quick-links are used for all recovery harness attachment points. See section 3.4.1.5 for recovery component selection.
TDR 3.7	A deployment bag SHALL be utilized for packing of the main parachute.	Deployment bags reduce the likelihood of parachute damage from hot ejection charge gasses and reduce reliance on folding technique for proper parachute deployment.	A deployment bag will be utilized to pack the main parachute.	Inspection	Recovery	Verified	A deployment bag is used to pack the main parachute. See section 3.4.1.4 for recovery component selection.
TDR 3.8	The onboard altimeters SHALL use one 9V battery for each flight.	StratoLogger CF Altimeters use one 9V battery each.	The avionics sled is designed to hold two 9V batteries, one for each altimeter.	Inspection	Recovery	Verified	Each altimeter is connected to a single 9V battery. See section 3.4.1.1 for avionics sled design.

TDR 3.9	A fresh 9V battery SHALL be selected for both onboard altimeters before each flight.	The system must be capable of remaining powered on for prolonged periods of time.	Each 9V battery placed on the avionics sled before flight must measure greater than 9 V before flight.	Inspection	Recovery	Not verified	See checklist item 4.1 in Section 5.2 for verification of battery voltage. The same procedure will be applied to the full scale launch vehicle. This requirement will be verified at the FRR milestone following installation of fresh 9V batteries for the VDF.
TDR 3.10	The recovery system SHALL be capable of recovering the launch vehicle within NASA Handbook requirements should the LOPSIDED-POS fail to separate from the launch vehicle.	The system must be robust enough to accommodate potential mission failures.	Descent calculations are within limits even should the payload fail to separate.	Analysis	Recovery	Verified	The recovery system meets all NASA handbook requirements with the LOPSIDED-POS still onboard. See section 3.5.6 for descent calculations.

TDR 4.1	The POS SHALL capture two separate 360-degree images, offset by 90 degrees.	Capturing two images provides redundancy in a variety of camera-failure events.	Each POS camera is capable of capturing at least a 180 degree field of view.	Demonstration	Payload Imaging	Not verified	The current POS design includes four cameras mounted at 90-degree angles from each other. Each camera has a 194-degree field of view. This allows for the capture of two separate 360-degree images. See section 4.3.3 for POS camera design. This requirement will be verified at the FRR milestone following demonstration of POS image capture performance.
TDR 4.2	POS cameras SHALL be protected from physical damage associated with launch, deployment, and landing while having a proper field of view for image capture.	If the camera modules are damaged, the ability of the payload to capture 360 degree images will be compromised.	The top section of LOPSIDED allows cameras to be housed with significant protection and field of view.	Analysis	Payload Imaging	Verified	The POS cameras are isolated within LOPSIDED to mitigate the risk of damage during flight. The polycarbonate section provides the POS cameras with an adequate field of view. See section 4.3.2.2 for description of current payload design.

TDR 4.3	POS electronics SHALL fit in a 69 x 69 x 190 mm volume.	The payload vehicle size is constrained by the 6 inch launch vehicle diameter, as well as hardware for the self-leveling system.	The POS electronics, not including the camera modules, successfully fit within LOPSIDED.	Inspection	Payload Imaging	Not verified	The POS electronics are designed to fit within the specified volume. See section 4.3.2.4 for description of current payload design. This requirement will be verified at the FRR milestone following construction of the POS electronics assembly.
TDR 4.4	POS electronics, excluding the camera modules, SHALL be contained below the pivoting axis of LOPSIDED's leveling system.	For the proposed leveling system to work, LOPSIDED must have an overall CG below the pivoting axis.	LOPSIDED is able to self-level after all POS components have been installed.	Inspection	Payload Imaging	Not verified	The POS electronics are designed to be installed below the pivoting axis of LOPSIDED. See section 4.3.2.4 for description of current payload design. This requirement will be verified at the FRR milestone following construction of LOPSIDED and the POS.
TDR 4.5	LOPSIDED SHALL fit within a 6 inch diameter constraint.	This allows the LOPSIDED to fit within the Launch Vehicle's payload bay.	LOPSIDED is able to fit within the launch vehicle's payload bay.	Inspection	Payload Vehicle	Not verified	The maximum diameter of LOPSIDED is 5.75 in. See section 4.3.2 for description of current payload design. This requirement will be verified at the FRR milestone following

							construction of LOPSIDED.
TDR 4.6	LOPSIDED SHALL remain locked in its neutral position until after landing and taking its initial orientation measurement.	The payload orientation system must remain locked in order to not damage the launch vehicle, interfere with any deployment mechanisms, and allow for an initial orientation measurement to be recorded.	The gimbal-based leveling system is not allowed to rotate until the initial orientation measurement is recorded.	Test	Payload Vehicle	Not verified	Four solenoid latches will hold LOPSIDED in its neutral position until its initial orientation has been recorded. See section 4.3.2.5 for description of current payload design. See section 6.1.3.3 for solenoid latch test design. This requirement will be verified at the FRR milestone following the completion of the LOPSIDED-POS Ground Performance Test.

TDR 4.7	LOPSIDED's legs SHALL deploy immediately after exiting the payload bay.	This will expand the payload's footprint from its stowed configuration, increasing its stability. By having this event happen immediately, this decreases the risk of the legs not deploying in time for landing.	LOPSIDED's legs deploy as soon as they are no longer constrained by the payload bay.	Test	Payload Vehicle	Not verified	LOPSIDED's legs are spring-loaded to deploy as soon as they are no longer constrained. See section 4.3.2.5 for description of current payload design. See section 6.1.3.3 for leg deployment test design. This requirement will be verified at the FRR milestone following the completion of the LOPSIDED-POS Ground Performance Test.
TDR 4.8	LOPSIDED's gravity-assisted self-levelling system SHALL allow the body to reorient within ~15 degrees of its neutral orientation.	Given the requirement of being withing 5 degrees of vertical, the design allows for the body to move 15 degrees, allowing LOPSIDED to land on grades of up to 20 degrees in any direction and still complete the mission.	LOPSIDED has at least a 15-degree range of motion about either axis.	Test	Payload Vehicle	Not verified	The leveling system is designed to reorient to a worst-case maximum of 18.5 degrees. See section 4.3.2.6 for description of current payload design. See section 6.1.3.3 for leveling system test design. This requirement will be verified at the FRR milestone following the completion of the LOPSIDED-POS Ground Performance Test.

TDR 4.9	LOPSIDED SHALL have an allotted volume of 69x69x69 cubic mm for the POS camera frame to fit within.	This will allow the POS to operate fully without any obstruction and will interface with the rest of LOPSIDED.	LOPSIDED has a 69x69x69 mm internal volume of air.	Analysis	Payload Vehicle	Verified	LOPSIDED has an allotted volume of 69x69x69 cubic mm for the POS camera frame. See section 4.3.2.2 for description of current payload design.
TDR 4.10	LOPSIDED SHALL have designated mounting point at the top.	This will interface with integration subsytem so that any forces it may recieve from that system will not destroy the payload and will allow for the parachutes to detach.	LOPSIDED has four screw rods at its top for the ARRD to be mounted to.	Analysis	Payload Vehicle	Verified	LOPSIDED has four screw rods at its top for mounting of the ARRD. See section 4.3.7 for description of current payload design.
TDR 4.11	LOPSIDED SHALL have a center of gravity beneath its pivoting axes.	This will allow the levelling system to utilize the force due to gravity and not require any motors to operate.	The LOPSIDED CG is below its pivoting axes.	Analysis	Payload Vehicle	Verified	LOPSIDED's design center of gravity lies below its pivoting axes. See section 4.3.2.5 for description of current payload design.
TDR 4.12	LOPSIDED-POS SHALL weigh no more than 10.5 lbs.	Maintaining a standard payload weight serves for a stable location of center of gravity for launch vehicle stability purposes.	LOPSIDED-POS has a total weight of 10.5 lbs or less.	Inspection	Payload Vehicle, Payload Integration, Payload Imaging	Not verified	The LOPSIDED-POS is designed to weigh 10.5 lbs. See section 4.3.1 for payload design. This requirement will be verified at the FRR milestone following construction of LOPSIDED-POS.

TDR 4.13	LOPSIDED SHALL exit within 3 seconds of deployment during jettison	Successful deployment of the payload vehicle depends on the payload being able to slide out of the payload bay	LOPSIDED is completely removed from the payload bay within 3 seconds of deployment.	Test	Payload Integration	Not verified	LOPSIDED is designed to be removed from the payload bay within 3 seconds of main deployment. See section 4.3.8 for payload design. See section 6.1.2.2 for deployment time test design. This requirement will be verified at the FRR milestone following completion of the Full Scale Ejection Test.
TDR 4.14	The POS SHALL transmit and receive images from up to 4500 feet from the team's ground station.	In the event of excessive wind drift after parachute deployment, image transmissions from the POS will still need to be received.	Images sent by the POS transmitter are successfully received by the ground station from up to 4500 feet away.	Test	Payload Imaging	Not verified	The current POS design will be capable of transmitting 5410 ft. See section 4.3.5 for payload transmitter design. This requirement will be verified at the FRR milestone following completion of the POS range test detailed in section 6.1.3.2.

TDR 4.15	All on-board LOPSIDED-POS electronics, with the exception of the payload altimeter, SHALL be powered with one battery pack.	Having one battery saves weight and volume on board the LOPSIDED-POS.	One 12V battery will be used to power all electronics housed within the LOPSIDED-POS, excluding the payload altimeter.	Inspection	Payload Vehicle, Payload Integration, Payload Imaging	Not verified	The current LOPSIDED-POS design includes a single battery pack. See section 4.3.4 for payload electronics design. This requirement will be verified at the FRR milestone following construction of LOPSIDED-POS.
TDR 4.16	LOPSIDED SHALL release the payload parachute upon landing.	Releasing the parachute once LOPSIDED has landed prevents the parachute from interfering with the leveling system if it were to inflate and apply a load.	The parachute detaches completely from LOPSIDED while also not covering POS.	Demonstration	Payload Vehicle, Payload Integration, Payload Imaging	Not verified	The current LOPSIDED-POS design includes a parachute release system. See section 4.3.8 for payload deployment and electronics. This requirement will be verified at the FRR milestone following construction and testing of LOPSIDED-POS.

6.3 Budgeting and Timeline

6.3.1 Budget

Table 6-18 below details the budget for the 2020-2021 NASA Student Launch competition.

Table 6-18 2020-2021 NASA Student Launch Competition Budget

	Item	Quantity	Price per Unit	Item Total
Subscale Structure	Aerotech I435T-14A motor	2	$56.00	$112.00
	Aero Pack 38mm Retainer	1	$27.00	$27.00
	Motor Casing	1	$340.00	(Already own) $0.00
	38mm G12 Airframe, Motor Tube	1	$64.00	$64.00
	4" Phenolic Airframe, 3 Slots	1	$33.50	$33.50
	4" Phenolic Airframe	2	$26.00	$52.00
	4" Phenolic Coupler	4	$21.00	$84.00
	Plastic 4" 4:1 Ogive Nosecone	1	$23.00	$23.00
	Domestic Birch Plywood 1/8"x2x2	6	$14.82	$88.92
	Rail Buttons	4	$2.50	$10.00
	U-Bolts	4	$1.00	$4.00
	Blast Caps	4	$2.50	$10.00
	Terminal Blocks	3	$7.00	$21.00
	Paint	1	$100.00	$100.00
	Key Switches	2	$12.00	$24.00
	Subtotal:			**$541.42**
Full-Scale Structure	6" G12 Airframe, Full Length (60"), 3 Slots	1	$300.00	$300.00
	6" G12 Airframe, Half Length (30")	1	$114.00	$114.00
	3"/75mm G12 Motor Tube, 22" length	1	$37.00	$37.00
	6” G12 Coupler 14” Length	2	$70.00	$140.00
	6" G12 Coupler 12" Length	2	$66.00	$132.00
	6" Fiberglass 4:1 Ogive Fiberglass Nosecone	1	$149.95	$149.95
	Domestic Birch Plywood 1/8"x2x2	8	$14.82	(Already own) $0.00
	Aerotech 75/3840 Motor Case	1	$360.00	(Already own) $0.00
	75 mm Motor Retainer	1	$72.00	$72.00
	Rail Buttons	4	$2.50	(Already own) $0.00
	U-Bolts	4	$1.00	(Already own) $0.00
	Aerotech L1520T motor	2	$224.00	$448.00
	Aerotech 75mm Forward Seal Disk	1	$37.50	$37.50
	Blast Caps	4	$2.50	(Already own) $0.00
	Terminal Blocks	3	$7.00	$21.00
	Paint	1	$100.00	$10.00
	Key Switches	2	$12.00	$24.00
	Subtotal:			**$1,485.45**

Payload	Arducam Camera w/fisheye lens	4	$29.00	$116.00
	Rasberrry Pi multi-camera adapter board	1	$50.00	$50.00
	Rasberrry Pi model 3	1	$35.00	$35.00
	5V battery supply	1	$40.00	$40.00
	Accelerometer	1	$8.00	$8.00
	433 MHz Transmitter	1	$9.95	$9.95
	FFP FPC ribbon cable extension	2	$4.75	$9.50
	SDR Receiver USB stick	1	$22.50	$22.50
	Voltage Converter with USB	1	$7.59	$7.59
	200 mm T8 Lead Screw	4	$10.99	$43.96
	1" OD carbon fiber tube 24" long	4	$39.99	$159.96
	Stepper motor	4	$19.95	$79.80
	Aluminum sheet metal	1	$21.48	$21.48
	1/4" thick acrylic Sheet 24x48	1	$55.37	$55.37
	Arduino uno	1	$17.60	$17.60
	Accelerometer	1	$15.95	$15.95
	Stratologger CF Altimeter	2	$69.95	(Already Own) $0.00
	ARRD	1	$119	$119
	Threaded Rods	3	$6.88	$20.64
	U-bolt	1	$2.66	$2.66
	T-track	2	$33.50	$67.00
	Southco Latch	2	$62.50	$125.00
	Wheels	1	$10.59	$10.59
	Ball bearing	4	$12.96	$51.84
	Subtotal:			**$1,089.39**
Recovery and Avionics	Standoffs	1	$10.99	(Already own) $0.00
	Iris Ultra 120" Parachute	1	$541.97	(Already own) $0.00
	Iris Ultra Compact 60" Parachute	1	$241.88	$241.88
	Stainless Steel Quick Links	14	$1.97	(Already own) $0.00
	5/8 inch Kevlar Shock Cord (yards)	26.7	$6.35	(Already own) $0.00
	Black powder	1	$17.95	$17.95
	E-matches	1	$80.25	$80.25
	Shear Pins Pack of 40	1	$1.00	$1.00
	StratoLogger CF	2	$49.46	(Already Own) $0.00
	Classic Elliptical 18" Parachute	1	$57.17	(Already Own) $0.00
	6" Deployment Bag	1	$46.23	$46.23
	21" Nomex Cloth	1	$27.00	$27.00

	Eggfinder TX Transmitter	1	$70.00	(Already own) $0.00
	Eggfinder TX Reciever	1	$55.00	(Already own) $0.00
	Lipo battery for Eggfinder	1	$17.69	$17.69
	4" Deployment Bag	1	$43.00	(Already Own) $0.00
	13" Nomex Cloth	1	$16.00	$16.00
	3/8 inch threaded rod 2' length	3	$2.58	$7.74
	3/8 inch spacer	12	$1.30	$15.60
	3/8 inch locknuts	8	$0.19	$1.52
	3/8 inch washers	16	$0.16	$2.56
	Subtotal:			**$475.42**
Miscell.	Epoxy Resin	2	$86.71	$173.42
	Epoxy Hardener	2	$45.91	$91.82
	Nuts (box)	1	$5.50	$5.50
	Screws (box)	1	$5.00	$5.00
	Washers	1	$5.00	$5.00
	Wire	1	$13.00	$13.00
	Zip Ties	1	$11.00	$11.00
	3M Electrical Tape	4	$8.00	$32.00
	9V Batteries	2	$14.00	$28.00
	Wood Glue	2	$3.00	$6.00
	Rubber Bands	1	$5.00	$5.00
	Paper Towels	1	$25.00	$25.00
	Battery Connectors	3	$5.00	$15.00
	Shipping			$1,000.00
	Incidentals (replacement tools, hardware, safety equipment)			$1,500.00
	Subtotal:			**$2,915.74**
Travel	Student Hotel Rooms – 4 nights (# rooms)	4	$791.70	$3,166.80
	Mentor Hotel Rooms – 4 nights (# rooms)	3	$1,178.10	$3,534.30
	Van Rentals (# cars)	2	$198.00	$396.00
	Gas (Miles)	1144	$0.60	$686.40
	Subtotal:			**$7,783.50**
Promotion	T-Shirts	40	$14.00	$560.00
	Polos	30	$25.00	$750.00
	Stickers/Pens	500	$0.37	$185.00
	Banner	1	$250.00	$250.00
	Subtotal:			**$1,745.00**
Total Expenses:				**$16,035.92**

Figure 6-1 below shows a budget breakdown for the 2020-2021 competition cycle.

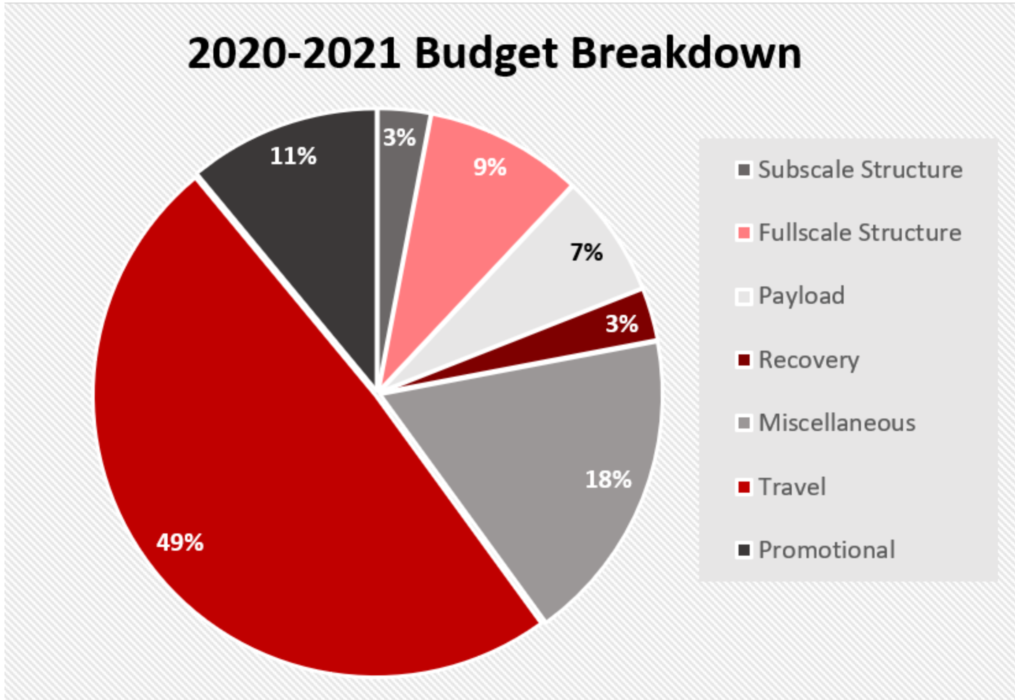


Figure 6-1 2020-2021 Budget Breakdown Chart

6.3.2 Funding Plan

HPRC receives all funds from multiple NC State University organization and North Carolina Space Grant (NCSG). Below is a breakdown of the team's current funding sources.

The NC State University Student Government Association's Appropriations Committee is responsible for distributing university funds to campus organizations. Each semester the application process consists a proposal, presentation, and an in-person interview. During the 2019-2020 academic year, HPRC received a total of $2,100: $1,030 in the fall semester and $1,070 in the spring semester. A request for $750 has been placed for the current fall semester and $1,350 will be requested in the spring semester, assuming that the Appropriations Committee budget will remain the same.

Educational and Technology Fee is an NC State University fund that allocates funding for academic enhancement through student organizations. Their funding of about $1,500 will primarily pay for the team's faculty advisors travel costs.

Student and mentor travel costs will be covered by NC State's College of Engineering Enhancement Funds. These funds come from a pool of money dedicated to supporting engineering extracurriculars at NC State. The total travel cost for University affiliated attendees comes to an estimated $5,500.

In addition to funding through NC State organizations, North Carolina Space Grant will provide a large amount of monetary support to the club. NCSG accepts funding proposals during the fall semester and teams can request up to $5,000 for participation in NASA competitions. NCSG has awarded the team the full amount requested. These funds have been made available for use as of November 2020.

In the past, HPRC has held sponsorships with Collins Aerospace, Jolly Logic, and more. The team is currently seeking out new sponsorships and reaching out to past sponsors. The team hopes to gain a couple thousand dollars more in funding from various companies.

These totals are listed in Table 6-19 below, which compares the projected costs and incoming grants for the 2020-2021 school year.

Table 6-19 Projected Funding for 2020-2021 Competition

Organization	Fall Semester Amount	Spring Amount	School Year Total
Engineering Technology Fee	-	-	$1,500.00
SGA Appropriations	$750.00	$1,350.00	$2,100.00
Sponsorships	-	-	$2,000
NC Space Grant	-	-	$5,000.00
College of Engineering	-	-	$5,500.00
Total Funding:			**$16,100.00**
Total Expenses:			**$16,035.92**
Difference:			**$64.08**

6.3.3 Project Timeline

Table 6-20 below shows a tabulated schedule for the 2021 Student Launch Project.

Table 6-20 2021 NASA Student Launch Schedule

Event/Task	Start Date	End Date/Submission
Request for Proposal Released	August 19, 2020	N/A
Proposal	August 19, 2020	September 21, 2020, 3 p.m. CDT
Preliminary Design Review (PDR) Q&A	October 07, 2020	N/A
PDR	October 07, 2020	November 02, 2020, 8 a.m. CST
PDR Team Teleconferences	November 03, 2020	November 22, 2020
Subscale Launch Opportunity	November 21, 2020	November 22, 2020
Critical Design Review (CDR) Q&A	November 23, 2020	N/A
CDR	November 23, 2020	January 04, 2021, 8 a.m. CST
CDR Team Teleconferences	January 07, 2021	January 26, 2021
Flight Readiness Review (FRR) Q&A	January 27, 2021	N/A
FRR	January 27, 2021	March 08, 2021, 8 a.m. CST

Full Scale Launch Opportunity	February 20, 2021	February 21, 2021
FRR Team Teleconferences	March 11, 2021	March 29, 2021
Launch Window for Teams Not Travelling to Launch Week	March 30, 2021	May 02, 2021
Post-Launch Assessment Review (PLAR) – Teams Not Travelling to Launch Week	March 30, 2021	14 Days After Launch
Launch Week Q&A	March 31, 2021	N/A
Team Travel to Huntsville, AL (if applicable)	April 07, 2021	N/A
Launch Readiness Review (LRR)	April 07, 2021	April 08, 2021
Launch Week Activities	April 08, 2021	April 09, 2021
Launch Day	April 10, 2021	N/A
Backup Launch Day	April 11, 2021	N/A
Post-Launch Assessment Review (PLAR) – Teams Travelling to Launch Week	April 12, 2021	April 27, 2021, 8 a.m. CDT

Figure 6-2 below show this same schedule in Program Evaluation and Review Technique (PERT), with additional details for each step.

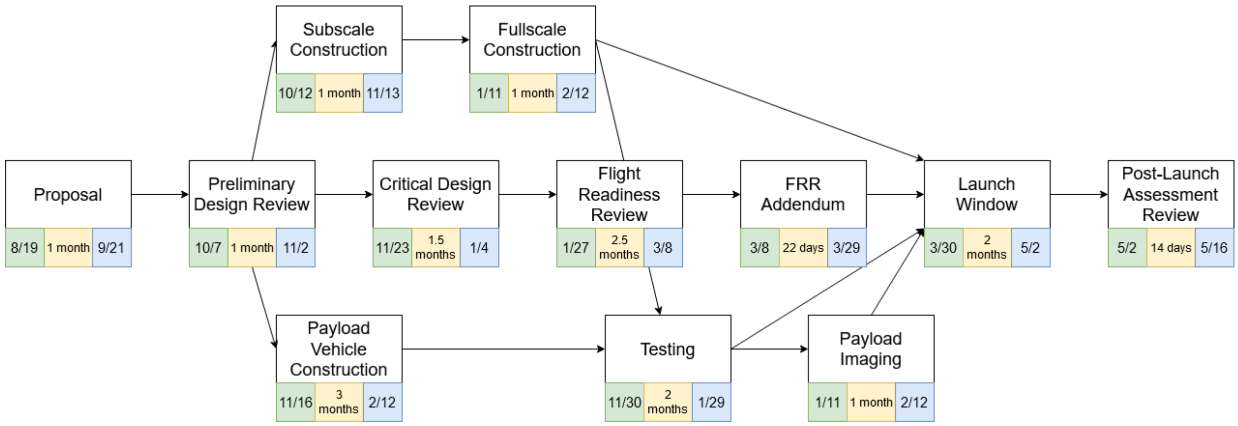


Figure 6-2 2021 Student Launch Project Timeline - PERT

Table 6-21 below shows the projected dates for completion of each step in the construction process along with the actual dates of completion. This comparison allows for a more accurate full scale build schedule to be developed

Table 6-21 Subscale Construction Plan Comparison

Task	Projected Completion	Actual Completion
Cut body tubes	October 14	October 15
Laser cut bulkheads and fins	October 15	October 12
Install couplers	October 16	October 16
Complete bulkhead and fin layups	October 19	October 14
Install bulkhead hardware	October 20	October 16
Install bulkheads, fins, and motor tube in fin can	October 23	October 22
Install payload bay hardware	October 25	November 5
Install nose cone bulkhead	October 26	October 16
Install rail buttons	October 27	October 23
Drill pressure ports	October 27	November 9
Drill altimeter switch holes	October 27	November 2
Prepare airframe for paint	October 29	November 10
Paint airframe	November 1	November 19
Write checklists	November 1	November 12
Conduct ejection demonstration	November 2	November 13
Practice assembly checklists	November 5	November 20
Launch subscale	November 21	November 21

As seen in Table 6-21, some tasks were completed close to their planned date, while others were significantly delayed, or completed out of order. Most delays in the early stages of construction (prior to airframe painting) were due to parts ordering and shipping. Some steps could not be completed while the team waited on parts to arrive, so other steps were completed earlier than planned to keep the construction as a whole on schedule. Tasks in the later stages of construction (beginning at airframe painting) were delayed due to team members encountering heavy workloads from courses with the approach of the end of the semester. Launch vehicle construction was intentionally scheduled with a few weeks of buffer for this very reason, and as such, the later tasks were delayed since they did not need to be completed as early as they were scheduled. Full scale construction will be conducted at the beginning of the Spring semester, so these delays are not likely to be encountered. Therefore, the team has deemed it acceptable that the full scale construction schedule has less of a buffer for delays than the subscale schedule.

The full scale construction window is two weeks shorter than that for subscale. However, due to experience from subscale construction, the team is confident that this window will be sufficient for complete construction of the launch vehicle and payload. Figure 6-3 shows the schedule for launch vehicle construction, with the first day of construction being January 19. Figure 6-4 shows the same information in Critical Path Analysis (CPA) form. The critical path, or the set of tasks that have the highest importance of being completed on time, is highlighted in red.

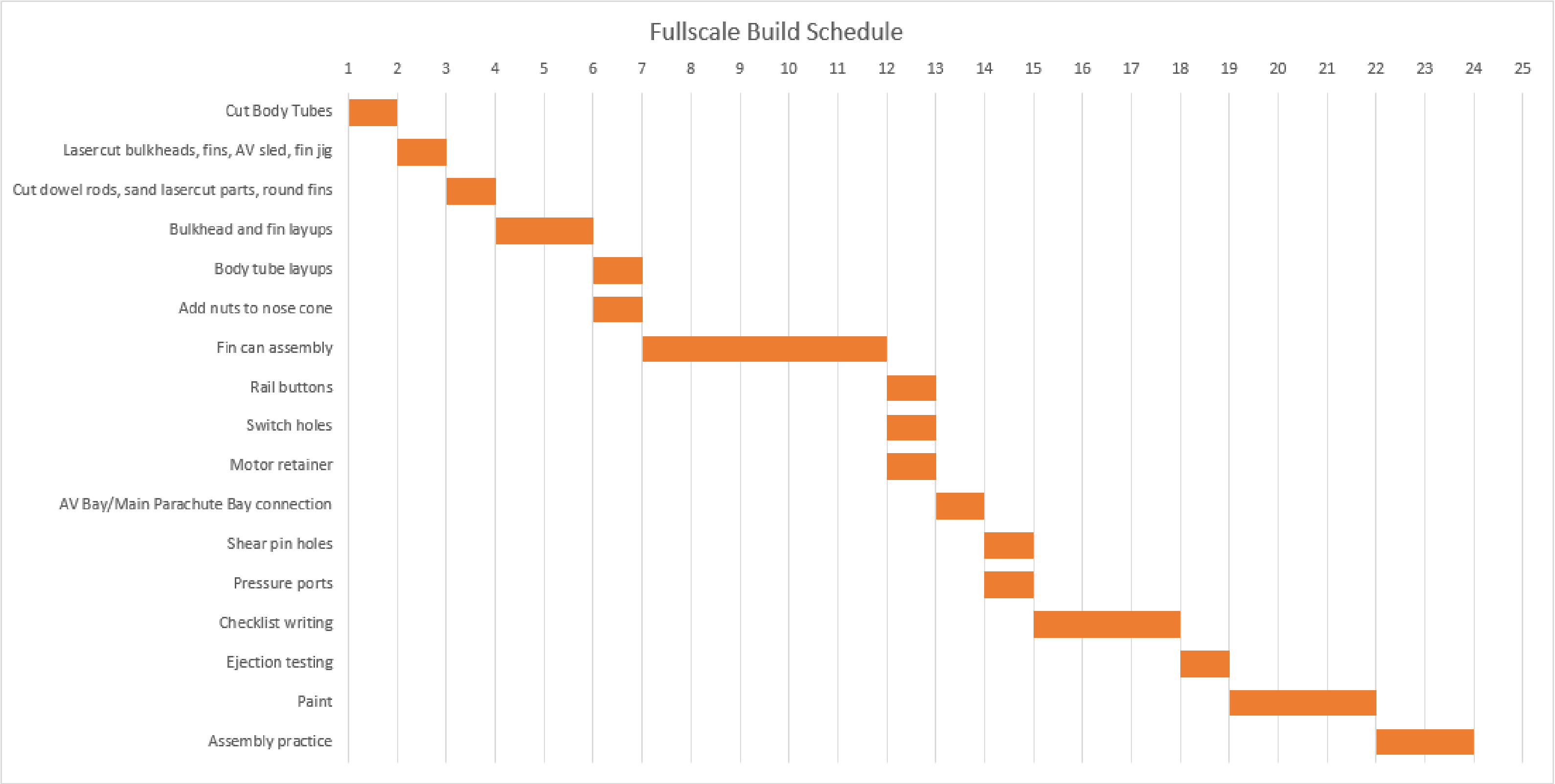


Figure 6-3 Full-Scale Build Schedule

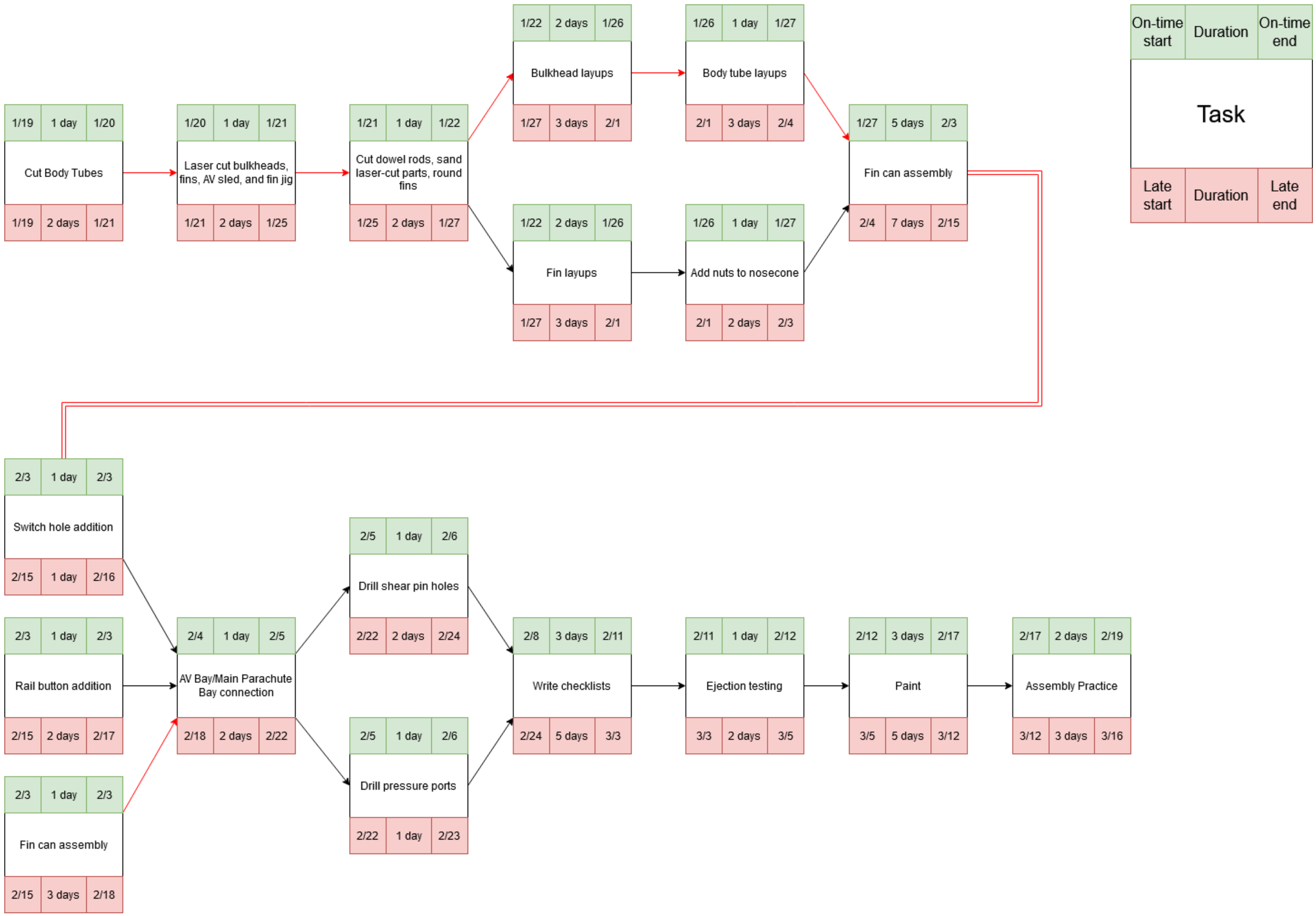


Figure 6-4 Launch Vehicle Construction Critical Path Analysis

Figure 6-5 below shows a similar CPA for the construction of the main competition payload.

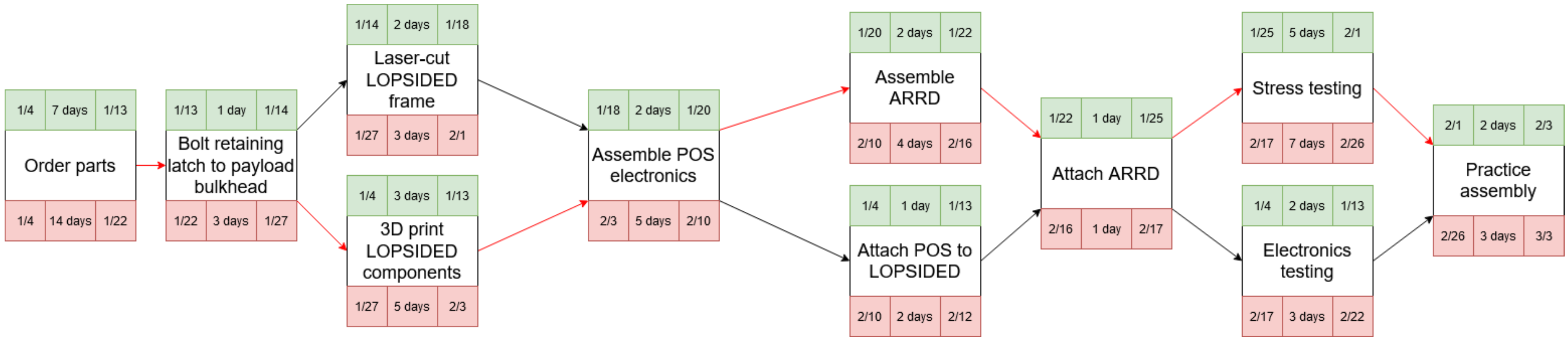


Figure 6-5 Payload Construction Critical Path Analysis