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**2020-2021**



**NOTRE DAME ROCKETRY TEAM**  
**FLIGHT READINESS REVIEW**

**NASA STUDENT LAUNCH 2021**

**PLANETARY LANDING SYSTEM AND APOGEE CONTROL SYSTEM**

Submitted March 8, 2021

365 Fitzpatrick Hall of Engineering  
Notre Dame, IN 46556

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# 1 Summary of FRR Report

<b>Team Name:</b>	Notre Dame Rocketry Team
<b>Location:</b>	365 Fitzpatrick Hall of Engineering Notre Dame, IN 46556
<b>Mentor:</b>	Dave Brunsting (NAR/TRA Level 3) e: dacsmemma@gmail.com p: (269)838-4275
<b>NAR/TRA Section:</b>	NAR: 85879 L3/TRA: 12369 L3
<b>Final Launch Location:</b>	18946 Avery Rd, Three Oaks, MI 49128
<b>Final Launch Dates:</b>	April 9th-11th & April 16th-18th
<b>Final Launch Club:</b>	Michiana Rocketry, NAR: 721, TRA: 078
<b>Final Launch Club Officer:</b>	Jerry Vida (NAR/TRA Level 3) e: jerry.vida@gmail.com
<b>Total Hours Logged:</b>	1627

## 1.1 Launch Vehicle Summary

**Table 1:** Summary of launch vehicle parameters

Target altitude (ft.)	Final motor choice	Total length (in.)	Outer diameter (in.)	Loaded mass (oz)	Rail size
5,300	Cesaroni L1395-P	133.25	6.170	795.0	12-foot 1515

**Table 2:** Summary of Recovery System

Parameter	Drogue	Main	Nose
Deployment Altitude	Apogee	575 ft	525 ft
Parachute Diameter (ft)	2	12	2
Parachute $C_d$	0.97	0.97	1.5

The Planetary Landing System (PLS) is this year's experimental payload, capable of jettisoning from the launch vehicle, landing, reorienting, and capturing and transmitting a 360 degree photo autonomously. The PLS will be retained within the payload bay during flight, and deployed at an altitude of 525 ft. Following deployment, it will descend under a parachute, land, and use three actively-controlled legs to orient within 5 degrees of the vertical (NASA Req. 4.3.3).

## 2 Changes Made Since CDR

A summary of all changes made to the launch vehicle criteria, payload criteria, and project plan criteria is provided in Table 3.

**Table 3:** Summary of changes made since CDR

Section	Change	Justification
<b>Changes Made to Vehicle Criteria</b>		
Launch Vehicle Ballast Section 3.1.1	Ballast added	To make up for lighter-than-expected airframe weight
Motor Retention Section 3.2.4	Centering rings shifted forward	To make room for the boattail shoulder
Motor Retention Section 3.3.2.4	Additional centering ring added	To fill the space between the motor mount tube and boattail aft opening
Apogee Control System Section 3.4.2	Mechanism Redesign	Ensure the mechanism central hub is constrained to rotational movement
Apogee Control System Section 3.4.2	Drag tabs placed in line with fins	Ensure ease of manufacturing and structural integrity of vehicle
<b>Changes Made to Recovery Subsystem</b>		
Attachment Hardware Section 3.5.2.2	3/16 in. quicklink replaced with 5/16 in. quicklink	No 3/16 in. quicklinks in inventory and new quicklink will only increase the robustness of the system
CRAS-M Section 3.5.2.3	O-ring was removed from design	Ensure that CRAS-M would slide in and out of the body tube
CRAS-S Section 3.5.2.4	Switches were changed from key-lock to pull-pin	Ensure that CRAS-S altimeters can be armed once vehicle is in upright position on launch pad
<b>Changes Made to Payload Criteria</b>		

Main Body Section 4.3.3	Addition of 3D-printed camera mounting box on the bottom side of the top bulkhead.	Ensure the cameras stayed in place, and could effectively take a 360 degree photo.
Payload Bay Section 4.6	Addition of spacer in bottom of payload bay	Ensure that PLS body would interface correctly with CRAS-S.
Nose Cone Section 3.2.1	Cut by an inch.	Compensate for additional spacer in the payload bay.
Data Transmission Section 4.3.3	Changed receiving antenna from a default spring antenna to a cross-dipole.	The new antenna provides better reception of the incoming signal.
<b>Changes Made to Project Plan</b>		
Vehicle Demonstration Launch Date Section 5	The vehicle demonstration flight was moved to February 27th.	This change was due to poor weather for the previous two launch dates.
Payload Demonstration Launch Date Section 5.9	Payload demonstration flight has been scheduled for March 13th.	The team was unable to complete the payload demonstration on February 27th.

## 2.1 CDR Action Items

The two action items from CDR were to

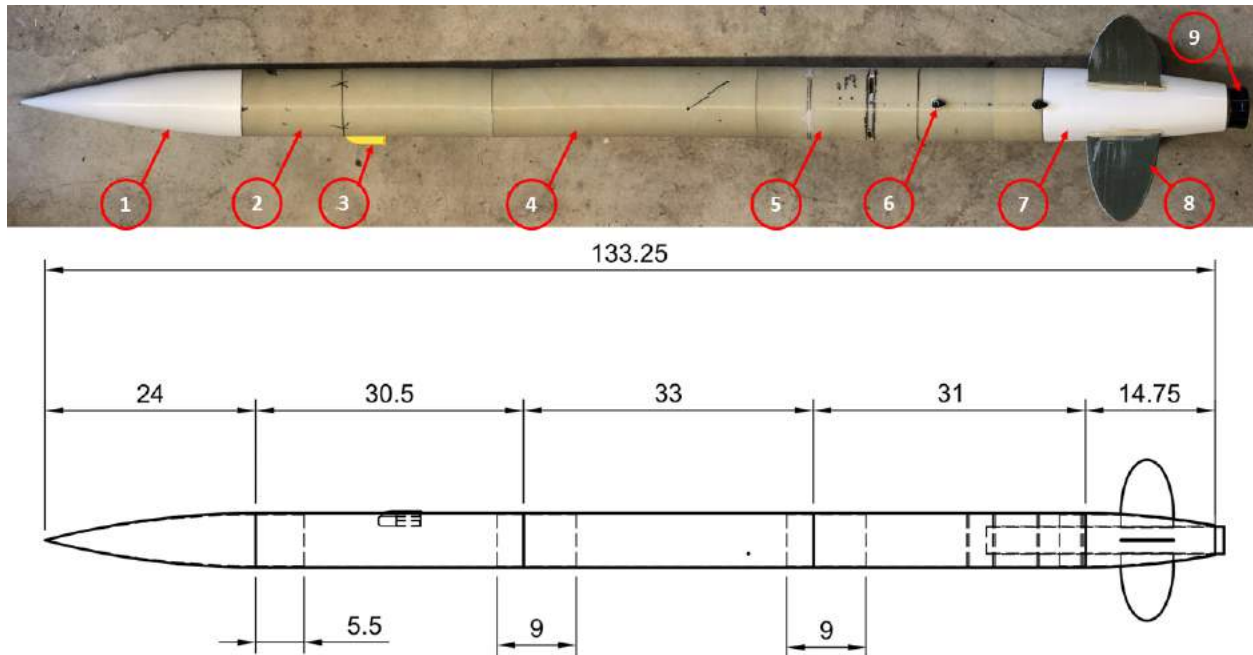
1. Ensure the RSO is made aware of the nosecone and payload recovery system, and
2. Thoroughly test the black powder calculations prior to landing.

The first was addressed by alerting the RSO to the design of the nose/payload jettison in advance of the launch and mitigating any of his concerns. For all future launches, the same protocol will be followed to notify the RSO of the design of the nose/payload jettison. The second was addressed by the completion of thorough ground testing, which is documented in Test [TR.3](#).

### 3 Design and Construction of Launch Vehicle

#### 3.1 Launch Vehicle Design Overview

An image of the fully constructed launch vehicle alongside its dimensioned CAD drawing is shown in Figure 1. The different visible components are numbered in the figure to correspond with Table 4.



**Figure 1:** Complete launch vehicle assembly with dimensions in inches

**Table 4:** Breakdown of launch vehicle components with materials and internal systems

Figure number	Component	Material	Contains
1	Nose cone	G10 Fiberglass	Nose parachute
2	Payload Tube	Kevlar and Fiberglass-Filament	CRAS-S, PLS, Bulkhead, Coupler
3	Camera Shroud	3D printed PLA	Mobius Actioncam
4	Recovery Tube	Kevlar and Fiberglass-Filament	CRAS-M, Main parachute, Drogue parachute, Coupler
5	Fin can	Kevlar and Fiberglass-Filament	ACS, Centering rings, partial motor mount tube
6	Rail buttons	Delrin-plastic	-
7	Boattail	G10 Fiberglass	Motor mount tube
8	Fins	G10 Fiberglass	-
9	Motor retainer	Aluminum	-

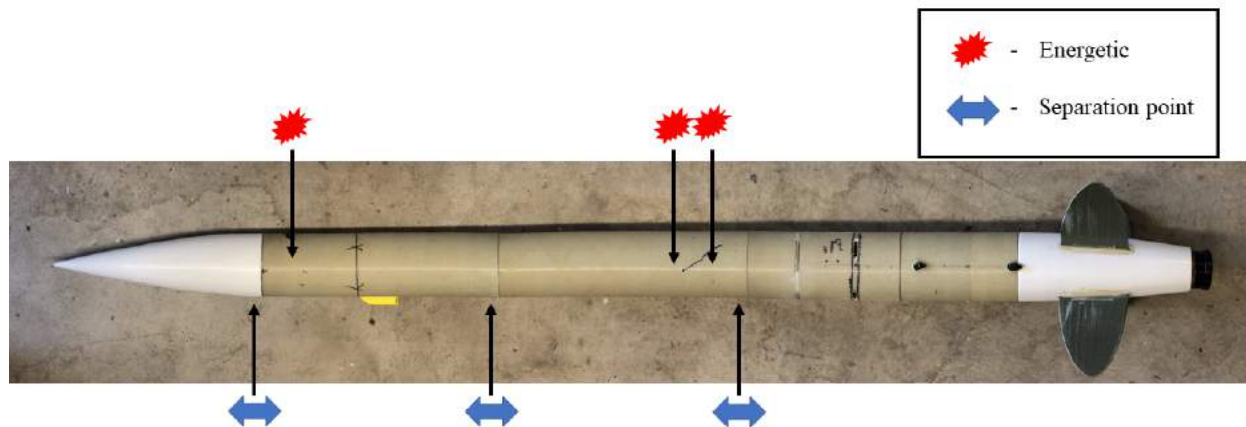
### 3.1.1 Changes from CDR

One change that occurred during construction was that the centering rings were shifted further forward to make room for the boattail shoulder, which was not accounted for previously. An additional small centering ring was added to the motor mount tube to attach it at the aft opening of the boattail. This step was found to be necessary during construction in order to ensure that the motor mount tube remained axially aligned with the boattail.

Many of the vehicle airframe components were found to be lighter than their listed weights online. The discrepancy was partially offset by an increase in recovery laundry weight, but the addition of ballast was still needed to ensure that the vehicle would not overshoot apogee excessively. 14 oz of ballast was added to the CRAS-M in the form of additional quicklinks, and 20 oz of ballast was added to the ACS in the form of enclosed steel rods.

### 3.1.2 Separation Points and Energetics

The locations of separation points and energetics did not change for the final launch vehicle design. There are a total of three separation points: nose cone & payload tube, payload tube & recovery tube, and recovery tube & fin can, each with one accompanying black powder energetic location. These are shown on the final launch vehicle assembly in Figure 2, and the measurements of the locations from the nose cone tip are provided in Table 5.



**Figure 2:** Separation points and energetics locations on the launch vehicle

**Table 5:** Locations of separation points and energetics as measured from the nose cone tip

Separating components	Separation point location (in.)	Black powder location (in.)
Nose cone & payload tube	24.0	29.0
Payload tube & Recovery tube	54.5	78.5
Recovery tube & Fin can	87.5	83.0

### 3.1.3 Mass Statement

sec:lv mass Table 6 shows the measured and allowable masses of the entire launch vehicle and its subsystems, while Table 7 shows the component-level measured masses of the empty airframe components.

**Table 6:** Overall Mass Statement

Component/Subsystem	Measured Mass (oz.)	Allowable Mass (oz.)
Airframe	297.3	303
Main Recovery System	145.2	160
Nose Recovery System	23.2	25
Payload	79.5	80
ACS	60.0	80
Motor	151.3	152
Ballast	36.7	N/A
<b>Total</b>	<b>793.7</b>	<b>800</b>

**Table 7:** Launch Vehicle Mass Statement

Component/Subsystem	Basic Mass Estimate (oz.)
Nose Cone	19.8
Payload Fairing	55.5
Payload Section Bulkhead	6.3
Payload Section Coupler	18.9
Camera Shroud	1.8
Recovery Tube	52.1
Recovery Tube Coupler	18.4
Fin Can Body Tube	52.6
Motor Mount	9.1
Centering Rings (x3)	8.6
Fins (x4)	20.1
Boattail	17.0
Epoxy	13.0
<b>Total</b>	<b>297.3</b>

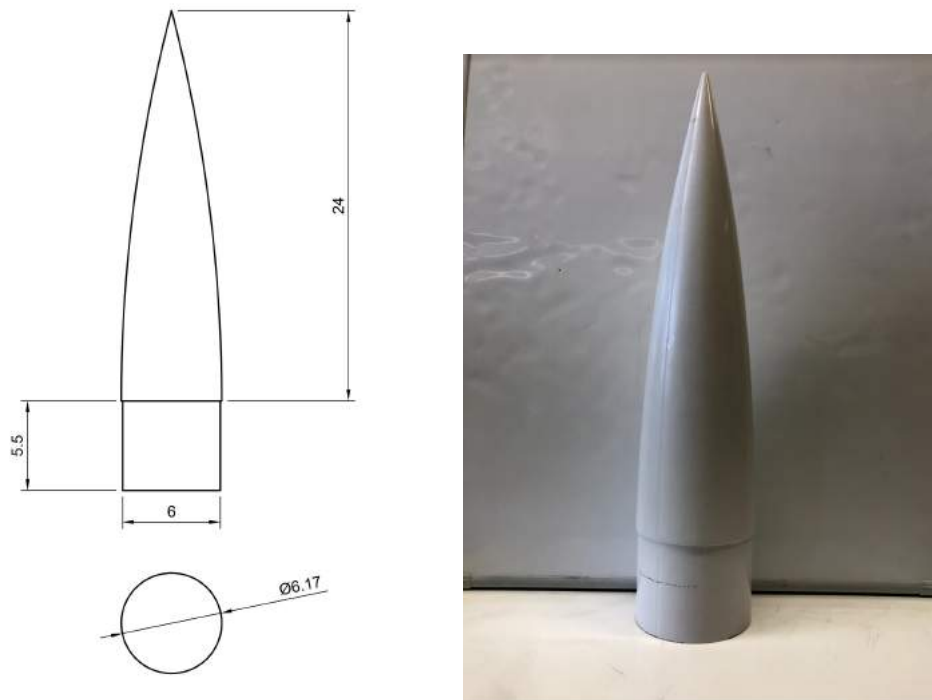
## 3.2 Structural Elements

### 3.2.1 Nose Cone

In order to allow for the PLS to jettison from the forward end of the payload tube, the nose cone detaches from the main vehicle and descends under its own parachute. The geometry of the nose cone is tangential ogive, chosen to provide the launch vehicle with a low-drag leading edge. The nose cone is the FNC-6.0 manufactured by Public Missiles LTD. Figure 3 depicts the nominal nose cone dimensions as well as the manufactured nose cone. Information about the dimensions, material properties, and weight are provided in Table 8.

**Table 8:** Characteristics of the nosecone

Characteristic	FNC-6.0 nose cone
Exposed length (in.)	24.0
Shoulder length (in.)	5.00
Shape parameter	Ogive
Material	G10 Fiberglass
Impact strength (ft-lbs/in)	12.0
Measured weight (oz)	19.8



**Figure 3:** Nose cone dimensions alongside the as-received nose cone

It is worth noting that the measured weight of the nose cone was significantly lower than the predicted weight of 28.0 oz from the manufacturer website. The combined effect of all weight differences was accounted for in the updated OpenRocket model, and ballast was added to ensure that performance predictions did not change drastically, as described in Section 3.6.1.

The impact strength of G10 Fiberglass is listed for reference because the impact loading at landing is the most critical loading scenario the nose cone is subjected to. The structural integrity of the nose cone under the impact stress of landing was verified in a drop test, outlined in Section 7.1.1.

### 3.2.2 Airframe Tubes

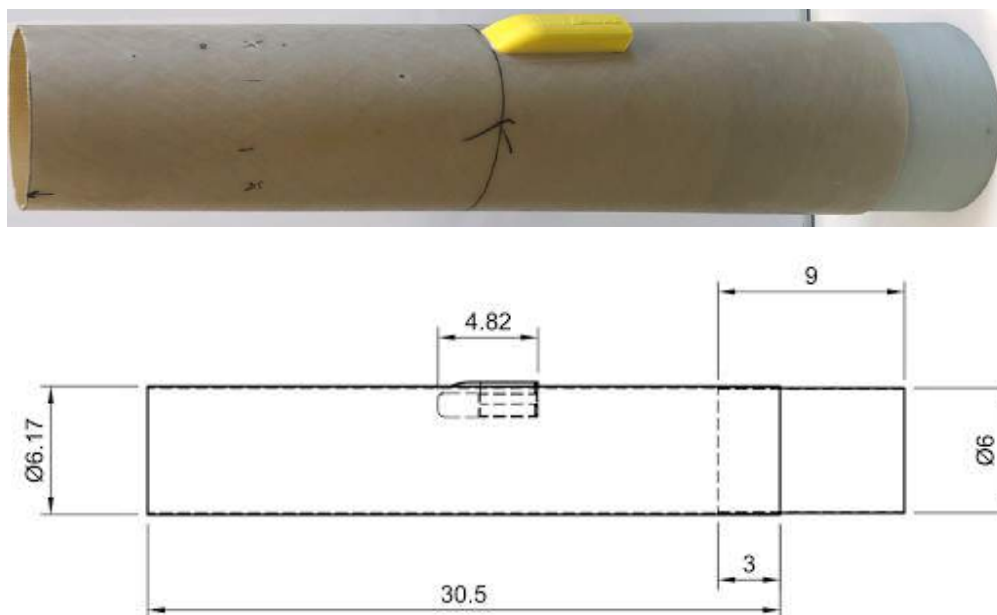
There are three airframe tubes used in the launch vehicle: the payload tube, recovery tube, and fin can. Each airframe tube is made of Kevlar and Filament-Fiberglass, supplied by Giant Leap Rocketry, with an outer diameter of 6.17in. and an inner diameter of 6.00 in.

The payload tube has a length of 30.5 in. and houses the PLS experimental payload, the Recovery CRAS-S subsystem, and the camera shroud. On the forward opening of the bay, the nose cone shoulder slides in and is secured with shear pins. On the aft end, the recovery tube is attached using a 9 in. G12 Fiberglass coupler. Table 9 gives the payload tube's expected weight,

measured weight, and the additional weight of the epoxy used in construction. Figure 4 compares the dimensioned CAD drawing with a picture of the physical payload tube assembly.

**Table 9:** Characteristics of the payload tube assembly

Characteristic	Payload tube assembly
Tube length (in.)	30.5
Expected weight (oz)	53.0
Measured weight (oz)	55.5
Coupler exposed length (in.)	6.00
Measured coupler weight (oz)	18.9
Coupler material	G12 Fiberglass
Epoxy weight (oz)	7.25
Total assembly weight (oz)	89.7

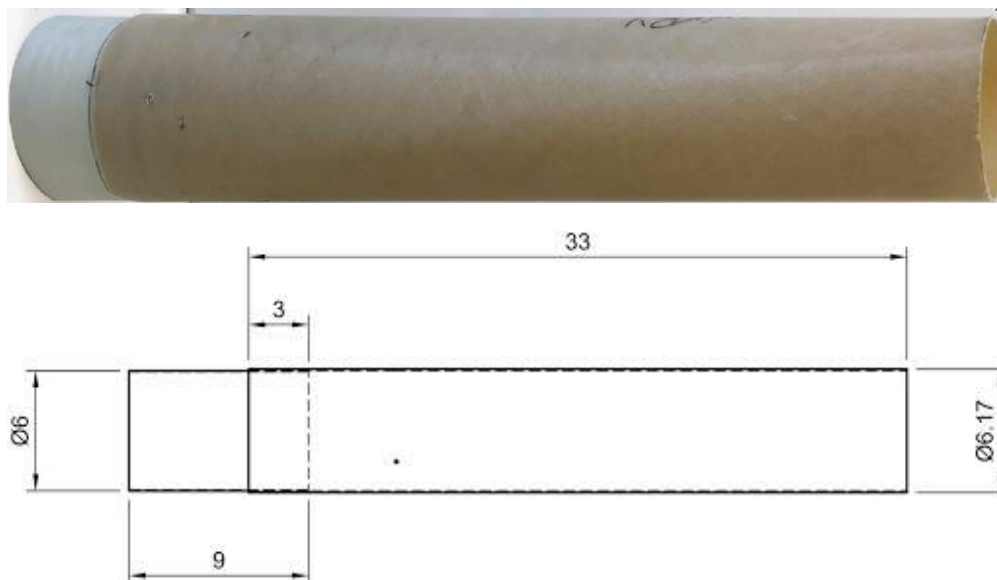


**Figure 4:** Constructed payload tube assembly and dimensions

The Recovery Tube has a length of 33.0 in., housing the CRAS-M recovery subsystem as well as the recovery main and drogue parachutes. The recovery tube connects to the payload tube and fin can via two 9 in. G12 Fiberglass couplers, which are epoxied into the fore and aft ends of the recovery tube. Table 10 lists the recovery tube's expected weight, actual weight, and epoxy weight used in construction. Figure 5 shows the completed recovery tube assembly as well as its dimensioned CAD drawing.

**Table 10:** Characteristics of the recovery tube assembly

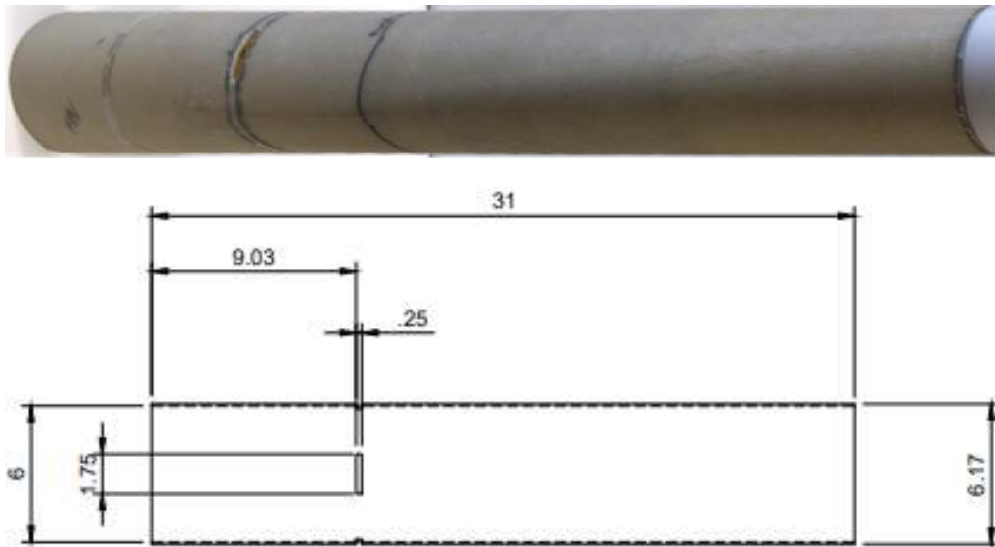
Characteristic	Recovery tube assembly
Tube length (in.)	33.0
Expected weight (oz)	57.3
Measured weight (oz)	52.1
Coupler exposed length (in.)	6.00
Measured coupler weight (oz)	18.4
Coupler material	G12 Fiberglass
Epoxy weight (oz)	0.7
Total assembly weight (oz)	71.2

**Figure 5:** Constructed recovery tube assembly and dimensions

The fin can, with a 31.0 in. length, contains the ACS subsystem, forward half of the motor retention system, and the rail buttons used to control the launch angle during launch. It features four rectangular slots aft of the CP location for the ACS tabs to deploy from. The fin can attaches to the recovery tube via the recovery tube's 9 in. G12 Fiberglass coupler, and to the boattail via the boattail's built-in shoulder. The fin can's expected weight, actual weight, and epoxy weight are given in Table 11. The total assembly weight includes the weight of the boattail, fins, and motor retention assembly, all of which are permanently epoxied to the fin can. Figure 6 displays a picture of the finished fin can and its dimensioned CAD drawing.

**Table 11:** Characteristics of the fin can

Characteristic	Fin can
Tube length (in.)	31.0
Expected weight (oz)	53.9
Measured weight (oz)	52.6
Epoxy weight (oz)	5.0
Total assembly weight (oz)	116.6

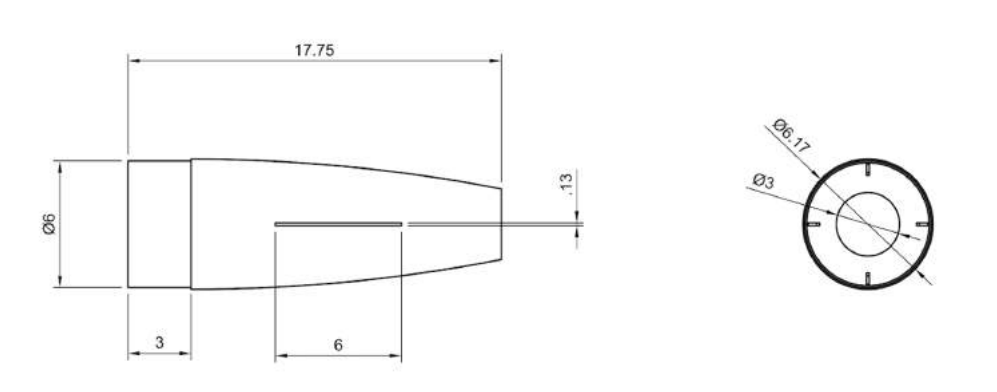
**Figure 6:** Constructed fin can and dimensions

### 3.2.3 Boattail

Attached to the aft end of the vehicle is the boattail, an ogive-shaped component which transitions from an outer diameter of 6.17 inches to 3.00 inches. The boattail used is the BTL-6.0.3.0, produced by Public Missiles Ltd. The boattail reduces the pressure drag on the launch vehicle by transitioning to a smaller diameter at the aft end, lessening the size of the low-pressure wake created by flow separation. Slotted into the boattail are the fins of the vehicle. A summary of the characteristics of the boattail is provided in Table 12, and a side-by-side comparison of a CAD drawing of the component and the actual component attached to the vehicle is seen in Figure 7.

**Table 12:** Characteristics of the boattail

Characteristic	Value
Exposed Length (in)	14.75
Shoulder Length (in)	3.00
Fore Diameter (in)	6.17
Aft Diameter (in)	3.00
Predicted weight (oz)	22
Actual weight (oz)	16.6
Material	G10 Fiberglass



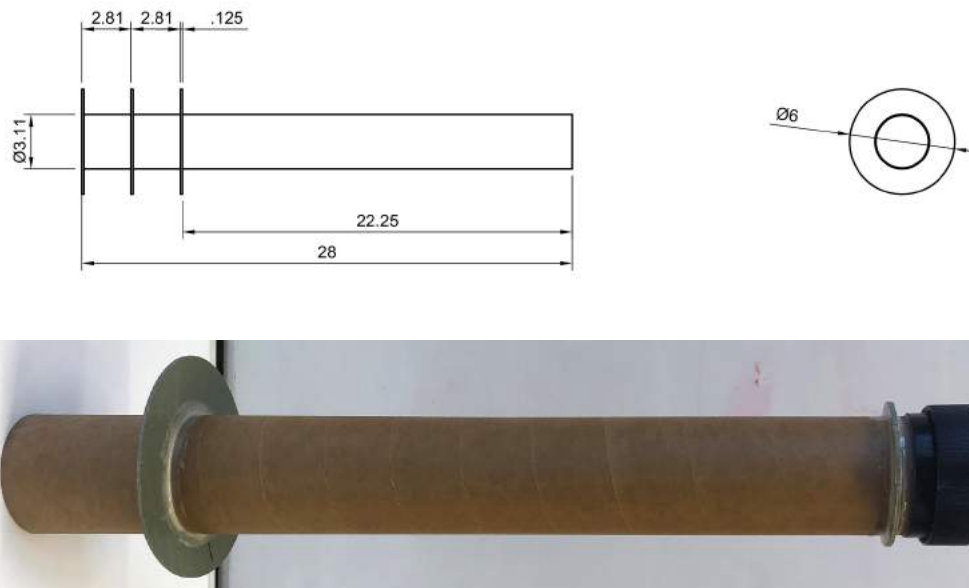
**Figure 7:** Constructed Boattail and dimensions in inches

### 3.2.4 Motor Retention Assembly

The motor retention assembly consists of the motor mount tube, three centering rings, and the motor retainer. This system secures the motor within the vehicle, and is necessary to center the thrust vector of the motor for stability during the vehicle's ascent. The phenolic motor mount tube, manufactured by Giant Leap Rocketry, has a 3 in. inner diameter, designed specifically for 75 mm motors such as the Cessaroni L1395. The tube is secured within the fin can by three 0.125 in. thick G10 fiberglass centering rings, which are epoxied to both tubes with Rocketpoxy. Finally, a threaded motor retainer cap is secured to the exposed end of the motor mount tube using J-B Weld, as shown in Figure 8. The weights of the individual components and the full assembly are provided in Table 13.

**Table 13:** Characteristics of the motor retention assembly

Component	Weight (oz)
Motor mount tube	9.10
Centering rings (3)	8.60
Motor retainer	3.50
<b>Total</b>	<b>21.2</b>



**Figure 8:** Constructed motor retention assembly and dimensions in inches

The assembly shown in the figure only includes one of the three centering rings. This is because the remaining two were attached after the assembly was epoxied into the fin can with

the boattail, as outlined in Section 3.3.2.4.

### 3.2.5 Fins

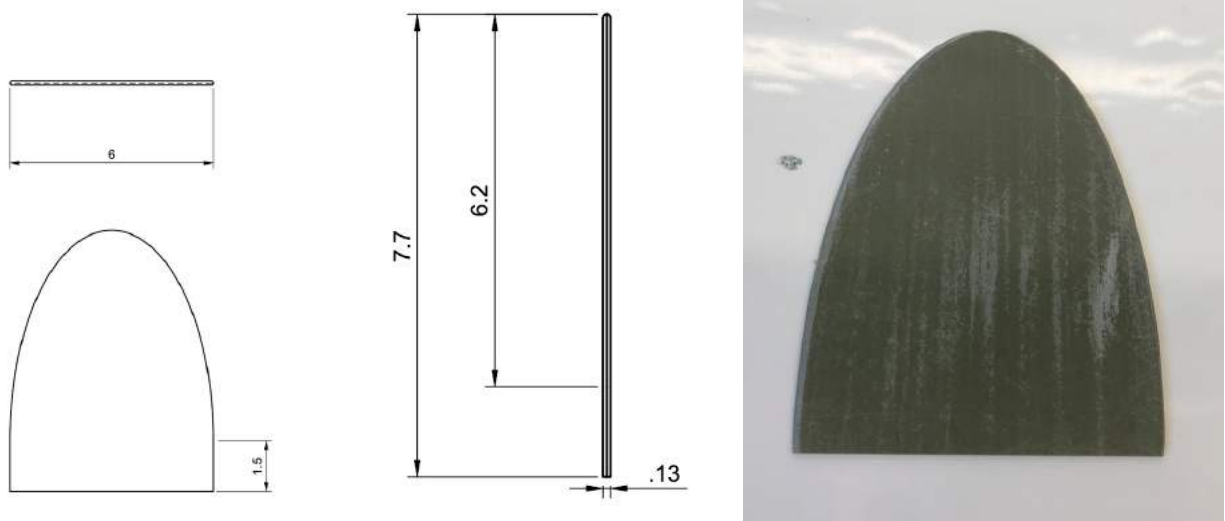
Fins are crucial to mission success because they stabilize the launch vehicle throughout the flight. Specifically, the fins were designed to ensure a static stability margin between 2.0 and 3.0 calibers throughout the flight (NASA Req 2.14, NDRT Req VD.7). From research conducted for PDR, elliptical fins constructed from G10 Fiberglass were determined to be the optimal planform and material for the vehicle design. An airfoil shape was added to the leading and trailing edge of the fins to decrease drag, as shown in Figure 9. The characteristics of the fin construction, including their measured weight, is shown in Table 14. Figure 10 compares the CAD drawing and physical pictures of the fins.



**Figure 9:** Airfoil cross-section of a fin with LE on the right and TE on the left

**Table 14:** Characteristics of as-built fins

Characteristic	Value
Number of fins	4
Cross-section	Airfoil
Material	G10 Fiberglass
Measured total weight (oz)	20.1



**Figure 10:** As-built fin alongside dimensions in inches

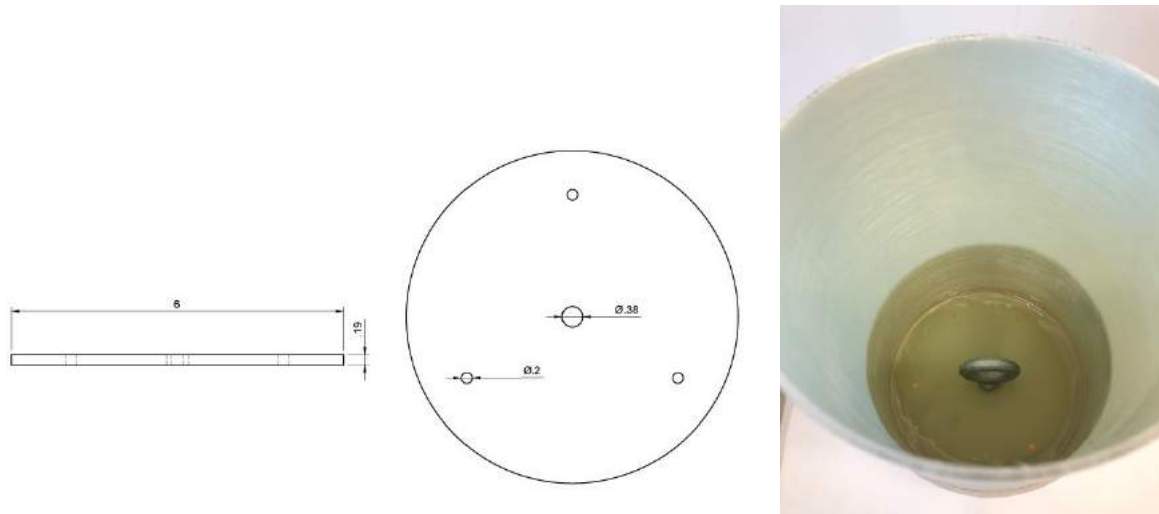
A fin impact test was successfully completed to test the structural integrity of the fins upon landing impact. The details of this test are provided in Test [TV.3](#).

### 3.2.6 Bulkhead

One bulkhead was fabricated and secured at the bottom of the payload tube at the edge of the coupler. This bulkhead adds structural integrity to the vehicle, and is attached to the main parachute shock cord via an eyebolt. Additionally, the bulkhead maintains pressure isolation between the two sections using an epoxy fillet, which also holds the bulkhead in place. The bulkhead bears the load caused by parachute deployment, and therefore a test article simulating it was strength tested to ensure the bulkhead and epoxy fillet do not fail in flight, as detailed in Test TV.1. The bulkhead was fabricated from G10 Fiberglass, with a thickness of 0.187 in. chosen to ensure a factor of safety of at least 2.0 during parachute deployment, as verified using FEA documented in CDR. The bulkhead characteristics are summarized in Table 15. The fabricated bulkhead is shown integrated within the payload tube in Figure 11.

**Table 15:** Characteristics of the bulkhead

Characteristics	Bulkhead
Material	G10 Fiberglass
Measured weight (oz)	6.3
Diameter (in)	6.0
Thickness (in)	.187



**Figure 11:** Bulkhead integrated within the payload tube alongside dimensions in inches

### 3.2.7 Camera Shroud

The camera shroud is a 3D printed PLA enclosure designed to hold a Mobius2 Actioncam during flights to record video footage of the various stages of the launch. The interior of the camera shroud was designed to be 0.5mm larger than the camera's length, width and height to accommodate some tolerance to ensure that the camera fit inside. The shroud was epoxied to the outer diameter diameter of the rocket's payload tube with the open end of the shroud facing in the aft direction. After initially epoxying the shroud to the payload tube, epoxy fillets were also added for increased strength and aerodynamic performance. After sliding the camera into the shroud, a small retaining wall fits into the gaps on the sides of the sides of the shroud to hold the camera in place during flight. The retaining wall is open in the center to provide a viewport for the lens of the camera. The placement of the camera shroud on the payload bay allows for video documentation of the ACS drag tabs to verify that they have successfully deployed during ascent, as well as both recovery deployment events. A side view of the 3D printed camera shroud epoxied to the payload bay can be seen in Figure 12.



**Figure 12:** Side view of the camera shroud epoxied to the payload tube

### 3.3 Project Milestones

#### 3.3.1 Flight Reliability Confidence

All launch vehicle components were constructed to their intended dimensions. FEA was conducted during CDR to ensure that all components would withstand the predicted loads in flight with a factor of safety of at least 2.0. The results of the FEA are provided in Table 16.

**Table 16:** FEA results for vehicle primary structures

Component	Material	Loading scenario	F.O.S.
Payload tube	Kevlar and Fiberglass-filament	Peak thrust	240
Recovery tube	Kevlar and Fiberglass-filament	Main parachute deployment	2.43
Fin can	Kevlar and Fiberglass-filament	Main parachute deployment	7.90
Fin flutter	G10 Fiberglass	Burnout velocity	15.6
Payload bulkhead	G10 Fiberglass	Main parachute deployment	2.55
Centering ring	G10 Fiberglass	Peak thrust	11.6

Additional structural testing was conducted for the payload bulkhead, fins, and nose cone, to further verify the structural integrity of the launch vehicle construction. Those tests are outlined in Section 7.1.1.

#### 3.3.2 Construction

The following sections outline the construction process, demonstrating that the launch vehicle is fully constructed. The dimensions and weights of the as-built assemblies do not

differ from those reported in the preceding structural element sections. The construction process in the order that it was conducted is summarized in Table 17.

**Table 17:** Launch Vehicle Construction Summary

Step	Description
1	Cut body tubes on the bandsaw
2	Cut fins, centering rings, and bulkhead on the Techno CNC router
3	Weigh each individual component before assembly
4	Epoxy coupler into recovery tube
5	Epoxy motor retainer threads to motor mount tube
6	Epoxy coupler and parachute bulkhead into payload tube
7	Sand fins to an airfoil shape
8	Epoxy aftmost centering ring to motor mount tube
9	Epoxy motor retention assembly and boattail into the fin can
10	Laser cut fin alignment jig
11	Epoxy the camera shroud to the payload tube
12	Epoxy the remaining two centering rings into the motor mount tube and fin can
13	Epoxy fins through the boattail slots using the fin alignment jig
14	Epoxy rail buttons to fin can

### 3.3.2.1 Bandsaw

The payload bay, recovery tube, and fin can were each cut to lengths of 30.5 in., 33 in., and 31 in. respectively out of kevlar and fiberglass-filament tubes on the DoAll bandsaw. In addition, the two fiberglass couplers were cut to a length of 9 in. on the bandsaw. The bandsaw used can be seen in Figure 13.



**Figure 13:** Alignment of the body tube to be cut on the bandsaw.

### 3.3.2.2 Techno Router

In order to cut the fins, centering rings, and bulkhead with the precision needed, the Techno CNC router was used. Four fins were cut from  $\frac{1}{8}$  in. G10 fiberglass. The CNC router configuration with the fiberglass can be seen in Figure 14. Three centering rings were cut from  $\frac{1}{8}$  in. G10 fiberglass. The bulkhead in the payload bay was cut out of  $\frac{3}{16}$  in. fiberglass. The CNC router was useful in accurately drilling the holes for hardware.



**Figure 14:** The  $\frac{1}{8}$  fiberglass clamped onto the CNC router bed.

### 3.3.2.3 Couplers and Bulkhead

The payload tube and recovery tube each include an integrated coupler for assembly at separation points, held together with epoxy. In each case, the inside of the body tube was sanded 3 in. deep to ensure that the epoxy would adhere to the surface. Then, epoxy was applied generously to the inner surface of the body tube, and the coupler was inserted 3 in. within, leaving 6 in. of exposed length. Finally, a popsicle stick was used to spread the excess epoxy into a fillet at the interface between the coupler edge and the body tube.

After the coupler was inserted into the payload tube, the bulkhead was gently slid into the tube until it met the inner coupler shoulder. Epoxy was then spread using a popsicle stick at the interface of the bulkhead and body tube in the shape of a fillet for additional strength. The final coupler and bulkhead assemblies within the payload tube and recovery tube are shown in Figure 15.



**Figure 15:** An assembled coupler (left) and the interior with the bulkhead attached (right)

#### 3.3.2.4 Motor Retention Assembly

The motor retention assembly consists of the motor mount tube, the motor retainer and cap, four centering rings, and the boattail, all attached to the fin can. First, the motor mount tube was cut to the appropriate length, 28 in. on the bandsaw. Then, the motor retainer cap was epoxied onto the end of the tube using J-B Weld for extra heat protection. This step was taken first in order to ensure that no epoxy would interfere with the alignment of the centering ring onto the tube. Figure 16 shows the retainer ring with and without the cap.



**Figure 16:** Motor retainer secured to the motor mount tube

Between every use of Rocketpoxy, the vehicle was left to rest for at least 6 hours in order to ensure that the epoxy dried and hardened completely. Next, the aftmost centering ring for was attached to the motor mount tube with Rocketpoxy. It was aligned using the boattail and leveled, both in order to ensure that it was completely perpendicular to the tube and to place it right at the edge of the boattail shoulder. An additional smaller centering ring was constructed from G10 Fiberglass and attached just below the motor retainer to align the motor mount tube with the aft opening of the boattail. Popsicle sticks were employed to make smooth fillets around the interfaces of the parts in order to make a stronger shape than a corner edge. Afterwards, the boattail was epoxied to the motor mount tube centering rings, and the fin can was epoxied onto the boattail shoulder. These two steps were executed at the same time in order to stabilize the boattail within the assembly.

Finally, the remaining two centering rings were epoxied into the assembly. They were first sanded so that they could slide into the body tube and onto the motor mount tube simultaneously, and next were epoxied onto the outside of the motor mount tube and inside of the fin can. These intersections were filleted as well. An image of the small centering ring attached at the aft opening of the boattail in the final assembly is shown in Figure 17.



**Figure 17:** Centering ring at the boattail aft opening in the finished motor retention assembly

### 3.3.2.5 Fin Alignment

After the fins were cut with the techno router, the fins edges were sanded into an airfoil shape by hand over a time period of four hours. Each fin was given a rounded leading edge and a pointed trailing edge to approximate an airfoil cross-section. This was done using wooden molds that sandpaper was wedged into.

Next, the fins were mounted to the motor mount through slots in the boattail using epoxy adhesive. The epoxy was applied to the edge of each fin to attach them to the motor mount, and an epoxy fillet was applied at the interface with the boattail to secure them in place. Excess epoxy was removed to minimize interference drag. Once all four fins were integrated with the boattail and motor mount, they were held in place with a custom laser-cut alignment jig that kept them at 90° from one another. In total, 5 oz of epoxy were used in the fin can/boattail/motor retention assembly. Figure 18 shows the fins being epoxied to the motor mount tube and boattail using the fin centering jig.



**Figure 18:** The epoxied fins held in place by the fin alignment jig

### 3.3.2.6 Rail Buttons

Rail buttons are used to keep the launch vehicle's trajectory straight in the beginning of its flight by interfacing with a rail that controls the launch angle. Two Delrin-plastic airfoiled rail buttons manufactured by Apogee Components were attached to the fin can. The rail buttons are located the maximum distance apart without interfering with the ACS subsystem, 13.25 in., to control the launch vehicle over a longer period of time and decrease the uncertainty in the launch angle during launch. The total weight, length, and outer diameter of the rail buttons can be found in Table 18.

**Table 18:** Characteristics of the rail buttons

Characteristic	Value
Measured weight (oz)	0.7
Measured Length (in)	1.260
Outer Diameter (in)	0.635

To attach the rail buttons, a string was tied to each end of the assembled launch vehicle and a line was drawn along the string where the rail buttons were to be connected. This was done

to ensure that the rail buttons were oriented parallel to the body of the launch vehicle, which is crucial for a controlled launch angle. The location for each rail button was marked, then the rail buttons were fastened to the fin can using screws and further secured with epoxy. Figure 19 shows a picture of the two rail buttons fully integrated into the launch vehicle.

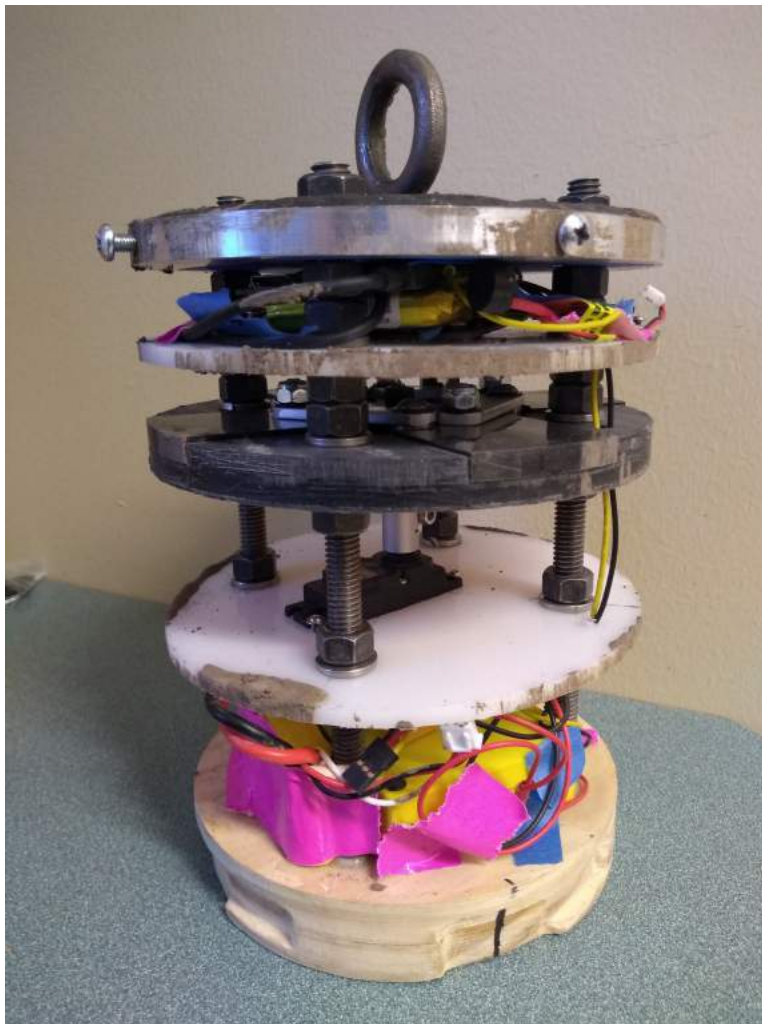


**Figure 19:** The two rail buttons used to control the launch angle fastened to the fin can

## 3.4 Apogee Control System

### 3.4.1 ACS Design Overview

The Apogee Control System (ACS) is the team's non-scoring payload, which aids the launch vehicle in successfully attaining a consistent apogee of 5300 ft (NDRT Req. [VE1](#)). In order to accomplish this objective, four drag surfaces, referred to as drag tabs, induce a controlled drag force on the launch vehicle during flight by extending and retracting from the body of the rocket, changing the effective surface area of the vehicle. This is accomplished with a closed-loop control system which relies on filtered flight data from sensors to make appropriate adjustments to the extension of the drag tabs. The flight data is filtered using a Kalman Filter written in Python in order to remove noise and provide a reasonable measure of velocity. Fourth-order Runge Kutta is used to predict apogee for the rocket, and this projection is used in a PID control algorithm to determine an appropriate drag tab extension. Figure 20 shows the completed system.

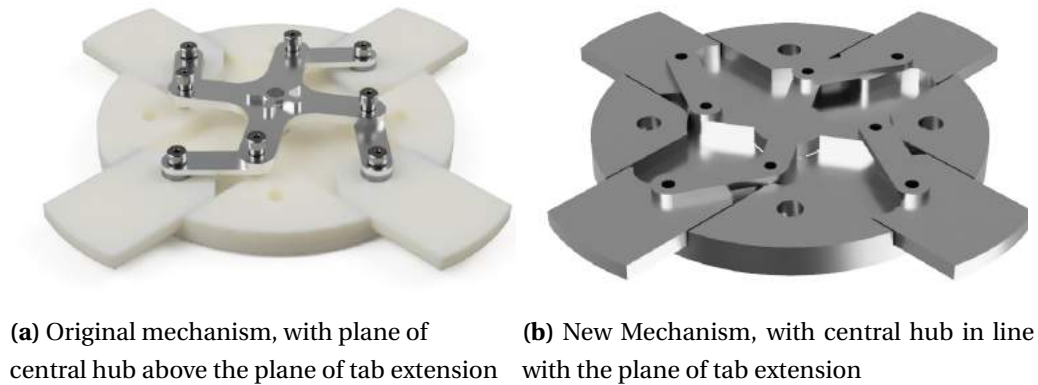


**Figure 20:** Fully Constructed ACS

### 3.4.2 Design Changes from CDR

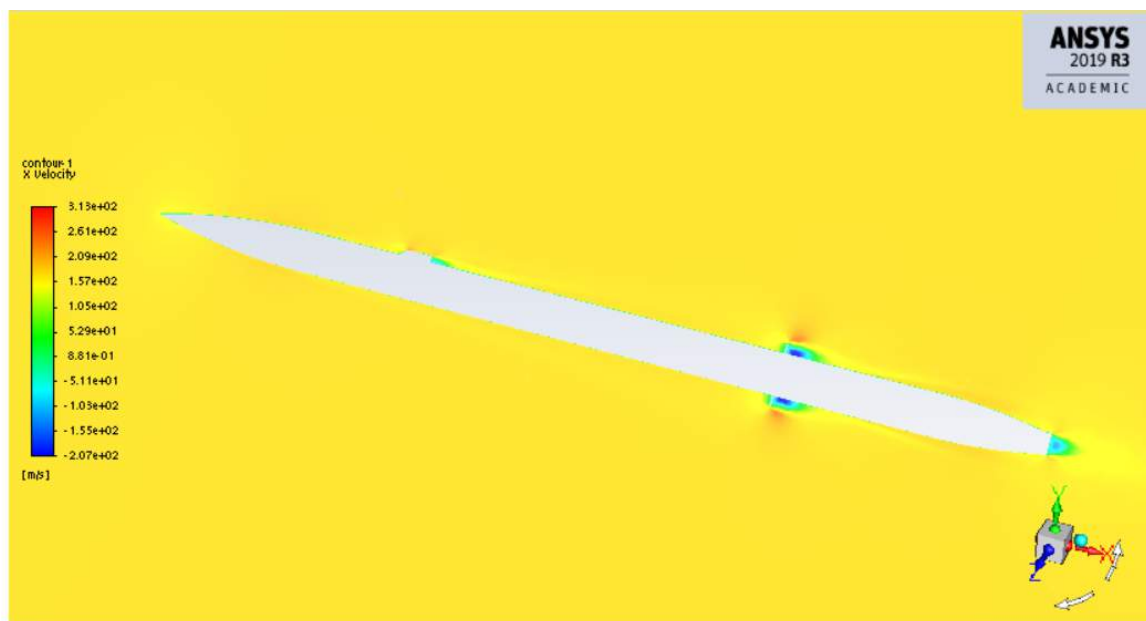
In order to facilitate ease of manufacturing and assembly, the design of the ACS mechanism was slightly altered, though the general premise of translating rotational motion from the servo motor to linear extension of the drag tab surfaces remains unchanged. The primary changes involved a reconfiguration of the drive shaft and central hub so that the rotation of the hub was in plane with the extension of the tabs. This was done to ensure that the central hub was restricted to move only rotationally, and not along the positive z axis. In making this change, the max extension of the tabs was lowered from 2" to 1.44". This lowers the max drag coefficient of the tabs, which then in turn changes the control code used to decelerate the launch vehicle from its max speed. The algorithm was updated in order to account for this discrepancy. A bearing was also integrated into the slotted deck to ensure that only rotational,

and not linear, motion was translated to the drag tabs. A comparison of the original design and design used for manufacturing is shown in Figure 21.



**Figure 21:** Original and Updated ACS drag tab mechanism

Additionally, in order to further facilitate ease of manufacturing and assembly, the ACS tabs are now lined up with the fins. The team has performed CFD to ensure that this change is safe and will not cause an unforeseen change in stability due to flow separation before the launch vehicle fins. Figure 22 shows that the flow separated at the drag tabs will reattach before reaching the fins.



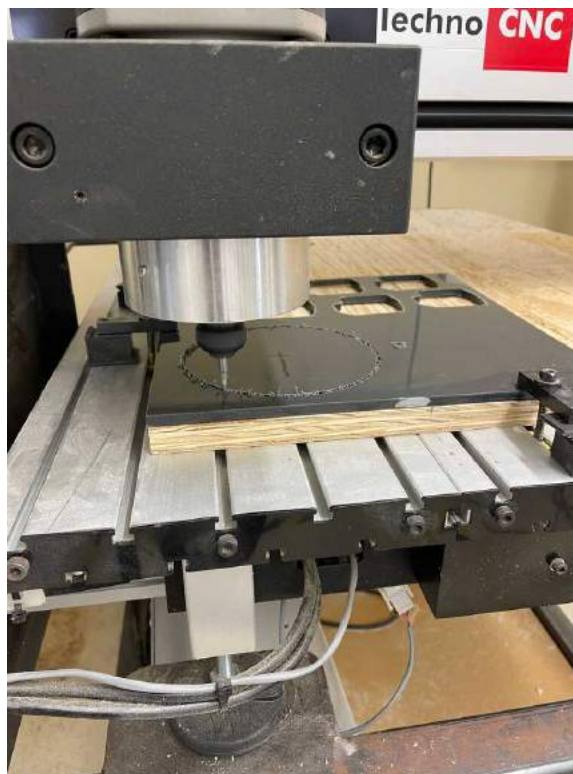
**Figure 22:** Drag Tab Flow Separation CFD. Note that the flow separated by the drag tabs reattaches before meeting the boattail.

### 3.4.3 Mechanical Design Construction

The construction of the ACS was conducted in three parts. First, the individual mechanism components were fabricated in the Notre Dame Student Fabrication Laboratory (SFL). After each component was manufactured, the system was assembled according to the design specifications. Finally, the system was tested, including testing the fit of the twist to lock mechanism and bulkheads, as well as testing the mechanism and servo motor assembly.

#### 3.4.3.1 Manufacturing

All manufacturing took place in the SFL using a Techno Router Automatic Mill, HAAS 2.5 Axis Mill, Lathe, and drill press. All circular decks, including the two HDPE plastic decks (which served to integrate the servo motor and electronics), as well as the Nylon slotted deck (which served to integrate the drag tabs) were manufactured using a computer aided manufacturing process, in which an NC code was generated to communicate with a Techno Router 2.5 axis mill. After manufacturing, each bulkhead was sanded in order to ensure smooth integration into the fin can. The drag tabs were manufactured out of nylon on the techno router using the same process. The manufacturing of the slotted deck is shown in Figure 23.



**Figure 23:** Manufacturing of the slotted deck on the Techno Router Automatic Mill

The twist to lock mechanism was also manufactured on the techno router, but in multiple units, which were then affixed with wood glue. Because of the limitations of a 2.5 axis mill, neither the twist to lock extrusion on the alignment ring nor the indentation on the wooden deck could be manufactured in one NC code. Therefore, both the alignment ring and wooden deck were split into two smaller decks, each with alignment holes. The alignment holes were used to ensure that the bottom and top halves of each component were aligned when affixing them to each other. The manufacturing of the twist to lock alignment ring is shown in Figure 24.



**Figure 24:** Manufacturing of the twist to lock mechanism alignment ring on the Techno Router

The aluminum bulkhead was manufactured using the same process as the HDPE and Nylon decks, but a different machine. Because the bulkhead must be able to transmit the load of the recovery system parachute to the body tube of the fin can, the decision was made to manufacture it out of aluminum, which must be milled using coolant. Therefore, the HAAS 2.5 axis mill was used to manufacture the aluminum bulkhead, as well as all other components which were specified to be made out of aluminum. These included the mechanism drive shaft, central hub, and linkages. The manufactured aluminum bulkhead is shown in Figure 25.



**Figure 25:** ACS Aluminum bulkhead.

Finally, the threaded rods were cut to four lengths of 8" from a 30" stock using a bandsaw. First, the lengths were measured and marked on the stock, then the stock was aligned with the bandsaw at a right angle. After cutting the stock to size, the ends were squared off using a lathe in order to ensure that the threaded rods would align perpendicularly to the wooden bulkhead to which they were mounted. A photo of the manufactured threaded rods mounted to the wooden bulkhead is shown in Figure 26.

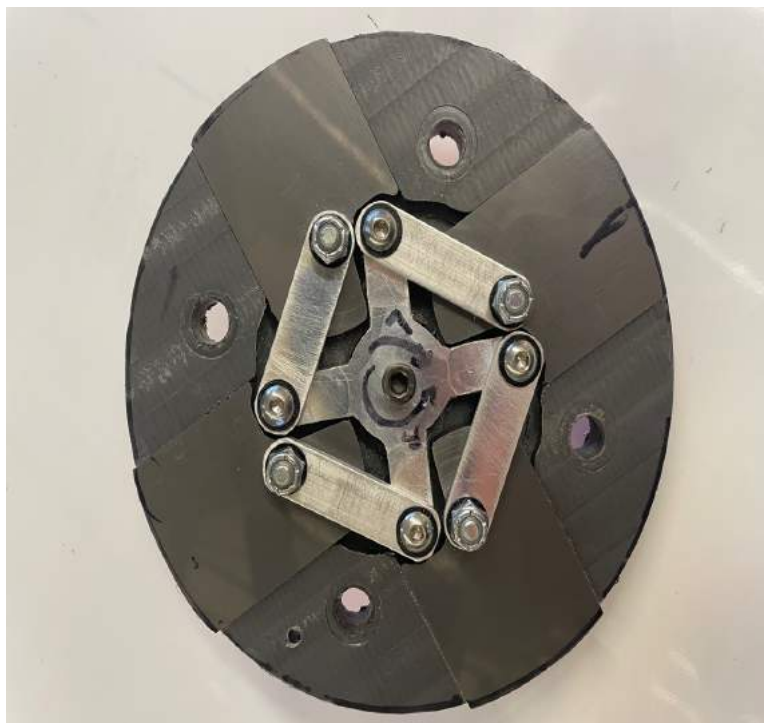


**Figure 26:** Threaded rods mounted to wooden bulkhead.

### 3.4.3.2 Assembly

The ACS system was assembled from base to top, beginning with screwing the threaded rods into the wooden base. In order to provide extra support, these rods were also affixed with RocketPoxy, which ensures that they will not become dislodged or rotate under any torsion applied to the aluminum bulkhead. Next, the servo motor was integrated into the servo motor deck and screwed in place. The servo motor deck was then slid onto the threaded rods and secured with nuts and locking washers on the top and bottom of the deck.

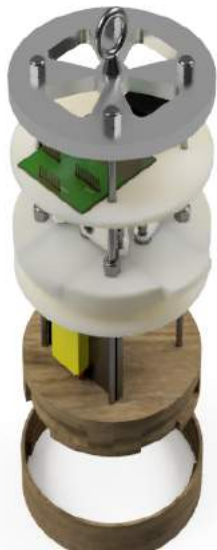
Next, the mechanism was assembled. First, the drive shaft was tightened onto the servo motor using a collar tightened with a screw. Then, a bearing was press fit into the slotted deck and the drive shaft was slid through the bearing for integration with the central hub on the other side. The central hub was manufactured with tight tolerancing such that a friction fit was sufficient to hold the hub to the drive shaft. However, for the sake of redundancy, a screw was used to hold the subassembly in place. The linkages were then attached to the central hub using cap screws and nylon washers to prevent excess aluminum-aluminum friction. Finally, the tabs were attached to the linkages using shoulder screws and locknuts, again using nylon washers to prevent excess friction. The assembled mechanism integrated into the slotted deck is shown in Figure 27.



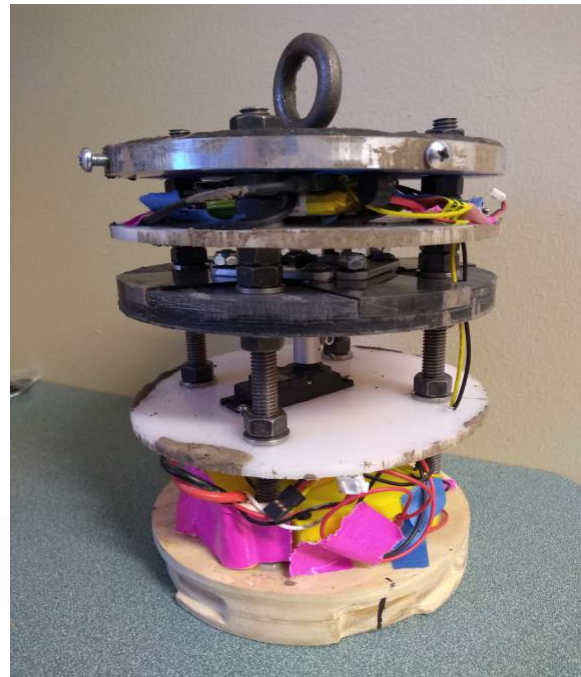
**Figure 27:** ACS Mechanism Assembly

The slotted deck was integrated into the system in the same manner as the servo deck, using nuts and locking washers on both the top and bottom of the deck. All electronics were integrated onto the electronics deck with wood screws, and the deck itself was integrated into

the system in the same manner as the other decks. Finally, an eyebolt was integrated into the center of the aluminum bulkhead using an oversized aluminum washer and lock nut, and the aluminum bulkhead was integrated into the system using nuts and locking washers. The fully integrated ACS is shown in Figure 28, along with a comparison to the 3D modeled version of the system.



(a) ACS Full System CAD



(b) ACS Full System

**Figure 28:** ACS Full System Comparison

The system itself was integrated into the body tube of the fin can using the twist to lock mechanism, as well as screws affixed to the aluminum bulkhead. First, the location of tab extension was marked in the fin can. A point 2 inches behind the center of pressure was chosen in order to increase stability. Then, the alignment ring was epoxied such that the tabs would sit flush with the location marked, and was allowed to cure for 24 hours. Following this, the system was integrated into the body tube, and the precise locations of each tab surface were marked in order to ensure that the twist to lock mechanism correctly lined up the tabs with the tab interfacing slots in the fin can.

Next, the tab interfacing slots were cut into the fin can. The edges were drilled using a power drill, and a hacksaw was used to cut the excess material out. Finally, a file and Dremel were used to smooth the cuts and ensure little friction in tab interfacing. The fin can tab interfaces are shown in Figure 29.

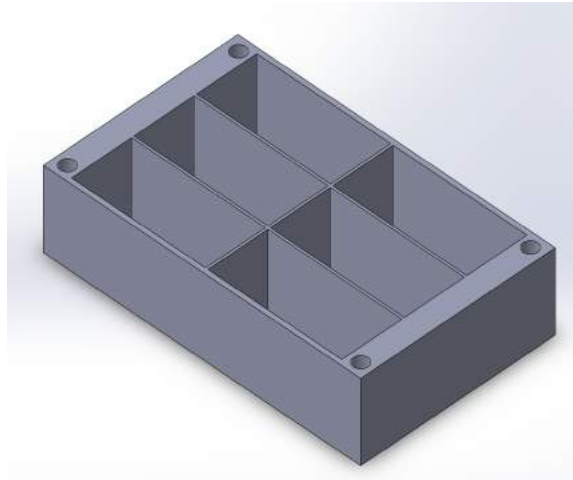


**Figure 29:** ACS Fin Can Tab Interfaces

Finally, the screw holes used for affixing the aluminum bulkhead to the fin can were drilled. Additionally, four air holes were drilled directly aft of the aluminum bulkhead to allow the altimeter to gather barometric pressure data.

After preparing all sections of the ACS system, it became apparent that the assembly was underweight. After reviewing the initial weight estimates, it was determined that 20 ounces needed to be added to the assembly to reach the design specifications. After more deliberation, it was determined that six segments of .75" diameter, 1.75" long, steel rods should be added as ballast. The plan was to create a box to house the six ballast segments, which would be placed on the bottom wooden bulkhead. The ballast box was designed so that the center of mass would be at the center of the bulkhead. The final design placed the six steel rods in a three-by-two configuration to fit in-between the threaded rods. Four holes were placed on the corners so that threaded inserts could be added to attach the lid of the box to the structure using bolts. A

CAD rendering of the main ballast box design is shown in Figure 30

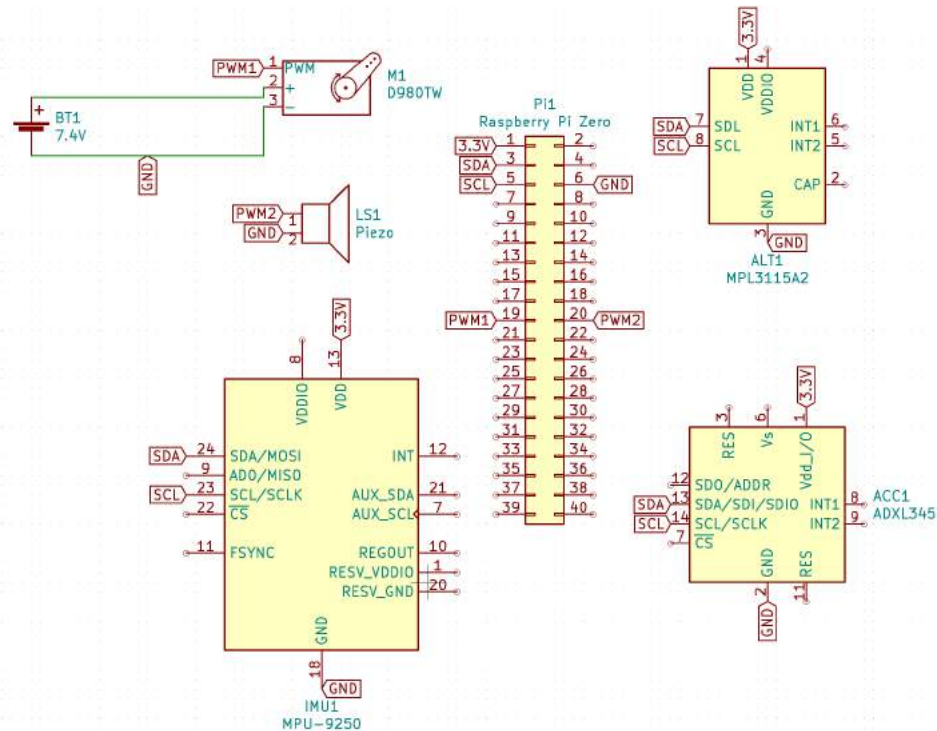


**Figure 30:** Ballast Box Design

Next, the ballast box and lid were printed using a MakerBot Replicator+ and then reprinted due to an error in the design's tolerances. Once the pieces were prepared, the threaded inserts were added into the four corner holes by heating them with a soldering iron. Finally, the ballast box was epoxied to the wooded bulkhead.

#### **3.4.4 Electrical Component Integration and Testing**

The ACS contains several electronic components which allow the system to sense the current state of the flight, determine an appropriate drag tab extension, and actuate the tabs. Figure 31 shows the full electrical structure of the ACS.



**Figure 31:** Final Electronic Schematic

The primary component of the ACS electronic system is the Raspberry Pi Zero W. The Pi acts as a microcontroller, reading in data from sensors and actuating the servo accordingly. The Pi is connected to the MPL3115A2 altimeter, ADXL345 accelerometer, and MPU9250/6500 inertial measurement unit (IMU) through a printed circuit board (PCB). Additionally, a piezo buzzer is connected to the Pi, which acts as a status indicator and gives the team an auditory confirmation that the system is working as expected.

Each of these components are powered by a Turnigy 3.7V, 2000mAh LiPo battery. This battery is connected to an Adafruit PowerBoost 500, which then powers the Raspberry Pi through a USB-microUSB cable. This ensures that the Raspberry Pi gets a sufficient and consistent supply of power during flight. Both the battery and the PowerBoost are attached to the electronics deck next to the PCB during flight.

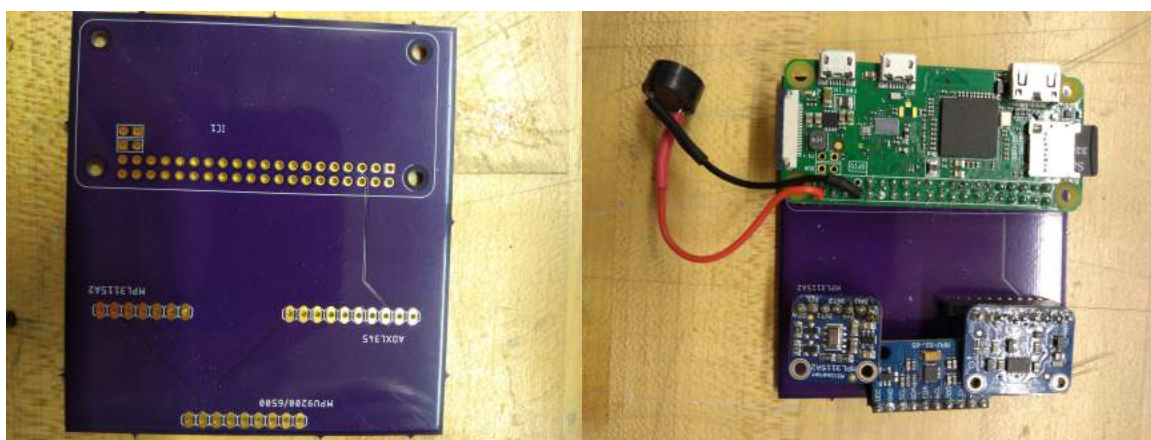
The final major component of the system is the HiTec D980TW servo motor. This motor is attached to its own HDPE deck aft of the mechanism, and is integrated into the mechanism. The servo is powered by a Zippy 7.4V 1300 mAh LiPo battery, which is attached to the underside of the servo deck. The servo is driven by a PWM signal sent from the Raspberry Pi along a wire. This wire is soldered to the servo wires on one side, and has a header pin soldered to the other side, allowing it to be detached from the Pi, but still providing a strong connection during flight. Additionally, a wire is soldered between the ground terminal of the servo and the ground pin

on the PowerBoost. This ensures that the entire system shares a common reference ground and prevents any issues with a floating ground, which the team has encountered in previous years.

The D980TW servo motor and its battery are isolated from the rest of the electronics, and both occupy opposite ends of the system. Additionally, a layer of copper tape isolates the two. The team has worked to create a Faraday cage and isolate the two circuits in order to ensure that the high current drawn by the servo does not distort any sensor readings.

#### 3.4.4.1 Printed Circuit Board

As stated in CDR, the team has designed a printed circuit board (PCB) to ensure that connections between the Pi and its sensors can be made safe, secure, and clean. The PCB was designed in Autodesk Eagle and sent to Oshpark for fabrication. Figure 32 (a) shows this board, while figure 32 (b) shows the board with all sensors and wires attached.



(a) Empty Board

(b) Components Attached

**Figure 32:** Printed Circuit Board

In order to integrate the electronic components onto the PCB, female header pins were soldered onto the PCB, while male header pins were soldered onto the Raspberry Pi, the ADXL345, the MPL3115A2, and the MPU9250/6500. One issue with the design of this board is that some sensors had a discrepancy between the number of needed pins and the number of pins actually provided. This discrepancy affected both the ADXL345 and the MPU9250/6500. The ADXL345 has nine pins, while the PCB provided ten pins for it. The issue with this is that the relevant pins are the 3V and GND pins, which occupy one end of the board, and SDA and SCL pins, which occupy the other end of the board. The team was able to circumvent this issue by soldering longer header pins to the SDA and SCL slots and bending them into position. This

provides the header pins a rigid structure, ensures that the pins do not short, and guarantees a solid connection that will not be dislodged during flight. A similar issue occurred with the MPU9250/6500. The board has 10 pins, but the PCB only provided 9. This issue was easier to fix because relative spacing was maintained, so the 10th pin was simply not connected to the PCB.

The entire PCB was affixed to the electronics deck with four wood screws which pass through pre-fabricated holes in the PCB. This ensures that the Pi and sensors remain securely affixed to the ACS during flight.

### 3.4.5 Control Algorithm Verification

The ACS is controlled by a Python program which is run on the Raspberry Pi. This program reads in data from sensors, filters that data with a Kalman filter, and then uses it to make adjustments to the extension of the drag tabs based on the current projected apogee of the launch vehicle. The program also performs miscellaneous tasks like logging data to disk and controlling a piezo buzzer to indicate that the system is functional. The behavior of this program is dictated by a state machine, which transitions between six stages based on the current state of the launch vehicle. The stages include: Armed, Launched, Burnout, Apogee, Overshoot, and Landed. The states and the transitions between them are encapsulated in the Figure 33.

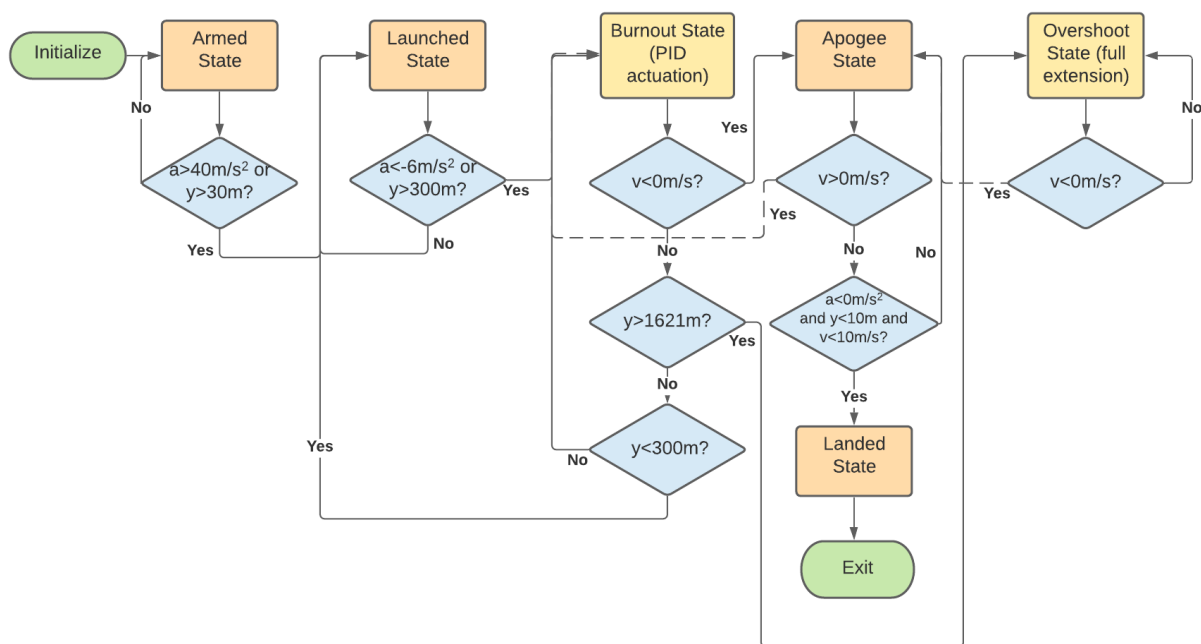
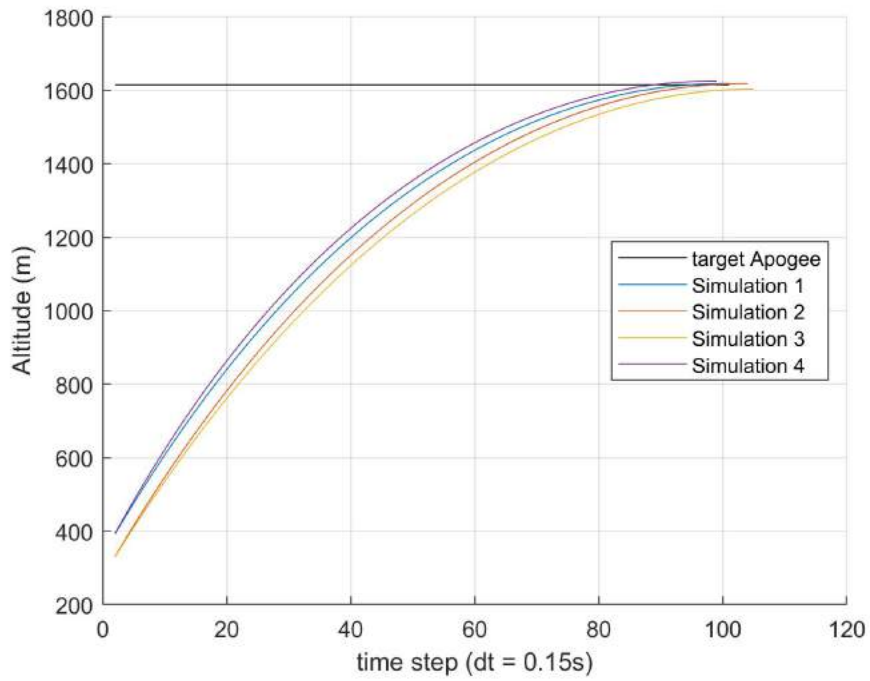


Figure 33: ACS State Machine

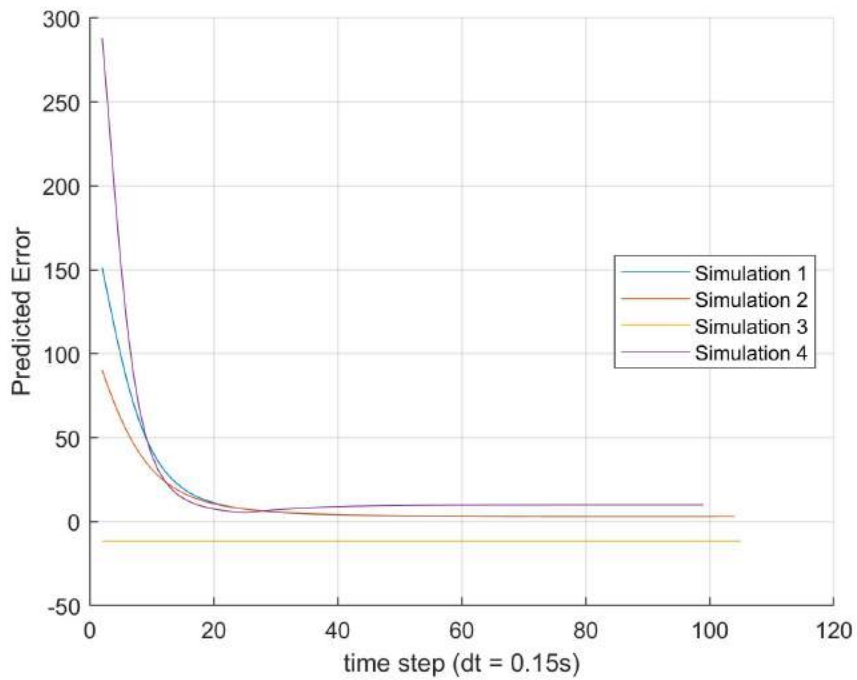
The state machine outlined in Figure 33 is that it contains several backwards transitions, which ensures that the system does not prematurely enter the burnout stage due to noisy sensor data and begin actuating the drag tabs at an inappropriate time. The control algorithm uses a Kalman filter to attenuate noise in the sensor data and perform sensor fusion, which produces an appropriate measure of vertical velocity given the height and vertical acceleration of the launch vehicle. Kalman gains have been fine-tuned based on data from the sub-scale and full-scale launches, as well as simulated test flights.

#### **3.4.5.1 Control Algorithm Changes**

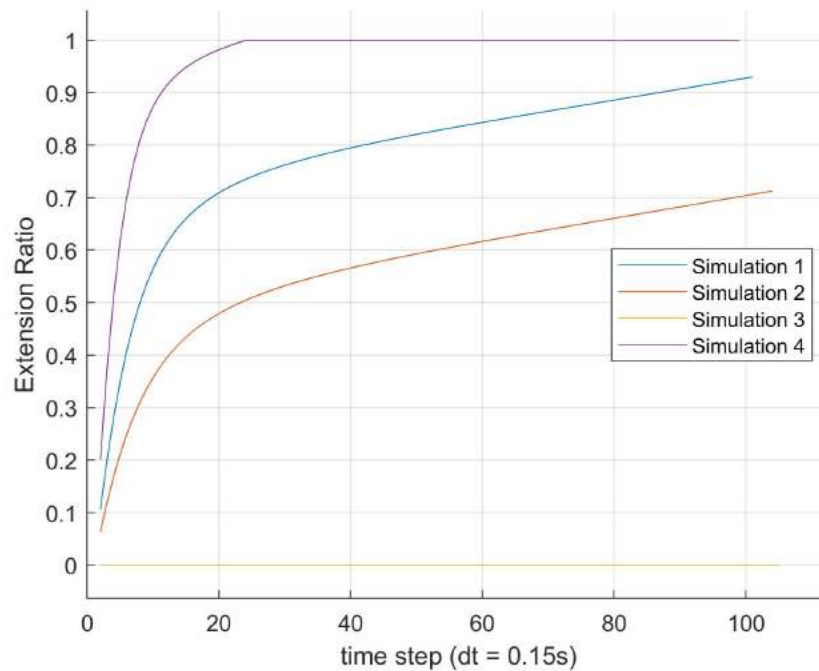
As outlined in CDR, the control algorithm was designed to combine model predictive elements with PID control and gain switching. Current sensor data would be fed into a Fourth Order Runge Kutta numerical integrator to find the predicted apogee under current conditions, and this predicted apogee would be subtracted from the target apogee to yield an error. This error would then be used with proportional, integral, and derivative control gains to calculate the change in extension for the tabs. These gains would change depending on the velocity regime of the rocket. However, when first tested with just a single, set proportional gain, simulations indicated that the simplified control structure would be sufficient when coupled with the model predictive elements. Figures 34, 35, and 36 show the adjusted flight paths, predicted error, and tab extension with ACS intervention for several flights with varying burnout conditions.



**Figure 34:** Simulated flight paths with varying burnout conditions with ACS intervention.



**Figure 35:** Predicted error throughout flight for the simulated flights, corresponding to Figure 34.



**Figure 36:** Tab extension throughout flight for simulated flights, corresponding to Figure 34.

While the controls system seems highly effectual, it can only operate if the rocket's unaffected trajectory falls within a certain range. This can be seen in Simulation 3 in the above figures, where the rocket is going to undershoot apogee. Since the error is always negative, the tabs never extend.

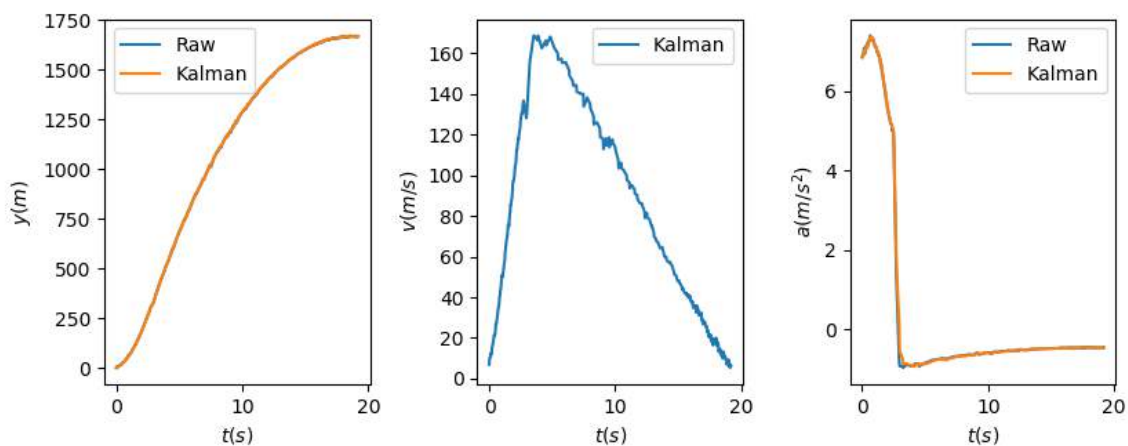
### 3.4.6 ACS Demonstration Flight

The Apogee Control System flew in its active state in the team's Vehicle Demonstration Flight. Drag tabs did not fully actuate as desired, but did actuate near the apogee of the launch vehicle's flight. This fulfils NASA Requirement 2.18.1.4, which states that any payload which causes a change to the external surface of the rocket must be active in the full-scale Vehicle Demonstration Flight.

Drag tabs did not actuate as desired during flight due to a bug in the underlying state machine managing the control system. As implemented on the day of flight, the state machine contained a reverse transition from the Burnout state, where tabs actuate, to the Launched state, where tabs do not actuate. This transition was based on acceleration data gathered by the ADXL345, but did not take into account differences in calibration between the ADXL345 accelerometer and the MPU 9250/6500 IMU. The result of this issue was that the system bounced between the Launched and Burnout state during ascent, and did not permanently

actuate the tabs. This backward transition has been pruned, which should prevent similar errors from occurring on future flights.

Despite this bug, the system worked largely as anticipated. Once the rocket went above its target apogee, the system transitioned into the Overshoot state and fully extended the tabs, which can be seen on video taken by the on-board camera. Additionally, the MPL3115A2 accelerometer and MPU9250/6500 functioned as anticipated and provided reasonable data. The ADXL345 was poorly calibrated, and its readings were ignored by the Kalman filter for this flight. Figure 37 shows the position, velocity, and acceleration of the launch vehicle, as measured by the ACS sensors and filtered by the Kalman filter. This figure shows how the Kalman filter is able to provide reasonable velocity data from the measured position and velocity data, while also smoothing out the position and velocity data.

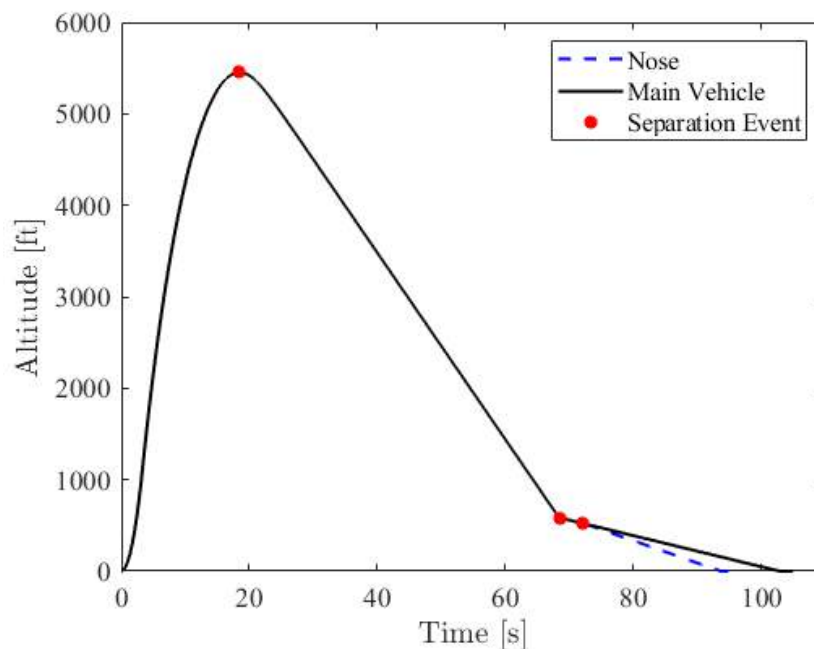


**Figure 37:** Vehicle Demonstration Flight Position, Velocity, and Acceleration ACS Data

## 3.5 Recovery Subsystem

### 3.5.1 Recovery System Design Overview

The recovery subsystem ensures that each section of the launch vehicle descends at a reliably reduced kinetic energy in accordance with NASA requirement 3.1. Deployment events will occur at apogee (drogue parachute), at 575 ft AGL (main parachute), and 525 ft (nose jettison) using black powder charges as the deployment mechanism in each case. Using a staged parachute system ensures that the vehicle's kinetic energy is reliably reduced while also ensuring that the drift radius and descent time remains within NASA's specifications (NASA Reqs. 3.1.1, 3.11). Figure 38 shows the flight and descent path of the launch vehicle with red dots demarcating separation events where the drogue, main, and nose cone parachutes will deploy.



**Figure 38:** General Vehicle Flight Path

The parachutes will be attached to the recovery bulkheads with shock cords, quick links, and eyebolts, and protected with fire-retardant Nomex. The same altimeters will be used to deploy the drogue and main parachute and will be located in the Compact Removable Avionics System-Main, or CRAS-M. The nose cone will jettison untethered from the launch vehicle and will have an independent recovery system, the Compact Removable Avionics System-Secondary, or CRAS-S. The CRAS-S will contain two altimeters which will deploy the nose cone parachute. Black powder ejection charges will be located in PVC charge wells on the CRAS-M and CRAS-S bulkheads to deploy all parachutes. To ensure redundancy and safety, the CRAS-M and CRAS-S will contain independently redundant electronics (NASA Req.3.4) which will not be connected to the payload circuitry and will remain entirely separate (NASA Req. 3.8).

### 3.5.2 Structural Elements

The following sections contain a thorough discussion of the robustness and flight readiness of the structural elements of the recovery system including the parachutes, attachment hardware, and internal structures.

#### 3.5.2.1 Parachutes

As stated in Section 3.5.1, the staged parachute system consists of a drogue parachute

deployed at apogee, a main parachute deployed at 575 ft AGL, and nose parachute, which deploys as the nose jettisons at 525 ft AGL. The parachute parameters are tabulated in Table 19. The descent speeds during the three stages of descent were calculated using the following

**Table 19:** Parachute Parameters

Parameter	Drogue	Pilot	Main	Nose
Diameter (ft)	2	2	12	2
$C_d$	0.97	1.5	0.97	1.5
Shape	Parabolic	Elliptical	Parabolic	Elliptical
Brand	Rocketman	FruityChutes	Rocketman	FruityChutes
Packing Volume (in <sup>3</sup> )	7.96	12.2	138.23	12.2
Mass (oz)	1.5	2.2	17	2.2
Shroud Lines	250 lb Nylon	220 lb Nylon	Nylon	220 lb Nylon
No. Shroud Lines	4	8	4	8

equation:

$$v = \sqrt{\frac{mg}{\frac{\pi}{8}\rho C_d D^2}}, \quad (1)$$

where  $v$  is the descent speed,  $m$  is the total mass slowed by the parachute,  $g$  is acceleration due to gravity,  $\rho$  is air density,  $C_d$  is the parachute's drag coefficient, and  $D$  is the parachute diameter. The resultant values are tabulated in Table 20, where the stages are denoted as follows:

1. Stage 1: descent under the drogue parachute
2. Stage 2: descent under the main parachute before nose jettison
3. Stage 3a: descent under the main parachute after nose deployment
4. Stage 3b: descent under the nose parachute after nose deployment

**Table 20:** Descent Velocities

Descent Stage	Velocity (ft/s)
1	110.8
2	18.47
3a	16.84
3b	21.91

The accelerations at the separation events was then calculated by assuming an instantaneous opening force on the parachute:

$$a = \frac{\frac{\pi}{8}\rho C_d D^2 v^2}{mg}, \quad (2)$$

where  $a$  is the acceleration of the vehicle under the parachute,  $\rho$  is the air density,  $C_d$  is the drag coefficient of the parachute that has just opened,  $D$  is the diameter of the parachute that has just opened,  $v$  is the descent velocity under the previous parachute,  $m$  is the mass under the parachute, and  $g$  is the acceleration due to gravity. The acceleration induced at each separation event is tabulated in Table 21. The velocity used to calculate the acceleration at

**Table 21:** Accelerations at Separation Events

Descent Stage	Acceleration (g)
Drogue Deployment	0.34
Main Deployment	36
Nose Jettison	0.59

drogue deployment was assuming the worst case scenario in which the deployment is delayed by two seconds, allowing the vehicle to free fall before the parachute opens. From these accelerations, the forces on different vehicle sections were calculated:

$$F = ma, \quad (3)$$

where  $F$  is the force on a vehicle section,  $m$  is the mass of that vehicle component, and  $a$  is the acceleration experienced by the vehicle at that time. The maximum forces experienced by each vehicle section are given in Table 22.

**Table 22:** Forces on Vehicle Components

Component	Time of Force	Forces (lbf)
Main Harness	Main Deployment	1602
Upper Recovery Attachment Hardware	Main Deployment	964
Lower Recovery/Fin Can Attachment Hardware	Main Deployment	446
Payload Bay Attachment Hardware	Main Deployment	479
Drogue Harness	Main Deployment	446

For protection from ejection gases and debris, the drogue parachute and recovery harness will be wrapped in a fire-retardant Nomex blanket chosen for its simplicity, low weight, and efficacy as demonstrated in previous years. The main parachute will also be stowed in a deployment bag, which offers increased protection from ejection gasses and aids unfettered and complete parachute deployment. The parachute folding and packing technique was tested in a drop test, as detailed in Test [TR.7](#)). The success of this test and the Demonstration Flight (Test [TR.4](#)) verifies that the recovery system parachutes will reliably reduce the vehicle's kinetic energy as it descends while remaining within drift and descent time requirements.

### 3.5.2.2 Attachment Hardware

Each of the parachutes described in Section 3.5.2.1 is connected to the vehicle by means of a recovery harness and various attachment hardware. The designed set-up for each parachute system is shown in Figure 39, and the as-built parachute systems are shown in Figure 40. As shown in these two figures, the parachute systems were constructed nearly as designed. The only difference in attachment hardware is that a 3/16 in. quicklink was replaced by a 5/16 in. quicklink in the nose parachute setup. This change was made due to a lack of 3/16 in. quicklinks in inventory and only increases the robustness of the system. Because of this, there is great confidence that recovery system attachment hardware will function as designed and simulated.

As shown in Figure 40, the 3/8 in. quicklinks attaching the recovery harness to the CRAS-M and CRAS-S eyebolts are tied to the harness via a bowline knot. A bowline knot was chosen over a conventional overhand knot due to the overhand knot's susceptibility to over-tightening, which produces a concentrated load on the cord and makes the knot difficult to untie. The parameters of the tubular nylon harness used in both the drogue and main parachute setup are shown in Table 23, and the parameters of the Kevlar harness used for the nose recovery is shown

**Table 23:** Drogue and Main Recovery Harness Parameters

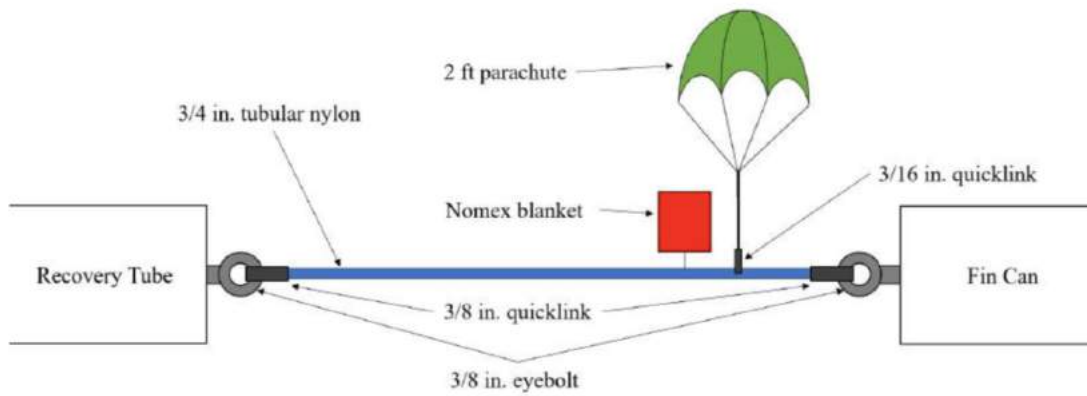
Parameter	Value
Width (in)	3/4
Length (ft)	50
Material	Tubular Nylon
Brand	OneBadHawk
Breaking Strength (lbs)	2300

in Table 24.

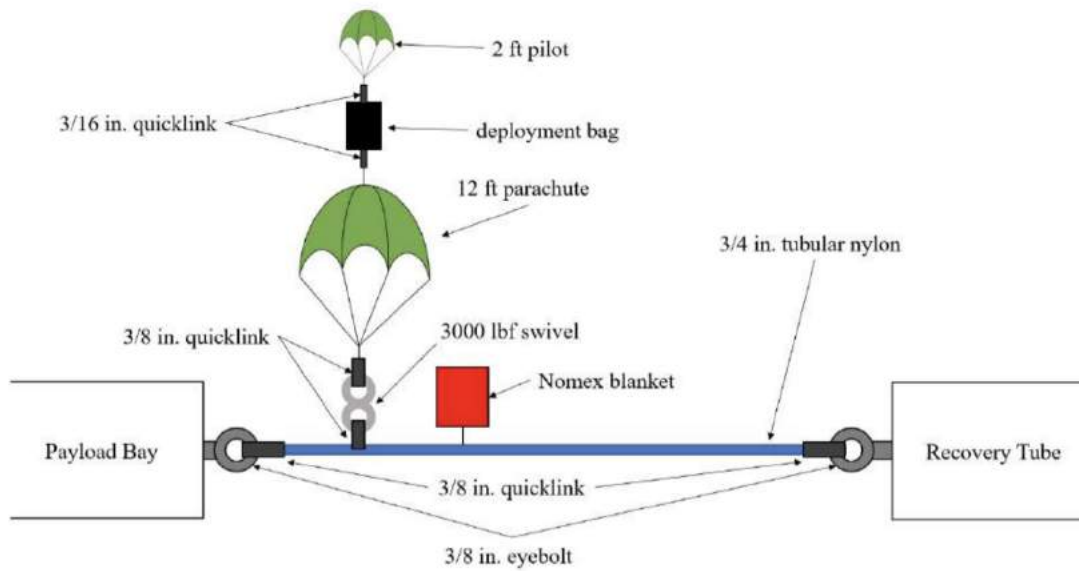
**Table 24:** Nose Recovery Harness Parameters

Parameter	Value
Width (in)	1/4
Length (ft)	25
Material	Kevlar
Brand	OneBadHawk
Breaking Strength (lbs)	1200

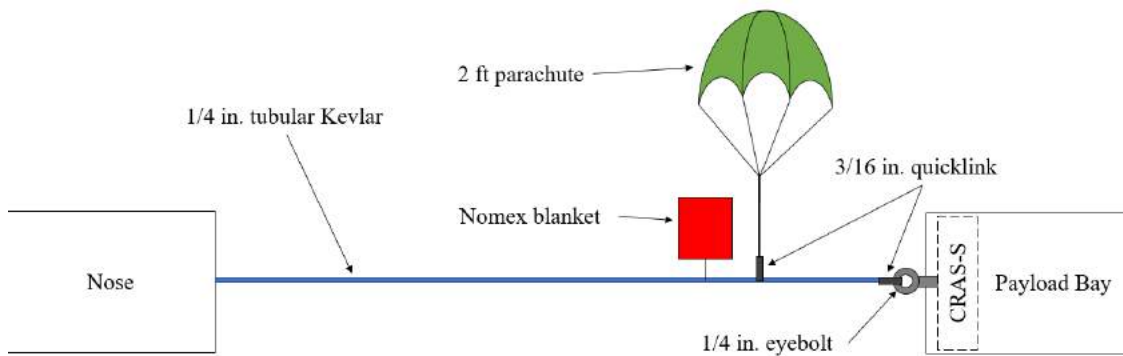
The recovery harnesses, eyebolts, and quicklinks are all shown in greater detail in Figure 41.



(a) Drogue Parachute Setup

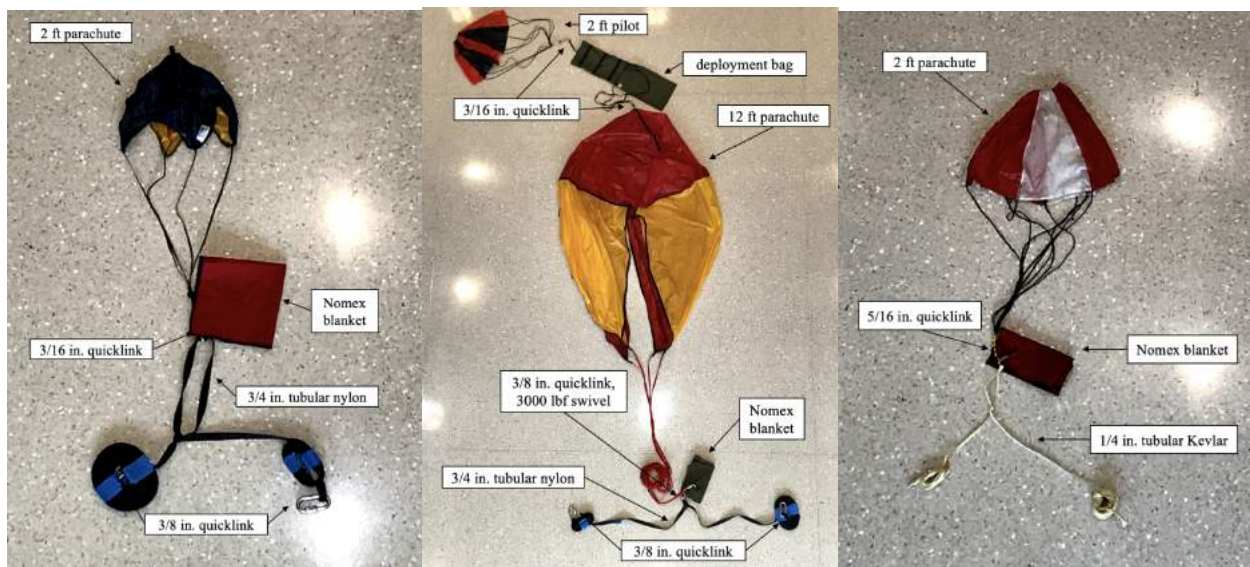


(b) Main Parachute Setup



(c) Nose Parachute Setup

**Figure 39: As-Designed Parachute Setups**



(a) Drogue Parachute Setup

(b) Main Parachute Setup

(c) Nose Parachute Setup

**Figure 40: As-Built Parachute Setups**



(a) Recovery Harness

(b) Eyebolts

(c) Quicklinks

(d) Swivel

**Figure 41: Recovery Attachment Hardware**

For each of the attachment pieces, a Factor of Safety was calculated using the largest load it experiences and the maximum load it can withstand. These values are tabulated in Table 25. Each of these Factors of Safety is at least 1.4, satisfying NDRT Req RE7. As stated in Section 3.5.2.1, the parachute systems were successfully tested in a drop test (Test TR.7), the ground test (Test TR.3), and in the demonstration flight (Test TR.4). Because of the consistency between the designed system and the as-built system, as well as the robustness of simulations, analysis, and testing, the team is confident the recovery system attachment hardware is fully capable of performing as expected during launch.

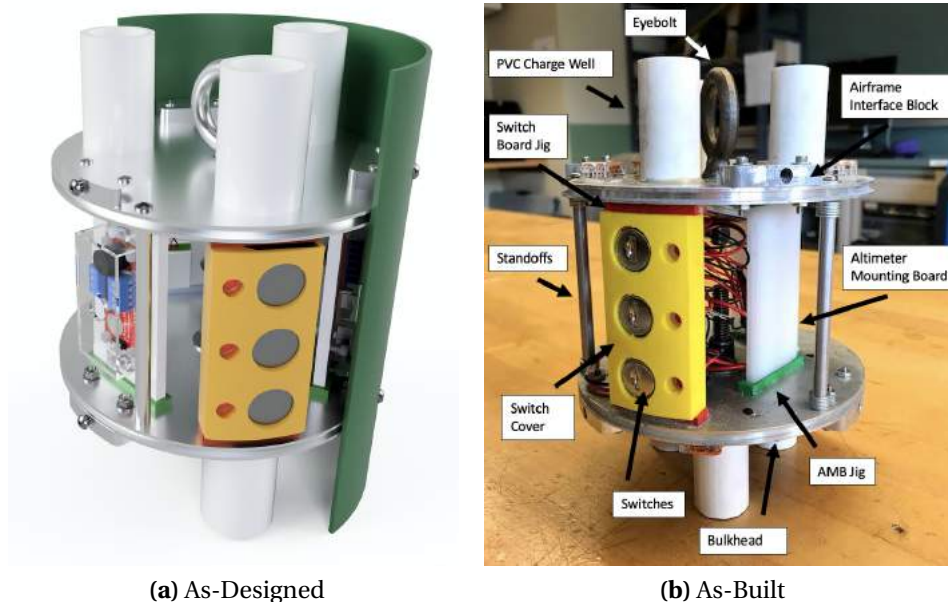
**Table 25:** Attachment Hardware Factors of Safety

Hardware	Location	Quantity	Max. Load (lbs)	FOS
Drogue Harness	Drogue Harness	1	2300	5.16
3/8 in. Quick Link	Recovery Tube	1	6000	6.22
3/8 in. Quick Link	Fin Can	1	6000	13.45
3/8 in. Eye Bolt	Recovery Tube	2	3100	3.22
3/8 in. Eye Bolt	Fin Can	2	3100	6.95
Main Harness	Main Harness	1	2300	1.44
3/8 in. Stainless Steel Quicklinks	Main Chute	2	6000	3.75
3/8 in. Stainless Steel Quicklinks	Payload Bay	1	6000	12.53
3/8 in. Stainless Steel Quicklinks	Recovery Tube	1	6000	6.22
3/8 in. Forged Steel Eyebolt	Recovery Tube	1	3100	3.21
3/8 in. Forged Steel Eyebolt	Payload Bay	1	3100	6.47
Swivel	Main Chute	1	3000	1.87
Nose Recovery Harness	Nose Harness	1	1200	779.2
5/16 in. Stainless Steel Quick Links	Nose Harness	2	875	632
1/4 in. Forged Steel Eye Bolt	CRAS-S	1	650	471

### 3.5.2.3 Compact Removable Avionics Module- Main

The CRAS-M is the structure that both houses the altimeters that control the deployments of the drogue and main parachutes, and transfers the loads from the attachment hardware to the vehicle body. It consists of two aluminum bulkheads enclosing three altimeters with corresponding keylock switches, accessible from the vehicle's exterior. The three altimeters, the Perfectflite Stratologger SL100, the Perfectflite Stratologger CF, and the Featherweight Raven4, are mounted on altimeter mounting boards machined from HDPE and shielded with 3-D printed PLA boxes lined with copper tape. The switches are also mounted on an HDPE switchboard and housed in a 3-D printed PLA shield, which aims to block any vortices from forming in the switch access holes on the body tube. The keylock switches are connected to LED lights to clarify when the altimeters have been powered on. Figure 42 shows the as-built CRAS-M in comparison to the designed CRAS-M.

The altimeter and switchboard mounting boards interface with the bulkheads through 3D printed jigs epoxied onto the inner face of the bulkheads. Each bulkhead also houses three PVC charge wells which will contain the black powder ejection charges during flight and are connected to the recovery harness via 3/8 in. forged steel eye bolts. Six WAGO 221 conductors are epoxied on the outer face of each bulkhead with two next to each PVC charge well for ease in placement of electrical wiring. In the CDR design, an O-ring was positioned around the bulkheads to ensure that no debris and gases were able to harm the integrated avionics packages enclosed within the system. After machining, it was determined that the O-ring



(a) As-Designed

(b) As-Built

**Figure 42:** As-Designed vs. As-Built CRAS-M

interfaced too tightly with the airframe and the tolerances of the bulkheads were tight enough to fit snugly against the air frame without an extra sealing mechanism. As a result, the system relies on tight tolerances to protect the electronics, a mechanism which was tested and found successful during ground testing (Test TR.3) and in the demonstration flight (Test TR.4).

Upon deployment, the bulkheads distribute the force from the parachutes to the air frame and secure the system in place. The bulkhead transmits the majority of the load through air frame interface mounting blocks and the interior of the CRAS-M will experience minimal load. Three Alloy Steel screws with a 12-24 thread and a length of 3/4 inch will be used to secure each bulkhead to the airframe. The factor of safety of each screw was calculated:

$$FOS = \frac{\tau \frac{\pi}{4} D^2}{\frac{1}{n} F} = 4.54 \quad (4)$$

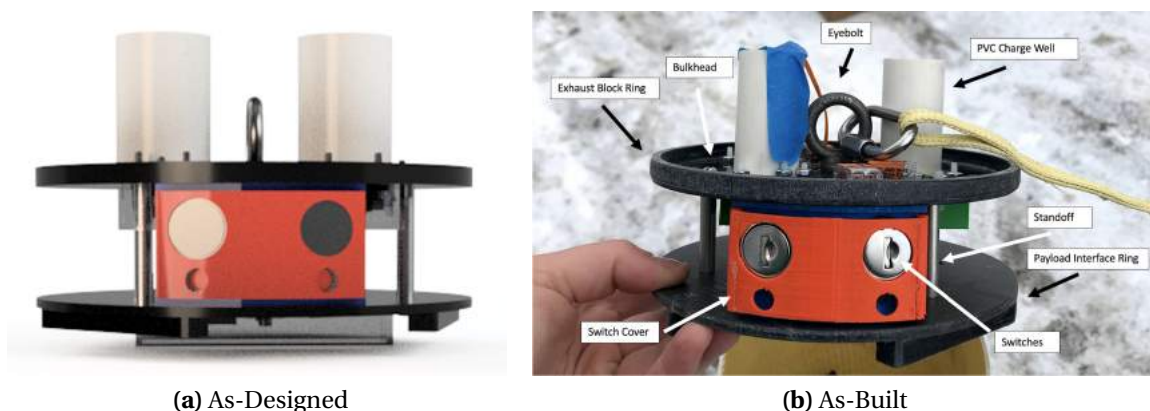
Where  $\tau$  is the maximum shear strength of the screw, 68400 psi,  $D$  is the minor diameter of the screw,  $n$  is the number of screws used, and  $F$  is the force from main deployment. Six screws in total will be used to secure the bulkheads to the air frame, but since the aluminum standoffs and altimeter mounting boards are minimally load bearing, a worst case scenario analysis was taken in calculating the factor of safety and only three screws were considered for the calculation. The minor diameter of the screw was also used to ensure a conservative estimate.

### 3.5.2.3.1 Construction

The aluminum bulkheads were first machined using a HAAS 2.5 axis mill and then a manual lathe was used to cut the channel for the o-ring and ensure a tight tolerance in the body tube. The airframe interface blocks were also machined in the HAAS 2.5 axis mill. The holes in the all of the aluminum parts were spotted on the mill and then drilled using a drill press. The holes for the airframe interface screws were also hand tapped. All of the plastic components were machined using a techno router and all holes were drilled using a hand drill. As stated in the previous section, the altimeter mounting board jigs, switch board jigs, and the switch cover were all 3-D printed out of PLA on a Makerbot Replicator+. The jigs were aligned on the bulkhead correctly by epoxying the first set of jigs on the first bulkhead and then placing the corresponding jigs with epoxy directly on top of the previously mounted jigs. The top bulkhead was then lowered onto the jigs and removed with the jigs attached. The PVC charge wells were cut to length from a PVC pipe using a bandsaw and then epoxyed to the bulkhead.

### 3.5.2.4 Compact Removable Avionics Module- Secondary

The CRAS-S is the structure that houses the altimeters that control the deployment of the nose cone parachute. It consists of two bulkheads, one made of Tecamid that interfaces with the PLS legs and one made of fiberglass, that are connected by steel standoffs. The two bulkheads enclose two altimeters, a Perfectflite StratologgerCF and a Perfectflite Stratologger SL100, and two switches with LED indicators. Figure 43 shows the CRAS-S as designed and as constructed. As an update since CDR, the CRAS-S key-lock switches will be replaced with pull-pin switches.



**Figure 43:** As-Designed vs. As-Built CRAS-S

This was decided after the vehicle demonstration flight, where the team discovered that the keyed switches were difficult to arm while the vehicle was in its fully upright position. In order to ensure that the altimeters can be armed in the launch configuration, they will be replaced before the payload demonstration flight. Further discussion of the switches is located in both Sections 3.5.4.2 and 5.3.

Both of the altimeters are enclosed in copper lined shielding boxes and secured directly to the inner face of the bulkhead using Nylon screws. An Eggfinder Mini GPS Transmitter is mounted on the outer face of the payload interface ring with its 2S Lithium Ion battery positioned on the inner face of the ring. The fiberglass bulkhead also houses two PVC charge wells which will hold the black powder ejection charges during the flight and is connected to the recovery harness by a 1/4 in. forged steel eyebolt. Four WAGO 221 conductors will be positioned near the PVC charge wells to increase the ease in connection of the wiring from the charge wells to the interior of the CRAS-S. Another 1/4 in. forged steel eyebolt is positioned in the payload interface ring as well to connect the CRAS-S to the deployment bag of the Planetary Landing System parachute to ensure it's deployment. The bulkhead will be 1/16 in. thick to ensure the safety of the system while also minimizing the weight of the CRAS-S.

To minimize the effects of the debris and gases from the black powder ejection charge mechanism on the altimeters and electronics of the CRAS-S, tight tolerances and an exhaust blocking ring will be utilized. As the CRAS-S will not be bolted directly into the airframe, traditional sealing mechanisms such as an O-ring or clay could not be used. The Nylon 6/6 exhaust blocking ring will increase the surface area of the bulkhead with the air frame which will aid in blocking the exhaust from impacting the integrated avionic packages enclosed within the system. This sealing method was proved successful during ground testing (Test [TR.3](#)) and in the demonstration flight (Test [TR.4](#)).

#### **3.5.2.4.1 Construction**

Both of the CRAS-S bulkheads were machined using the techno router. The holes were spotted with this router and then drilled using a drill press. The switchboard, switch cover, and switchboard jigs were 3-D printed using PLA on a Makerbot Replicator+. The jigs were epoxied in place using the method described in Section 3.5.2.3.1. The PVC charge wells were cut to length on a bandsaw and then epoxied to the bulkhead.

#### **3.5.3 Deployment**

Each of the three separation events employ black powder ejection charges to deploy the parachutes, which complies with NASA Req. [3.1.3](#), which prohibits the use of motor ejection as a form of deployment. The amount of black powder required to safely deploy the parachutes was calculated in Appendix 7.3. Table 26 below shows the charges used in our first full-scale demonstration flight in comparison to predicted values.

**Table 26:** Predicted and Actual Black Powder Allocations

Event	Charge	Predicted Mass (g)	Actual Mass (g)
Drogue	Primary	2.0	3.0
	Secondary	2.0	3.0
	Tertiary	2.0	3.0
Main	Primary	4.5	4.5
	Secondary	4.5	4.5
	Tertiary	4.5	4.5
Nose	Primary	2.0	2.0
	Secondary	2.0	2.0

The predicted values of the black powder charges have changed somewhat since CDR for a few reasons. For one, the CRAS-M is mounted a few inches further from the fin can than was planned in CDR due to epoxy residue in the tube. This changed the volumes that needed to be pressurized for each separation event. The shear pins were also changed so that the main vehicle used #4 size Nylon screws and the nose used #2 size Nylon screws. The actual mass of black powder used was determined in ground testing (Test TR.3, Section 7.1.3). The ground testing confirmed the accuracy of the black powder calculations and also confirmed that each of the sealing and protection methods chosen for the system were sufficient, as no recovery hardware, parachutes, or electronics were damaged in the tests. Specifically in the case of the CRAS-M, there was no black powder residue left in the interior of the subsystem, which means that the toleranced fit was enough to ensure that the electronics would be protected.

### 3.5.4 Electrical Components

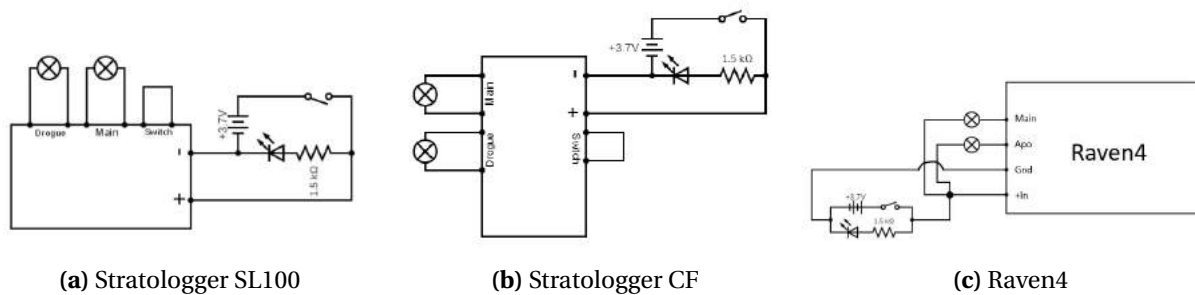
The following sections contain discussion of the robustness and flight readiness of the electrical components of the recovery system, including altimeters, switches, transmitters, and batteries.

#### 3.5.4.1 Altimeters

As discussed in Sections 3.5.2.3 and 3.5.2.4, five altimeters are used to control the three separation events in order to ensure redundancy in the system: two Perfectflite Stratologger SL100s, a Featherweight Raven4, and two Perfectflite Stratologger CFs. The parameters for each of the altimeters used can be seen in Table 27, and the electrical schematics for each altimeter are shown in Figure 44. Wires screwed into the altimeter terminal blocks were

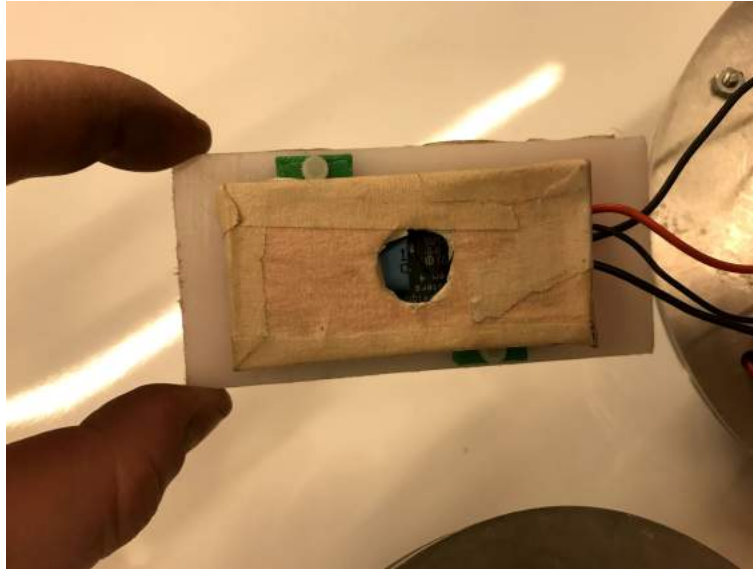
**Table 27:** Recovery Altimeter Parameters

Parameter	SL100	SLCF	Raven4
Dimension (in.)	2.75 x 0.9 x 0.5	2 x 0.84 x 0.5	1.8 x 0.8 x 0.5
Power (V)	4-16	4-16	3.8-16
Max Output Current (A)	10	5	9
Max Capacity (mAh)	–	–	170
Mass (oz)	0.45	0.38	0.23
Current Draw (mA)	1.5	1.5	<5

**Figure 44:** Altimeter Electrical Schematics

directly connected to the other electrical elements either through commercial connectors or through soldered connections. The battery was connected to the circuit using a JST PH 2 connector. The LED indicator, resistor, and the switch were directly soldered to the circuit. The e-matches were connected using a WAGO 21 connector, which allows the e-match to be changed easily between flights. After the circuits were constructed, a digital multimeter was used to test the integrity of the connections and each altimeter setup was tested according to the procedure outlined in Test TR.1 located in Section 7.1.3.

In order to prevent electromagnetic interference including interference from the Eggfinder GPS transmitters, the altimeters are both physically separated from any RF or EMF inducing device and shielded with boxes lined with copper (NASA Req 3.13; NASA Req 3.13.2; NASA Req 3.13.3; NASA Req 3.13.4). The shielding boxes, shown in Figure 45, are both lined on the outside of the box with copper tape and then covered with masking tape to prevent any possibly short circuiting. The hole in the shielding box is to allow the altimeter free and unadulterated access to the surrounding pressure, which is necessary for its functioning. The hole size was deemed small enough to not drastically impact the altimeter's sensitivity to electromagnetic fields produced by on-board electronics. The altimeter mounting boards and the mounting location of the altimeters on the CRAS-S bulkhead are also lined with copper tape and then covered in masking tape.



**Figure 45:** Altimeter Shielding Box

### 3.5.4.2 Switches

Each altimeter is armed on the launchpad with a switch that accessible through holes in the air frame of the vehicle (NASA Req 3.6). As mentioned in Section 3.5.2.3, the CRAS-M altimeters will be armed with keyed switches. The CRAS-S altimeters, in comparison, will be armed with pull-pin switches, which are more easily disarmed at greater heights. Figure 46 shows the two switch types. The placement of the switches expedites the arming process on launch day (



(a) Keyed Switch

(b) Pull-Pin Switch

**Figure 46:** Recovery Altimeter Switches

NDRT Req RD.6, NDRT Req RD.7), and the choice of key-lock and pull-pin switches ensures a simple, low-profile that is unaffected by in-flight forces (NASA Req 3.7).

### 3.5.4.3 Transmitters

Two Eggfinder GPS transmitters are included in the recovery system (NASA Req 3.12). One Eggfinder GPS transmitter will be located on the CRAS-S to track the location of the nose cone while the other transmitter will be located on the Planetary Landing System retention to track the position of the payload once it has landed (NASA Req 3.12.1). The specifications of the GPS transmitters can be seen in table 28.

**Table 28:** GPS Transmitter Specifications

Component	Location	Frequency (MHz)	Wattage (mV)	Range (mile)
Eggfinder Mini GPS Transmitter	CRAS-S	909	100	3
Eggfinder TX GPS Transmitter	PLS	921	100	3

To protect the Eggfinder GPS transmitters and ensure accuracy in the position readings, the devices are located in 3D printed PLA boxes. The functionality of the Eggfinder GPS transmitters was verified through Test TR.6 during which the VisualGPS program the Eggfinder GPS transmitters utilized accurately displayed the location of the devices within 10 yards, indicating the functionality of the components. The two transmitters are set to different frequencies, ensuring that they will not interfere. The transmitters also transmit on a different frequency band than the payload transmitters, further ensuring no interference. As stated in Section 3.5.4.1, the on-board altimeters will be shielded from transmitting devices with copper tape lined boxes. In the case of the CRAS-M altimeters, the altimeters are also additionally contained between two aluminum bulkheads, which should provide even more protection. Furthermore, the ACS electronics are also protected behind an aluminum bulkhead. Because of this, the recovery electronics are not particularly sensitive to devices that generate electromagnetic fields.

#### 3.5.4.4 Batteries

Each altimeter is powered by a Tattu 1S LiPo battery and each Eggfinder GPS transmitter is powered by a Turnigy Nano-Tech 2S LiPo battery. The specifications for these batteries can be seen in table 29.

**Table 29:** Battery Specifications

	Tattu 1S LiPo	Turnigy 2S LiPo
Capacity (mAh)	380	500
Voltage (V)	3.7	7.4
Constant Discharge Rate (C)	25	25

A preliminary battery life estimate for each battery was calculated using the current consumption for each device, tabulated in Table 30, and the specifications found in Table 29.

**Table 30:** Recovery Electronic Components Current Consumption

Component	Current Consumption (mA)
Stratologger SL100 Altimeter	1.5
Stratologger CF Altimeter	1.5
Featherweight Raven 3 Altimeter	N/a
Eggfinder Mini GPS Transmitter	70

These parameters were input to the following equations:

$$c = 0.85C, \quad (5)$$

$$A_{\text{avg}} = \frac{A_w w}{3600000}, \quad (6)$$

$$D = \frac{c}{24A_{\text{avg}}}, \quad (7)$$

where  $C$  is the capacity rating of the battery in milliamp hours (mAh),  $c$  is the derated capacity of the battery in milliamp hours (mAh) due to estimated self-discharge,  $A_w$  is the current consumption of the device when awake,  $A_{\text{avg}}$  is the average current consumption of the device over one hour (3,600,000 milliseconds) in milliamps, and  $D$  is the battery life expressed in days assuming that the batteries are constantly powered on for the duration of their battery life. The results of these calculations can be seen in table 31 where it is clear that the batteries chosen are able to power the electrical components of the CRAS-M and CRAS-S throughout the needed time duration.

**Table 31:** Battery Life Estimations

Battery	Electronic Component	Battery Life (days)
Tattu 1S LiPo	Stratologger SL100 Altimeter	8.97
Tattu 1S LiPo	Stratologger CF Altimeter	8.97
Tattu 1S LiPo	Featherweight Raven 3 Altimeter	N/a
Turnigy Nano-Tech 2S LiPo	Eggfinder Mini GPS Transmitter	0.25

These values were further validated through a battery life test described in Test [TR.2](#) in which the altimeters and LED lights were connected to the batteries and placed outside in a box with the temperature reading 13°F to simulate the actual launch conditions. The batteries continued to power the altimeters and LED lights for over two hours, satisfying NASA Req [2.7](#) and the batteries were cleared to be used for the full scale launch.

### 3.5.5 Redundancies

In order to ensure the efficacy and safety of the recovery subsystem, multiple redundancies have been added to reduce single point failures. The main and drogue parachutes are each controlled by three independent commercial altimeters, the Perfectflite Stratologger SL100, the Perfectflite Stratologger CF, and the Featherweight Raven4, all of which have completely independent circuitry and electrical elements. All altimeters are wired to trigger the black powder charge mechanism at three different times with one second delays between each stimulus to the ejection mechanism. Similarly, the nose jettison is controlled by two altimeters, the Perfectflite Stratologger CF and the Featherweight Raven4, both of which are completely independent and wired to trigger the black powder charge mechanism at 525 ft AGL with a one second delay between each altimeter's trigger to the ejection mechanism. Not only are these systems redundant in the number of independent altimeters, but each of the altimeters controlling a separation event have different software and hardware, ensuring that altimeter specific failure will not occur. In the case of the payload jettison, the CRAS-S can be removed from the body tube by two different methods once separation occurs. The first is by being pulled out of the tube by the force of the nose parachute deployment and opening if the payload bay is oriented upwards, and the second is by the weight of the payload itself if the payload bay is oriented downward.

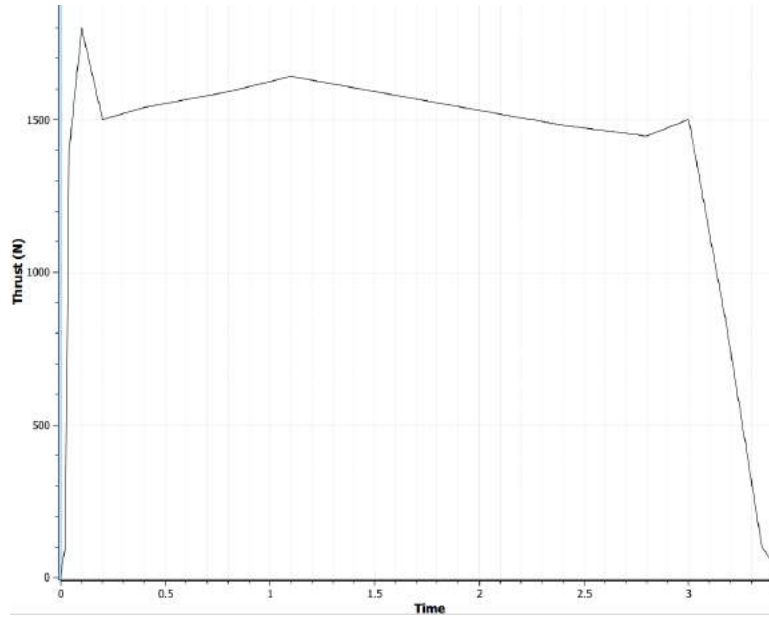
## 3.6 Mission Performance Predictions

Verification of the launch vehicle structural integrity is provided in Section 3.3.1. A breakdown of component weights can be found in Section 3.1.

### 3.6.1 Flight Ascent

All flight simulations were performed using the chosen Cessaroni L1395-P rocket motor. The motor thrust curve as simulated in RockSim is shown in Figure 47.

Flight simulations were performed in both OpenRocket and RockSim using identical updated models of the launch vehicle, with measured component and subsystem weights. The validity of the simulation models is verified by the similarity between the simulated CG location and the measured CG location, as outlined in Section 3.6.2. Each simulation was performed five times, and the average apogee altitude was taken. The results for 0-20 mph windspeeds and launch rail cant angles of 5°, 7°, and 10° are provided in Tables 32, 33, and 34 respectively. In all cases, an off-rail velocity of 69.1 ft/s was recorded using OpenRocket and 68.9 ft/s on RockSim.



**Figure 47:** Thrust curve for the Cesaroni L1395-P motor simulated using Rocksim

**Table 32:** OpenRocket and RockSim Simulation Apogee Results for Launch Angle of 5°

Average Wind Speed (mph)	OpenRocket Apogee (ft)	RockSim Apogee (ft)
0	5765	5713
5	5716	5686
10	5665	5650
15	5632	5624
20	5570	5574

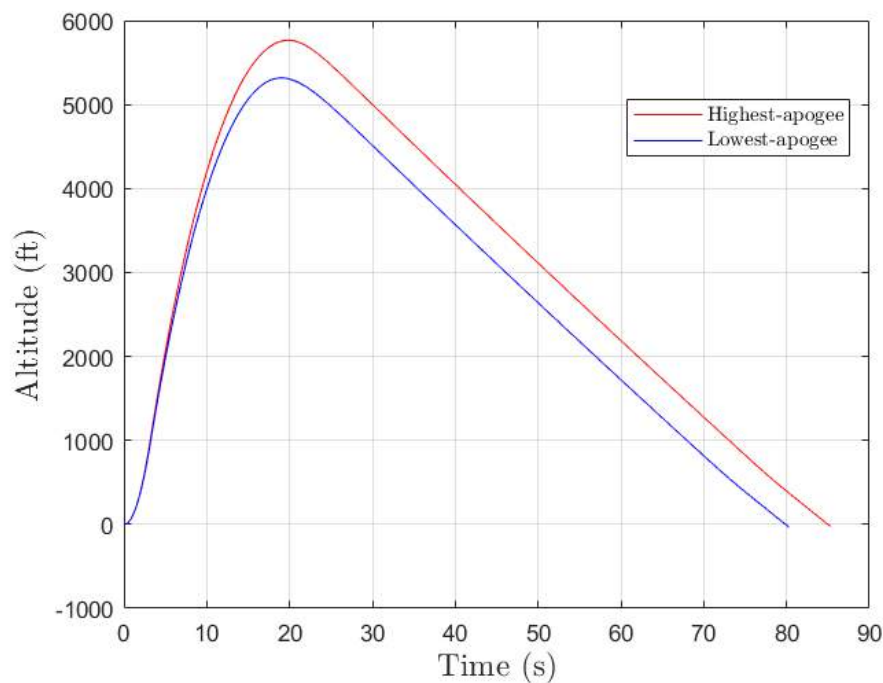
**Table 33:** OpenRocket and RockSim Simulation Apogee Results for Launch Angle of 7°

Average Wind Speed (mph)	OpenRocket Apogee (ft)	RockSim Apogee (ft)
0	5709	5653
5	5647	5624
10	5578	5587
15	5526	5544
20	5470	5497

**Table 34:** OpenRocket and RockSim Simulation Critical Values for Launch Angle of 10°

Average Wind Speed (mph)	OpenRocket Apogee (ft)	RockSim Apogee (ft)
0	5589	5528
5	5542	5493
10	5430	5445
15	5370	5394
20	5299	5328

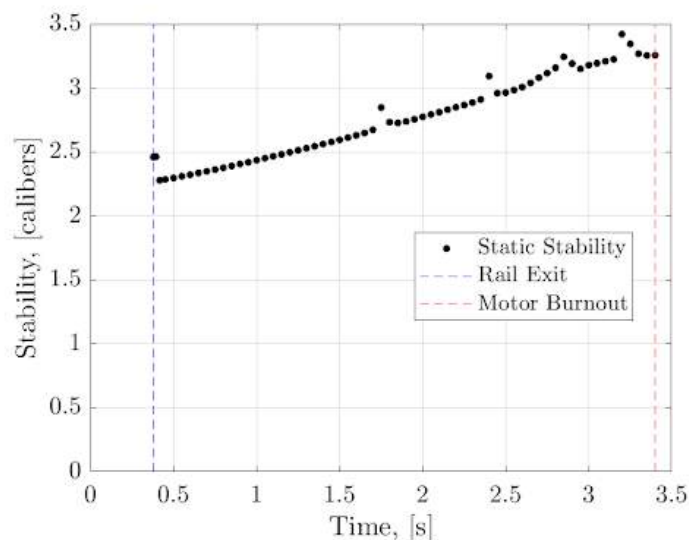
As a representation of the full range of simulated flight paths, the highest-apogee and lowest-apogee flights were plotted together in Figure 48.

**Figure 48:** Plot representing the full range of simulated flight profiles

### 3.6.2 Stability

The static stability of the launch vehicle at the rail exit was simulated in OpenRocket, and was found to be 2.26 when launched vertically, with an off-rail velocity of 68.9 ft/s. This value agrees well with the measured off-rail velocity of 71.9 ft/s found from the demonstration flight data. A plot of OpenRocket simulated stability throughout flight from launch rail clearance to motor burnout is shown in Figure 49. It is worth noting that the static stability exceeds 3.0 calibers for a portion of the flight, but the vehicle has a large enough vertical velocity by that time that

weathercocking is not a concern.

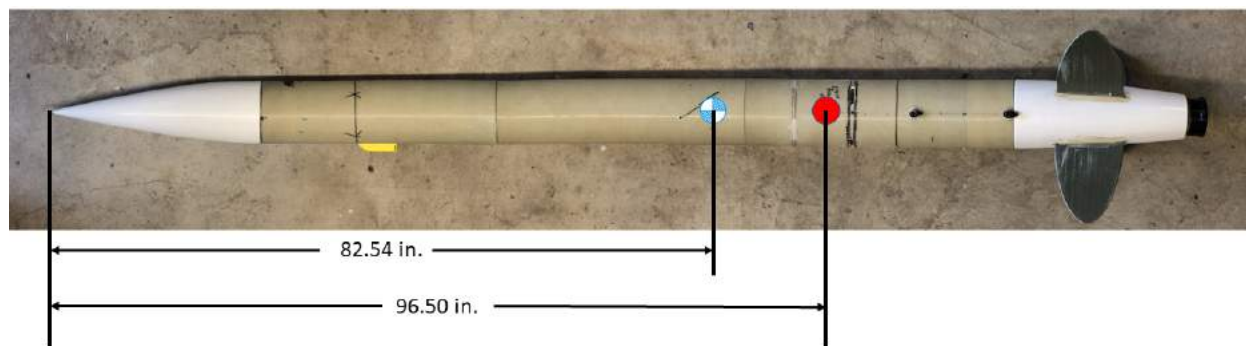


**Figure 49:** Plot of static stability from burnout to apogee simulated in OpenRocket

Using the center of pressure (CP) and the center of gravity (CG), the measured static stability was found to be 2.26 (NASA Req 2.26, NDRT Req ). This value was calculated using a CP 96.5 in. aft of the tip of the nose cone, a CG 82.54 in. aft of the nose cone, and the outer diameter of the vehicle, 6.17 in., using Eqn 8.

$$\text{Stability} = \frac{CP - CG}{d_{\text{outer}}}. \quad (8)$$

Within Openrocket, the CP was calculated using Barrowman stability equations. For the launch vehicle, the CG was determined by physically balancing the full vehicle assembly before launched, as outlined in the Demonstration Flight Test Section TV.2. The CP and CG are shown on the vehicle in Figure 50, where the red dot is CP and the blue dot is CG. A summary of stability information pertaining to the final launch vehicle design is provided in Table 35.



**Figure 50:** As-built CP and CG locations

**Table 35:** Summary of launch vehicle stability information

Measured CG Location (in.)	Barrowman CP Location (in.)	Static Stability Margin (cal.)	Simulated Off-Rail Stability Margin (cal.)	Measured Off-Rail Velocity (ft/s)
82.54	96.5	2.26	2.46	71.9

### 3.6.3 Flight Descent Simulations

Each of the parameters used to assess the vehicles descent, which are kinetic energy, descent time, and drift radius, were calculated using three independent methods:

1. An in-house MATLAB flight simulator, which uses the Euler Method to integrate the governing differential equations of vehicle motion to obtain the terminal velocities of each section, which are then used to calculate kinetic energy, descent time, and other parameters.
2. A commercial flight simulator, OpenRocket, which provides the velocities, descent times, and other parameters which were used to calculate kinetic energy.
3. Hand calculations, which used the drag equation was used to determine terminal velocity under each parachute which was then used to calculate the resultant kinetic energy and descent time.

The results from each of these methods were then compared to ensure that the vehicle would comply with the corresponding NASA Requirements in every possible expected flight scenario. Variations in the values obtained using each of the methods can be attributed to the differences in the calculation processes employed by the three.

The hand calculations, which were the simplest of the three simulations, did not account for any initial rail cant in determining horizontal velocity and relied on an input apogee, for which the highest expected apogee from Section 3.6.1 was used to ensure that even in the worst-case scenario the maximum descent time would be under 90 s. The kinetic energy of each section was calculated using the descent velocity under the parachute and the measured mass of each section:

$$KE = \frac{1}{2}mv^2, \quad (9)$$

where  $KE$  is the kinetic energy,  $m$  is the section mass, and  $v$  is the terminal velocity of the section as it descends under its parachute. The descent velocities used in the hand calculations were obtained using the methods described in Section ???. The descent times were calculated

by integrating the velocities of each section over the vehicles descent from apogee to landing:

$$t = \int_0^h \frac{1}{v(y)} dy, \quad (10)$$

where  $t$  is the total descent time,  $h$  is the maximum expected vehicle apogee,  $v(y)$  is a piecewise function that contains the vertical velocity during each stage of descent: under drogue, under main before payload jettison, and then under main after jettison or under the nose chute, depending on the vehicle section. This calculation assumed that each separation event and parachute deployment occurred instantaneously, which may have introduced some error into the result. Finally, the drift radius was calculated using the descent time and the horizontal velocity of the vehicle:

$$r_d = v_x t, \quad (11)$$

where  $r_d$  is the drift radius and  $v_x$  is the horizontal velocity, which was assumed to be constant and have a value equal to the wind speed.

The OpenRocket simulation computes the aerodynamic properties of the vehicle from the size, shape, and mass of the components that are input. These aerodynamic properties are then used in a fourth-order Runge-Kutta simulation to obtain a full flight profile. This simulation takes into account how vehicle parameters, such as drag and pressure coefficients, and atmospheric conditions change during the course of the flight. The simulation also takes into account lifting forces from the vehicle body and fins, which cause the vehicle to turn into the wind. This affects the drift predictions by causing the vehicle to change directions during descent. In order to use the most conservative estimate and ensure that the NASA Req 3.10 would be met in even the most extreme of cases, the total distance travelled by the vehicle was used for drift value rather than the vehicle's displacement. The OpenRocket simulation also lacked the ability to simulate nosecone jettison at a specific altitude. Instead, this had to be simulated by designating the nose as a second stage, without a motor, that actuated at a certain time after launch. Since this time varied based on the apogee achieved during each flight, it had to be altered for each simulation run. This may have introduced slight error into the descent time and drift calculations, but the kinetic energy calculation should be unaffected. The drift radii and descent times tabulated in the following sections were obtained by inspecting the simulation's output plots, and the kinetic energy was calculated using Equation 9 and the given descent velocities.

The in-house MATLAB flight simulator used inputted vehicle parameters in an Euler method numerical integration of the governing differential equations of the vehicle's motion. A convergence study was conducted to ensure that the chosen time-step produced accurate results. Because many properties are input rather than calculated, the simulation uses a single

coefficient of drag for the vehicle as it ascends as well as a constant atmospheric density. The simulation accounts for differences in launch angle and can simulate the nosecone jettison at the proper altitude, though it does assume instantaneous separation events and parachute deployment. The simulation also approximates lifting force due to the vehicle body and fins with a moment calculation based on flight angle. The apogees reported by the simulation were compared to the apogees obtained using OpenRocket and RockSim for the same wind speed and launch angle to assess the simulation's accuracy. While there were variations between the reported apogees, these can be attributed to the simplifications made in the in-house simulator's calculation process.

### 3.6.3.1 Kinetic Energy

The launch vehicle descends in four sections; the fin can, recovery bay, and payload bay descend tethered together under the main parachute and the nose descends under its own parachute. During the descent from apogee to main deployment, all sections descend under the drogue parachute. The properties of each of these parachute are summarized in Table 36.

**Table 36:** Selected Parachute Parameters

Parameter	Drogue	Main	Nose
$C_d$	0.97	0.97	1.5
Diameter (ft)	2	12	2
Descent Speed (ft/s)	110.38	16.57	21.90
Shape	parabolic	parabolic	elliptical
Brand	Rocketman	Rocketman	Fruity Chutes

The kinetic energies calculated using each of the three methods described in Section 3.6.3 are shown in Table 37. As shown in the table, all of the calculated kinetic energies are lower

**Table 37:** Kinetic Energy of Vehicle Sections at Landing in ft-lb

Section	MATLAB	OpenRocket	Hand Calcs
Fin Can	53.88	56.45	54.34
Recovery Tube	62.52	65.51	63.06
Payload Bay	24.46	25.63	24.67
Jettisoned Nose	20.69	16.06	20.70

than the maximum of 75 ft-lb stated in NASA Req 3.3. The fin can, recovery tube, and payload bay kinetic energies are within a 4.6% difference, which is sufficient validation of each of the calculation methods' validity. The calculated kinetic energies for the jettisoned nose are all

within 29%, which is higher than that of the other vehicle sections, but the values of the kinetic energies are much lower than the maximum set in NASA Req 3.3 , so this error was deemed acceptable.

### 3.6.3.2 Descent Time

The three calculation methods were also used to calculate descent times for wind speeds of 0-20 mph, and the maximums of these descent times are tabulated in Table 38. These maximum

**Table 38:** Descent Time of Vehicle Sections in s

Section	MATLAB	OpenRocket	Hand Calcs
Main Launch Vehicle	80.4	79.35	80.4
Jettisoned Nose	73.1	75.85	73.1

descent times were all experienced for the simulation ran with no wind speed and a launch angle of five degrees, which is consistent with what was expected since increasing both launch angle and wind speed reduces apogee and thus descent time. All of these descent times are also under the maximum of 90 seconds set in NASA Req 3.11.

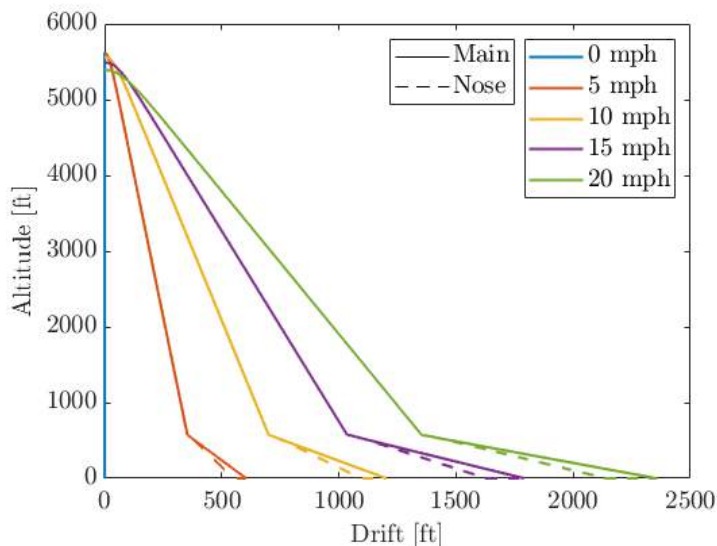
### 3.6.3.3 Drift

The launch vehicle drift for each of the sections was calculated using the methods described in Section 3.6.3. The drift radii was calculated for wind speeds of 0-20 mph for each of the vehicle sections, and the results are shown in Table 39. The results of the in-house MATLAB flight simulator are also plotted in Figure 51. There are some variations in the

**Table 39:** Drift Radius of Vehicle Sections in ft

Wind (mph)	MATLAB		OpenRocket		Hand Calcs	
	Main Body	Nose Cone	Main Body	Nose Cone	Main Body	Nose Cone
0	0	0	270	270	0	0
5	590	536	720	695	589	534
10	1179	1070	1250	1200	1170	1063
15	1750	1590	1785	1710	1747	1587
20	2369	2155	2190	2090	2251	2036

distances calculated using the three different methods, but these can be accounted for in differences between the assumptions and approximations that each method employed, as discussed in Section 3.6.3. Each of the three sets of drift radii follow the expected trend that the jettisoned nose would have a lower drift radius than the main vehicle for each wind speed, and



**Figure 51:** Drift Radius Calculation Completed in MATLAB

that drift radius would increase for both the main vehicle and the nose as the wind speed increases. For every simulation completed, all of the drift radii calculated are under the maximum of 2500 ft set in NASA Req 3.10.

### 3.6.4 Planetary Landing System Descent Simulation

The PLS is predicted to jettison from the launch vehicle at an altitude of 525 ft, descend at an approximate velocity of 17.5 ft/s, and have a maximum drift of 830 ft. These values are achieved through the use of the Fruity Chute, Spectra 36 inch selected parachute. The parameters of this parachute are found below 40.

**Table 40:** PLS Parachute Parameters

Parameter	Value
Brand	Fruity Chutes
Diameter (in)	36
$C_d$	1.5
Shape	Elliptical
Packing Volume (in <sup>3</sup> )	18
Descent Velocity (ft/s)	17.6
Descent Time (s)	28
Max Drift (ft)	830
Mass (oz)	1.5
Parachute Bag (in)	3 x 6

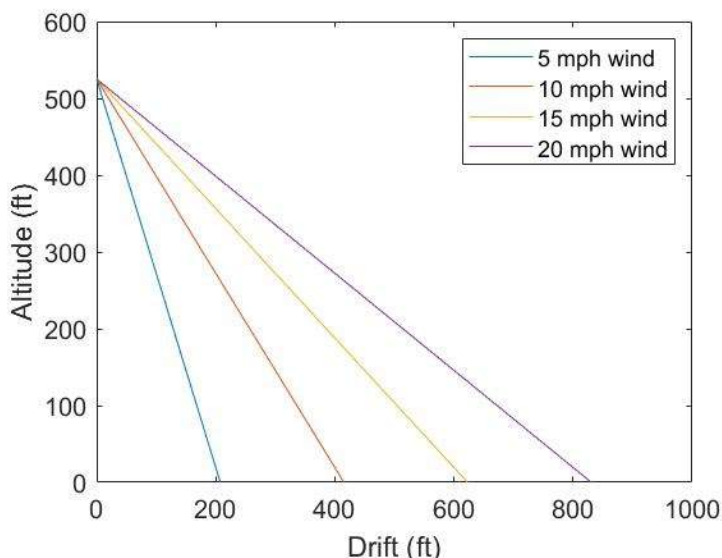
Table 41 shows the different calculation performed to corroborate these values and ensure they were below the required limit.

**Table 41:** Descent and Kinetic Energy Value Calculations

Parameter	Hand Calcs	MATLAB	Max. Allowed
Terminal Kinetic Energy (ft-lb)	19.4	19.26	75
Descent Time (s)	28	29.8	90

Calculations were performed using the PLS body and recovery system basic mass estimate of 65 oz. As seen in the table, all values are well under the maximum allowed values.

The drift radius was calculated by multiplying the descent time by the wind speed, assuming the apogee is directly above the launchpad. The maximum value was found using a maximum wind speed of 20 mph. The maximum calculated drift of 830 ft is well within the launch field, thus there is room for uncertainty in the apogee location and parachute deployment and acceleration time while still fulfilling the max drift requirement. Figure 52, created in MATLAB, shows the simulated drift for varying wind speeds, assuming a constant wind speed during descent.



**Figure 52:** Drift radii of the PLS for varying wind speeds

Additionally, hand calculations were performed to ensure that the drift radius of the PLS did not exceed the allowed 25000 ft required by NASA Req. 3.10. Table 42 shows these calculations below.

**Table 42:** Drift Radius of PLS Sections in ft

Wind (mph)	Hand Calcs	MATLAB
0	0	0
5	205	207
10	411	415
15	616	623
20	821	831

## 4 Payload Criteria

### 4.1 Planetary Landing System Design Overview

The Planetary Landing System (PLS) is the Notre Dame Rocketry Team’s Experimental Payload for the 2020-2021 NASA Student Launch Competition. It is designed to eject from the launch vehicle at an altitude of 525 ft, land within the launch field, autonomously reorient itself to within 5 degrees of vertical, and capture and transmit a 360 degree photo in order to meet the basic mission requirements referenced in Table 72. The PLS must have a maximum

diameter of 6 inches, length of 21 inches, and weight of 80 ounces to be successfully retained within the payload tube.

The PLS is comprised of a cylindrical body made up of three manufactured fiberglass bulkheads, which are connected by nylon and polypropylene spacers. The PLS descends under a 4 ft Fruity Chutes parachute stored in a 4 in. x 6 parachute bag and attached to a 9 in. shock cord. It is attached to the PLS through an eyebolt on the top bulkhead. Additionally, the middle bulkhead will feature space for the four cameras in the imaging subsystem. All three bulkheads house various electronics, orientation correction servos, and communication equipment for the proper operation of the PLS. The bottom bulkhead features three machined holes to interface with the retention subsystem. This subsystem utilizes three wooden dowels to prevent rotational motion of the PLS within the payload tube. It also utilizes a centering ring to prevent axial shifting as well as direct the load of deployment onto the legs of the PLS. The PLS has three carbon fiber legs that are connected to its bottom bulkhead with aluminum hinges.

The three carbon fiber legs feature support arms attached to threaded rods that are essential to the orientation correction of the PLS upon landing. A Raspberry Pi, located on the bottom bulkhead, will detect the landing of the PLS to initiate the orientation correction process. One leg will be held fixed in place while the Pi reorients the other two legs to achieve a vertical orientation within the required tolerance of 5 degrees from vertical. The fully assembled PLS is shown in Figure 53 below



**Figure 53:** Fully Assembled PLS

## 4.2 Changes from CDR

The constructed PLS differs from previous iterations of the design in several aspects. A critical difference was the dimensioning of the retention system interface. A bulkhead positioned too low in the payload tube caused a need for a spacer between the bulkhead and the retention system. The coupler used was an inch longer than necessary, which necessitated the removal of 1 in. of material on the nose cone shoulder. Longer screws (used to constrain the retention system) had to be used to account for this difference. Additionally, the wooden retention dowels were too long to effectively interface with the PLS and were cut down by roughly 0.5 in. These edits to the retention system were necessary to meet the purpose of the system to constrain the PLS within the launch vehicle.

Several additions were also completed. The four cameras were successfully mounted to the PLS on a 3D printed box via screws and nuts. This box was then secured on the top bulkhead. Furthermore, a support for the secondary system battery was 3D printed to secure it to the spacer without interfering with the translation of the collar on the threaded rod.

There were also processes that had not been previously considered. One of these processes was generating a separate board to mount the orientation correction electronics. This board used the space within the center of the PLS bottom bulkhead more effectively. Additionally, the three carbon fiber legs were sanded at their ends to better interface with the bottom CRAS-S bulkhead. Lastly, the nylon spacers were extended and changed to aluminum within the top bulkhead. This allowed more space for the camera and data transmission systems.

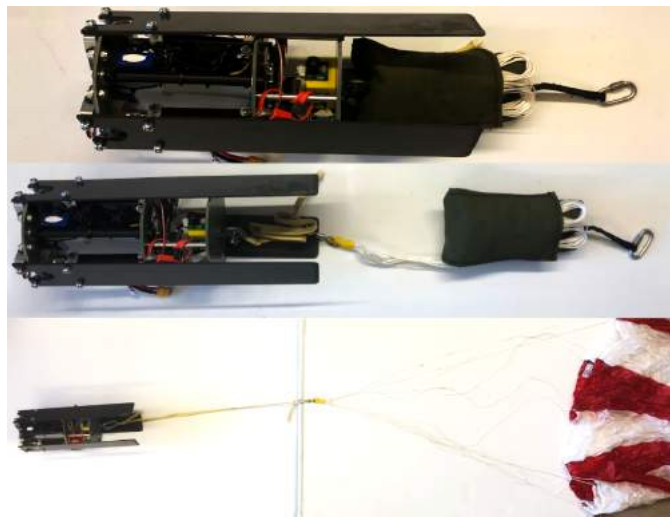
## 4.3 Design Features

This section will describe the main structural and electrical elements that make up the PLS. Some of the main elements include the carbon fiber legs, retention subsystem, orientation correction, imaging, and data transmission electronics.

### 4.3.1 Recovery Subsystem

After ejection, the payload relies on the recovery subsystem to be able to descend and land safely. In order to ensure proper deployment of the PLS parachute, a system consisting of a shock cord, parachute, and parachute bag was design and assembled. The parachute bag will be tethered only to the CRAS-S recovery system, which is expected to vacate the payload bay at nosecone ejection. At CRAS-S ejection this component will take with it the parachute bag and extend the PLS parachute out of the payload bay. The parachute is tethered only to the PLS body

so the pull from the parachute bag in order to facilitate parachute deployment without affecting the payload once the parachute leaves the bag. Once the parachute is free the air drag on the parachute together with the force of gravity on the payload bay (which will be open side down), will allow the PLS to evacuate the payload bay, detach from the jumper pin, and safely initiate it's ejection sequence. Figure 54 shows the sequence of events narrated above. The rightmost quick link will be attached to CRAS-S.



**Figure 54:** PLS Recovery Sequence

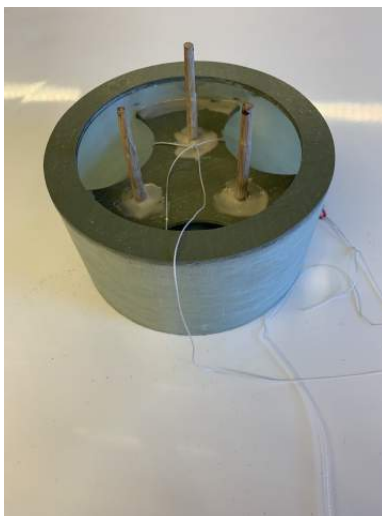
#### 4.3.2 Structural Elements

The main structural elements are the carbon fiber legs and the retention system. The main body of the PLS consists of the three carbon fiber legs, located on the outside of the PLS and spaced 120 degrees apart. Each leg is attached to the main body by two arms connecting it to a metal collar around a threaded rod, which is controlled by a servo motor. The servo motor system, with the collars and arms is shown in Figure 55 below. These legs take the load of the black powder ejection charge from the CRAS-S, absorb the shock from landing, and allow the PLS to reorient post-landing.



**Figure 55:** PLS legs subsystem: servo motor, threaded rod, bronze shaft, and arms

The retention system is the other structural component of the payload system. The retention system is a cylindrical section that screws into the bottom of the payload tube against the main parachute bulkhead. The retention system interfaces with the bottom of the PLS legs to prevent any rotation or axial shifting during flight. Additionally, this component takes the load transferred from the legs during nose cone ejection. A picture of the assembled retention system is found below in Figure 56.



**Figure 56:** Fiber glass PLS retention system

#### 4.3.3 Electrical Elements

The two main electrical systems of the PLS are the orientation correction and the imaging and data transmission system. Both contain a battery and 5 V boost converter. These

components ensure that the systems can be powered for two hours on the launch pad (NASA Req 2.7, NDRT Req PE.3).

The orientation correction system is activated after the system detects ejection through a jumperpin. Each servo motor is connected to an Arduino Nano board and an IMU with an accelerometer, with the electronic configuration shown below in Figure 57.



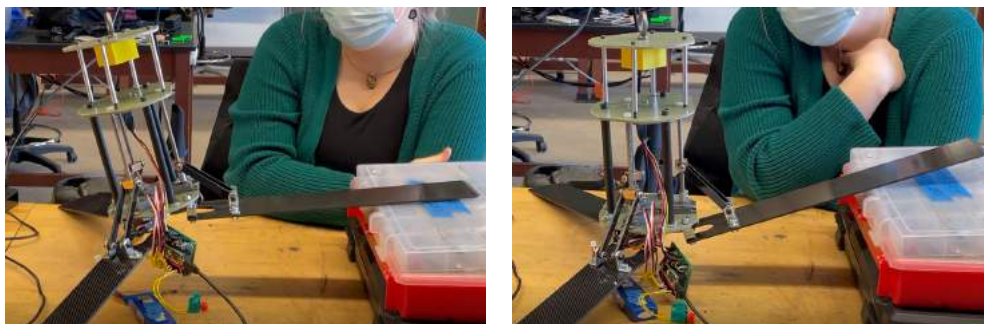
**Figure 57:** Electronic configuration of Arduino controlling the servo motors.

Each leg is initially parallel to the PLS, allowing it to fit into the payload bay. On activation, the Arduino directs the servo system to rotate the threaded rods, moving the metal collar downward until the legs form a 90 degree angle with the rest of the payload system. This resulting landing configuration can be seen in Figure 58, with each leg parallel to the ground. Each of the carbon fiber legs maintains this 90 degree angle until the PLS has landed.



**Figure 58:** Payload legs in landing configuration.

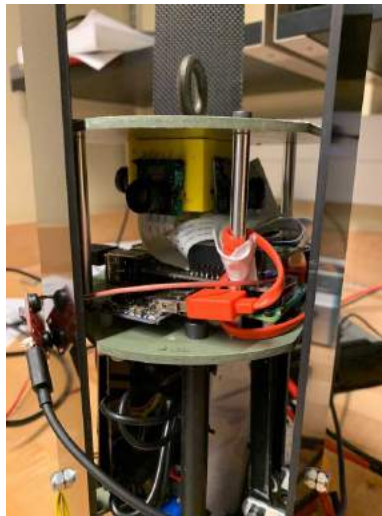
Once the PLS detects landing, the IMU's internal accelerometer measures the payload's orientation and calculates the angle between the normal of the payload deck and the vertical. The Arduino uses this data to adjust each of the 3 legs incrementally using continuous angle measurements through a for loop. The legs are adjusted by rotating the threaded rods to which they are connected. By adjusting each arm's angle individually to compensate for irregular terrain, the PLS adjusts its orientation to within 5 degrees of vertical (NASA Req 4.3.3). A demonstration of one successful test of this mechanism is shown in Figure 59. Note, that the final configuration of the system is 3 degrees from vertical, which is within the required tolerance.



**Figure 59:** PLS before and after reorienting

Once the payload has oriented the next electrical subsystem activates. An Adafruit Itsy Bitsy

microcontroller is connected to three servo motors and the orientation sensor, which allows the orientation system to autonomously orient the PLS and sends a confirmation via serial communication. A Raspberry Pi within the imaging subsystem is connected to a transmitter, which will allow it to send the orientation system's confirmation of success to the receiver, as well as the panoramic photo (NASA Req 4.3.4, NDRT Req PF.12). The Raspberry Pi is also connected to the camera adapter, which is connected to four Raspberry Pi cameras. The cameras will take four separate photos of the landing site. The adapter will stitch these photos together into a 360-degree image so that the Raspberry Pi can send the finalized panorama. The transmitter is wirelessly connected to the receiver. The receiver and second Raspberry Pi make up the transmission subsystem; it will be off board and powered by a laptop computer (NDRT Req PF.13). While connected to the host computer, they can receive the orientation and photographic data from the transmitter. The as-built imaging and data transmission system is seen in Figure 60.



**Figure 60:** Imaging and Data Transmission System

#### 4.4 Flight Reliability

The safety team formulated a set of Failure Mode and Effects Analysis (FMEA) tables in order to establish safety criteria for a successful launch. Table 59 of the FMEA tables outlines risks, mitigations, and verifications for the PLS Vehicle. Table 60 outlines all identified risks of mission failure and states mitigative action taken in regards to the PLS deployment and integration. The team is committed to meeting competition derived requirements including ensuring that the PLS jettisons from the from the launch vehicle during descent at 500-1000ft AGL, lands in upright position, reorients within 5 degrees of the vertical, takes a 360 degree panoramic photo of the landing site, and transmits this image to the control site. These

requirements were verified with a series of tests described in Table 43.

**Table 43:** PLS testing

Test Name	Description
Retention Test <a href="#">TP7</a>	Simulate the flight conditions after apogee to ensure that there will not be premature ejection of CRAS-S due to the payload force on the system and that the PLS will be safely secured through flight.
Ejection Test <a href="#">TP2</a>	Position payload bay to simulate ejection position and ensure the PLS is able to leave the payload bay.
Leg Deployment Test <a href="#">TP5</a>	Pull jumper pins to ensure that pulling either jumper pin will trigger the leg deployment sequence and legs will deploy from 0 to 90 degrees.
Landing Detection Test <a href="#">TP4</a>	Simulate descent speed by dropping PLS from a fixed height and ensuring that the PLS is able to detect landing and differentiate it from descent.
Orientation Test <a href="#">TP6</a>	Test the orientation correction algorithm in different surface roughness and inclinations.
Demonstration Flight <a href="#">TP1</a>	Test the system holistically to demonstrate payload safety and mission success.

## 4.5 Construction and Assembly

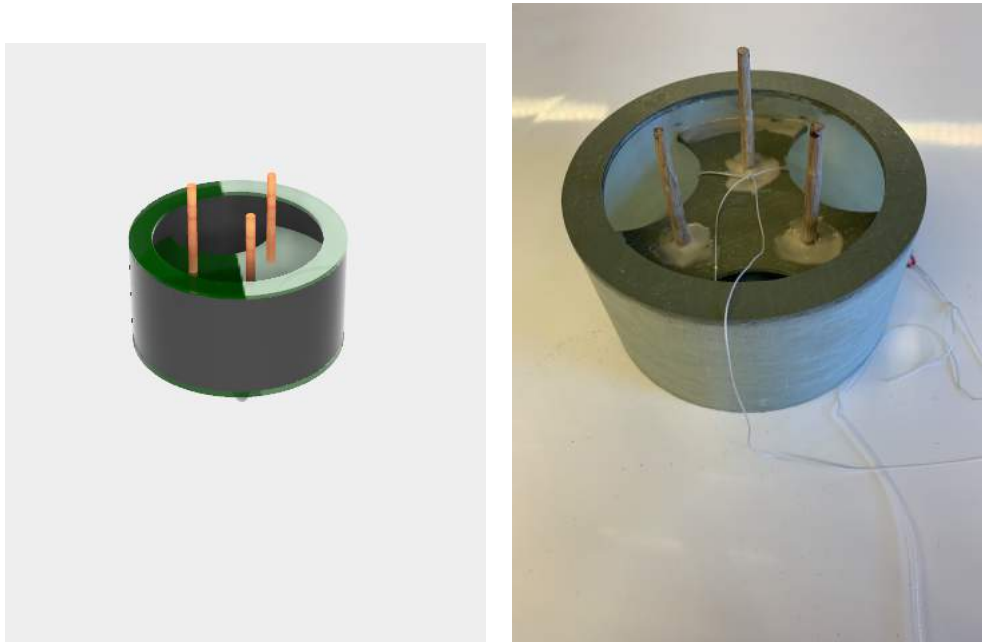
In order to complete the testing measures described in Section 7.1.4, the PLS was constructed utilizing team derived Standard Operating Procedures (SOPs), detailed in Section 6.4.3. There were also FMEA tables done in Tables 6.1.2.5 and 6.1.2.6 that further depict risks and mitigations in payload construction and testing. Assembly of the PLS began with part acquisition. The Techno router was used to cut 6 nylon arms, 3 carbon fiber legs, 5 fiberglass bulkheads, and a centering ring to the predetermined CAD specifications. The Band saw was utilized to cut the spacers, 3 dowels, and a coupler; a Belt Sander was used to sand 18 hinges.

For each leg, No. 10 screws and regular hex nuts were used to attach the hinges to the legs and the nylon arms to hinges. The collar was then attached to the arm. After placing the bottom bulkhead, the shaft coupling was attached to the 3 servos which fit in their designated holes. The legs were attached to the bottom bulkhead using No. 10 screws and regular hex nuts. Each threaded rod was attached to a shaft by screwing the collar nuts (with the legs) to the rods. The cut black nylon spacer were hand tapped to the No. 10 screws to the bottom bulkhead.

Before adding the top bulkhead the orientation correction circuitry was added, including the servo motors, Arduino Nano, and altimeter. A row of header pins was added to enable the removal of this system for debugging purposes. A breadboard with its batteries and the servo motors it runs were attached to a piece of HDPE and vertically fasted to the spacers between the bottom two PLS body bulkheads and secured in place.

The imaging and data transmission electronics were secured to the top of this structure. White nylon spacers were hand tapped to No. 4 screws and joined this bulkhead to the electronics one using dowels and No. 4 screws. An eyebolt was attached to this bulkhead to secure the parachute's Quick Link. The underside of this bulkhead holds a 3-D printed box to attach the cameras.

The retention system was constructed from several bulkheads and sections of a coupler tube. One machined fiberglass bulkhead was epoxied to a piece of coupler. This design allows for the subsystem to be screwed into the payload tube bulkhead. A large section of the fiberglass coupler tube was epoxied on top of the bulkhead. An internal support ring made of fiberglass was epoxied in the middle of the coupler to allow for the storage of a GPS transmitter for the vehicle's payload bay. Three wooden dowels were epoxied into the holes in the bottom bulkhead and the support ring. Finally, a fiberglass centering ring was attached to the top of the coupler, allowing for contact with the PLS legs rather than the Servo motors. Fiberglass was chosen due to its strength and availability in the workshop. Wood was used for the dowels as it was readily available and easily sized. A comparison between the as-built and designed retention is seen in Figure 61.



**Figure 61:** PLS retention subsystem design and as-built

## 4.6 Retention System

The performance of the payload retention system is paramount to team success. Its design restricts the motion of the PLS in the vertical and axial directions, as well as providing a path for the force from the nose cone deployment to bypass the Servo motors, and storage for ballast and a GPS transmitter.

When the subsystem was constructed and put in position in the launch vehicle, it was found that the payload tube bulkhead was attached lower than expected. To rectify this problem, an extra piece of fiberglass coupler was added beneath the retention subsystem and longer screws were added to the bottom bulkhead. The nose cone shoulder then had to be shortened to fit into the vehicle.

The retention system was put through various tests in order to determine how well it would meet requirements. The retention subsystem was screwed into position in the payload tube along with the PLS and the upper retention bulkhead present on the CRAS-S. A flight simulation test was performed, in which various movements and forces mimicking flight were applied to the payload tube. An inversion test was also performed, in which the payload tube was flipped in order to test if the retention system allowed for easy PLS deployment. Both tests were successful and, along with FEA done on the centering ring and bulkhead, indicate the retention system functions as designed.

Additionally, the retention system and the PLS were flown in the vehicle demonstration flight and the retention system proved to be successful. While the PLS was unable to deploy due to incomplete CRAS-S deployment, the PLS was safely retained through launch and landing within the payload bay.

## 4.7 Payload Demonstration Flight

During the vehicle demonstration flight the payload demonstrated successfully retention within the system regardless of obstruction during jettison event. This was considered a success for the team since the design proved reliable and safe during a non-ideal flight situation. A picture of the payload bay after landing is found below in Figure 62.



**Figure 62:** PLS inside payload bay post vehicle demonstration flight landing

Before the payload demonstration flight, which will take place on Saturday March 13, the CRAS-S will be tested more robustly, in order to ensure that the payload has a free path for evacuation of the payload bay. A summary of the test procedures for the CRAS-S can be found in Table [7.1.3](#).

## 5 Demonstration Flights

### 5.1 Demonstration Flight Overview

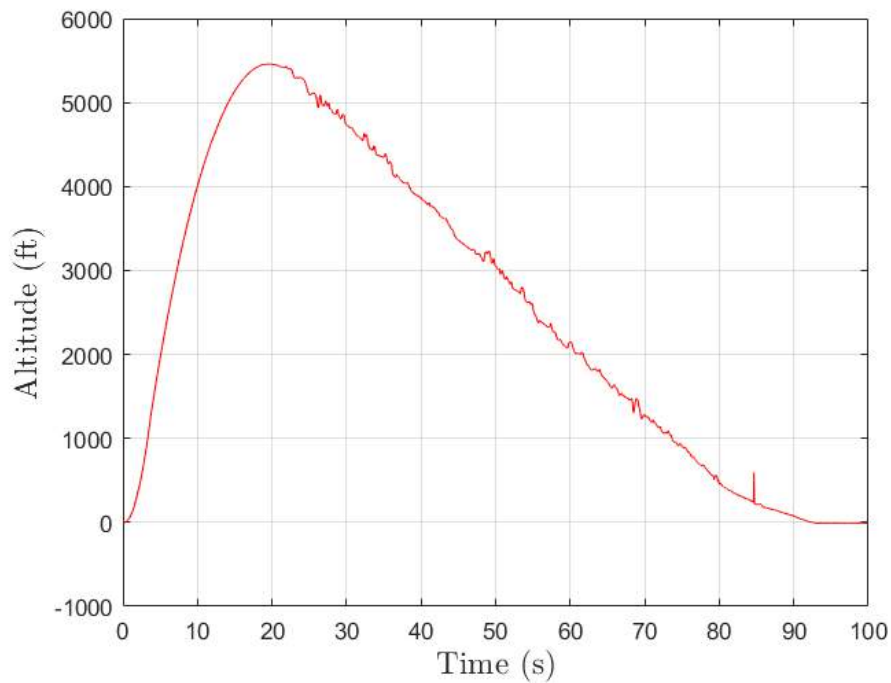
The first vehicle demonstration flight took place on February 27th, 2021 at the launch site in Three Oaks, Michigan. A summary of the flight is provided in Table 48.

**Table 44:** Flight Summary

Variable	Summary
Flight Type	Vehicle Demonstration Flight
Date of Flight	2/27/2021
Location of Flight	Three Oaks, Michigan
Launch Conditions	8 mph winds, 43 °F
Motor Flown	Cessaroni L1395 BS
Ballast Flown (lbs.)	2.125
Final Payload Flown (Y/N)	Y
Apogee Control System Status	Active
Official Target Altitude (ft.)	5300
Predicted Altitude (ft.)	5565
Measured Altitude (ft.)	5472

## 5.2 Flight Profile

The flight profile taken from the Recovery altimeter is shown plotted in Figure 63.



**Figure 63:** Plot of demonstration flight altitude data from recovery altimeter

### 5.3 Vehicle / Recovery System Verification

All mission-critical launch vehicle and recovery components functioned as intended during the launch. The launch vehicle experienced a very stable ascent with minimal wind-induced roll. All separation events occurred as intended; the primary altimeter deployed its drogue charge right after apogee and the main charge at an altitude around 600 feet. The secondary altimeter deployed its drogue charge around 1 second after apogee and the main charge at an altitude of around 550 feet. The tertiary altimeter deployed its drogue charge around 2 seconds after launch and its main charge at an altitude of around 500 feet. After each of the separation events, each of the corresponding parachute systems deployed as intended; the parachutes completely opened and slowed down the launch vehicle such that all components landed with a kinetic energy below 75 lb-ft. Finally, the launch vehicle and its subsystems sustained no damage, from landing or other in-flight events, and required no repairs after the launch.

There were three major off-nominal events during the launch. First, the Apogee Control System was unable to deploy the drag tabs at a time that would affect the speed of the launch vehicle. There was a slight extension of the drag tabs near the flight's apogee, but the launch vehicle was moving too slow at the time for the extensions of the drag tabs to make a substantial difference on the apogee altitude. Therefore, because of the failure of the Apogee Control System to properly deploy, the target apogee was not met. Lastly, the CRAS-S and the payload were unable to jettison from the launch vehicle. This problem likely occurred because of an excess of friction between the CRAS-S bulkheads and the body tube. This prevented the CRAS-S from sliding out immediately from the body tube, and once the nose parachute had fully deployed, the payload bay was lifted so that the majority of the weight of the payload was no longer pushing the CRAS-S. Figure 64 contains a photo taken during the vehicle's descent and shows this off-nominal event.



**Figure 64:** In-Flight Photos of CRAS-S Deployment Off-Nominal Event

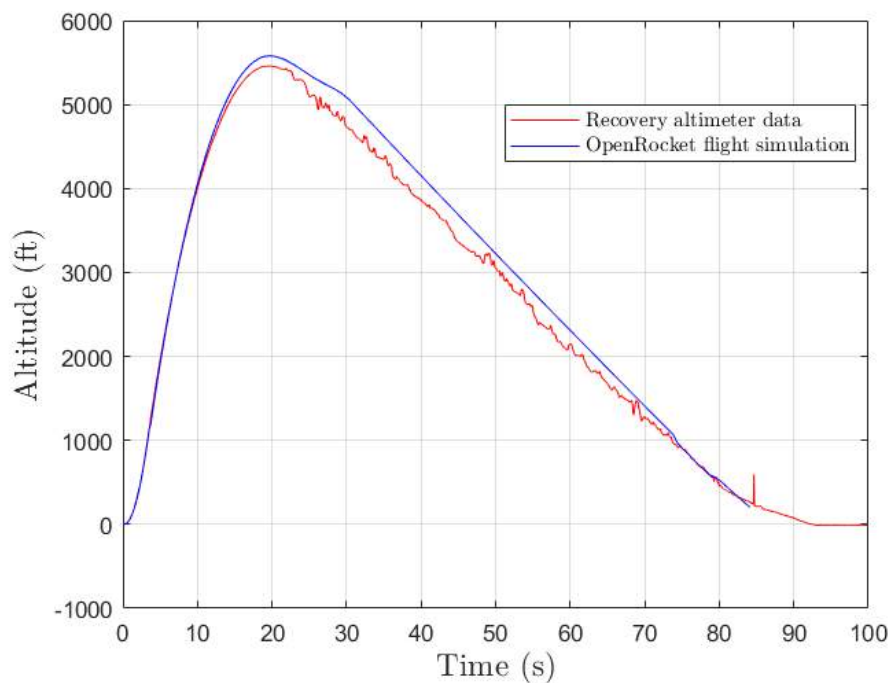
There are a couple lessons that the Notre Dame Rocketry Team has learned from the

demonstration flight. First, the Apogee Control System code must be modified to ensure that the drag tabs extend when appropriate to meet the apogee altitude. Second, the team must eliminate the friction fit between the inner walls of the payload tube and the CRAS-S and PLS in order to ensure that the payload jettisons from the launch vehicle as intended. Third, upon analysis of the flight compared to flight simulation in Section 5.5, it was discovered that the drag on the launch vehicle was higher than simulated. This was likely due to the surface of the launch vehicle being unfinished, whereas OpenRocket and RockSim utilized smooth surface finish estimations. For the upcoming Payload Demonstration flight, the launch vehicle will have a smooth painted finish, so the drag characteristics will better match those predicted in the simulations. Fourth, the team discovered that the keyed switches were difficult to arm when the vehicle was in its full upright position. Because of this, the keyed switches in the CRAS-S will be replaced with pull-pin switches, which are much easier to arm at that height.

## **5.4 Payload System Verification**

## **5.5 Vehicle Demonstration Flight Analysis**

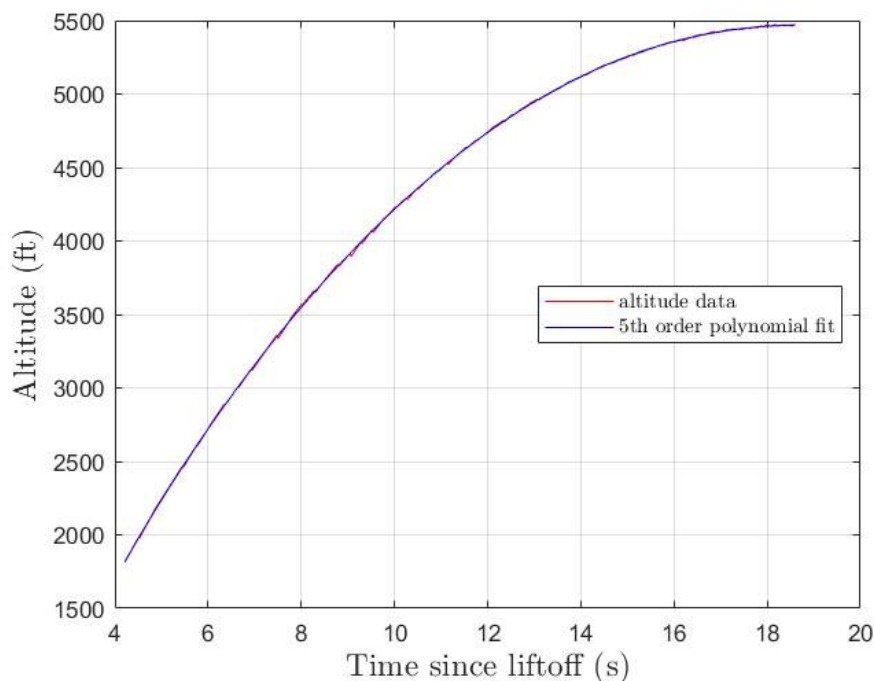
Using OpenRocket, the average simulated apogee over five flight simulations of the demonstration flight was 5,565 ft. This simulation was conducted with data from the launch, including an average wind speed of 8 mph, turbulence intensity of 10%, temperature of 43 °F, pressure of 1013 mbar, launch rod length of 132 in., and a launch rod angle of 7 degrees. Although the actual length of the launch rod was 12 ft, the launch rod length in the simulation was set to 11 ft because the aftmost rail button of the vehicle was 1 ft above the bottom of the vehicle, allowing the vehicle to only stay in contact with the rail for 11 ft. In the actual flight, the vehicle reached an apogee altitude of 5,472 ft. These two apogee values are similar but not exactly the same, with the simulated value being approximately 100 ft higher than the actual value. This discrepancy is a result of the inability to control the drag coefficient in OpenRocket. In the OpenRocket model of the vehicle used, the surface finish of each component was set to smooth paint, which resulted in a low drag coefficient being used in the simulation. For the vehicle demonstration flight, the components were not painted, so the drag in the actual launch was higher than that in the simulation. However, this OpenRocket simulation is a good prediction of the flight behavior in the upcoming Payload demonstration flight, for which the vehicle will be painted with a smooth finish. A comparison of the altitude data taken from the recovery altimeter and the simulated OpenRocket flight is shown in Figure 65.



**Figure 65:** Comparison of flight altitude data and OpenRocket simulation

As shown in the figure, the descent time calculations were very accurate to the real flight. The drift radius calculations were also very accurate to what was simulated. The distance between the GPS coordinates at the launch site and at the landing site was calculated using an online calculator. A measurement of 897 ft was recorded, which is between the 917 ft and 831 ft predicted for the main vehicle and jettisoned nose, respectively, for the wind conditions and apogee of the actual flight. Since the payload did not jettison and the vehicle descended together, this is expected and serves as validation for the mission performance predictions calculated in Section 3.6.3.

In order to obtain a prediction of the drag coefficient,  $C_d$ , of the launch vehicle, the ACS altimeter data, which was passed through a Kalman filter for smoothness, was taken for the burnout-to-apogee portion of the flight, and a 5th order polynomial fit of the data was applied. The data with the fit overlaid is shown in Figure 66.



**Figure 66:** Altitude burnout-to-apogee data with 5th order polynomial fit overlaid

The equation for the polynomial fit was then differentiated with respect to time to obtain expressions for the velocity and acceleration during that portion of flight. Those expressions are shown in Eqns. 12, 13, and 14.

$$y(t) = 0.0009t^5 - 0.0538t^4 + 1.3194t^3 - 21.4582t^2 + 295.4764t - 392.7580 \quad (12)$$

$$v(t) = 0.0043t^4 - 0.2150t^3 + 3.9582t^2 - 42.9165t + 295.4764 \quad (13)$$

$$a(t) = 0.0174t^3 - 0.6451t^2 + 7.9164t - 42.9165 \quad (14)$$

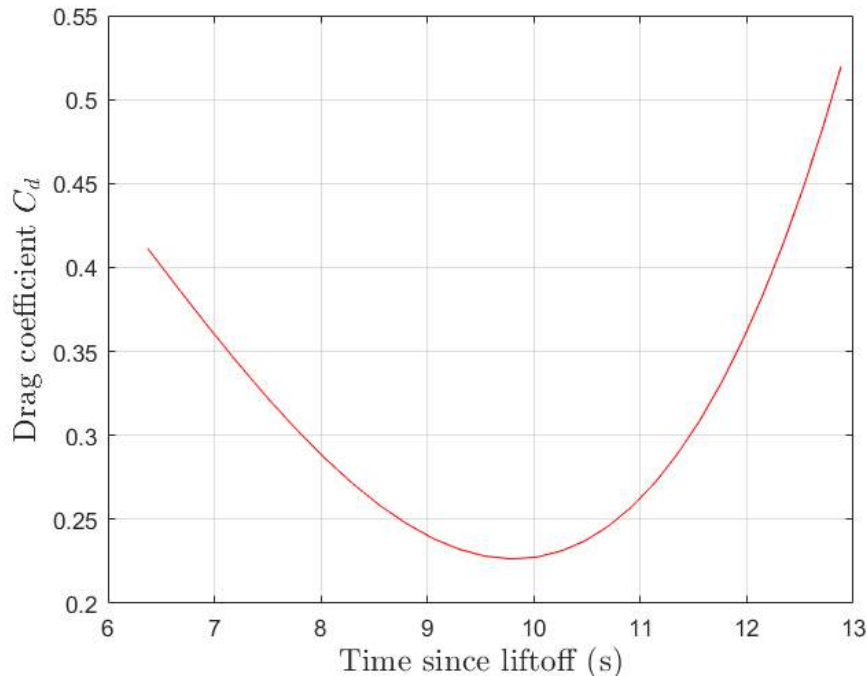
The expression for acceleration was then used to estimate a value for the drag force on the launch vehicle at every data point from burnout to apogee, where the only forces acting are drag and weight, using Eqn. 15.

$$F_d = ma - mg \quad (15)$$

Finally, the drag coefficient was estimated at every data point from burnout to apogee using the drag equation, Eqn. 16.

$$C_d = \frac{2F_d}{\rho Av^2} \quad (16)$$

A plot of the estimated drag coefficients for the relevant portion of ascent using this method is shown in Figure 67.



**Figure 67:** Plot of estimated launch vehicle drag coefficient,  $C_d$ , between burnout and apogee

Taking the average drag coefficient over this range yielded a prediction of  $C_d = 0.31$ . Because OpenRocket does not allow for direct control over the drag coefficient, this value was applied to the identical RockSim model of the launch vehicle, and a new simulation was performed. Over five simulations, the average apogee altitude was found to be 5,484 ft, which agrees much better with the actual apogee altitude of 5,472 ft. Therefore, it was determined that the simulation drag coefficient was the cause of the discrepancy between prediction and result. The OpenRocket simulations performed in Section 3.6.1 assumed a smooth paint finish, whereas the launch vehicle during the demonstration flight had an unfinished surface. However, the launch vehicle will be painted with a smooth finish prior to the Payload demonstration flight, so the previous simulations are assumed to provide valid performance predictions for future flights.

## 5.6 Comparison to Subscale

The full-scale flight involved a more consistent vertical flight with less spiraling rotation in comparison to the subscale flight. In terms of stability, the full-scale launch vehicle

experienced a more stable flight than the sub-scale. The main reason for this is the sub-scale vehicle experienced an average windspeed of 12 mph while the full-scale vehicle flight experienced 8 mph winds. This resulted in some weathercocking off the launch rail during the subscale flight, despite the fact that the full-scale launch vehicle had a slightly lower static stability margin. A comparison of subscale and full-scale stability parameters is provided in Table 45.

**Table 45:** Comparison of full-scale stability parameters to subscale

Model	CG Location (in.)	CP Location (in.)	Static Stability margin (cal.)
Full-scale	82.5	96.5	2.26
Subscale	34.5	40.4	2.29

The dimensions between the sub-scale vehicles and full scale vehicle were intended to match a 42.3% scale ratio. The differences in scaling were small enough to assume that the full-scale model would experience a similar drag coefficient to the subscale. The dimension comparisons between the full-scale vehicle and the subscale vehicle can be seen in Table 46 below.

**Table 46:** Subscale launch vehicle dimensions and scaling error

Component	Full-scale dimension (in.)	Subscale dimension (in.)	Scaling error
Nose cone exposed length	24.0	10.38	0.0%
Body tubes length	94.5	40.21	0.6%
Body tubes outer diameter	6.17	2.63	0.8%
Boattail length	14.75	5.75	7.84%
Fin root chord	6.0	2.538	0.0%
Fit height	6.2	2.52	3.91%

The subscale drag coefficient predictions from CDR are provided for reference in Table ??

**Table 47:** Subscale drag coefficient estimates for different velocity ranges

Velocity range (ft/s)	Drag coefficient, $C_d$
28-160	0.5440
45-122	0.4278
65-106	0.3517
65-85	0.4064
80-96	0.3078

Comparing the  $C_d$  values in the table above to those plotted for the full-scale vehicle in Figure 67 reveals that both models experienced a similar range of drag coefficients from burnout to apogee, further verifying the scaling similarity between the two.

## **5.7 Post Flight Structural Integrity**

### **5.7.1 Vehicle**

Upon post-flight inspection, there was no damage to any launch vehicle structural components incurred during the demonstration flight. No components required repair or replacement after the flight. This verifies the launch vehicle's ability to sustain all loads experienced throughout a nominal flight, and its ability to re-fly without the need for any repairs.

### **5.7.2 Recovery**

None of the recovery components were damaged due to the flight. This fact serves as verification for all of the analysis and testing completed prior to the flight, and is verification of the system's ability to safely guide the vehicle to landing so it can be reflown.

### **5.7.3 Payload**

The PLS was successfully flown and retained in the payload bay during flight and descent. Due to a failure in CRAS-S deploying the payload bay the PLS had no chance of successfully completing the jettison event. The extra weight in the payload bay during descent increased the kinetic energy at landing experiences by the PLS. While the system is predicted to take a total of 19.5 lb-ft during the vehicle demonstration flight it withstood a total of 30 lb-ft. Even under this landing conditions all structural elements of the payload remained intact and ready for the payload demonstration flight.

Even though the system is structurally sound the imaging subsystem was impacted. Two of the cameras detached from their connection point at impact. In order to ensure these are secured for future flights extra hardware securing around the cameras will be added. Current considerations include velcro and zip-ties.

## 5.8 Payload Mission Sequence

Before the rocket takes off, all systems of the payload are turned on. First, the jumper pin is put onto the Arduino board in the payload. Then, the retention system is slid in and screwed. The batteries are turned on, and the payload body is slid into the payload bay. The payload then sits in the rocket as the launch commences. The payload mission sequence begins when it jettisons from the rocket at an altitude between 500-1000 ft (NASA Req 4.3.1). When the payload ejects from the rocket, a multi-step sequence of events occurs to prepare the payload for landing. As the payload is exiting the payload bay, a string connected to the bay pulls a jumper switch off the Arduino Nano board. This signals to the payload that it is free to start opening the carbon fiber legs after a slight delay to account for any error.

As the carbon fiber legs are opening to their designated 90 degree angles, the parachute deploys to slow the descent of the payload to a reasonable landing speed. Once the payload lands, the IMU uses its accelerometer to measure the angle from vertical and the Arduino actuates the legs to move the payload to its desired orientation within 5 degrees of vertical (NASA Req 4.3.3). Once the payload has vertically oriented, the four camera system takes a picture, transmits it to the team prep area, and stitches it together. By this point, the mission will have been successfully completed. In the first test flight, the payload was unable to leave the payload bay. While most systems were not able to be verified the team was able to verify the retention system's safe performance.

## 5.9 Timeline Verification and Future Flights

**Table 48:** Future Flights

Date	Flight Type	Objectives
3/13/2021	Payload Demonstration Flight	Fulfill Req 4.3
3/20/2021	Payload Demonstration Flight (Backup)	Fulfill Req 4.3
4/10/2021	Competition Flight	Fulfill Req 6.2
4/17/2021	Competition Flight (Backup)	Fulfill Req 6.2

## 6 Safety and Procedures

### 6.1 Safety and Environment (Vehicle and Payload)

All hazards were assessed on the same scales of probability and severity to apply consistent, effective mitigations. Hazards considered include personnel hazards, failure modes and effects analysis (FMEA), and environmental hazards. Every hazard was identified by a member of the Safety team and documented with appropriate causes, outcomes, mitigations and verifications. All hazards have been assigned a pre-assessment numerical value reflecting the combined probability and severity of the hazard before mitigation. Similarly, all hazards have been assigned a post-assessment value reflecting the combined probability and severity of the hazard after mitigation implementation. Mitigations of hazards with larger pre-assessment values were prioritized over hazards with smaller values, although the team is confident all hazards have been successfully mitigated. Table 49 displays the values and occurrence definitions for hazard probability. Additionally, Table 50 displays the values and definitions for hazard severity in multiple contexts, specifically personnel, vehicle, and environmental hazards.

**Table 49:** Probability Value Criteria

Definition	Value	Probability of Occurrence
Improbable	1	Less than 1%
Rare	2	1 to 10%
Sporadic	3	10 to 25%
Likely	4	25 to 50%
Frequent	5	More than 50%

**Table 50:** Severity Value Criteria

Definition	Value	Personnel Injury	Vehicle and Payload Damage	Environmental Effects
Negligible	1	Minor	Insignificant	Insignificant
Minimal	2	Moderate	Slight	Completely reversible
Dangerous	3	Serious	Severe	Somewhat reversible
Catastrophic	4	Critical	Complete Loss	Irreversible

An overall assessment can be made by multiplying the values of probability and severity. Table 51 displays all potential combinations of probability and severity and their respective risks, as well as assigning color values to each combination. The key and definition for each color assignment can be seen in Table 52.

**Table 51:** Overall Risk Assessment

Probability	Severity			
	Negligible (1)	Minimal (2)	Dangerous (3)	Catastrophic (4)
Improbable (1)	1	2	3	4
Rare (2)	2	4	6	8
Sporadic (3)	3	6	9	12
Likely (4)	4	8	12	16
Frequent (5)	5	10	15	20

**Table 52:** Risk Assessment Color Code

Color	Description	Risk Value Range
Green	Low or No Risk	Less than 5
Yellow	Moderate Risk	Between 5 and 9
Red	High Risk	10 or greater

When risks were identified and prioritized, mitigations were simultaneously identified to decrease the potential risks of each hazard. To ensure these mitigations were implemented and adhered to, verifications have been applied to each mitigation. Verifications are actions taken by specific individuals or resources provided to all team members. In this way, all mitigations have been properly carried out by informed, trained, responsible individuals, thus ensuring effective risk reduction.

All risks identified are labeled with a respective code. This allows members of the Notre Dame Rocketry Team to quickly locate and utilize safety information. The alpha-numeric format for all labels is AAA.N, where A can be any amount of letters up to 3 letters, and N is a number. For example, the fifth risk in the Vehicles Structures FMEA Table is labeled as VS.5. Table ?? outlines the naming conventions for each category.

## 6.1.1 Personnel Hazard Analysis

### 6.1.1.1 Construction

**Table 53: Construction**

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
C.1	Skin contact with strong adhesive materials (epoxy, etc.)	Improper application of adhesive materials	1. Severe allergic reaction 2. Severe skin irritation or permanent skin damage	3	3	9	1. All team members have completed applicable workshop safety training 2. Team members working with adhesives are required to wear chemical-resistant gloves and have been provided step-by-step procedures for safe operation 4. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operating Procedure 2.3.1 outlines the correct procedure for epoxying. 3. The NDRT Safety Data Sheet Document is readily available for all members 4. The NDRT Standard Operating Procedures is readily available for all members 5. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity	2	2	4
C.2	Contact with the rotating component of a tool or machine	Improper use of a portable drill, drill press, a dremel, or other rotary tools	1. Severe injury to, or loss of, extremities 2. Severe skin abrasions or cuts	3	4	12	1. All team members participating in construction have completed applicable workshop safety training 2. Team members working with rotating tools or machines have been provided step-by-step procedures for safe operation 3. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation. 2. Standard Operating Procedures outline the correct procedure for operating a dremel (SOP 2.1.2), portable drill (SOP 2.1.4), drill press (SOP 2.2.4), lathe (SOP 2.2.6), and techno router (SOP 2.2.8) 3. The NDRT Standard Operating Procedures is readily available for all members 4. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity	1	4	4

C.3	Materials become unsecured during construction	Parts are loose due to improper use of motion-restriction tools	1. Injury: cuts, abrasions, or blunt bodily damage 2. Unsecured part endangers nearby team members	3	3	9	1. All team members participating in construction have completed applicable workshop and hand tool safety training 2. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operating Procedure 2.1.1 outlines the correct procedure for using a clamp.	1	3	3
C.4	Contact with the cutting blade of any type of tool or machine	Improper use of a band saw, scroll saw, hand saw, exacto knife, or any other type of cutting tool	1. Severe damage to, or loss of, extremities 2. Cuts or abrasions to the contact region	3	4	12	1. All team members participating in construction have completed applicable workshop and hand tool safety training 2. Team members working with sharp tools or machines have been provided step-by-step procedures for safe operation 3. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operation Procedures outline the correct procedure for operating a hand saw (SOP 2.1.3), wire cutters and strippers (SOP 2.1.6), band saw (SOP 2.2.2), and scroll saw (SOP 2.2.7) 3. The NDRT Standard Operating Procedures is readily available for all members 4. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity	1	4	4
C.5	Contact with the abrasive surface of any type of tool or machine	Improper use of a belt sander, circular sander, portable sander, sandpaper, and other tools or machines with abrasive surfaces	1. Injury including cuts and abrasions 2. Burns on skin	3	4	12	1. All members participating in construction have completed applicable safety training 2. Team members working with abrasive tools or machines have been provided step-by-step procedures for safe operation 3. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operating Procedures outline the correct procedure for operating a belt and disc sander (SOP 2.2.3), and sandpaper (SOP 2.3.2) 3. The NDRT Standard Operating Procedures is readily available for all members 4. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity	1	4	4

C.6	Inhalation of airborne particulates resulting from part manufacturing	Performing work such as sanding or cutting that creates harmful airborne particulates, such as carbon fiber and fiberglass	Short and long term respiratory health issues	4	4	16	<ol style="list-style-type: none"> <li>1. All team members participating in construction have completed applicable safety training</li> <li>2. Members working with airborne particles must wear a respirator</li> <li>3. Required PPE for given tasks are provided in respective Standard Operating Procedures</li> <li>4. PPE usage information is available in the NDRT Safety Handbook</li> <li>5. Material properties are listed in the NDRT Safety Data Sheet Document</li> </ol>	<ol style="list-style-type: none"> <li>1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies</li> <li>2. The NDRT Standard Operating Procedures are readily available for all members</li> <li>3. The NDRT Safety Handbook is readily available for all members</li> <li>4. The NDRT Safety Data Sheet Document is readily available for all members</li> <li>5. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity</li> </ol>	2	3	6
C.7	Inhalation of toxic fumes from glue, epoxy, or spray paint	Performing work such as sanding or heating that creates harmful toxic fumes	Short and long term respiratory health issues	4	4	16	<ol style="list-style-type: none"> <li>1. All team members participating in construction have completed applicable safety training</li> <li>2. Team members working with any toxic fumes must wear a respirator</li> <li>3. Required PPE for given tasks are provided in respective Standard Operating Procedures</li> <li>4. PPE usage information is available in the NDRT Safety Handbook</li> <li>5. Material properties are listed in the NDRT Safety Data Sheet Document</li> </ol>	<ol style="list-style-type: none"> <li>1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies</li> <li>2. The NDRT Standard Operating Procedures are readily available for all members</li> <li>3. The NDRT Safety Handbook is readily available for all members</li> <li>4. The NDRT Safety Data Sheet Document is readily available for all members</li> <li>5. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity</li> </ol>	2	3	6
C.8	Baggy clothes or hair getting caught in machinery	Use of rotating or fast-moving machinery	Potential injury or death	3	4	12	<ol style="list-style-type: none"> <li>1. All team members participating in construction have completed applicable safety training</li> <li>2. Team members participating in construction must wear long pants, short sleeves, and tie long hair back</li> <li>3. Required PPE for given tasks are provided in respective Standard Operating Procedures</li> <li>4. PPE usage information is available in the NDRT Safety Handbook</li> </ol>	<ol style="list-style-type: none"> <li>1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies</li> <li>2. The NDRT Standard Operating Procedures are readily available for all members</li> <li>3. The NDRT Safety Handbook is readily available for all members</li> <li>4. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity</li> </ol>	1	4	4

C.9	Blunt body damage	1. Improper usage of heavy tools 2. Improper handling of heavy stock materials	Potential bodily damage, especially to extremities	4	2	8	1. All team members have completed applicable workshop safety training 2. Members performing construction must wear closed-toed shoes 3. Members must not perform construction alone in case help is needed to handle heavy items 4. Required PPE for tasks is provided in Standard Operating Procedures 5. PPE usage information is available in the NDRT Safety Handbook	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. The NDRT Safety Handbook is readily available for all members 3. The NDRT Standard Operating Procedures are readily available for all members 4. The NDRT Safety Data Sheet Document is readily available for all members 5. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity	2	2	4
C.10	Contact with a hot surface	Operating a tool or machine that expels heat during use	Burns or scarring	2	3	6	1. All team members have completed applicable workshop safety training 2. Members working with hot surfaces must wear heat-resistant gloves 3. Members working with tools with hot surfaces have been provided procedures for safe operation 4. Required PPE for given tasks are provided in respective Standard Operating Procedures. 5. PPE usage information is available in the NDRT Safety Handbook	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operating Procedure 2.1.5 outlines correct procedure for soldering iron operation 3. The NDRT Standard Operating Procedures are readily available for all members 4. The NDRT Safety Handbook is readily available for all members 5. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity	1	3	3
C.11	Electric shock	Exposed wiring or a buildup of static electricity	Burns or electrocution potentially leading to long term injuries or death	3	4	12	1. All team members have completed applicable workshop safety training 2. Tools are not connected to power sources while not in use 3. Team members working with electronics ensure power sources are disconnected while performing work 4. Required PPE for given tasks are provided in respective Standard Operating Procedures 5. PPE usage information is available in the NDRT Safety Handbook	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. The NDRT Standard Operating Procedures are readily available for all members 3. The NDRT Safety Handbook is readily available for all members 4. A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity	1	4	4

C.12	Prolonged exposure to loud machinery or construction tools	Operating a tool or machine that generates unsafe levels of sound during use	Temporary or long-term hearing loss	3	3	9	<ol style="list-style-type: none"> <li>All team members have completed applicable workshop safety training</li> <li>Members participating in construction producing loud noise must wear hearing protection</li> <li>Required PPE for tasks is provided in Standard Operating Procedures</li> <li>PPE usage information is available in the NDRT Safety Handbook</li> </ol>	<ol style="list-style-type: none"> <li>All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation</li> <li>The NDRT Standard Operating Procedures are readily available for all members</li> <li>The NDRT Safety Handbook is readily available for all members</li> <li>A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity</li> </ol>	1	3	3
C.13	Tripping or falling	Obstacles on the floor such as loose cords, fluid spills, or build materials	Potential injury or disruption of other work, leading to consequent injuries	4	2	8	<ol style="list-style-type: none"> <li>All team members have completed applicable workshop safety training</li> <li>Team members are required to clean up the entire workspace and any mess after performing a task</li> <li>Required clean up procedures for given tasks are provided in respective Standard Operating Procedures</li> <li>PPE usage information is available in the NDRT Safety Handbook</li> </ol>	<ol style="list-style-type: none"> <li>All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies</li> <li>The NDRT Standard Operating Procedures are readily available for all members</li> <li>The NDRT Safety Handbook is readily available for all members</li> <li>A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity</li> </ol>	1	2	2
C.14	Fire	Overheating parts, electric components short-circuiting, Lithium-Polymer battery explosion, sparks during metal cutting, improper soldering iron placement	<ol style="list-style-type: none"> <li>Burns leading to short term health effects or death</li> <li>Burn damages and scarring on skin and extremities</li> <li>Smoke inhalation, leading to short and long term health effects or death</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>All team members have completed applicable workshop safety training</li> <li>Team members must consult the NDRT Safety Data Sheet Document before handling flammable materials</li> <li>Team members must not wear loose clothing when dealing with flammable materials</li> <li>Team members are required to clean up the entire workspace and any mess after performing a task</li> <li>Fire-prevention materials are always present in the NDRT Workshop</li> <li>Required cleaning procedures are provided in respective SOPs</li> <li>PPE usage information is available in the NDRT Safety Handbook</li> <li>Material properties are listed in the NDRT Safety Data Sheet Document</li> </ol>	<ol style="list-style-type: none"> <li>All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies</li> <li>The NDRT workshop adheres to all University of Notre Dame building codes and maintains a fire extinguisher and fire blanket in the event of a fire</li> <li>The NDRT Standard Operating Procedures are readily available for all members</li> <li>The NDRT Safety Handbook is readily available for all members</li> <li>The NDRT Safety Data Sheet Document is readily available for all members</li> <li>A near miss reporting form has been created and made available in the workshop to more effectively address safety hazards that arise during workshop activity</li> </ol>	1	4	4

C.15	Contracting Sickness, specifically SARS-CoV-2	Respiratory transmission of a highly contagious virus	<ol style="list-style-type: none"> <li>1. Contracting SARS-CoV-2 potentially leading to long-term health effects or death</li> <li>2. Increased chance of transmission to other team members</li> <li>3. Potential of spreading to general population</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. All team members have completed applicable workshop safety training</li> <li>2. Workshop capacity is set at 20 persons at all times</li> <li>3. All persons must sign in and out of the workshop for contact tracing</li> <li>4. Masks must be worn at all times</li> <li>5. Persons working on workshop must maintain safe distance between each others</li> <li>6. All non construction team meetings have been held on Zoom or other video chat platforms for the entirety of the mission cycle</li> <li>7. Team members attending construction, launch, or other team activities in-person must not experience any symptoms or have close contact with a sick individual</li> </ol>	<ol style="list-style-type: none"> <li>1. The Safety Officer and team officers have verified all pandemic prevention procedures issued by NDRT the University of Notre Dame, St. Joseph's County, and. the State of Indiana are followed at all times.</li> <li>2. All team members were required to sign and agree to all guidelines and are held accountable with University of Notre Dame officials</li> <li>3. Team members attending any team event in-person must present a University Health Services "Green Pass", affirming they are not experiencing any symptoms and are not a close contact to any sick individuals</li> </ol>	1	4	4
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### 6.1.1.2 Launch Operations

**Table 54: Launch Operations**

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
L.1	Catastrophic Failure	1. Imperfections in motor 2. Motor improperly integrated into vehicle body	1. Motor explosion occurs near launch area	3	4	12	1. All motors have been thoroughly inspected prior to launch 2. All motors have been correctly and carefully installed 3. The motor has been purchased from a reputable vendor that has successfully fired this motor model thousands of times	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Motor Preparation contains guidelines for proper motor handling and installation 3. All members ordering a motor must consult the trusted vendor list and past motor data	1	4	4
L.2	Uncontrollable launch towards any personnel	1. Launch rail leans over during launch sequence 2. Vehicle stability is unacceptable for launch conditions	1. Potential high velocity impact with personnel and property 2. Injury and cuts due to direct impact to personnel and civilians	3	4	12	1. The launch rail will be carefully inspected prior to launches for safety 2. Motors will be installed correctly and carefully by a qualified individual at the launch site 3. Static stability is within 2 to 3 calipers (NASA Req 2.14, NDRT Req VD.8) 4. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR). 5. Any civilians are discouraged to enter the landing area	1. Only NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) may install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail and is made available to all members 3. Calculations in Section 3.6.2 show the static stability value of the vehicle is 2.17, which is within the acceptable range of 2 to 3 4. The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications	1	4	4

L.3	Uncontrollable vehicle descent towards personnel	<ol style="list-style-type: none"> <li>The vehicle lands on personnel upon descent under parachute</li> <li>The parachute does not deploy and the vehicle body descends vertically from apogee</li> </ol>	<ol style="list-style-type: none"> <li>High velocity impact with personnel and property leading to injury or death</li> <li>Injury and cuts due to direct impact to personnel and civilians</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>All energetics are installed correctly and carefully by a qualified individual</li> <li>The recovery design has been tested to show reliability and redundancy</li> <li>Vehicle drift has been restricted to 2,500 feet (NASA Req <a href="#">3.10</a>)</li> <li>Maximum allowable kinetic energy of the vehicle is 75 ft-lbf (NASA Req <a href="#">3.3</a>)</li> <li>Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).</li> <li>Any civilians are discouraged to enter the launch area</li> </ol>	<ol style="list-style-type: none"> <li>Only NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) may handle energetics and will obey NAR/TRA guidelines and procedures when doing so</li> <li>Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail and is made available to all members</li> <li>Test <a href="#">TR.1</a>, which outlines proper procedures and success criteria for testing altimeters battery life, was successfully passed</li> <li>Test <a href="#">TR.2</a>, which outlines proper procedures and success criteria for testing altimeters simulated flight, was successfully passed</li> <li>Test <a href="#">TR.3</a>, which outlines proper procedures and success criteria for testing black powder separation, was successfully passed</li> <li>Test <a href="#">TR.5</a>, which outlines proper procedures and success criteria for testing deployment charge redundancy, was successfully passed</li> <li>Calculations in CDR Section 3.9.5.1 show the maximum expected drift radius of the vehicle is 2,397 ft, which is within the acceptable range of 2,500 ft and satisfies NASA req. 3.10</li> <li>Calculations in Section ?? shows main parachute sizing to be 12 ft in diameter and and CDR Section 3.9.4.1 shows maximum expected kinetic energy of the vehicle to be 73.98 ft-lbf, within the acceptable range of 75 ft-lbf (NASA Req <a href="#">3.3</a>)</li> <li>The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications</li> </ol>	2	3	6
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L.4	PLS uncontrolled descent	1. PLS separates from vehicle during launch 2. PLS recovery failure	1. Personnel injury and building damage via impact	3	3	9	<ol style="list-style-type: none"> <li>1. All energetics will be installed correctly and carefully by a qualified individual</li> <li>2. The recovery design has been tested to show reliability and redundancy</li> <li>3. Payload drift has been restricted to a maximum of 2,500 feet (NASA Req 3.10)</li> <li>4. Maximum allowable kinetic energy of the PLS is 75 ft-lbf (NASA Req 3.3)</li> <li>5. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).</li> <li>6. Any civilians are discouraged to enter the launch area</li> </ol>	<ol style="list-style-type: none"> <li>1. Only NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) may handle energetics and will obey NAR/TRA guidelines and procedures when doing so</li> <li>2. Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail and is made available to all members</li> <li>3. Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, was successfully passed</li> <li>4. Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, was successfully passed</li> <li>5. Test TR.3, which outlines proper procedures and success criteria for testing black powder separation, was successfully passed</li> <li>6. Test TR.5, which outlines proper procedures and success criteria for testing deployment charge redundancy, was successfully passed</li> <li>7. Calculations in CDR Section 3.9.5.2 show the maximum expected drift radius of the PLS is 830 ft, which is within the acceptable range of 2,500 ft (NASA Req 3.10)</li> <li>8. Calculations in CDR Section 4.4.2 shows PLS parachute sizing to be 3 ft in diameter and and CDR Section 3.9.4.2 shows expected maximum kinetic energy of the PLS to be 18.5 ft-lbf, within the acceptable range of 75 ft-lbf (NASA Req 3.3)</li> <li>9. The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications</li> </ol>	2	2	4
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L.5	Nose cone uncontrolled descent	<ol style="list-style-type: none"> <li>Nose cone separated from vehicle during launch</li> <li>Nose cone recovery failure</li> </ol>	<ol style="list-style-type: none"> <li>Personnel injury and building damage via impact</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>All energetics will be installed correctly and carefully by a qualified individual</li> <li>The recovery design has been tested to show reliability and redundancy</li> <li>Nose cone drift has been restricted to 2,500 feet (NASA Req 3.10)</li> <li>Maximum allowable kinetic energy of the nose cone is 75 ft-lbf (NASA Req 3.3)</li> <li>Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).</li> <li>Any civilians are discouraged to enter the launch area.</li> </ol>	<ol style="list-style-type: none"> <li>Only NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) may handle energetics and will obey NAR/TRA guidelines and procedures when doing so</li> <li>Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail and is made available to all members</li> <li>Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, was successfully passed</li> <li>Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, was successfully passed</li> <li>Test TR.3, which outlines proper procedures and success criteria for testing black powder separation, was successfully passed</li> <li>Test TR.5, which outlines proper procedures and success criteria for testing deployment charge redundancy, was successfully passed</li> <li>Calculations in CDR Section 3.9.5 show the maximum expected drift radius of the nose cone is 2,094 ft, which is within the acceptable range of 2,500 ft and satisfies NASA req. 3.10</li> <li>Calculations in Section ?? shows nose cone parachute sizing to be 2 ft in diameter and CDR Section 3.9.4.1 shows expected maximum kinetic energy of the nose cone to be 27.74 ft-lbf, within the acceptable range of 75 ft-lbf (NASA Req 3.3)</li> <li>The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications</li> </ol>	2	2	4
L.6	High temperature of motor when ignited	<ol style="list-style-type: none"> <li>Motor is hot after landing</li> <li>Personnel are located too close to launchpad during motor burn</li> </ol>	<ol style="list-style-type: none"> <li>Potential skin burns and scarring</li> <li>Potential for explosive breakage of motor</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>Personnel will not touch the vehicle immediately after landing</li> <li>Personnel will not enter launch field until RSO grants permission</li> <li>Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).</li> </ol>	<ol style="list-style-type: none"> <li>Launch Checklist: Post-Flight Recovery and Analysis outlines proper procedures for safely recovering the vehicle and PLS after landing and is made available to all members</li> <li>The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications</li> <li>The Range Safety Officer is the only individual controlling movement of personnel on or off of the launch pad and launch field</li> </ol>	1	2	2

L.7	Battery leakage or explosion	1. Battery is subject to large vibrations and high temperatures during launch	1. Personnel receive chemical burn from battery acid 2. Potential for battery to explode and injured persons. 3. Potential chemical leakage from battery.	3	3	9	1. Team members working with batteries have completed required safety training 2. Team members are required to wear rubber gloves if handling a ruptured lithium-polymer battery 3. Team members handling batteries on launch day have been provided step-by-step procedures for safe handling 4. Required PPE for given tasks are provided in respective launch procedures 5. All batteries will be checked for leakage and deformation before and after use 6. More information on PPE usage is available in the NDRT Safety Handbook	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outline proper handling of batteries on launch day and are made available to all members 3. The NDRT Safety Handbook is readily available for all members	2	2	4
L.8	Excessive Sunlight Exposure	1. Direct exposure to sun for an extended period of time without use of sunscreen or sun protection	1. Sunburn resulting in an increased risk of long term health effects such as skin cancer 2. Sun exposure leads to dizziness and potential heatstroke	3	1	3	1. The team leads will inform personnel attending the launch that they must wear proper clothes and sunscreen for long term exposure to sun 2. The team leads will inform personnel to bring enough water for launch day	1. Written announcements about potential weather hazards for team personnel will be sent in a full team email prior to launch 2. The Safety Officer will provide a weather reminder during pre-launch training sessions 3. Launch Checklist: Packing List outlines a launch day packing list, including sunscreen, and is made available to all members	1	1	1
L.9	Pinch-points	1. Vehicle assembly includes dangerous procedures with small clearances for extremities	1. Potential for cuts and bruises 2. Personnel's fingers stuck in launch materials	4	1	4	1. All team members participating in vehicle assembly have completed applicable workshop and hand tool safety training 2. Team members working with any pinch-points are required to wear cut-resistant gloves 3. Team members participating in vehicle assembly have been provided step-by-step procedures for safe assembly 4. Required PPE for given tasks are provided in respective launch procedures 5. More information on PPE usage is available in the NDRT Safety Handbook	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. Launch Checklist: Packing List outlines a launch day packing list, including necessary PPE, and is made available to all members 3. Launch Checklist: Launch Vehicle Preparation outlines proper procedures for assembling the vehicle and is made available for all members 4. The NDRT Safety Handbook is readily available for all members	2	1	2

L.10	Extreme cold	1. Inclement weather conditions	1. Hypothermia 2. Frostbite	2	3	6	1. The team leads will inform personnel attending the launch that they must wear proper clothes for long term exposure to cold weather	1. Written announcements about potential weather hazards for team personnel will be sent in a full team email prior to launch 2. The Safety Officer will provide a weather reminder during pre-launch training sessions 3. Launch Checklist: Packing List outlines a launch day packing list, including extra blankets, hats, and gloves, and is made available to all members	1	3	3
L.11	Car accident to/from the launch site	1. Bad traffic/road conditions to and from the launch site due to weather or other drivers	1. Personnel injury or death	1	4	4	1. Only drivers who are properly licensed and certified are allowed to drive to team events of any type	1. Project Manager will confirm driver licenses and car details the day before the launch 2. Travel requiring more than one hour of driving will require University driver's training	1	2	2
L.12	Sharp tools used in assembling the launch vehicle of interior systems	1. System assemblies may require pliers, scissors, and other sharp tools	1. Cuts or abrasions to skin 2. Potential for deep cuts	3	3	9	1. All team members participating in vehicle assembly have completed applicable workshop and hand tool safety training 2. Team members working with any pinch-points are required to wear cut-resistant gloves 3. Team members participating in vehicle assembly have been provided step-by-step procedures for safe assembly 4. Required PPE for given tasks are provided in respective launch procedures 5. More information on PPE usage is available in the NDRT Safety Handbook	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. Launch Checklist: Packing List outlines a launch day packing list, including necessary PPE, and is made available to all members 3. Launch Checklist: Launch Vehicle Preparation outlines proper procedures for assembling the vehicle and is made available for all members 4. The NDRT Safety Handbook is readily available for all members	2	2	4
L.13	Dropping the launch vehicle	1. Improper handling while transporting the vehicle body and components	1. Bruising, cuts, or broken bones 2. Injuries to extremities	2	2	4	1. A minimum of 4 team members must be involved in the transportation of the launch vehicle, with one additional team member making sure the transport path is clear during movement.	1. Launch Checklist: Launch Vehicle Preparation outlines a safe procedure for transporting the launch vehicle to the launch pad and is made available to all members	1	2	2

## 6.1.2 Failure Modes and Effects Analysis

### 6.1.2.1 Vehicle Flight Mechanics

**Table 55: Vehicle Flight Mechanics**

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VFM.1	Motor ignition failure	1. E-match malfunction 2. Motor imperfections	Scrubbed launch, resulting in mission failure	3	1	3	<ol style="list-style-type: none"> <li>All motors will be thoroughly inspected prior to launch</li> <li>Only qualified individuals will handle and install the motor and igniter</li> <li>The motor was purchased from a well reputable vendor that has successfully fired this motor model thousands of times</li> <li>Additional motors are brought to each launch event to ensure a backup is available during each flight waiver</li> </ol>	<ol style="list-style-type: none"> <li>NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install motors and will obey NAR/TRA guidelines and procedures when doing so</li> <li>Launch Checklist: Launch Setup outlines a checklist for setting up launch equipment and is readily available for all members</li> <li>Launch Checklists: Motor Preparation and Igniter Installation outline checklists and plans for installing the motor and igniter and is readily available for all members</li> <li>The selected motor has been successfully flown thousands of times by the manufacturer</li> </ol>	1	1	1
VFM.2	Vehicle fails to clear launch rail	<ol style="list-style-type: none"> <li>Deformation of launch rail</li> <li>Improper motor selection</li> <li>Motor imperfections</li> <li>Rail buttons deform or break during motor burn</li> </ol>	Failed launch results in mission failure and potential harm to vehicle or personnel	2	3	6	<ol style="list-style-type: none"> <li>The mass budget of the vehicle, located in Section ?? included mass growth allowance and margin to ensure each system remained below maximum allowable mass for successful launch</li> <li>The design of the vehicle has been derived from available motors</li> <li>The motor will be properly inspected and handled during integration in the launch vehicle</li> <li>All launch equipment, including the launch rail, will be inspected prior to launch according to detailed launch checklists</li> <li>The motor has been selected based on calculations and simulations to achieve a minimum velocity of 52 feet per second at rail exit</li> </ol>	<ol style="list-style-type: none"> <li>NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install motors and will obey NAR/TRA guidelines and procedures when doing so</li> <li>Calculations in Section 3.6.2 show the static stability value of the vehicle is 2.17 and the off-rail stability is 2.33, which is within the acceptable range of 2 to 3 (NASA Req. 2.14).</li> <li>Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail</li> <li>Launch Checklist: Launch Vehicle Preparation outlines proper procedures for determining center of mass on launch day and is made available to all members</li> <li>Completed construction and attachment of the rail buttons can be seen in Section 3.3.2</li> <li>The selected motor has been successfully flown thousands of times</li> </ol>	1	3	3

VFM.3	Failure of vehicle to reach sufficient velocity upon exiting launch rail	<ol style="list-style-type: none"> <li>1. Improper motor selection</li> <li>2. Motor imperfections</li> <li>3. Excessive weight in vehicle</li> <li>4. External forces acting on the launch vehicle are larger than expected</li> </ol>	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	2	3	6	<ol style="list-style-type: none"> <li>1. The motor has been selected based on calculations and simulations to achieve a minimum velocity of 52 feet per second at rail exit (NASA Req 2.16)</li> <li>2. Only qualified individuals will handle and install the motor and igniter</li> <li>3. The motor was purchased from a well reputable vendor that has successfully fired this motor model thousands of times</li> <li>4. Weight budgets have been allocated to each subsystem with a 21.61% total margin</li> <li>5. Camera shroud shape and location were designed to minimize drag</li> </ol>	<ol style="list-style-type: none"> <li>1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install motors and will obey NAR/TRA guidelines and procedures when doing so</li> <li>2. "Launch Checklist: Launch Setup" outlines a checklist and plan for setting up launch equipment and is readily available for all members</li> <li>3. "Launch Checklists: Motor Preparation and Igniter Installation" outline checklists and plans for installing the motor and igniter and is readily available for all members</li> <li>4. Mass budgets for each subsystem were strictly enforced by the Chief Engineer and can be located in ??</li> <li>5. Completed construction and attachment of the camera shroud can be seen in Section 3.3.2</li> <li>6. The selected motor has been successfully flown thousands of times by the manufacturer</li> <li>7. Section 3.6.1 confirms the rail exit velocity of the vehicle was 68.9 ft/s during simulations, satisfying NASA Req 2.16</li> <li>8. Test TV.6 outlines proper procedures and success criteria for testing the motor capability during a demonstration flight and is readily available for all members</li> </ol>	1	3	3
VFM.4	Fin Flutter	<ol style="list-style-type: none"> <li>1. Fins are not manufactured to specifications</li> <li>2. Fins are not properly secured to the vehicle</li> </ol>	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	3	3	9	<ol style="list-style-type: none"> <li>1. Fin design and material were chosen based on calculations, simulations and testing to reach a static stability margin of at least 2.0 (NASA Req 2.14)</li> <li>2. Fin can was constructed carefully and accurately</li> <li>3. Fins were properly attached and adhered to the fin can and vehicle body</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for fin design can be found in Section 3.2.5 and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>2. Calculations in Section 3.6.2 show the static stability value of the vehicle is 2.17 and the off-rail stability is 2.26, which is within the acceptable range of 2 to 3 and satisfies NASA Req. 2.14.</li> <li>3. Completed construction and installation of the fin can can be seen in Section 3.3.2</li> <li>4. Completed construction and attachment of the fins can be seen in Section 3.3.2</li> <li>5. Test TV.3 outlines proper procedures and success criteria for testing fin structural integrity during impact</li> </ol>	2	1	2

VFM.5	Failure of launch vehicle to travel in intended direction	1. Incorrect motor alignment 2. Improper rail buttons alignment	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	3	3	9	<ol style="list-style-type: none"> <li>Centering rings were constructed using proper procedures and techniques</li> <li>Rail buttons were properly attached and adhered to the fin can and vehicle body</li> <li>The motor will be installed correctly and carefully</li> <li>The static stability will be within 2 to 3 calibers (NASA Req 2.14, NDRT Req VD. 8)</li> </ol>	<ol style="list-style-type: none"> <li>NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install motors and will obey NAR/TRA guidelines and procedures when doing so</li> <li>"Launch Checklists: Launch Setup" outlines a checklist and plan for setting up launch equipment and is readily available</li> <li>"Launch Checklists: Motor Preparation and Igniter Installation" outline checklists and plans for installing the motor and igniter and is readily available for all members</li> <li>The selected motor (Cessaroni L1395 BS) has been successfully flown thousands of times</li> <li>Calculations in Section 3.6.2 show the static stability value of the vehicle is 2.17 and the off-rail stability is 2.26, which is within the acceptable range of 2 to 3 and satisfies NASA Req. 2.14.</li> <li>Completed construction and installation of the centering rings can be seen in Section 3.3.2</li> <li>Completed construction and attachment of the rail buttons can be seen in Section 3.3.2</li> </ol>	2	1	2
VFM.6	Vehicle is over-stable	Center of pressure is too far below the center of mass	Vehicle turns into the wind, may not reach the desired apogee, resulting in potential harm to vehicle or personnel	3	2	3	<ol style="list-style-type: none"> <li>All computer simulations determining the centers of pressure and mass involved the Vehicles Design Lead, Chief Engineer, and Graduate Student Mentor to ensure accuracy</li> <li>Center of pressure was mathematically determined using Open Rocket software</li> <li>Center of mass was calculated in CAD software and by physically balancing the vehicle before launch</li> <li>Fin shape and placement carefully considered stability</li> </ol>	<ol style="list-style-type: none"> <li>Calculations and simulations for the center of pressure can be found in CDR and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>Calculated expected center of mass can be located in Section 3.6.2 and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>Calculations and simulations for fin design can be found in Section 3.2.5 and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>Calculations in Section 3.6.2 show the static stability value of the vehicle is 2.17 and the off-rail stability is 2.26, which is within the acceptable range of 2 to 3 (NASA Req 2.14).</li> <li>Launch Checklists: Launch Vehicle Preparation outlines proper procedures for determining center of mass on launch day and is made available to all members</li> </ol>	1	2	2

### 6.1.2.2 Vehicle Structures

**Table 56: Vehicle Structures**

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VS.1	Bulkhead failure	<ol style="list-style-type: none"> <li>1. Improper construction</li> <li>2. Bulkhead adhesive failure</li> <li>3. Bulkhead material and design cannot withstand loading</li> </ol>	<ol style="list-style-type: none"> <li>1. Internal components damaged</li> <li>2. Unintentional vehicle separation</li> </ol>	3	3	9	<ol style="list-style-type: none"> <li>1. The material and design of each bulkhead were carefully selected based on mathematical calculations and structural FEA</li> <li>2. The application of adhesives was precise and thorough, with fillets applied to reduce stress concentrations</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and safety factors for the vehicle structural bulkhead can be located in Section 3.2.6 and have been approved by both the Safety Officer and Chief Engineer</li> <li>2. Completed construction and installation of all structural bulkheads can be seen in Section 3.3.2</li> <li>3. Standard Operating Procedure 2.3.1 outlines the correct procedure for epoxying.</li> </ol>	1	2	2
VS.2	Motor explosion	<ol style="list-style-type: none"> <li>1. Improper installation of motor casing</li> <li>2. Imperfections within the motor</li> </ol>	<ol style="list-style-type: none"> <li>1. Vehicle and payload sustain considerable damages during flight</li> <li>2. People nearby are potentially injured</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>1. All motors are thoroughly inspected prior to launch</li> <li>2. The motor is installed correctly and carefully by a qualified individual</li> <li>3. The motor was purchased from a reputable, high fidelity vendor that has successfully fired this motor model thousands of times in the past</li> </ol>	<ol style="list-style-type: none"> <li>1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the the only individual permitted to install motors and will obey NAR/TRA guidelines and procedures when doing so</li> <li>2. The chosen motor has been sourced from a trusted vendor and been approved by the Vehicles Design Lead and Chief Engineer</li> <li>3. Launch Checklist: Motor Preparation outlines a checklist and plan for installing the motor into the vehicle body and is readily available for all members</li> </ol>	1	4	4

VS.3	Nose cone detachment	1. Shear pin failure 2. Premature CRAS-S black powder charge	1. Unpredictable flight path leads to potential high velocity impact, which may damage internal components 2. Loss of PLS structure during flight	2	3	6	1. Calculations and simulations were performed to determine proper nose cone size and shape 2. Each black powder charge and altimeter combination is entirely independent 3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding 4. All PLS components are properly retained to the vehicle body, not the nose cone	1. Calculations and simulations for nose cone design (Section 3.2.1) have been approved by both the Safety Officer and Chief Engineer 2. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 3. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 4. Test TR.3 outlines proper procedures and success criteria for testing separation 5. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy 6. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures 7. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for attaching the nose cone and securing with shear pins and is readily available	1	3	3
VS.4	Structural failure upon landing	1. Vehicle body is constructed with improper materials	1. The vehicle may be damaged or entirely destroyed upon impact 2. Damage or injury to property and people	3	3	9	1. The material and design of vehicle structural components were carefully selected based on mathematical calculations and structural FEA 2. The vehicle structures was tested to ensure structural integrity upon landing 3. Detailed CAD models and drawings were used to accurately fabricate the launch vehicle, and were created prior to initiating construction	1. Calculations and simulations for vehicle structural components (Section 3.2) have been approved by both the Safety Officer and Chief Engineer 2. Test TV.3 outlines proper procedures and success criteria for testing fin structural integrity during impact 3. Test TV.4 outlines proper procedures and success criteria for testing nose cone structural integrity during impact 4. Test TV.5 outlines proper procedures and success criteria for testing vehicle structural integrity during a shake test 5. A complete construction outline of the launch vehicle can be seen in Section 3.3.2	1	3	3
VS.5	Fin failure	Fins are improperly attached to the vehicle body	Flight path becomes unpredictable and vehicle does not follow the intended trajectory	3	3	9	1. The material and design of fins was be carefully selected based on mathematical calculations and structural FEA 2. Fins were properly fabricated and attached to the fin can and vehicle body using detailed procedures 3. Fin structural integrity was tested prior to launch	1. Calculations and simulations for the fin design (Section 3.2.5) have been approved by both the Safety Officer and Chief Engineer 2. Test TV.3 outlines proper procedures and success criteria for testing fin structural integrity during impact 3. Completed construction and attachment of the fins can be seen in Section 3.3.2	1	2	2

VS.6	Dropping vehicle	1. Carelessness of team members when transporting the vehicle 2. Vehicle falls off of staging table due to high winds	1. Potential damages to interior payload components 2. Potential damages to exterior vehicle body, especially components such as fins and the nose cone	2	3	6	1. Multiple team members are required to transport the vehicle	1. "Launch Procedure: Launch Vehicle Preparation" outlines a checklist for transporting the vehicle to and from the launch site and is readily available for all members 2. "Launch Procedure: Launch Vehicle Preparation" outlines a checklist for handling the vehicle at the launch site and is readily available for all members	1	1	1
VS.7	Centering Ring Failure	1. Centering rings improperly attached 2. Centering ring imperfections	1. Motor is not properly aligned and the vehicle does not reach the desired apogee 2. Potential injury and harm to people nearby due to unexpected flight path	3	4	12	1. The materials and design of the centering rings were carefully selected based on calculations 2. The centering rings were properly and carefully installed based on created procedures	1. Calculations and simulations for the centering ring designs can be located in Section 3.2.4 and have been approved by both the Safety Officer and Chief Engineer 2. Completed construction and attachment of the centering rings can be seen in Section 3.3.2	1	4	4
VS.8	Coupler Failure	1. Couplers sized incorrectly 2. Couplers improperly attached to vehicle body tube	1. Improper vehicle separation resulting in damage to vehicle and payload	3	4	12	1. The materials and design of the couplers were carefully selected based on calculations 2. The couplers were properly and carefully installed based on created procedures	1. Calculations and simulations for the coupler design can be located in Section 3.2.2 and have been approved by both the Safety Officer and Chief Engineer 2. Completed construction and attachment of the centering rings can be seen in Section 3.3.2	1	4	4
VS.9	Electronic tracking devices fail to transmit the positions of each independent section of the vehicle	1. Radio frequency interference from shielding material inhibits transmission 2. Tracking devices are disrupted by transmitters in other components of the vehicle	NASA Req 3.12 to track the vehicle and its components accurately during the flight is not fulfilled.	3	2	6	1. Materials surrounding the electronic tracking device were chosen both for strength and for radio frequency transparency 2. The transmitting frequencies of other electronic devices were carefully chosen to avoid potential interference	1. All transmitters are designed to be located in unshielded locations on the PLS 2. "Launch Procedure: Planetary Landing System Preparation" outlines a checklist and plan for installing and arming transmitters in the PLS and is readily available for all members 3. All transmitter frequencies will be reported to NASA prior to launch and compared to other devices at the launch site 4. Test TR.6 outlines proper procedures and success criteria for testing GPS transmitters and is readily available for all members	1	1	1

### 6.1.2.3 Apogee Control System

**Table 57: Apogee Control System**

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
ACS.1	Power system failure	1. Damaged circuits from poor construction 2. Damaged circuits during launch and/or flight 3. Insufficiently charged batteries	An overshoot of target apogee due to electrical system system and loss of control of extending tab	4	3	12	1. All electronic components have been checked thoroughly prior to testing and each launch 2. All batteries used during launch are required to be fully charged and tested prior to launch	1. Launch Checklist: Packing List outlines a checklist and plan for ensuring all batteries are fully charged prior to departure from the workshop and is readily available for all members 2. Launch Checklist: Packing List outlines a packing list for all ACS components, including charged batteries, and is readily available for all members 3. Launch Checklist: Apogee Control System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members 4. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing ACS electronics into the vehicle and is readily available for all members	2	2	4
ACS.2	Incorrect or unavailable sensor data	1. Sensors are improperly installed and programmed prior to launch 2. Loss of power to the electrical system	The launch vehicle will reach an apogee outside of the acceptable range of 5300 ± 30 ft	4	3	12	1. All system code operating in the apogee control system has been tested prior to launch 2. All electrical sensors in the apogee control system have been tested prior to launch	1. Test TA.3, which outlines proper procedures and success criteria for testing a control algorithm with sample data, was successfully passed 2. Test TA.4, which outlines proper procedures and success criteria for testing servo actuation with sample data, was successfully passed 3. Test TA.6, which outlines proper procedures and success criteria for testing sensors and a data filter during subscale flight, was successfully passed	2	2	4
ACS.3	Improper command signals from microcontroller	1. Electronic system is incorrectly programmed 2. Computations of live sensor data result in unexpected errors	The launch vehicle will reach an apogee outside of the acceptable range of 5300 ± 30 ft	3	3	9	1. All system code operating in the apogee control system has been tested prior to launch	1. Test TA.3, which outlines proper procedures and success criteria for testing a control algorithm with sample data, was successfully passed 2. Test TA.3, which outlines proper procedures and success criteria for testing servo actuation with sample data, was successfully passed	2	2	4

ACS.4	Mechanical tab extension mechanism failure	1. Insufficient material strength 2. Improper construction techniques	Tab extensions cannot correctly deploy, resulting in the launch vehicle reaching an apogee outside of the acceptable range of 5300 ± 30 ft.	3	3	9	1. Tab extension materials are chosen based on simulations and calculations 2. Detailed CAD models and drawings were used to accurately fabricate the tab extension mechanism, and were created prior to initiating construction 3. The University of Notre Dame Student Fabrication Lab Manager will approve processes and toolpaths before machining each part	1. Calculations for tab extensions can be located in CDR and have been approved by both the Safety Officer and Chief Engineer 2. Test <a href="#">TA.1</a> outlines proper procedures and success criteria for testing tab extensions during demonstration flight loads and is available to all members 3. Completed construction of the mechanical tab extension mechanism is located in Section <a href="#">3.4.3.2</a>	2	2	4
ACS.5	Shearing of structural components that anchor the Apogee Control System within the launch vehicle via a twist-to-lock mechanism	1. Insufficient material strength 2. Improper construction techniques	Apogee Control System is unable to properly deploy and potentially shifts inside the vehicle body, resulting in internal component damage and unexpected changes in mass distribution	3	4	12	1. Structural components are chosen based on simulations and calculations 2. Detailed CAD models and drawings were used to accurately fabricate the twist-to-lock mechanism, and were created prior to initiating construction. 3. The University of Notre Dame Student Fabrication Lab Manager will approve processes and toolpaths before machining each part	1. The twist-to-lock mechanism design can be located in CDR and has been approved by both the Safety Officer and Chief Engineer 2. Test <a href="#">TA.1</a> , which outlines proper procedures and success criteria for testing structural integrity during demonstration flight, was successfully passed 3. Test <a href="#">TV.5</a> , which outlines proper procedures and success criteria for testing structural integrity during a vehicle shake test, was successfully passed 4. Completed construction of the ACS structure can be located in Section <a href="#">3.4.3.2</a> .	2	2	4
ACS.6	Apogee Control System has a slow response time, preventing effective adjustments being made in flight	1. Data filters leave too much data for the control system to quickly process 2. The amount of flight data collected exceeds the Apogee Control System's memory	Loss of effective ACS function leading to an apogee likely outside of the acceptable range of 5300 ± 30 ft.	3	2	6	1. The Kalman Filter data filtration system has been chosen with significant considerations for speed and memory. 2. The software program for the Apogee Control System system has been tested prior to launch.	1. Test <a href="#">TA.3</a> , which outlines proper procedures and success criteria for testing a control algorithm with sample data, was successfully passed 2. Test <a href="#">TA.4</a> , which outlines proper procedures and success criteria for testing servo actuation with sample data, was successfully passed 3. Test <a href="#">TA.6</a> , which outlines proper procedures and success criteria for testing sensors and a data filter during subscale flight, was successfully passed	2	1	2

ACS.7	Internal friction in drag tab mechanism	<ol style="list-style-type: none"> <li>The servo motor lacks the torque to overcome the reactionary friction force on the tab extensions during deployment and withdrawal</li> <li>Batteries are insufficiently charged to effectively power the servo motor</li> </ol>	Tab extensions completely, or partially, fail to extend resulting in an apogee outside of the acceptable range of 5300 ± 30 ft.	3	2	6	<ol style="list-style-type: none"> <li>Materials are chosen based on simulations and calculations results</li> <li>Detailed CAD models and drawings were used to accurately fabricate the tab extension mechanism, and were created prior to initiating construction.</li> <li>The servo motor is selected based on simulations and calculations, and is tested prior to construction</li> <li>All batteries used during launch are required to be fully charged.</li> </ol>	<ol style="list-style-type: none"> <li>Calculations for tab extension friction can be located in Section 3.7.6.2 in CDR and have been verified by both the Safety Officer and Chief Engineer</li> <li>Test TA.4, which outlines proper procedures and success criteria for testing servo actuation with sample data, was successfully passed</li> <li>Team members consulted the trusted vendor document, past servo motor data, the ACS Design Lead, and Chief Engineer prior to selecting a servo motor</li> <li>Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members</li> <li>Launch Checklist: Packing List outlines a packing list for all ACS components, including charged batteries, and is readily available for all members</li> <li>Launch Checklist: Apogee Control System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members</li> </ol>	2	1	2
ACS.8	Incorrectly assembled battery pack leads to the destruction or damage of the microcontroller	<ol style="list-style-type: none"> <li>The battery pack fails to consistently output a voltage within the microcontroller's acceptable range</li> <li>Improper construction techniques</li> </ol>	Shutdown of the electrical system and loss of control of tab extensions resulting in an apogee outside of the acceptable range of 5300 ± 30 ft.	3	3	9	<ol style="list-style-type: none"> <li>All electronic components have been carefully inspected prior to testing and each launch</li> <li>All batteries are required to be fully charged prior to launch</li> </ol>	<ol style="list-style-type: none"> <li>Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members</li> <li>Launch Checklist: Packing List outlines a packing list for all ACS components, including charged batteries, and is readily available for all members</li> <li>Launch Checklist: Apogee Control System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members</li> <li>Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing ACS electronics into the vehicle and is readily available for all members</li> <li>Completed construction of the ACS electrical system can be seen in Section 3.4.3.2.</li> </ol>	1	2	2

6.1.2.4 Recovery

Table 58: Recovery

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
R.1	Vehicle separation failure at apogee	1. Black powder charges are insufficient for separation 2. Black powder charges are set incorrectly 3. Avionics are not turned on or malfunction	Drogue and pilot parachutes do not deploy. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req. 3.3) with potential for vehicle damage and personnel injury	3	4	12	1. The black powder charges and altimeters were designed to be redundant 2. Each black powder charge and altimeter combination is entirely independent 3. Altimeters were supplied from trusted vendors and are surrounded by electromagnetic shielding	1. Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, has successfully passed 2. Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, has successfully passed 3. Test TR.3, which outlines proper procedures and success criteria for testing black powder separation, has successfully passed 4. Test TR.5, which outlines proper procedures and success criteria for testing deployment charge redundancy, has successfully passed 5. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures	1	4	4
R.2	Vehicle separation failure at 575 ft AGL	1. Black powder charges are insufficient for separation 2. Black powder charges are set incorrectly 3. Avionics are not turned on or malfunction	Main parachute does not deploy. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req. 3.3) with potential for vehicle damage and personnel injury	3	4	12	1. The black powder charges and altimeters were designed to be redundant 2. Each black powder charge and altimeter combination is entirely independent 3. Altimeters were supplied from trusted vendors and are surrounded by electromagnetic shielding	1. Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, has successfully passed 2. Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, has successfully passed 3. Test TR.3, which outlines proper procedures and success criteria for testing black powder separation, has successfully passed 4. Test TR.5, which outlines proper procedures and success criteria for testing deployment charge redundancy, has successfully passed 5. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures	1	4	4

R.3	Vehicle separation during motor burn	<ol style="list-style-type: none"> <li>1. Shear pins fail prematurely under launch loading</li> <li>2. Incorrect altimeter reading cause premature black powder ignition</li> </ol>	<ol style="list-style-type: none"> <li>1. The vehicle would shear causing interior and exterior components to be damaged</li> <li>2. Potential shrapnel and debris could seriously injure personnel and damage property</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Shear pins were supplied from a trusted vendor with a history of successful operations</li> <li>2. Shear pins were carefully selected based on calculations</li> <li>3. Altimeters were purchased from trusted vendors and are surrounded by electromagnetic shielding</li> <li>4. Black powder separation has been properly installed prior to launch</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and safety factors for shear pins were reported in CDR and have been approved by both the Safety Officer and Chief Engineer</li> <li>2. Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, has successfully passed</li> <li>3. Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, has successfully passed</li> <li>4. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures when doing so</li> </ol>	1	4	4
R.4	Vehicle components fully separate after apogee	<ol style="list-style-type: none"> <li>1. Shock cords connecting separating components fail</li> <li>2. Structural component failure due to high loading</li> <li>3. Black powder detonation damages shock cords</li> </ol>	<p>Vehicle components descend with unacceptably high kinetic energy (failing to comply with NASA Req 3.3) with potential for vehicle component damage and personnel injury</p>	3	4	12	<ol style="list-style-type: none"> <li>1. Shock cords were supplied from a trusted vendor with a history of successful operations</li> <li>2. Shock cords were carefully selected based on calculations</li> <li>3. Shock cords are connected to CRAS-M using secure connections</li> <li>4. Vehicle separation has been tested and repeated on the ground prior to demonstration launches to demonstrate reliability</li> <li>5. The material, model, and design of each structural component was carefully selected based on mathematical calculations</li> <li>6. All avionics are properly sealed from any black powder residue following detonation</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and safety factors for shock cords can be located in Section ?? and have been approved by both the Safety Officer and Chief Engineer</li> <li>2. Calculations and safety factors for recovery structural components can be located in Section ?? and have been approved by both the Safety Officer and Chief Engineer</li> <li>3. Test TR.4, which outlines proper procedures and success criteria for testing CRAS-M structural integrity during a separation ground test, has successfully passed</li> <li>4. Completed construction of the CRAS-M assembly can be seen in Section ??</li> <li>5. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures when doing so</li> </ol>	1	4	4

R.5	Main parachute fails to properly reduce descent velocity after deployment	<ol style="list-style-type: none"> <li>1. Improperly sized main parachute</li> <li>2. Main parachute is deployed at an improper time</li> <li>3. Main parachute shroud cords tangle and the main parachute chute does not deploy correctly</li> <li>4. Black powder charges damage some or all of the main parachute upon deployment</li> </ol>	Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req 3.3) with potential for vehicle damage and personnel injury	3	4	12	<ol style="list-style-type: none"> <li>1. Calculations and simulations have been performed to determine proper main parachute size and shape</li> <li>2. Altimeters were purchased from trusted vendors and are surrounded by electromagnetic shielding</li> <li>3. Parachute folding has been practiced and will be performed in accordance with manufacturer instructions for launches</li> <li>4. Nomex cloth and insulation are used to protect the parachute from damage</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for main parachute size can be found in Section ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>2. Launch Checklist: Recovery Preparation outlines a checklist and plan for folding, protecting, and insulating the main parachute and is readily available for all members</li> <li>3. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures when doing so</li> </ol>	2	2	4
R.6	Drogue and pilot parachutes fail to properly reduce descent velocity after apogee	<ol style="list-style-type: none"> <li>1. Improperly sized drogue or pilot parachute</li> <li>2. Drogue or pilot parachute is deployed at an improper time</li> <li>3. Pilot parachute shroud cords tangle and the main parachute chute does not deploy correctly</li> <li>4. Black powder charges damage drogue or pilot parachute upon deployment at apogee</li> </ol>	Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req 3.3) with potential for vehicle damage and personnel injury	3	4	12	<ol style="list-style-type: none"> <li>1. Calculations and simulations have been performed to determine proper drogue and pilot parachute sizes and shapes</li> <li>2. Altimeters were purchased from trusted vendors and are surrounded by electromagnetic shielding</li> <li>3. Parachute folding is practiced and performed in accordance with manufacturer instructions</li> <li>4. Nomex cloth and insulation is used to protect the parachute from damage</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for drogue parachute size can be found in Section ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>2. Calculations and simulations for pilot parachute size can be found in Section ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>3. Launch Checklist: Recovery Preparation outlines a checklist and plan for folding, protecting, and insulating the drogue and pilot parachutes and is readily available for all members</li> <li>4. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures when doing so</li> </ol>	1	4	4

R.7	Nose cone parachute fails to properly reduce descent velocity after apogee	<ol style="list-style-type: none"> <li>1. Improperly sized nose cone parachute</li> <li>2. Nose cone parachute is deployed at an improper time</li> <li>3. Nose cone parachute shroud cords tangle causing incomplete parachute deployment</li> <li>4. Black powder charges damage some or all of the nose cone parachute upon deployment</li> </ol>	Nose cone descends with unacceptably high kinetic energy (failing to comply with NASA Req 3.3) with potential for nose cone or payload damage, or personnel injury	3	3	9	<ol style="list-style-type: none"> <li>1. Calculations and simulations have been performed to determine proper nose cone parachute size and shape</li> <li>2. Altimeters were purchased from trusted vendors and are surrounded by electromagnetic shielding</li> <li>3. Parachute folding is practiced and performed in accordance with manufacturer instructions</li> <li>4. Nomex cloth and insulation is used to protect the parachute from damage</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for nose cone parachute size can be found in Section ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>2. Launch Checklist: Recovery Preparation outlines a checklist and plan for folding, protecting, and insulating the nose cone parachute and is readily available for all members</li> <li>3. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures when doing so</li> </ol>	1	3	3
R.8	Main parachute separates from vehicle	<ol style="list-style-type: none"> <li>1. Structural component failure due to high loading</li> <li>2. Shock cord failure due to high loading</li> <li>3. Improper integration of parachute and shock cord</li> </ol>	<ol style="list-style-type: none"> <li>1. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req 3.3) with potential for vehicle damage and personnel injury</li> <li>2. Structural component failure; damage to vehicle</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>1. Material, design, and model of structural components were selected based on careful calculations</li> <li>2. Shock cords were supplied from a trusted vendor with a history of successful operations</li> <li>3. Shock cords were carefully selected based on calculations</li> <li>4. Shock cords are securely connected to CRAS-M using secure connections</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for shock cords can be found in Section ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>2. Calculations and safety factors for recovery structural components can be located in Section ?? and have been approved by both the Safety Officer and Chief Engineer</li> <li>3. Test TR.3, which outlines proper procedures and success criteria for testing CRAS-M structural integrity during a separation ground test, has successfully passed</li> <li>4. Completed construction of the CRAS-M assembly can be located in Section ??</li> </ol>	1	4	4

R.9	Drogue parachute separates from vehicle	<ol style="list-style-type: none"> <li>Structural component failure due to high loading</li> <li>Shock cord failure due to high loading</li> <li>Improper integration of parachute and shock cord</li> </ol>	<ol style="list-style-type: none"> <li>Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req 3.3) with potential for vehicle damage and personnel injury</li> <li>Structural component failure; damage to vehicle</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>Material, design, and model of structural components were selected based on careful calculations</li> <li>Shock cords were supplied from a trusted vendor with a history of successful operations</li> <li>Shock cords were carefully selected based on calculations</li> <li>Shock cords are securely connected to CRAS-M using secure connections</li> </ol>	<ol style="list-style-type: none"> <li>Calculations and simulations for shock cords can be found in Section ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>Calculations and safety factors for recovery structural components can be located in Section ?? and have been approved by both the Safety Officer and Chief Engineer</li> <li>Test TR.3, which outlines proper procedures and success criteria for testing CRAS-M structural integrity during a separation ground test, has successfully passed</li> <li>Completed construction of the CRAS-M assembly can be located in Section ??</li> </ol>	1	4	4
R.10	Pilot parachute separates from vehicle	<ol style="list-style-type: none"> <li>Structural component failure due to high loading</li> <li>Shock cord failure due to high loading</li> <li>Improper integration of parachute and shock cord</li> </ol>	<ol style="list-style-type: none"> <li>Vehicle impacts ground at high velocity damaging vehicle and/or personnel</li> <li>Structural component failure; damage to vehicle</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>Material, design, and model of structural components were selected based on careful calculations</li> <li>Shock cords were supplied from a trusted vendor with a history of successful operations</li> <li>Shock cords were carefully selected based on calculations</li> <li>Shock cords are securely connected to CRAS-M using secure connections</li> </ol>	<ol style="list-style-type: none"> <li>Calculations and simulations for shock cords can be found in Section ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>Calculations and safety factors for recovery structural components can be located in Section ?? and have been approved by both the Safety Officer and Chief Engineer</li> <li>Test TR.3, which outlines proper procedures and success criteria for testing CRAS-M structural integrity during a separation ground test, has successfully passed</li> <li>Completed construction of the CRAS-M assembly can be seen in Section ??.</li> </ol>	1	4	4
R.11	Nose cone parachute separates from nose cone	<ol style="list-style-type: none"> <li>Structural component failure due to high loading</li> <li>Shock cord failure due to high loading</li> <li>Improper integration of parachute and shock cord</li> </ol>	<ol style="list-style-type: none"> <li>Nose cone impacts ground at high velocity damaging vehicle and/or personnel</li> <li>Potential damage to payload during separation</li> </ol>	2	3	6	<ol style="list-style-type: none"> <li>Material, design, and model of structural components were selected based on careful calculations</li> <li>Shock cords were supplied from a trusted vendor with a history of successful operations</li> <li>Shock cords were carefully selected based on calculations</li> <li>Shock cords are securely connected to CRAS-M using secure connections</li> </ol>	<ol style="list-style-type: none"> <li>Calculations and simulations for shock cords can be found in Section ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>Calculations and safety factors for recovery structural components can be located in Section ?? and have been approved by both the Safety Officer and Chief Engineer</li> <li>Test TR.3, which outlines proper procedures and success criteria for testing CRAS-S structural integrity during a separation ground test, has successfully passed</li> <li>Completed construction of the CRAS-S assembly can be seen in Section ??.</li> </ol>	1	3	3

R.12	Vehicle drift exceeds allowed drift radius of 2,500 ft (failing to comply with NASA Req 3.10)	1. Main, drogue, or pilot parachutes deploy early (before 600 ft AGL; 5000 ft AGL respectively) 2. Main, drogue, or pilot parachutes are too large	1. Vehicle could cause personnel or property damage while drifting outside the allowable range 2. Payload mission success is compromised due to a landing zone outside the allowable range	3	2	6	1. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding 2. The black powder charges and altimeters were designed to be twice redundant 3. Main, drogue, and pilot parachutes are sized based on calculations and simulations	1. Calculations in CDR showed the maximum expected drift radius of the vehicle is 2,397 ft, satisfying NASA Req 3.10 2. Calculations and simulations for all parachute sizes (Sections ??, ??, ??) have been verified and approved by the Safety Officer and Chief Engineer 3. Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, has successfully passed 4. Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, has successfully passed 5. Test TR.1, which outlines proper procedures and success criteria for testing black powder separation, has successfully passed 6. Test TR.5, which outlines proper procedures and success criteria for testing deployment charge redundancy, has successfully passed 7. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures	1	2	2
R.13	Compact Removable Avionics System - Main (CRAS-M) separates from vehicle body	1. The material and design used to construct the CRAS-M is insufficient in supporting the loads of the main, drogue, and pilot parachutes	1. Damaged internal components of vehicle 2. Vehicle descends with unacceptably high kinetic energy, potential for vehicle damage or injury	3	4	12	1. The CRAS-M has been designed and manufactured according to calculations and detailed CAD designs 2. The CRAS-M is secured to the vehicle body using components that were chosen according to calculations	1. CRAS-M securing mechanism design analysis (Section 3.5.2.3) has been verified and approved by the Safety Officer and Chief Engineer 2. Completed construction of the CRAS-M assembly can be seen in Section ??. 3. Completed construction of the CRAS-M airframe interface blocks can be seen in Section ??.	1	4	4
R.14	Compact Removable Avionics System - Secondary (CRAS-S) separates from nose cone	1. The material and design used to construct the CRAS-S is insufficient in supporting the loads of the nose cone parachute	1. Damaged internal components of vehicle 2. Nose cone descends with unacceptably high kinetic energy, potential for vehicle damage or injury	3	3	9	1. The CRAS-S has been designed and manufactured according to calculations and detailed CAD designs 2. The CRAS-S is secured to the nose using components that were chosen according to calculations	1. CRAS-S securing mechanism design analysis (Section 3.5.2.4) has been verified and approved by the Safety Officer and Chief Engineer 2. Completed construction of the CRAS-S assembly can be seen in Section ?? 3. Completed construction of the CRAS-S shock cord harness connection can be seen in Section ??	1	3	3

### 6.1.2.5 Planetary Landing System

**Table 59:** Planetary Landing System Vehicle

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PV.1	Power system failure	<ol style="list-style-type: none"> <li>Damaged circuits from poor construction</li> <li>Damaged circuits during launch and/or flight</li> <li>Insufficiently charged batteries</li> </ol>	Payload is unable to complete mission	3	3	9	<ol style="list-style-type: none"> <li>All electronic components will be checked thoroughly prior to launch</li> <li>All batteries used during launch will be fully charged and tested prior to launch</li> <li>Batteries will remain OFF until just prior to launch</li> </ol>	<ol style="list-style-type: none"> <li>Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members</li> <li>Launch Checklist: Packing List outlines a packing list for all PLS components, including charged batteries, and is readily available for all members</li> <li>Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members</li> <li>Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing and arming PLS electronics into the vehicle and is readily available for all members</li> </ol>	1	3	3
PV.2	Radio transmission signal disruption	<ol style="list-style-type: none"> <li>Radio frequency interference from shielding material inhibits transmission</li> <li>Tracking devices are disrupted by transmitters in other components of the vehicle</li> </ol>	PLS is unable to transmit the image from the system to a team device, failing to comply with NASA req. 4.3.4	3	2	6	<ol style="list-style-type: none"> <li>Materials surrounding the transmitter were chosen both for strength and for radio frequency transparency</li> <li>The transmitting frequencies of other electronic devices were chosen so as not to interfere with transmitters</li> </ol>	<ol style="list-style-type: none"> <li>All transmitters are designed to be located in unshielded locations on the PLS</li> <li>Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for installing and arming transmitters in the PLS and is readily available for all members</li> <li>All transmitter frequencies will be reported to NASA prior to launch and compared to other devices at the launch site</li> <li>Test TP.3, which outlines proper procedures and success criteria for testing image transmission between PLS and a team device, was successfully passed</li> </ol>	2	2	4

PV.3	Electronic tracking device on the payload fails to transmit the position of the PLS	<ol style="list-style-type: none"> <li>1. Radio frequency interference from shielding material inhibits transmission</li> <li>2. Tracking devices are disrupted by transmitters in other components of the vehicle</li> </ol>	PLS fails to comply with NASA req. 3.12, which states that all independent components of the launch vehicle contain and electronic tracker	3	2	6	<ol style="list-style-type: none"> <li>1. Materials surrounding the electronic tracking device were chosen both for strength and for radio frequency transparency</li> <li>2. The transmitting frequencies of other electronic devices were carefully chosen to avoid potential interference</li> </ol>	<ol style="list-style-type: none"> <li>1. All transmitters are designed to be located in unshielded locations on the PLS</li> <li>2. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for installing and arming transmitters in the PLS and is readily available for all members</li> <li>3. All transmitter frequencies will be reported to NASA prior to launch and compared to other devices at the launch site</li> <li>4. Test TR.6, which outlines proper procedures and success criteria for testing GPS transmitters, was successfully passed</li> </ol>	1	2	2
PV.4	Camera Obstruction	<ol style="list-style-type: none"> <li>1. PLS system fails to secure the parachute in an area outside of the camera's line of sight upon landing</li> <li>2. Parachute or parachute cords get caught in the camera rotation mechanism</li> </ol>	The captured image does not include a full 360 degrees of view, failing to comply with NASA req. 4.3.4	4	2	8	<ol style="list-style-type: none"> <li>1. Parachute and parachute cords will be packed correctly and carefully to prevent entanglement</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for folding, protecting, and insulating the PLS parachute and is readily available for all members</li> <li>2. Test TP.3, which outlines proper procedures and success criteria for evaluating transmitted image quality between PLS and a team device, was successfully passed</li> </ol>	2	1	2
PV.5	Low quality image	<ol style="list-style-type: none"> <li>1. Image is unviewable due to the glare created by the reflection of the sun</li> <li>2. Dust interferes with the camera lens</li> <li>3. Camera is not turned on</li> </ol>	Camera unable to capture an acceptable image, failing to comply with NASA req. 4.3.4	3	2	6	<ol style="list-style-type: none"> <li>1. Camera housing will prevent debris from affecting the overall quality of the image</li> <li>2. Only fully charged batteries will be used during flight operations</li> <li>3. Electrical connections will be checked before flight</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members</li> <li>2. Launch Checklist: Packing List outlines a packing list for all PLS components, including charged batteries, and is readily available for all members</li> <li>3. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members</li> <li>4. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing PLS electronics into the vehicle and is readily available for all members</li> <li>5. Camera selection can be located in Section 4.3.3 and has been approved by the Payload Design Lead and Chief Engineer</li> </ol>	1	1	1

PV.6	Active Orientation Failure	<ol style="list-style-type: none"> <li>1. Parachute restricts leg movement due to entanglement</li> <li>2. Debris buildup restricts leg movement</li> <li>3. Power Failure will be prevent servo motors from running</li> <li>4. Improper circuitry configuration will result in active orientation failure</li> </ol>	Orientation will not be within the 5 degree allowance, failing to comply with NASA req. 4.3.4	3	2	6	<ol style="list-style-type: none"> <li>1. Parachute and parachute cords will be packed correctly and carefully to prevent entanglement</li> <li>2. Active orientation system were built to protect against outside debris</li> <li>3. Active orientation system were tested in multiple starting positions to ensure orientation ability can overcome exaggerated obstacles</li> <li>4. Only fully charged batteries will be used during flight operations</li> <li>5. Electrical connections will be checked before flight</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for folding, protecting, and insulating the PLS parachute and is readily available for all members</li> <li>2. Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members</li> <li>3. Launch Checklist: Packing List outlines a packing list for all PLS components, including charged batteries, and is readily available for all members</li> <li>4. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members</li> <li>5. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing PLS electronics into the vehicle and is readily available for all members</li> <li>6. Active orientation design can be located in 4.3</li> <li>7. Test TP5, which outlines proper procedures and success criteria for testing PLS leg deployment, was successfully passed</li> <li>8. Test TP6, which outlines proper procedures and success criteria for testing PLS orientation, was successfully passed</li> </ol>	2	1	2
PV.7	Damaged Camera	<ol style="list-style-type: none"> <li>1. Large forces before or during deployment</li> <li>2. Large impact force</li> </ol>	Camera components damaged and the camera is unable to capture an image, failing to comply with NASA req. 4.3.4	3	3	9	<ol style="list-style-type: none"> <li>1. Camera was chosen for both durability and quality of image</li> <li>2. PLS recovery system was tested prior to launch for proper reduction in descent kinetic energy, in compliance with NASA req. 3.3</li> </ol>	<ol style="list-style-type: none"> <li>1. Test TP8, which outlines proper procedures and success criteria for testing PLS structural integrity during a shake test, was successfully passed</li> <li>2. Camera selection can be located in Section 4.3.3 and has been approved by the Payload Design Lead and Chief Engineer</li> </ol>	1	3	3

PV.8	Failure for all support legs to deploy	<ol style="list-style-type: none"> <li>1. Launch vehicle leg retention system retains one or multiple legs in locked position</li> <li>2. Servo motors do not successfully deploy legs</li> </ol>	Orientation will not be within the 5 degree allowance, failing to comply with NASA req. 4.3.3	2	4	8	<ol style="list-style-type: none"> <li>1. Servo motors were chosen with multiple considerations, including torque, reliability, and weight</li> <li>2. Leg deployment and orientation was tested before launch</li> </ol>	<ol style="list-style-type: none"> <li>1. Servo motor selection can be located in CDR and has been approved by the Payload Design Lead and Chief Engineer</li> <li>2. Test TP2, which outlines proper procedures and success criteria for testing PLS ejection, was successfully passed</li> <li>3. Test TP5, which outlines proper procedures and success criteria for testing PLS leg deployment, was successfully passed</li> <li>4. Test TP6, which outlines proper procedures and success criteria for testing PLS orientation and is readily available for all members</li> </ol>	1	2	2
PV.9	Failure of image receiving hardware, specifically a laptop	<ol style="list-style-type: none"> <li>1. The data file containing the image is corrupted through the process of file transmission</li> <li>2. The competition is unable to process the photo obtained from the PLS</li> <li>3. The PLS sends a photo to the competition viewing platform, however does not save one to its own files</li> </ol>	The image capturing and processing systems are unable to adequately receive and distribute the PLS image	2	3	6	<ol style="list-style-type: none"> <li>1. The file format of the photograph was chosen to be easily viewable</li> <li>2. Image data transmission was tested in order to ensure viability</li> <li>3. The image capture program was tested to ensure a copy of the image is saved upon transmission</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Checklist: Post-Flight Recovery and Analysis outlines a checklist and plan for distributing the final image to competition officials and is readily available for all members</li> <li>2. Test TP3, which outlines proper procedures and success criteria for evaluating transmitted image quality between PLS and a team device, was successfully passed</li> </ol>	1	2	2

### 6.1.2.6 Planetary Landing System Deployment and Integration

**Table 60:** Planetary Landing System Deployment and Integration

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PL1	Nose cone separation failure	Black powder charges do not generate enough force to properly separate the nose cone from the vehicle body	PLS is unable to deploy and exit from the vehicle body payload bay	2	4	8	<ol style="list-style-type: none"> <li>1. The black powder charges and altimeters are designed to be redundant</li> <li>2. Each black powder charge and altimeter combination is entirely independent</li> <li>3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding.</li> </ol>	<ol style="list-style-type: none"> <li>1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to handle any energetics and will obey NAR/TRA guidelines and procedures when doing so</li> <li>2. Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, was successfully passed</li> <li>3. Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, was successfully passed</li> <li>4. Test TR.3, which outlines proper procedures and success criteria for testing black powder separation, was successfully passed</li> <li>5. Test TR.5, which outlines proper procedures and success criteria for testing deployment charge redundancy, was successfully passed</li> </ol>	1	4	4

PI.2	Excessive drag from PLS legs against vehicle body interior	PLS legs deploy while PLS is secure in the vehicle body	<ol style="list-style-type: none"> <li>1. Payload cannot deploy from vehicle body, violating NASA req. 4.3.1</li> <li>2. Total mass under the main parachute is larger than intended resulting a larger descent velocity than intended, potentially violating NASA req. 3.3</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. PLS legs will be restrained during flight by an in-flight locking mechanism</li> <li>2. A jumper cable ejection detection system will disengage the in-flight locking system and inform PLS to rotate legs to landing position only after ejection</li> <li>3. Main parachute was selected to account for a total vehicle mass including the PLS</li> </ol>	<ol style="list-style-type: none"> <li>1. Test TP2, which outlines proper procedures and success criteria for testing PLS ejection, was successfully passed</li> <li>2. Test TP5, which outlines proper procedures and success criteria for testing PLS leg deployment, was successfully passed</li> <li>3. Test TP7, which outlines proper procedures and success criteria for testing PLS retention, was successfully passed</li> <li>4. Calculations and simulations for main parachute size can be found in ?? and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>5. Launch Checklist: Recovery Preparation outlines a checklist and plan for folding, protecting, and insulating the main parachute and is readily available for all members</li> <li>6. Launch Checklist: Vehicle Preparation outlines a checklist and plan for integrating the PLS into the vehicle body prior to launch, including engaging the jumper cable ejection detection system, and is readily available for all members</li> </ol>	1	4	4
PI.3	PLS retention failure	Structural components in the retention mechanism fail during flight	PLS moves freely in the payload bay, potentially damaging internal components or the vehicle and shifting stability margin of the vehicle, potentially violating NASA req. 2.14	3	4	12	<ol style="list-style-type: none"> <li>1. Structural components were designed to adequately secure the PLS in place prior to deployment</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for PLS structural components can be found in Section 4.3.2 and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>2. Test TP7, which outlines proper procedures and success criteria for testing PLS retention, was successfully passed</li> <li>3. Test TV8, which outlines proper procedures and success criteria for testing PLS structural integrity during a vehicle shake test, was successfully passed</li> </ol>	1	4	4

PI.4	PLS parachute fails to properly reduce descent velocity after apogee	<ol style="list-style-type: none"> <li>1. Improperly sized PLS parachute</li> <li>2. PLS parachute is not deployed at 550 ft. AGL</li> <li>3. PLS parachute shroud cords tangle and the PLS parachute chute does not deploy correctly</li> <li>4. Black powder charges damage some or all of the PLS parachute upon deployment</li> </ol>	Nose cone descends with unacceptably high kinetic velocity, violating NASA req. 3.3	3	4	12	<ol style="list-style-type: none"> <li>1. Calculations and simulations have been performed to determine proper PLS parachute size and shape</li> <li>2. Each black powder charge and altimeter combination is redundant and entirely independent, in compliance with NASA req. 3.4</li> <li>3. Altimeters were supplied from trusted vendors and are surrounded by electromagnetic shielding in the vehicle</li> <li>4. Parachute folding is practiced and performed in accordance with manufacturer instructions</li> <li>5. Nomex cloth and insulation is used to protect the parachute from damage</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and simulations for PLS parachute size can be found in CDR and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>2. Test TR.2, which outlines proper procedures and success criteria for testing altimeters shielding, was successfully passed</li> <li>3. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for folding, protecting, and insulating the PLS parachute and is readily available for all members</li> <li>4. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures when doing so</li> </ol>	1	4	4
PI.5	PLS parachute separates from PLS	<ol style="list-style-type: none"> <li>1. Structural component failure due to high loading</li> <li>2. Shock cord failure due to high loading</li> </ol>	<ol style="list-style-type: none"> <li>1. PLS impacts ground at high velocity damaging vehicle and/or personnel</li> <li>2. Damage to PLS due to component failure</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Material, design, and model of structural components were selected based on careful calculations</li> <li>2. Structural components were supplied from a trusted vendor with a history of successful operations</li> </ol>	<ol style="list-style-type: none"> <li>1. Calculations and safety factors for PLS structural components can be located in Section 4.3.2 and have been approved by both the Safety Officer and Chief Engineer</li> <li>2. Test TR.4, which outlines proper procedures and success criteria for testing PLS structural component integrity during a separation ground test and is readily available</li> <li>3. Completed construction of the PLS assembly can be seen in Section 4.5.</li> </ol>	1	4	4
PI.6	Nose cone separation during motor burn	<ol style="list-style-type: none"> <li>1. Shear pins fail prematurely under launch loading</li> <li>2. Incorrect altimeter reading cause premature black powder ignition</li> </ol>	<ol style="list-style-type: none"> <li>1. The PLS would shear causing interior and exterior components to be damaged</li> <li>2. Potential shrapnel and debris seriously injure personnel</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. Shear pins were supplied from a trusted vendor with a history of successful operations</li> <li>2. Shear pins were carefully selected based on calculations</li> <li>3. Altimeters were supplied from trusted vendors and are surrounded by electromagnetic shielding</li> <li>4. Black powder will be properly installed prior to launch</li> </ol>	<ol style="list-style-type: none"> <li>1. Shear pins were selected using verified calculations and a safety factor approved by both the Safety Officer and Chief Engineer</li> <li>2. Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, was successfully passed</li> <li>3. Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, was successfully passed</li> <li>4. Test TR.3, which outlines proper procedures and success criteria for testing black powder separation and is readily available</li> <li>5. Test TR.5, which outlines proper procedures and success criteria for testing deployment charge redundancy and is readily available</li> <li>6. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures</li> </ol>	1	4	4

PI.7	PLS drift exceeds allowed drift radius of 2,500 ft, violating NASA req. 3.10	1. PLS parachute deploys from vehicle body at a higher altitude than 550 ft AGL 2. PLS parachute is too large	1. PLS could cause personnel or property damage while drifting outside the allowable range 2. PLS mission success is compromised due to a landing zone outside the allowable range	3	2	6	1. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding 2. The black powder charges and altimeters are designed to be twice redundant, and entirely independent, in accordance with NASA req 3.4 3. PLS parachute size is based on calculations and simulations	1. Calculations in CDR show the maximum expected drift radius of the PLS is 830 ft, which is within the acceptable range of 2,500 ft 2. Calculations and simulations for PLS parachute size can be found in Section 4.4.2 and have been verified and approved by the Safety Officer and Chief Engineer 3. Test TR.1, which outlines proper procedures and success criteria for testing altimeters battery life, was successfully passed 4. Test TR.2, which outlines proper procedures and success criteria for testing altimeters simulated flight, was successfully passed 5. Test TR.3, which outlines proper procedures and success criteria for testing black powder separation, was successfully passed 6. Test TR.5, which outlines proper procedures and success criteria for testing deployment charge redundancy, was successfully passed 7. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual permitted to install any energetics and will obey NAR/TRA guidelines and procedures when doing so	1	2	2
PI.8	Orientation legs fail to deploy in air during descent	1. Servo motor power failure 2. Servo motor torque insufficient for overcoming opposing forces during descent	1. PLS tips laterally onto the ground due to no leg stability 2. Legs are unable to orient PLS within the acceptable 5° range from vertical	3	2	6	1. PLS legs will not deploy until after the PLS has exited the vehicle body 2. The PLS legs have been tested for deployment in a descent simulation 3. The jumper cable ejection detection system is reliable	1. Test TP2, which outlines proper procedures and success criteria for testing PLS ejection, was successfully passed 2. Test TP5, which outlines proper procedures and success criteria for testing PLS leg deployment, was successfully passed 3. Test TP6, which outlines proper procedures and success criteria for testing PLS orientation and is readily available for all members	1	2	2

### 6.1.2.7 Launch Support Equipment

**Table 61: Launch Support Equipment**

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
LE.1	Launch rail is at an improper angle, violating NASA req. 1.12	1. Launch equipment is improperly set 2. Vehicle is improperly placed on launch pad	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	3	2	6	1. Launch equipment will be set up according to NAR standards 2. The NDRT mentor and RSO recommendations will be followed when setting up the vehicle on the launch pad 3. The angle of the launch rail will be between 0 and 5 degrees from vertical prior to launch	1. The RSO will verify that launch equipment is properly set up in accordance to Section 9 of NAR's High Powered Rocketry Safety Code 2. Launch Checklist: Launch Setup outlines a checklist and plan for aligning the launch pad and rail and setting up the vehicle on the launch rail and is readily available for all members 3. Launch Checklist: Launch Procedures requires approval from NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification), RSO, LCO to proceed with launch	1	2	2
LE.2	Launch controller fails to ignite motor	Wire connection or controller is faulty	Motor does not ignite and flight does not occur	3	2	6	1. An official rocketry club's controllers will be used for all launch operations 2. All launch equipment will be thoroughly inspected prior to use	1. The RSO will verify that launch equipment is properly set up in accordance to Section 9 of NAR's High Powered Rocketry Safety Code 2. The Project Manager and Team Mentor will ensure that only rocketry clubs with reliable and consistent records of successful launches are used for team launches	1	2	2
LE.3	Launch ignition wires are live during set up	Launch controller unit is faulty	Premature motor ignition with potential for damage to vehicle and personnel injury	3	4	12	1. An official rocketry club's controllers will be used in all launch scenarios 2. All launch equipment will be thoroughly inspected prior to use	1. The RSO will verify that launch equipment is properly set up in accordance to Section 9 of NAR's High Powered Rocketry Safety Code 2. The Project Manager and Team Mentor will ensure that only rocketry clubs with reliable and consistent records of successful launches are used for team launches 3. Launch Checklist: Launch Setup outlines a checklist and plan for aligning the launch pad and rail and setting up the vehicle on the launch rail and is readily available for all members 4. Launch Checklist: Launch Procedures requires approval from NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification), RSO, LCO to proceed with launch	1	4	4

### 6.1.3 Environmental Risks

#### 6.1.3.1 Environmental Risks to Vehicle

**Table 62:** Environmental Risks to Vehicle

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
EV.1	Damage to electrical circuits, batteries, and payload electronics	High humidity, rain, or snow causes electric discharge	1. Potential recovery failure 2. Planetary landing system is unable to complete mission 3. Apogee control system is unable to deploy and operate	3	4	12	1. Electronic components are stored in re-sealable electrostatic discharge (ESD) shielding bags before launch 2. Once placed in the launch vehicle, the altimeters for recovery, payload, and apogee control system are shielded in faraday cages	1. Launch Checklist: Recovery Preparation outlines a checklist for safe handling and integration of recovery electronics and is readily available for all members 2. Launch Checklist: Apogee Control System Preparation outlines a checklist for safe handling and integration of ACS electronics and is readily available for all members 3. Launch Checklist: Planetary Landing System Preparation outlines a checklist for safe handling and integration of PLS electronics and is readily available for all members	1	4	4
EV.2	Damage to launch vehicle during assembly and launch preparations	High winds at the launch site	Potential structural damage to launch vehicle, launch equipment, or PLS	3	2	6	1. The static stability margin is less than 3 calipers, per NASA req. 2.14 2. Launch will be postponed if wind speeds exceed 20 miles per hour	1. Calculations for the stability margin of the launch vehicle can be found in 3.9.2 and have been verified and approved by the Safety Officer and Chief Engineer 2. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially wind speed, and is readily available for all members	2	2	4
EV.3	Weather cocking	High winds (greater than 20 mph) at the launch site	Unexpected, and unpredictable, flight path	3	4	12	1. The static stability margin is less than 3 calipers, per NASA req. 2.14 2. Launch will be postponed if wind speeds exceed 20 miles per hour	1. Calculations for the stability margin of the launch vehicle can be found in 3.9.2 and have been verified and approved by the Safety Officer and Chief Engineer 2. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially wind speed, and is readily available for all members	1	4	4

EV.4	Excessive vehicle drift under parachute	High winds (greater than 20 mph) at the launch site	Vehicle lands outside the allowable drift radius, violating NASA req. 3.10, and potentially harming personnel or property in the area	3	2	6	<ol style="list-style-type: none"> <li>The parachute is designed primarily to properly reduce descent velocity, but also limit drift radius when possible</li> <li>Launch will be postponed if wind speeds exceed 20 miles per hour</li> </ol>	<ol style="list-style-type: none"> <li>Calculations and simulations for drogue (??), main (??), nose cone (??), and PLS (CDR Section 4.4.2) parachutes have been verified by the Safety Officer and Chief Engineer</li> <li>Expected drift calculations can be located in CDR and have been verified and approved by the Safety Officer and Chief Engineer</li> <li>Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially wind speed</li> </ol>	1	2	2
EV.5	Unexpected loss of battery charge	Cold temperatures	Loss of power to electronics in the vehicle	2	4	8	<ol style="list-style-type: none"> <li>Batteries are stored in a temperature-controlled environment until installation during assembly</li> <li>Batteries are required to be fully charged prior to transportation to launch site</li> <li>Batteries are not charged at temperatures below freezing (32°F)</li> <li>Multiple batteries must be packed for launch in case a battery loses charge</li> <li>The launch vehicle is assembled in a manner which allows electronics to be installed immediately prior to launch</li> <li>Launch will not occur if the RSO deems the temperature to be too cold</li> </ol>	<ol style="list-style-type: none"> <li>Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially wind speed</li> <li>Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop</li> <li>Launch Checklist: Packing List outlines a packing list for all vehicle components, including extra charged batteries</li> <li>Launch Checklist: Packing List outlines a checklist and plan for testing batteries with a multimeter prior to launch</li> <li>Launch Checklist: Packing List outlines a checklist and plan for installing and arming PLS electronics into the vehicle</li> </ol>	1	2	2
EV.6	Weakening of Bonding Materials	Humidity, Rain, and Heat	<ol style="list-style-type: none"> <li>Bulkhead failure</li> <li>Shifting interior components</li> <li>Changes to static stability margin, potentially violating NASA req. 2.14</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>All adhesives have been purchased from reputable vendors with past success in high-load scenarios</li> <li>Structures with bonding materials such as epoxy are kept in dry, cool environments until assembly when possible</li> <li>Bonding materials are allowed to set and cure for the maximum necessary curing time before launch day</li> <li>Team members working with adhesives have been provided step-by-step procedures for safe operation</li> <li>Important material properties are listed in the NDRT Safety Data Sheet Document</li> </ol>	<ol style="list-style-type: none"> <li>Standard Operating Procedure 2.3.1 outlines the correct procedure for epoxying</li> <li>NDRT Safety Data Sheet Document Sections 4.12, 4.15, and 4.16 contains the SDS documents for multiple bonding materials in the NDRT Workshop, and is readily available for all members</li> </ol>	1	3	3

EV.7	Wetting of launch vehicle propulsion materials	High humidity, contact with swampy ground, snow, rain	Complete or partial failure to ignite motor	3	2	6	<ol style="list-style-type: none"> <li>1. Motors stored by the team mentor in protective case until integration</li> <li>2. Motors are stored with silica gel desiccant for moisture absorption in event that water enters the bag</li> </ol>	<ol style="list-style-type: none"> <li>1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) is the only individual able to store and handle motors and will obey NAR/TRA guidelines and procedures when doing so</li> </ol>	1	3	3
EV.8	Electronics UV exposure	Long exposure to sunlight	Potentially severe damage to electronics and sensors within the launch vehicle	2	4	8	<ol style="list-style-type: none"> <li>1. Electronics are stored in ESD bags, which reflect UV rays, before assembly</li> <li>2. All electronics will not be exposed to direct sunlight once integrated into vehicle</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation List outline checklists and plans for setting up electronic systems on launch day, and is readily available for all members</li> <li>2. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing electronics in the vehicle, and is readily available for all members</li> </ol>	1	4	4
EV.9	Blunt Force Damage to Vehicle	Hail	<ol style="list-style-type: none"> <li>1. Vehicle geometry is altered resulting in changed flight dynamics</li> <li>2. Structural integrity of the vehicle is compromised, points of high stress created along the length of the vehicle</li> </ol>	2	3	6	<ol style="list-style-type: none"> <li>1. All adhesives have been approved for strength and reliability</li> <li>2. All adhesives have been purchased from reputable vendors with past success in high-load scenarios</li> <li>3. Structures with bonding materials such as epoxy are kept in dry, cool environments until assembly at the launch site</li> <li>4. Launch will not occur if the RSO deems the weather to be unfavorable, especially in the event of precipitation</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially wind speed, and is readily available for all members</li> <li>2. The RSO will have full authority on when launches may proceed</li> </ol>	1	1	1
EV.10	Animal Interference	Local animal population in and around the launch site	<ol style="list-style-type: none"> <li>1. Potential structural damage to the launch vehicle before or after flight</li> <li>2. Potential injury or death to nearby animals</li> </ol>	3	2	6	<ol style="list-style-type: none"> <li>1. Launches will occur in an open field away from any animals</li> </ol>	<ol style="list-style-type: none"> <li>1. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, including checking for wildlife, and is readily available for all members</li> </ol>	2	1	2

EV.11	Structural components change geometry due to swelling	Humidity or temperature changes	Components do not fit together properly, causing difficulty in assembly	2	3	6	1. Parts have been transported in a safe manner before assembly and construction 2. Tools brought to launch can be used to make minor adjustments, if absolutely necessary, so that parts fit properly together	1. Launch Checklists: Packing List outlines a packing list for launch, including necessary tools and equipment 2. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for assembling the vehicle on launch day 3. Launch Checklists: Packing List outlines a checklist and plan for storing components prior to integration in the vehicle	1	2	2
EV.12	Launch pad is not level	Soft or uneven ground under launch pad	1. Apogee is less than the target of 5300 ft 2. Moment acting on the vehicle is greater than expected, altering flight direction	3	3	9	1. A level has been used to ensure launch pad is even with respect to the ground	1. Launch Checklist: Launch Setup outlines a checklist and plan for setting up launch equipment, specifically launch pad and rail, and is readily available for all members	1	1	1
EV.13	Poor visibility of vehicle during flight	Low cloud cover	Failure of team to track flight path, leading to potential loss of vehicle	3	4	12	1. Launch will not occur when cloud cover prohibits the team from maintaining sight of the vehicle during the entire flight	1. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially cloud cover, and is readily available for all members 2. The RSO will have full authority on when launches may proceed	1	3	3
EV.14	Vehicle landing in trees	1. Trees in launch area 2. Vehicle drift exceeds allowed drift radius, violating NASA req. 3.10	Loss or damage of vehicle and/or payload components	3	4	12	1. Main and drogue parachute sizing is based on calculations and flight simulations 2. Launches will occur in an open field away from any trees	1. Calculations in CDR show the maximum possible simulated drift of the vehicle is 2,397 ft, which is within the acceptable range of 2,500 ft (NASA Req 3.10) 2. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially launch area terrain	1	3	3
EV.15	Wireless Signal Interference	Fog, trees, or other teams	Disrupted communication between systems	3	4	12	1. Launch will not occur when fog or landscape prohibits the transmitters from operating properly during the entire flight 2. All transmission frequencies have been reported prior to flight 3. Transmitters have been tested prior to launch 4. Electronics are transported in ESD bags unless assembly	1. All transmitter frequencies have been reported to NASA prior to launch and compared to other devices at the launch site 2. Test TP3 outlines proper procedures and success criteria for testing image transmission between PLS and a team device 3. Test TR.7 outlines proper procedures and success criteria for testing GPS transmitters 4. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially cloud and fog cover members 5. The RSO will have full authority on when launches may proceed	1	4	4

### 6.1.3.2 Vehicle Risks to Environment

**Table 63:** Vehicle Risks to Environment

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VE.1	Airborne fiberglass particulates (styrene gas)	Sanding of bulkhead or other fiberglass materials inside launch vehicle	1. Emission of toxins depletes local air quality 2. Contaminating land used for agriculture	3	4	12	1. Quantity of styrene gas produced in environment will be minimal so as to make effects on personnel or environment negligible 2. Components that require possible sanding, and styrene gas production, will be made clear in step-by-step fabrication procedures 3. All potential styrene gas production will be completed in a space with capable ventilation and air filtration 4. Important material properties are listed in the NDRT Safety Data Sheet Document	1. All members participating in construction have passed a Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Construction procedures outlining proper steps for sanding fiberglass materials will be created and made readily available 3. NDRT Safety Data Sheet Document Section 4.10 contains the Fiberglass G10 SDS, and is readily available for all members	1	3	3
VE.2	Excessive Carbon Dioxide emission	1. Motor and black powder charges in the recovery system will produce carbon dioxide emissions when ignited	Increased levels of carbon emissions contributes to expedited climate change	5	2	10	1. Carbon dioxide emissions from the motor and black powder charges will be minimal so as to make effects on environment negligible 2. Motor propellant safety documentation will be kept available for team members 3. Black powder safety documentation will be kept available for team members	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will inspect all motors and energetics before use and will obey NAR/TRA guidelines and procedures 2. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be the only individual to install any motors or energetics and will obey NAR/TRA guidelines and procedures 3. NDRT Safety Data Sheet Document Section 4.4 and 4.6 contain the Black Powder and Cesaroni L1395 Safety Data Sheets, respectively.	5	1	5

VE.3	Hydrogen Chloride emission	Ammonium perchlorate motor produces hydrogen chloride	Hydrogen chloride reacts with water to form hydrochloric acid leading to contaminated water and habitat	3	2	6	<p>1. Hydrogen Chloride emissions from black powder charges will be minimal so as to make effects on environment negligible</p> <p>2. Motor propellant safety documentation will be kept available for team members</p>	<p>1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will inspect all motors and energetics before use and will obey NAR/TRA guidelines and procedures when doing so</p> <p>2. NDRT Safety Data Sheet Document Section 4.6 contains the Cesaroni L1395 Motor Propellant SDS, and is readily available for all members</p> <p>3. The RSO will ensure the launch site located so as to leave no trace on surrounding wildlife habitats or water sources</p>	3	1	3
VE.4	Components detach from vehicle	Components within vehicle are improperly secured	<p>1. Wildlife could ingest small components</p> <p>2. Wildlife could be harmed by sharp or abrasive materials</p> <p>3. Crops could be harmed or destroyed on agricultural land surrounding launch site</p>	3	3	9	<p>1. Components in the vehicle were designed to be secured using fasteners, adhesives, shear pins, or twist-to-lock mechanisms</p> <p>2. Vehicle was tested to ensure components do not detach during launch or induced vibrations</p> <p>3. Recovery hardware was tested to ensure components do not detach during separation, descent, or induced vibrations</p>	<p>1. Calculations and simulations for vehicle structural components(Section 3.2) and recovery structural components (Section ??) have been approved by both the Safety Officer and Chief Engineer</p> <p>2. Calculations and simulations for the ACS twist-to-lock mechanisms can be located in CDR and have been approved by both the Safety Officer and Chief Engineer</p> <p>3. Test TR.3 outlines proper procedures and success criteria for testing recovery structural integrity during a separation ground test and is readily available for all members</p> <p>4. Test TV.1 outlines proper procedures and success criteria for testing vehicle structural integrity during a bulkhead assembly strength test and is readily available for all members</p> <p>5. Test TV.5 outlines proper procedures and success criteria for testing vehicle structural integrity during a shake test and is readily available for all members</p> <p>6. Detailed CAD models and drawings were used to accurately assembling the launch vehicle, and were created prior to initiating construction</p> <p>7. Detailed CAD models and drawings were used to accurately assemble the CRAS-S and CRAS-M, and were created prior to initiating construction</p>	1	2	2

VE.5	Battery acid leak	Battery ruptured by sharp object or impact	<p>1. Battery acid contaminates soil</p> <p>2. Battery acid contaminates groundwater</p> <p>3. Contaminating land used for agriculture</p>	2	4	8	<p>1. Batteries will be housed in battery bag when not in use</p> <p>2. All batteries will be thoroughly inspected before being placed in the vehicle</p> <p>3. Batteries will be properly installed in the vehicle assembly</p> <p>4. Battery safety documentation will be kept available for team members</p>	<p>1. Launch Checklist: Packing List outlines a checklist and plan for storing and transporting batteries and is readily available for all members</p> <p>2. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outline checklists and plans for testing batteries with a multimeter prior to launch and is readily available for all members</p> <p>3. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outlines a checklist and plan for installing batteries into sub-systems and is readily available for all members</p> <p>4. NDRT Safety Data Sheet Document Section 4.13 contains the Lithium Polymer Battery SDS, and is readily available for all members</p>	1	4	4
VE.6	Paint chips off of vehicle body during transportation or flight	Paint is used to design the exterior of the vehicle	<p>1. Paint chips scatter in the local area, becoming a danger to wildlife through ingestion</p> <p>2. Contaminating land used for agriculture</p>	2	2	4	<p>1. Quantity of paint contaminated in the environment will be minimal so as to make effects on personnel or environment negligible</p> <p>2. Painting will be done professionally in a licensed paint shop with appropriate coatings</p> <p>3. Motor propellant safety documentation will be kept available for team members</p> <p>4. Vehicle exterior was tested for paint loss from impact</p>	<p>1. All professional paint shops must licensed vendors with proper certifications</p> <p>2. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for safely transporting the vehicle and is readily available for all members</p> <p>3. Test TV.3 outlines proper procedures and success criteria for testing paint loss during a fin impact test and is readily available for all members</p> <p>4. Test TV.4 outlines proper procedures and success criteria for testing paint loss during a nose cone impact test and is readily available for all members</p> <p>5. The vehicle has been professionally painted by a licensed paint shop</p> <p>6. NDRT Safety Data Sheet Document Section 4.1 contains the Acrylic Enamel Paint SDS, and is readily available for all members</p>	1	1	1

VE.7	Plastic Waste	Prototyping and subscale construction use plastic due to lost cost and high functionality	1. Wildlife could potentially ingest or be harmed by plastic 2. Contaminating agricultural land 3. Plastics disposed in a landfill can take over 1,000 years to decompose	4	3	12	1. When possible, all plastics will be disposed of properly according to local recycling guidelines to avoid landfill contribution 2. If recycling is not an option,, all plastics will be disposed of properly according to local landfill guidelines 3. All members completing construction using plastics will minimize plastic waste	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. A recycling bin will always be present in the team workshop, and the NDRT Workshop Safety Agreement requires team members to prioritize recycling when possible 3. The NDRT Safety Handbook is readily available for all members 4. The NDRT Safety Data Sheet Document is readily available for all members	2	1	2
VE.8	Wire Waste	Wires are used as connections in all electrical components	1. Wildlife could potentially ingest or be harmed by wires 2. Contaminating agricultural land 3. Electronics disposed in a landfill may never fully decompose	4	3	12	1. When possible, wires will be disposed of properly according to local recycling guidelines to avoid landfill contribution 2. If recycling is not an option, wires will be disposed of properly according to local landfill guidelines 3. All members completing construction using wires will minimize plastic waste	1. All members participating in construction have passed a Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. A recycling bin will always be present in the team workshop, and the NDRT Workshop Safety Agreement requires team members to prioritize recycling when possible 3. Proper procedures outlining steps for disposing of wire waste have been created and are available in the team workshop	2	1	2
VE.9	Solder Waste	Solder is used to secure wire connections in many electrical components	1. Wildlife could potentially ingest or be harmed by solder 2. Contaminating land used for agriculture 3. Electronics disposed in a landfill may never fully decompose	4	3	12	1. When possible, solder will be disposed of properly according to local recycling guidelines to avoid landfill contribution 2. If recycling is not an option, solder will be disposed of properly according to local landfill guidelines 3. All members completing construction using solder will minimize solder waste 4. When possible, alternative wire connection mechanisms will be used instead of solder, such as lever wire connectors	1. All members participating in construction have passed a Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement 2. A recycling bin will always be present in the team workshop, and the NDRT Workshop Safety Agreement requires team members to prioritize recycling when possible 3. Proper procedures for operating a soldering iron and disposing of consequent solder waste will be created and are readily available for all members 4. The NDRT Safety Handbook is readily available for all members 5. The NDRT Safety Data Sheet Document is readily available for all members	2	1	2

VE.10	Fire	<ol style="list-style-type: none"> <li>1. Motor burnout</li> <li>2. Electrical components short circuit</li> </ol>	<ol style="list-style-type: none"> <li>1. Damage to surrounding vegetation</li> <li>2. Damage to animals' natural habitats</li> <li>3. Greenhouse emissions as a result of combustion</li> <li>4. Destroying land used for agriculture</li> </ol>	2	4	8	<ol style="list-style-type: none"> <li>1. Motor will be installed by a qualified individual with proper NAR/TRA certifications</li> <li>2. Fire extinguishers will be included on the launch checklists to be packed for launch</li> <li>3. All electronics will be carefully inspected prior to launch</li> <li>4. All electronics will remain OFF until power is necessary for mission success</li> <li>5. The launch pad will be positioned in a location free of debris or flammable objects</li> </ol>	<ol style="list-style-type: none"> <li>1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will inspect all motors and energetics before use</li> <li>2. Launch Checklist: Packing List outlines a packing list for all necessary launch materials, including fire extinguishers</li> <li>3. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outline checklist and plans for testing electronics with a multimeter prior to launch</li> <li>4. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outline checklists and plans for installing ACS, recovery, and PLS electronics into the vehicle</li> <li>5. The RSO will designate staging zones at least 300 ft from the launch pad</li> </ol>	1	4	4
VE.11	High velocity impact, in violation of NASA req. 3.3	<ol style="list-style-type: none"> <li>1. High wind speeds cause vehicle to enter an unexpected trajectory flight path</li> <li>2. Recovery fails to properly reduce vehicle descent velocity</li> </ol>	<ol style="list-style-type: none"> <li>1. Damage to nearby personnel or property</li> <li>2. Damage to power lines leading to potential fires</li> <li>3. Destroying habitats or injuring wildlife in the area</li> <li>4. Destroying land used for agriculture</li> </ol>	3	4	12	<ol style="list-style-type: none"> <li>1. The motor will be installed correctly and carefully</li> <li>2. The launch rail will be inspected prior to launch</li> <li>3. The recovery system is designed to be reliable and redundant for all separations, in accordance with NASA req. 3.4</li> <li>4. The recovery system was tested to ensure reliability and redundancy for all separations</li> <li>5. Personnel will stand at least 300 ft. from the launch pad to view the launch as required by the NAR</li> </ol>	<ol style="list-style-type: none"> <li>1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so</li> <li>2. The chosen motor has been sourced from a trusted vendor and been approved by the Vehicles Design Lead and Chief Engineer</li> <li>3. Launch Checklist outlines a checklist and plan for installing the motor into the vehicle body (Motor Preparation), and inspecting and setting up launch equipment (Launch Setup)</li> <li>4. Recovery design can be located in Section 3.5.5 and has been approved by the Chief Engineer and Safety Officer</li> <li>5. Proper procedures and success criteria for testing: altimeter battery life (TR.1), altimeter simulated flight (TR.2), Separation (TR.3), and charge redundancy (TR.5) have been made</li> <li>6. The Range Safety Officer will designate safe staging zones at least 300 ft from the launch pad, in accordance with NAR specifications</li> </ol>	1	4	4

VE.12	Noise Impact	Excessive noise generation from the launch vehicle's motor on launch or from team during launch operations	Noise could permanently harm wildlife, bystanders, and nearby structures	1	4	4	1. Noise produced will be temporary and will not exceed EPA regulations, as stipulated by the Noise Control Act of 1972 (42 U.S.C §4901 et. seq.)	1. Launch Checklist: Launch Setup outlines a checklist and plan for inspecting the launch site and ensuring no wildlife are in the area and is readily available for all members 2. The Range Safety Officer will designate safe staging zones at least 300 ft from the launch pad, in accordance with NAR specifications 3. The Rocketry Association will affirm that it maintains the correct noise permits to launch at the site prior to launch day	1	2	2
VE.13	Vehicle and PLS debris	Motor explosion during flight	1. Sharp or abrasive debris can harm wildlife 2. Small components could be ingested by wildlife 3. Contamination of agricultural land	2	4	8	1. The motor will be installed correctly and carefully 2. The launch rail will be inspected prior to launch 3. Personnel will stand at least 300 ft. from the launch pad to view the launch as required by the NAR	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 3 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. The chosen motor has been sourced from a trusted vendor and been approved by the Vehicles Design Lead and Chief Engineer 3. Launch Checklist: Motor Preparation outlines a checklist and plan for installing the motor into the vehicle body 4. Launch Checklist: Launch Setup outlines a checklist and plan for inspecting and setting up launch equipment 5. The Range Safety Officer will designate safe staging zones at least 300 ft from the launch pad, in accordance with NAR specifications	1	4	4

## 6.2 Project Plan Risk Analysis

**Table 64:** Project Risks

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PR.1	Complete destruction or loss of full scale or subscale vehicle	1. Uncontrolled descent 2. Energetics improperly installed or used	Team must build an entirely new vehicle causing project delays and doubling the costs of the project	2	4	8	1. All components have been tested individually prior to full-scale assembly 2. Detailed CAD models and drawings were used to accurately manufacture all systems and were created prior to initiating construction	1. A complete test operation plan can be found in Section 7.1 2. Complete construction of the launch vehicle, recovery system, ACS, and PLS can be located in Sections 3.3.2, ?? 3.4.3.2, and 4.5, respectively	1	4	4
PR.2	Failure to conduct subscale flight by January 4th and/or vehicle demonstration flight by March 8th	1. Poor weather conditions 2. Incomplete construction 3. Failure to schedule a launch date that is suitable for both the team and mentor	Inability to participate in competition	2	3	6	1. Multiple dates and locations have been chosen for flights to provide the team with multiple options 2. The team has implemented a Technology Readiness Level schedule to ensure that all subsystems are meeting each deadline comfortably 3. The team intends to launch on the first available date for subscale and demonstration flights.	1. The team has completed a subscale flight on November 13th in order to meet the subscale flight deadline 2. The team has chosen demonstration flights on February 13th and 20th in order to meet the vehicle demonstration flight deadline. 3. The team uses a Gantt chart to track TRLs of individual subsystems in order to identify potential obstacles prior to deadlines. 4. The team began subscale construction two weeks prior to subscale flight. 5. The team began full scale construction more than two weeks prior to the first potential demonstration flight date.	1	3	3
PR.3	Lack of funds/ exceeding budget	1. Allocation of funds to a subsystem is insufficient 2. Parts are not properly sourced	Team takes on debt or funds from travel or other subsystems diminish	3	3	9	1. The allocation of funds has been based off of previous years' spending and designs 2. Parts have been sourced to find the best combination of quality and cost 3. Each purchased part was considered from at least three vendors when possible	1. To limit excessive spending from the team account, the team card will have a spending cap of \$2500 which can be replenished given a request to department administrators 2. Team members submit their receipts and report all purchases to ensure all spending is properly tracked	2	2	4

PR.4	Shipping/ manufacturing delays from vendors	1. Parts have an anticipated arrival date in direct conflict with team deadlines 2. The shipped part is incorrect or does not meet the team needs	Project delays and/or mission failure	3	3	9	1. Custom parts have been ordered in advance to avoid project delays and large shipping costs 2. Extra components were ordered in the event a custom part is defective 3. NDRT has compiled a trusted vendor list to ensure quality of parts	1. All custom parts have been ordered before December 15 2. Design leads have ordered additional stock material if they determined additional stock was required 3. All team members ordering parts have consulted the trusted vendor document 4. All purchases from new vendors have been approved by the Project Manager and Chief Engineer	2	2	4
PR.5	Team member leaves team	1. Injury or illness 2. Covid-19 quarantine or isolation 3. Member prioritizes other commitments	Project delays and/or incomplete work	4	2	8	1. Multiple team members have been assigned to the same task to ensure completion 2. Multiple team members have been made aware of the details and expectations of each task	1. All progress of designs and tests have been, and will continue to be, well documented in a team Google Drive in the event a reallocation of tasks occurs	2	1	2
PR.6	Safety violations	1. Insufficient PPE 2. Insufficient training	Injury to personnel and the potential revocation of workshop space	3	3	9	1. PPE will always be stocked and made readily available in the workshop and a part of the Safety budget 2. All personnel participating in construction have been certified in the Student Fabrication Lab according to university regulations. 3. All personnel must initial and sign the Workshop Safety Agreement, acknowledging all team safety rules	1. The Safety Officer has taken inventory of PPE in the workshop on a bi-weekly schedule, and additional times prior to construction 2. Additional PPE has been ordered by November 11th to ensure a delivery date prior to the team returning to University of Notre Dame's campus for the Spring semester 3. Students must confirm their completion of Student Fabrication Lab training before entering the workshop to participate in construction	1	3	3
PR.7	Insufficient materials and parts to fully complete construction	1. Parts to complete the project are not ordered	Project delays or inability to complete the competition	2	4	8	1. Personnel have made an itemized list of machined and commercially sourced parts in their designs.	1. Construction assembly procedures will provide a list of all parts required to be ordered and machined 2. Detailed CAD drawings include full assemblies with all required parts 3. The construction operation plan details all parts required to be fabricated prior to the demonstration flight	1	4	4
PR.8	Violation of FAA by exceeding approved altitude	1. Launch site does not have proper waiver for the team's altitude requirement	Potential legal action	2	3	6	1. The team have not and will not use any launch sites without a proper FAA waiver	1. NDRT leadership will confirm with prospective launch sites one week prior to launch that the proper waiver has been attained for NDRT's selected altitude of 5300 ft.	1	3	3

PR.9	Improper testing equipment	<ol style="list-style-type: none"> <li>1. Equipment does not perform to standards</li> <li>2. Inability to use University resources for complex testing</li> <li>3. Restriction on lab access due to Covid-19 regulations</li> </ol>	Incorrect or missing data could lead to faulty analyses and/or design decisions	3	2	6	<ol style="list-style-type: none"> <li>1. The team will confirm all tests with calculated results and simulations.</li> <li>2. The team has reached out to applicable test facilities early to ensure lab time and comply with regulations at each facility.</li> <li>3. The team will work with campus resources to perform tests in spaces that are restricted to full-time researchers</li> </ol>	<ol style="list-style-type: none"> <li>1. The test operation plan contains all test results and was shared with the team upon completion</li> <li>2. All test procedures are readily available for all members</li> <li>3. The team has reached out to all applicable test facilities to date to schedule testing times if available</li> </ol>	1	2	2
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## 6.3 Launch Operations Procedures

## 6.4 Vehicle Demonstration Flight

### 6.4.1 Packing List



### STANDARD LAUNCH PROCEDURE

### VEHICLE DEMONSTRATION CHECKLIST

### PRE-DEPARTURE PACKING LIST

### Required Personnel

**NAR/TRA Level 3 Certified Launch Manager (LM):** Dave Brunsting

**Safety Officer (SO):** Jacob Shapiro

**Project Manager (PM):** Brooke Mumma

**Chief Engineer (CE):** Joseph Sutton

**Vehicles Lead (VL):** Benjamin Tompoles

**ACS Lead (AL):** Patrick Faley

**Recovery Lead (RL):** Katherine Fink

**PLS Lead (PL):** Estefania Castillo Villarreal

If absolutely necessary, a qualified team member may assume the duties of a design lead given approval by the Safety Officer and applicable Design Lead.

**Note:** Handle All Equipment With Care! Store in cars and/or toolboxes until assembly or use is required.

### PERSONAL PROTECTIVE EQUIPMENT

PM: \_\_\_\_\_ SO: \_\_\_\_\_

- |   |  |  |
|---|--|--|
| <input type="checkbox"/> Box of nitrile gloves        | <input type="checkbox"/> Fire resistant battery bags | <input type="checkbox"/> Pair of heat resistant gloves |
| <input type="checkbox"/> Pair of cut resistant gloves | <input type="checkbox"/> Dust masks                  | <input type="checkbox"/> Leather gloves                |
| <input type="checkbox"/> First aid kit                | <input type="checkbox"/> Safety glasses              |  |

### TOOLS

PM: \_\_\_\_\_ SO: \_\_\_\_\_

- |  |   |  |
|--|---|--|
| <input type="checkbox"/> 1 hand drill, fully charged | <input type="checkbox"/> Drill bit case with standard range of bits | <input type="checkbox"/> Standard wrenches       |
|  |   | <input type="checkbox"/> Standard Allen wrenches |

- |  |   |  |
|--|---|--|
| <input type="checkbox"/> Screwdriver set       | <input type="checkbox"/> Exacto knives    | <input type="checkbox"/> Needlenose pliers |
| <input type="checkbox"/> Scissors              | <input type="checkbox"/> Metal files      | <input type="checkbox"/> Dial caliper      |
| <input type="checkbox"/> Butane soldering iron | <input type="checkbox"/> Wire cutters     | <input type="checkbox"/> Tape measure      |
| <input type="checkbox"/> Butane gas canister   | <input type="checkbox"/> Wire strippers   |  |
| <input type="checkbox"/> Digital multimeter    | <input type="checkbox"/> Bluntnose pliers |  |

**GENERAL EQUIPMENT**

PM: \_\_\_\_\_ SO: \_\_\_\_\_

- |   |   |   |
|---|---|---|
| <input type="checkbox"/> Electrical tape    | <input type="checkbox"/> Garbage bags                   | <input type="checkbox"/> Pens/pencils                     |
| <input type="checkbox"/> Duct tape          | <input type="checkbox"/> Wooden vehicle support stand   | <input type="checkbox"/> Assorted screws, bolts, and nuts |
| <input type="checkbox"/> Masking tape       | <input type="checkbox"/> PVC vehicle support stands (2) | <input type="checkbox"/> Sandpaper                        |
| <input type="checkbox"/> Folding tables (2) | <input type="checkbox"/> JB Weld 5 Minute Epoxy         | <input type="checkbox"/> Epoxy applicators                |
| <input type="checkbox"/> Scale              | <input type="checkbox"/> Lead solder                    | <input type="checkbox"/> Extra wire spool                 |
| <input type="checkbox"/> Tarp               |   |   |

**VEHICLE EQUIPMENT**

VL: \_\_\_\_\_ SO: \_\_\_\_\_

- |   |  |   |
|---|--|---|
| <input type="checkbox"/> Nose cone              | <input type="checkbox"/> Fin can and boattail assembly | <input type="checkbox"/> Motor retention cap      |
| <input type="checkbox"/> Payload tube assembly  | <input type="checkbox"/> Shear pins                    | <input type="checkbox"/> Camera                   |
| <input type="checkbox"/> Recovery tube assembly | <input type="checkbox"/> Motor casing                  | <input type="checkbox"/> Camera shroud lock piece |

**ACS EQUIPMENT**

AL: \_\_\_\_\_ SO: \_\_\_\_\_

- |  |   |   |
|--|---|---|
| <input type="checkbox"/> Assembled ACS structure | <input type="checkbox"/> 6-32 nylon screws                            | <input type="checkbox"/> Turnigy 2000 mAh battery charger |
| <input type="checkbox"/> ACS electronics toolbox | <input type="checkbox"/> 6-32 nylon lock nuts                         | <input type="checkbox"/> Fully charged laptop             |
| <input type="checkbox"/> Fire-proof battery case | <input type="checkbox"/> 10-32 nylon lock nuts                        | <input type="checkbox"/> Extra ballast mass               |
| <input type="checkbox"/> 10-32 nylon screws      | <input type="checkbox"/> Fully charged Turnigy 2000 mAh batteries (2) |   |

**RECOVERY EQUIPMENT**

RL: \_\_\_\_\_ SO: \_\_\_\_\_

- |   |   |  |
|---|---|--|
| <input type="checkbox"/> Assembled CRAS-M structure | <input type="checkbox"/> Featherweight Raven3 altimeter (1) | <input type="checkbox"/> altimeters (2)                      |
| <input type="checkbox"/> Assembled CRAS-S structure | <input type="checkbox"/> Stratologger SL100 altimeters (2)  | <input type="checkbox"/> Fully Charged 170 mAh batteries (6) |
| <input type="checkbox"/> Power switch keys (2)      | <input type="checkbox"/> Stratologger CF                    | <input type="checkbox"/> 170 mAh battery charger             |
|   |   | <input type="checkbox"/> Assembled altimeter                 |

- |  |   |   |
|--|---|---|
| <input type="checkbox"/> perfboards  | <input type="checkbox"/> 12 ft parabolic Rocketman main parachute     | <input type="checkbox"/> Sealing clay   |
| <input type="checkbox"/> Box of E-matches                                  | <input type="checkbox"/> 2 ft parabolic Rocketman drogue parachute    | <input type="checkbox"/> Fully charged laptop with Featherweight Interface Program and Perfectflite DataCap installed |
| <input type="checkbox"/> 1/4 in eyebolts (2)                               | <input type="checkbox"/> 2 ft parabolic Rocketman nose cone parachute | <input type="checkbox"/> Data cable for Raven altimeters  |
| <input type="checkbox"/> 3/8 in eyebolts (2)                               | <input type="checkbox"/> Main Parachute Deployment Bag                | <input type="checkbox"/> Data cable for Stratologger altimeter  |
| <input type="checkbox"/> 3/8 in quick links (4)                            | <input type="checkbox"/> 24 in Nomex blankets (2)                     |   |
| <input type="checkbox"/> 3/16 in quick links (5)                           |   |   |
| <input type="checkbox"/> 35 ft long 3/4 in diameter tubular nylon harness  |   |   |
| <input type="checkbox"/> 25 ft long 1/4 in diameter tubular kevlar harness |   |   |

**PLS EQUIPMENT**

PL: \_\_\_\_\_ SO: \_\_\_\_\_

- |   |  |   |
|---|--|---|
| <input type="checkbox"/> Assembled PLS vehicle                      | <input type="checkbox"/> Jumper cable                                | <input type="checkbox"/> kevlar harness       |
| <input type="checkbox"/> Full charged lithium polymer batteries (2) | <input type="checkbox"/> 4 ft elliptical Fruity Chutes PLS parachute | <input type="checkbox"/> 3/16 in quick link   |
| <input type="checkbox"/> Battery charger                            | <input type="checkbox"/> 1/4 in diameter tubular                     | <input type="checkbox"/> Fully charged laptop |
|   |  | <input type="checkbox"/> Extra ballast mass   |

**LAUNCH MANAGER-HANDLED EQUIPMENT**

LM: \_\_\_\_\_ SO: \_\_\_\_\_

Note: Confirmation with Launch Manager must occur at least 1 week prior to launch date

- |  |  |   |
|--|--|---|
| <input type="checkbox"/> Cesaroni L1395 Blue | <input type="checkbox"/> Streak Rocket Motor (3) | <input type="checkbox"/> 120 g black powder |
|--|--|---|

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

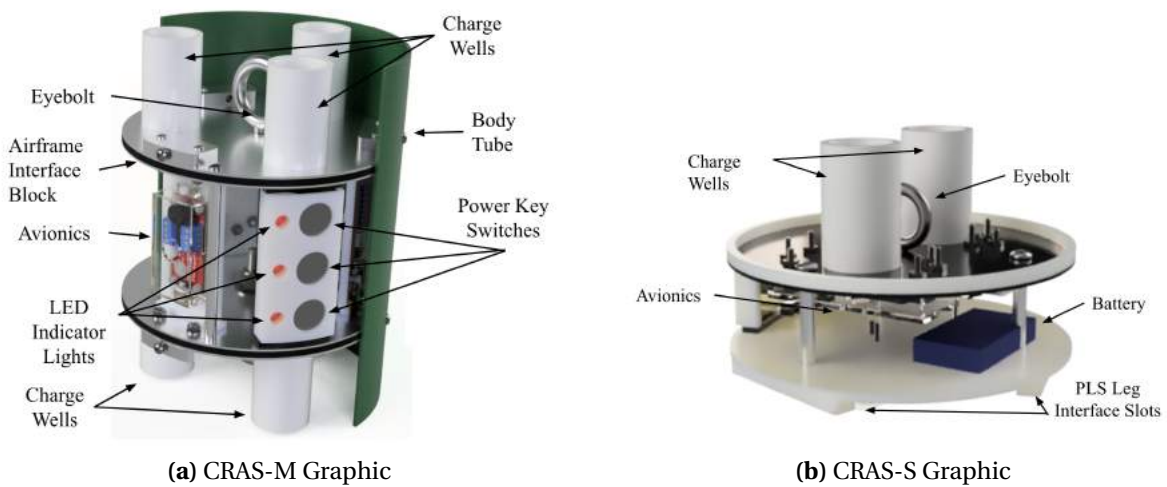
6.4.2 Recovery Preparation



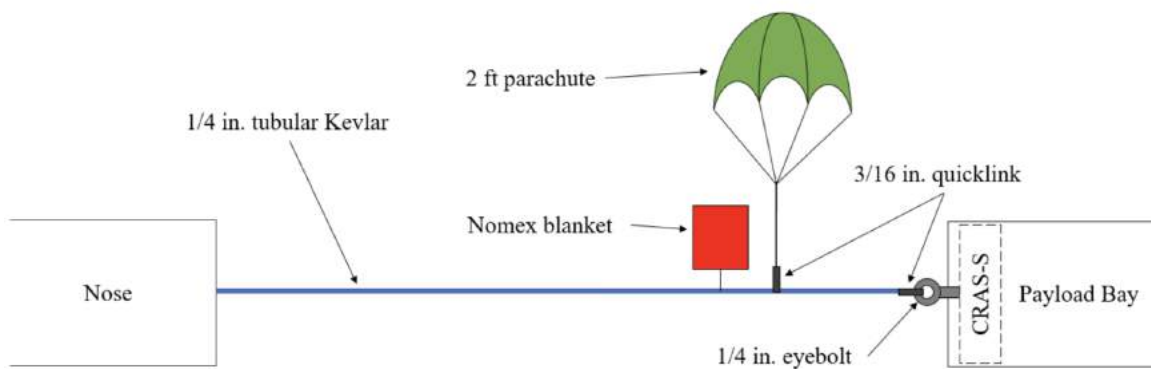
**STANDARD LAUNCH PROCEDURE  
VEHICLE DEMONSTRATION CHECKLIST  
RECOVERY PREPARATION**

**Required Personnel:** Recovery Lead, Safety Officer, Launch Manager

**Required PPE:** Leather gloves, Nitrile gloves, Safety glasses



**Figure 68:** Recovery Avionics Systems

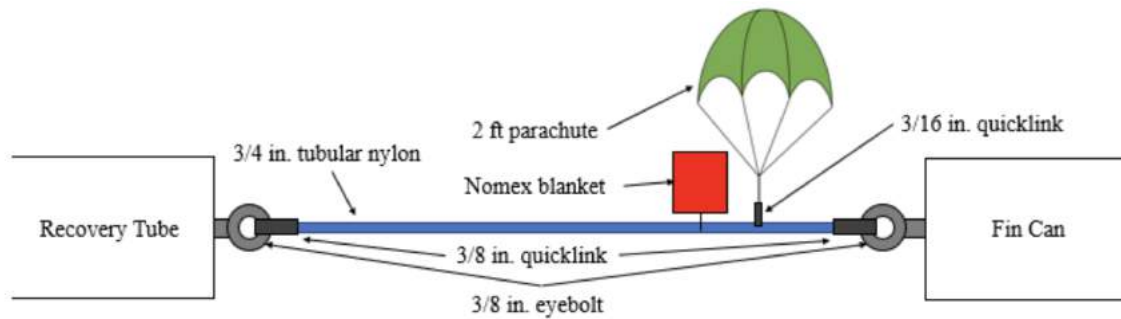


**Figure 69:** Nose Cone Parachute Layout

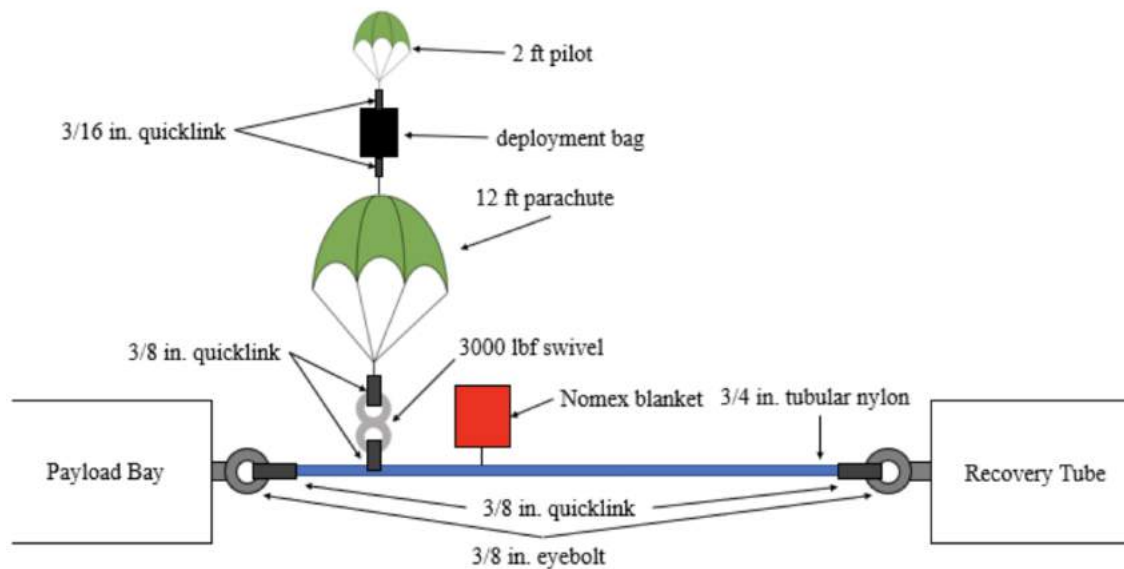
**INSPECTION**

RL: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps could result in the following failure modes: R.1 - R.13, VS.3, VS.9, or an unidentified failure mode and thus a failed launch.**



**Figure 70: Drogue Parachute Layout**



**Figure 71: Main and Pilot Parachute Layout**

- Inspect epoxied shock cord harness in nose cone. Give the shock cord a light tug to ensure adhesives are secure.
- Inspect bulkhead and eyebolt on CRAS-S. Give the eyebolt a light tug to ensure adhesives are secure.
- Inspect bulkheads and eyebolts on CRAS-M. Give the eyebolts a light tug to ensure adhesives are secure.
- Inspect bulkhead and eyebolt on ACS structure. Give the eyebolts a light tug to ensure adhesives are secure.
- Inspect bulkhead and eyebolt on PLS retention bulkhead. Give the eyebolts a light tug to ensure adhesives are secure.
- Ensure that the ends of all 3 shock cords have loops to connect with quick links. Check shock cords for holes or wear. Use a backup cord if any damages are noticed.
- Check all the lithium polymer batteries are fully charged by measuring voltage with a

multimeter.

- Ensure Recovery Lead has power switch keys for CRAS-M and CRAS-S.

### PRE-FLIGHT CHECKLIST

RL: \_\_\_\_\_ SO: \_\_\_\_\_

**⚠ Failure to complete the following steps could result in the following failure modes: R.1 - R.13, VS.3, VS.9, or an unidentified failure mode and thus a failed launch.**

**⚠ The following step requires at least three team members including the Recovery Lead.**

- Main Parachute Folding RL: \_\_\_\_\_
  - Raise the parachute in the air, making sure all 4 shroud lines are straight and that the loop is on the top of the parachute.
  - Shake the parachute lightly to untangle the cords if needed.
  - Attach a quicklink to the open loop at the end of the shroud lines. Hold this quicklink to keep parachute from flying away.
  - Line all of the shroud lines up such that they are the same length. Use masking tape to group the shroud lines at this position to make folding easier. **Tape must be removed prior to launch or failure mode R.5 will occur!**

**⚠ The next steps require at least 3 personnel.**

- Hold the parachute up 2 shroud lines meet in the middle and there is one shroud line at each edge. Make sure every connection/quick link are securely tight to the parachute.
- Fold the parachute in half so that the shroud lines at the edges meet. Fold in half again so that all shroud lines meet in the middle.
- Fold both sides of the parachute into the middle tightly. Adjust how far the sides of the parachute are folded into the middle to fit the diameter of the vehicle.
- Fold the parachute in half the opposite direction. The parachute should be roughly a rectangle in shape.

**⚠ Remove tape from the shroud lines before proceeding.**

- Zig-zag shroud lines carefully on the middle of parachute. **Tangled shroud lines could result in failure mode R.5**
- Fold the parachute in thirds, top to bottom, such that the sides cover up the shroud lines twice.
- Screw quicklink to recovery harness quicklink.

**⚠ Ensure quicklink is attached to recovery harness before proceeding.**

- Slide the parachute into the deployment bag, and then fold the flap over the bag.
- Make sure the loop on the deployment bag is secure on the shroud line.
- Main parachute is now ready to be installed into the vehicle.
- Pilot Parachute Folding RL: \_\_\_\_\_
  - Take the parachute and lay it out on a flat surface so that the shroud lines are untangled and in pairs

- Fold the chute in thirds, first folding over the right third and then folding over the left third
- Gather the shroud lines and fold the chute's edges in half so they meet in the middle.
- "Z" fold the parachute into thirds. Fold the outer edges into the center and then fold slightly over the crease.
- Take the shroud lines and bring them into the crease. About 1/3 from the end, pull the shroud lines out of the parachute and begin to wrap them around the chute neatly down towards the bottom of the chute. DO NOT overlap any shroud lines. Make sure the parachute loop is on the same side as where the shroud lines connect to the chute
- Take the folded parachute and connect the parachute loop to the recovery harness loop using a quicklink
- Attach parachute quicklink to main recovery harness quicklink.

**⚠️ Ensure quicklink is attached to recovery harness via swivel before proceeding.**

- Make sure the loop on the nomex blanket is secure on the quicklink.
- Z-fold the main recovery harness.
- Pilot parachute is now ready to be installed into the vehicle.
- Nose Cone Parachute Folding RL: \_\_\_\_\_
  - Raise the parachute in the air, making sure all 8 shroud lines are straight.
  - Shake the parachute lightly to untangle the cords if needed.
  - Attach a quicklink to the open loop at the end of the shroud lines. Hold this quicklink to keep parachute from flying away.
  - Line all of the shroud lines up such that they are the same length. Use masking tape to group the shroud lines at this position to make folding easier. **Tape must be removed prior to launch or failure mode R.7 will occur!**
  - Lay the parachute out on the ground, and make sure every connection/quick link are securely tight to the parachute.
  - Fold over the parachutes panels on both sides towards the center twice.
  - Z-fold the parachute into thirds.
  - Fold edges towards the center and then lightly fold in half.
  - Bring the shroud line bundle up the crease to about 1/3 of the distance from the end. **Do not bring the shroud lines to the very end.**
  - Now start to wrap the shroud lines around the parachute. Ensure the back of the parachute is smooth with the material all pulled around into the crease.
  - Stop wrapping when you reach the end of the parachute. If needing to store, tape shroud lines down.

**⚠️ Be sure to remove tape prior to flight.**

- Attach quicklink to nose cone recovery harness.

**△ Ensure quicklink is attached to nose cone recovery harness before proceeding.**

- Z-fold the nose cone recovery harness.
- Loosely roll the parachute in the nomex blanket, and then fold the blanket so that it fits in the nose cone.
- Make sure the loop on the nomex blanket is secure on the quicklink.
- Pilot parachute is now ready to be installed into the nose cone.
- Drogue Parachute Folding RL: \_\_\_\_\_
  - Raise the parachute in the air, making sure all 4 shroud lines are straight and that the loop is on the top of the parachute.
  - Shake the parachute lightly to untangle the cords if needed.
  - Attach a quicklink to the open loop at the end of the shroud lines. Hold this quicklink to keep parachute from flying away.
  - Lay the parachute out on the ground, and make sure every connection/quick link are securely tight to the parachute.
  - Fold the parachute in half so that the shroud lines at the edges meet. Fold in half again so that all shroud lines meet in the middle.
  - Fold both sides into the middle tightly.
  - Fold the parachute in half the opposite direction. The parachute should be roughly a rectangular in shape.
  - Zig-zag shroud lines carefully on the middle of parachute. **Tangled shroud lines could result in failure mode R.6**
  - Fold the parachute in thirds such that the sides cover up the shroud lines twice.
  - Attach quicklink to drogue recovery harness quicklink.

**△ Ensure quicklink is attached to recovery harness before proceeding.**

- Z-fold the drogue recovery harness.
- Loosely roll the parachute in the nomex blanket, and then fold the blanket so that it fits in the vehicle body.
- Make sure the loop on the nomex blanket is secure on the quicklink.
- Drogue parachute is now ready to be installed into the vehicle.

**△ Lithium-polymer batteries are a potential fire hazard and should always be inspected for swelling or punctures before use. Store batteries in the fire proof battery case until required.****△ Electronics must remain OFF until immediately prior to launch.**

- Integrated Avionics Package Setup RL: \_\_\_\_\_
- CRAS-M Pre-Flight Assembly RL: \_\_\_\_\_

**△ Ensure key power switches are in the OFF position and check all LED indicator lights are off before proceeding.**

- Check to make sure CRAS-M is completely assembled except for batteries and black powder, and that all wiring connections are secure via visual inspection. Ensure 2 wires are connected to each key power switch and orange levered wire connection. Ensure altimeters are labeled 1, 2, and 3.

**⚠ Make sure batteries are fully charged with multimeter before performing next step.**

- Insert 3 fully charged altimeter batteries into battery slots.
- Plug each battery into the JST port on each respective perfboard.

CRAS-S Assembly

RL: \_\_\_\_\_

**⚠ Ensure key power switches are in the OFF position before proceeding.**

- Check to make sure CRAS-S is completely assembled except for batteries and black powder, and that all wiring connections are secure. Ensure 2 wires are connected to each key power switch and orange levered wire connection. Ensure altimeters are labeled 4 and 5.

**⚠ Make sure batteries are fully charged with multimeter before performing next step.**

- Insert 2 fully charged altimeter batteries into battery slots.
- Plug each battery into the JST port on the respective perfboard.

**⚠ The next steps should ONLY be performed by the Launch Manager Dave Brunsting. Nitrile gloves and safety glasses should be worn.**

- Black powder separation charges
- Create eight ejection charges using e-matches and black powder. Ensure that the e-match loose wires are shunted together to prevent accidental ignition of the black powder. The sizes of the charges are in the next steps.

- |  |  |
|--|--|
| <input type="checkbox"/> CRAS-M main charge 1: 4.5 g   | <input type="checkbox"/> CRAS-M drogue charge 2: 3.0 g |
| <input type="checkbox"/> CRAS-M main charge 2: 4.5 g   | <input type="checkbox"/> CRAS-M drogue charge 3: 3.0 g |
| <input type="checkbox"/> CRAS-M main charge 3: 4.5 g   | <input type="checkbox"/> CRAS-S charge 1: 2.0 g        |
| <input type="checkbox"/> CRAS-M drogue charge 1: 3.0 g | <input type="checkbox"/> CRAS-S charge 2: 2.0 g        |

**Re-check to ensure that the key power switches are all OFF position**

- Connect each e-match wire to the corresponding orange lever wire connector.
- Place each ejection charge in its corresponding PVC charge well, covering the full well with masking tape. Leave a slight opening for air movement to allow charge to fully separate vehicle sections.

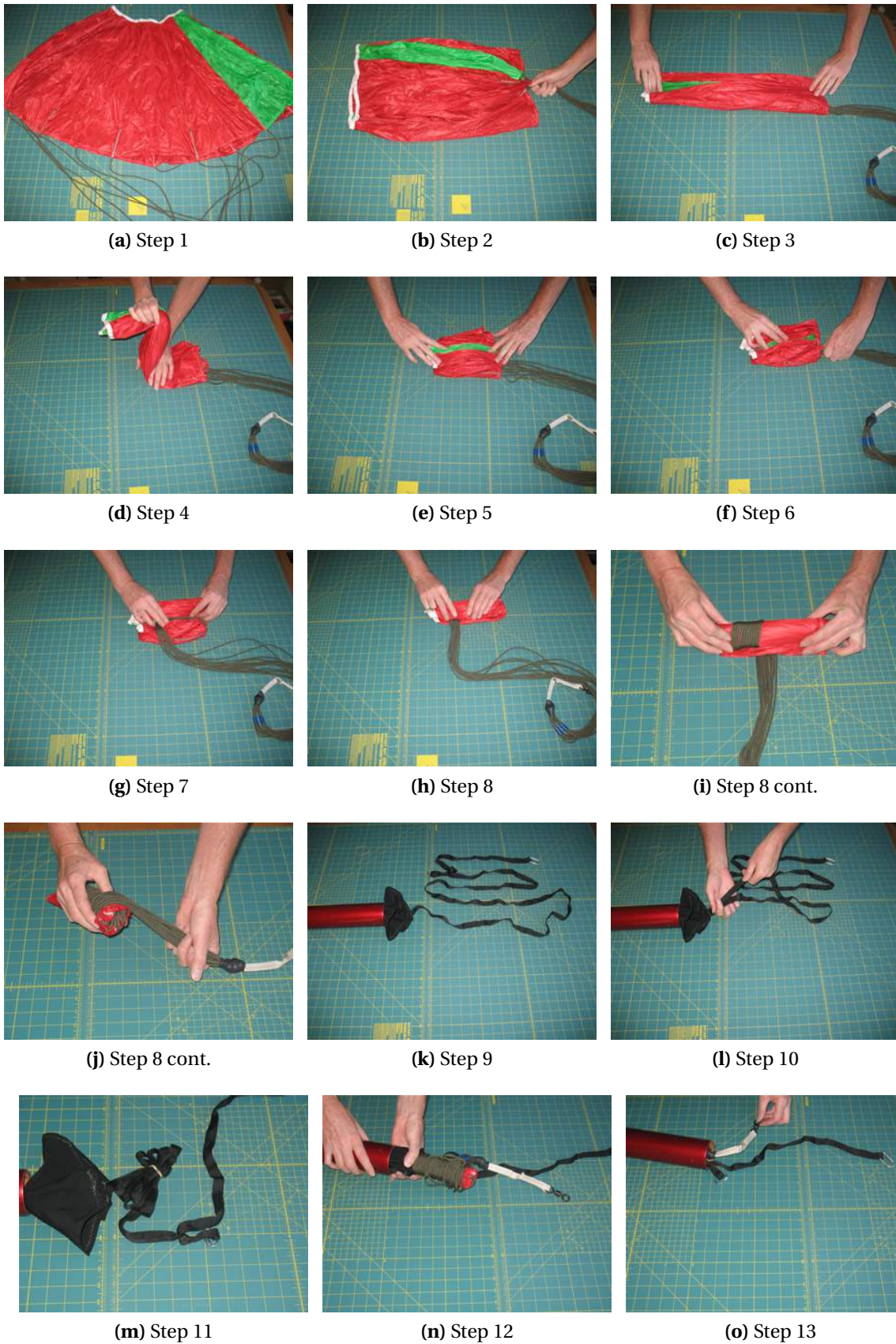
**This concludes the steps that must be performed by the Launch Manager LM: \_\_\_\_\_**

- Use sealing clay to cover the bottom of the PVC charge well to ensure a proper seal.

- Parachute Integration RL: \_\_\_\_\_
- Remove all tape prior to integrating parachutes into launch vehicle.**
  - Ensure that all both the parachutes are properly connected to the shock cords and enclosed in the Nomex parachute protectors.
  - Fold the excess shock cord together in an accordion fashion and loosely tape it together with a single layer of painters tape.
  - See "Vehicle Preparation" to finish parachute integration.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_



**Figure 72:** Fruity Chutes parachute folding guide.



(a) Step 1



(b) Step 2



(c) Step 3



(d) Step 4



(e) Step 5



(f) Step 6a



(g) Step 6b



(h) Step 6c



(i) Step 7



(j) Step 7b



(k) Step 7c



(l) Step 7d

**Figure 73:** Rocketman parachute folding guide.

### 6.4.3 Planetary Landing System Preparation



## STANDARD LAUNCH PROCEDURE

## VEHICLE DEMONSTRATION CHECKLIST

## PLANETARY LANDING SYSTEM PREPARATION

**Required Personnel:** PLS Lead, Safety Officer, Launch Manager

**Required PPE:** Leather gloves, Nitrile gloves, Safety glasses

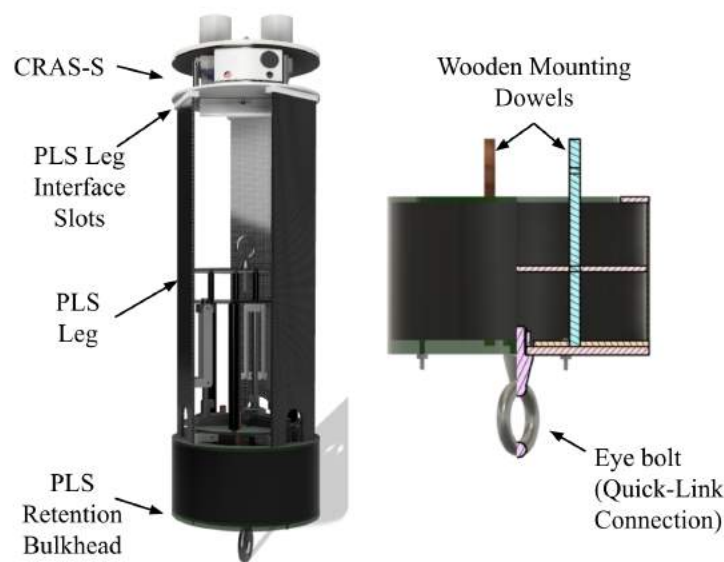


Figure 74: PLS and Retention Graphic

### INSPECTION

PL: \_\_\_\_\_ SO: \_\_\_\_\_

**⚠ Failure to complete the following steps could result in the following failure modes: EV.1, EV.8, L.7, PI.4, PV.1, PV.2, PV.3, PV.4, PV.5, PV.6, VE.5, VE.10, VS.9, or an unidentified failure mode and thus a failed launch.**

- Inspect PLS retention bulkhead and eyebolt. Give the eyebolt a light tug to ensure adhesives are secure.
- Inspect PLS vehicle to ensure no structural components or electrical connections are damaged.

**⚠ Lithium-polymer batteries are a potential fire hazard and should always be inspected for swelling to punctures before use. Store batteries in the fire proof battery case until required.**

**⚠ Electronics must remain OFF until immediately prior to installing PLS in vehicle.**

**PRE-FLIGHT CHECKLIST**

PL: \_\_\_\_\_ SO: \_\_\_\_\_

**⚠ Failure to complete the following steps could result in the following failure modes: EV.1, EV.8, L.7, PI.4, PV.1, PV.2, PV.3, PV.4, PV.5, PV.6, VE.5, VE.10, VS.9, or an unidentified failure mode and thus a failed launch.**

- PLS Parachute Folding RL: \_\_\_\_\_
- Raise the parachute in the air, making sure all 8 shroud lines are straight and that the loop is on the top of the parachute.
  - Shake the parachute lightly to untangle the cords if needed.
  - Attach a quicklink to the open loop at the end of the shroud lines. Hold this quicklink to keep parachute from flying away.
  - Line all of the shroud lines up such that they are the same length. Use masking tape to group the shroud lines at this position to make folding easier. **Tape must be removed prior to launch or failure modes R.6 will occur!**
  - Lay the parachute out on the ground, and make sure every connection/quick link are securely tight to the parachute.
  - Fold over the parachute panels on both sides towards the center. You want to organize the parachute until it is about 15% of the diameter of the parachute size.
  - Z-fold the parachute into thirds.
  - Pull the fabric from the sides of the parachute around the edge and onto the top. You want the fabric on the underside to be smooth with no folds.
  - Form a crease down the center of the folded parachute.
  - Bring the shroud line bundle up the crease to about 1/3 of the distance from the end. **Do not bring the shroud lines to the very end.**
  - Now start to wrap the shroud lines around the parachute. Ensure the back of the parachute is smooth with the material all pulled around into the crease.
  - Stop wrapping when you reach the end of the parachute.

**⚠ Ensure quicklink is attached to PLS eyebolt before proceeding**

- Slide the parachute into the deployment bag, and then fold the flap over the bag.
- Make sure the loop on the deployment bag is secure on the shroud line.
- Parachute is now ready to be connected to the PLS eyebolt with a quicklink.

**⚠ Electronics must remain OFF until immediately prior to installing PLS in vehicle.**

- PLS Pre-Flight Assembly PL: \_\_\_\_\_

**⚠ Ensure all electronics are in the OFF position before proceeding.**

- Check to make sure PLS is completely assembled except for batteries and all wiring connections are secure.

**⚠ Make sure batteries are fully charged before performing next step.**

- Use multimeter to ensure batteries are fully charged.

- Insert fully charged battery into battery slot.
- Plug battery into the power port on the electronics bay.
- Inspect PLS once more before integration.
- Connect PLS Parachute
  - Use quicklink to attach parachute shock cord harness to the PLS eyebolt. Lightly tug on the shock cord to check the connection, but gently so as to not disrupt the folded parachute.
- See "Vehicle Preparation" to complete PLS integration into vehicle body.

**TROUBLESHOOTING**

RL: \_\_\_\_\_ SO: \_\_\_\_\_

- The Raven altimeter performs a continuity check before flight to ensure that all ejection charges are properly connected. Should the altimeter fail this check on the launch pad, the altimeters may need to be removed and examined.
- ⚠️ Ensure that the battery box switches are in the "off" position. Failure to turn off the altimeters could result in unintentional black powder ignition.**
  - Take the rocket off of the launch pad and back to the preparation table.
  - Remove the shear pins from the rocket and separate the sections.
  - Remove the parachute, Nomex protector and shock cords from the rocket.
  - Separate the fin can and recovery tube.
  - Unbolt the CRAS-M from the aft recovery bulkhead.
  - Slide the CRAS-M out of the rocket.
- ⚠️ Recheck to ensure that the battery box switches are in the "off" position. Failure to do so could result in unintentional black powder ignition.**
  - Disconnect the black powder charges from the lever nut wire connections.
  - Unbolt and remove the CRAS-M upper bulkhead and filler.
  - Remove the CRAS-M core and examine the altimeter wire connections for defects. If none are detected, plug the Raven altimeters into a computer for diagnostics. Consult the user's manual for more information.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

#### 6.4.4 ACS Preparation



## STANDARD LAUNCH PROCEDURE VEHICLE DEMONSTRATION CHECKLIST ACS PREPARATION

**Required Personnel:** ACS Lead, Safety Officer, Launch Manager

**Required PPE:** Leather gloves, Nitrile gloves, Safety glasses

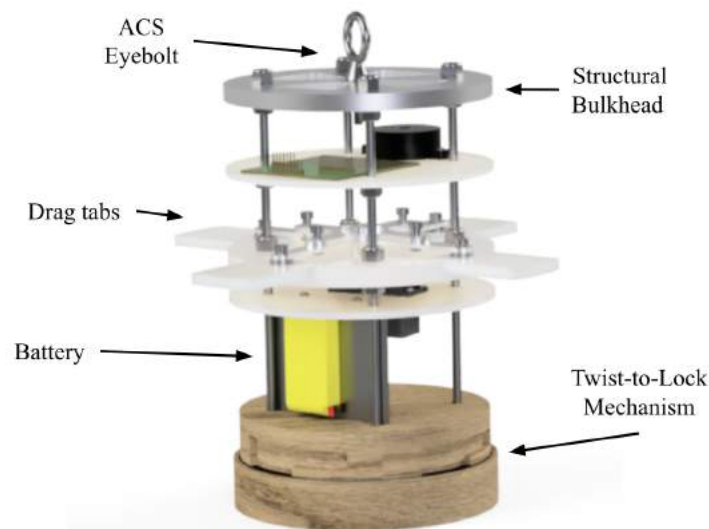


Figure 75: ACS Graphic

#### INSPECTION

AL: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps could result in the following failure modes: ACS.1, ACS.7, ACS.8, EV.1, EV.8, L.7, VE.5, VE.10, or an unidentified failure mode and thus a failed launch.**

- Inspect ACS for structural damage or defects.
- With the battery disconnected from the circuit board, inspect electronics for secure connections and mounting.
- Verify batteries are fully charged using the LED status of Turnigy lithium polymer battery charger.
- Verify the proper control code has been installed on the Raspberry Pi.

#### PRE-FLIGHT CHECKLIST

AL: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps could result in the following failure modes: ACS.1,**

**ACS.7, ACS.8, EV.1, EV.8, L.7, VE.5, VE.10, or an unidentified failure mode and thus a failed launch.**

**△ Lithium polymer batteries are a potential fire risk and should always be inspected for swelling to punctures before use. When not in use batteries should be housed in the fire-proof battery case.**

- Ballast Integration
  - Insert steel weights into 3D printed ballast bed. Attach securely.
- Battery Integration
  - Test batteries with a multimeter to ensure each battery is fully charged.
  - Install the 3.7 V battery in the appropriate slot on the electronics bed.
  - After the 3.7 V battery has been plugged in, install and plug in the 7.4 V battery.
- Ensure the SD card is inserted in the Raspberry Pi prior to powering ON the system.
- Inspect the status LEDs for the sensors and SD card to ensure the Raspberry Pi controller is properly receiving sensor data and writing to the SD card.
- Turn ON the arming switch. Ensure the arming LED turns on. **Ensure the launched state phase LED is OFF**
- Check that the drag tabs are flush with the channel bulkhead.
- Complete ACS Integration in "Vehicle Preparation".

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

#### 6.4.5 Launch Vehicle Preparation



### STANDARD LAUNCH PROCEDURE

### VEHICLE DEMONSTRATION CHECKLIST

### LAUNCH VEHICLE PREPARATION

**Required Personnel:** Vehicles Lead, Recovery Design Lead, ACS design Lead, PLS Design Lead, Safety Officer, Launch Manager

**Required PPE:** Leather gloves, Heat resistant gloves, Safety glasses

#### TRANSPORTATION

VL: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps could result in the following failure modes: L.5, L.8, L.11, L.13, VFM.4, VFM.5, VFM.6, VS.1, VS.2, VS.3, VS.5, VS.6, VS.7, VS.8, VS.9, or an**

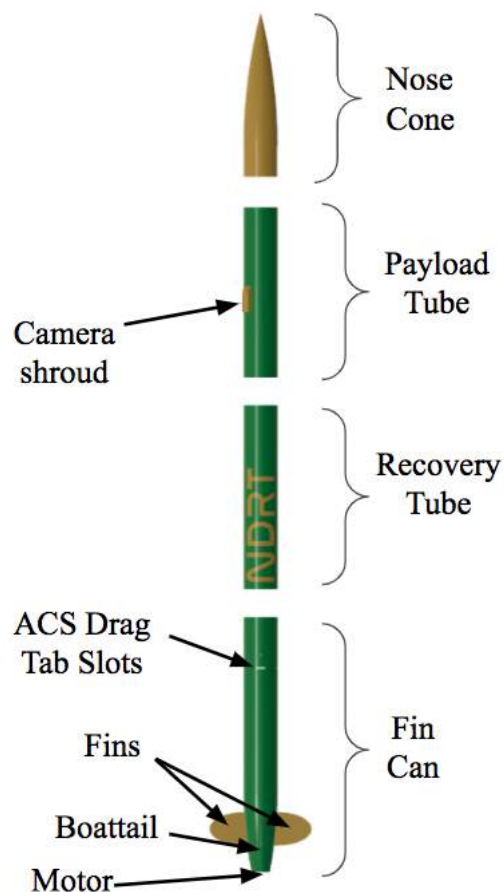


Figure 76: Launch Vehicle Graphic

**unidentified failure mode and thus a mission failure**

- Confirm weather is suitable for driving. Avoid driving in snow or ice if possible and obey all weather ordinances issued by county and state.
- When possible, transport components in padded containers, or against soft materials that could provide protection from damages.

**⚠ Do not haphazardly throw components into vehicles at any time. This is unacceptable behavior and can directly cause damage to launch vehicle.**

**INSPECTION**

VL: \_\_\_\_\_ SO: \_\_\_\_\_

**⚠ Failure to complete the following steps could result in the following failure modes: L.5, L.8, L.11, L.13, VFM.4, VFM.5, VFM.6, VS.1, VS.2, VS.3, VS.5, VS.6, VS.7, VS.8, VS.9, or an unidentified failure mode and thus a mission failure**

- Confirm weather is suitable for launch with RSO and LCO. If launch is postponed or cancelled, pack up equipment and return to team workshop.
- Inspect nose cone, payload tube, recovery tube, fin can and boattail assemblies for

deformations or cracks to ensure there is no damage

- Light tug on eyebolts or extruded components to check adhesive strength at each connection to make sure they are strong.
- Visually inspect fins for any cracks or deformations.

### PRE-FLIGHT CHECKLIST

VL: \_\_\_\_\_ SO: \_\_\_\_\_

**⚠ Failure to complete the following steps in order could result in the following failure modes: L.5, L.8, L.11, L.13, VFM.4, VFM.5, VFM.6, VS.1, VS.2, VS.3, VS.5, VS.6, VS.7, VS.8, VS.9, or an unidentified failure mode and thus a failed launch**

- Complete ACS Preparation** AL: \_\_\_\_\_
- ACS Integration** AL: \_\_\_\_\_
  - Insert ACS into fin can and secure using the built-in ACS twist-to-lock mechanism. See Figure 77(a) for a visual aide in identifying the alignment ring. Due to the symmetrical design of the system, there is no need for a specific orientation.
  - Inspect all 4 drag tab cutouts in the fin can to ensure that the tabs are visible and have clearance to extend. See Figure 77(b) for a visual depiction of the tab extension slots.
  - Inspect through the barometric vent holes to ensure that the piezzo buzzer is audible and indicating the system is not in the launched state.
  - If the buzzer indicates a premature launched state, the ACS system must be removed and ACS Preparation must be repeated until satisfactory.
  - Make a final inspection of the system's installation by reviewing drag tab clearances, piezzo buzzer, and twist-to-lock security. Revisit ACS Preparation if needed.



(a) ACS Twist-To-Lock Alignment Ring



(b) ACS Tab Extension Slots

**Figure 77:** Important ACS components for launch preparation.

- At this point, each section of the vehicle should remain independent and no parachutes should be attached to bulkheads yet.**

**Complete PLS Preparation** PL: \_\_\_\_\_

**PLS Integration** PL: \_\_\_\_\_

- Ensure PLS jumper cable and pin are attached to PLS retention assembly.
- Power ON PLS vehicle.
- Connect PLS transmitter with team ground station.
- Insert PLS retention assembly into payload tube. Secure using 3 screws and holes in the payload tube.
- Ensure PLS parachute is attached to the PLS eyebolt with a quick link and shock cord.
- Insert jumper cable pin into PLS pin slot BEFORE inserting into vehicle.
- Slide PLS into payload tube, placing the end with servo motors in first.
- Align bulkhead with 3 retention pins and gently slide until PLS meets payload tube barrier bulkhead.
- Ensure PLS parachute is sitting gently between the PLS legs and is not stuck on any components.

**At this point, each section of the vehicle should remain independent and no parachutes should be attached to bulkheads yet.**

**CRAS-S Integration** RL: \_\_\_\_\_

- Ensure nose cone parachute shock cord is securely attached to the CRAS-S eyebolt with a quick link.
- Attach other end of nose cone parachute shock cord to nose cone eye bolt with a quicklink.

**⚠ The next steps require at least four team members.**

**⚠ DO NOT attempt to force any parachute into the vehicle. This can prevent separation at apogee and potentially damage the rocket or parachute. See "Troubleshooting" below for help.**

- Position payload tube vertically such that PLS opening is facing upward. **Two members must hold payload tube to maintain stability and prevent dropping.**
- Place CRAS-S flat on the PLS legs such that the nose cone parachute is free and the payload tube is sealed.
- One member hold nose cone parachute in the nose cone while another member positions nose cone shock cord on top of CRAS-S to prevent tangling.
- Seal nose cone on to payload bay with the designed friction fit.
- Rotate nose cone and payload tube assembly to be horizontal.

**⚠ This ends the steps requiring at least four team members.**

- Secure nose cone to payload bay using 4 shear pins and the provided holes.
- Attach loose end of main parachute shock cord to PLS retention bulkhead eyebolt using

a quicklink.

- Slide recovery and payload tubes together.
- Complete Recovery Preparation** RL: \_\_\_\_\_
- CRAS-M Integration** RL: \_\_\_\_\_

- Ensure both main and drogue parachute shock cords are securely attached to the CRAS-M eyebolts with quick links. **Make certain the main parachute is fore of the CRAS-M and the drogue parachute is aft of the CRAS-M!**
- Insert CRAS-M into recovery tube
- Secure CRAS-M using 6 screws and holes cut out of recovery tube. **One end of each shock cord should still be loose**

⚠ **DO NOT attempt to force any parachute into the vehicle. This can prevent separation at apogee and potentially damage the rocket or parachute. See "Troubleshooting" below for help.**

- Insert folded main parachute in fore section of recovery tube. Ensure that the parachute is not packed so tightly that it cannot be pulled out. Ensure shock cord is loose and available to attach to payload tube.
- Insert folded parachute in fore section of recovery tube. Ensure that the parachute is not packed so tightly that it cannot be pulled out. Ensure shock cord is loose and available to attach to payload tube.
- Ensure that the eye bolt in the payload tube is secure.
- Attach main parachute shock cord to the payload bay eyebolt with a quicklink.
- Flight Camera Integration** VL: \_\_\_\_\_
  - Insert the MicroSD card into the back of the camera.
  - Press power button and wait for steady yellow light from camera.
  - Press the recording button (camera icon) and wait for a flashing yellow light.
  - Insert the camera into the camera shroud so that the lens is facing downward.
  - Once camera is fully inserted into camera shroud, slide in the plastic locking piece to restrict movement. Give gentle tug to ensure camera will not fall out.

⚠ **The next step requires at least four team members.**

- Perform a shake test of vehicle assembly to ensure secure connection. **All components should be secure. If shaking components are heard, launch vehicle must be disassembled and procedures must restart from beginning. If a component is damaged, locate a replacement in team toolboxes. Failure to replace a damaged part will result in a failed launch.**
- Complete Motor Preparation** LM: \_\_\_\_\_

⚠ **The next steps should be performed by the Vehicles Lead**

- Center of gravity and stability check

VL: \_\_\_\_\_

**⚠️ The next step requires four members to be positioned to catch the rocket should it slip.**

- Perform center of gravity (CG) test to ensure the center of gravity matches the simulated CG by placing the fully assembled vehicle on a thin wooden stand so that it is cantilevered on both sides. Make slight adjustments to the vehicle position until it perfectly balances. Figure 78 depicts a CG test being performed prior to launch.



**Figure 78:** CG Location and Stability Check

- Mark the measured CG and simulated CG on the vehicle.
- Ensure the simulated center of pressure (CP) is indicated on the vehicle with a marker.
- Ensure calculated stability corresponds to predicted value.
- Re-open vehicle and ballast as necessary to maintain a stability margin of  $>2$  calipers or within 10% of predicted margin (whichever is greater).
- Slide recovery and payload tubes together if opened.
- Secure the recovery tube to the payload bay with 4 shear pins.

### TROUBLESHOOTING

SO: \_\_\_\_\_

**⚠️ If the folded parachute is too tight inside the parachute bay, it may not slide out upon separation, which will result in the vehicle descending much faster than normal.**

- Unfold the parachute and restart the applicable parachute folding procedure outlined above in the Pre-Flight Checklist.
- Ensure that folds are crisp and that the parachute is tightly rolled but not compressed or balled up.
- Proceed to install the parachute in the rocket using the procedure outlined in the Pre-Flight Checklist above. A generous layer of talcum powder on the parachute and coupler may also help the parachute to slide in.

**⚠️ If believed to be damaged, battery should not be used AT ALL. While the team is still at the**

**launch site, the battery should be housed in a fire proof battery case. The battery should then be disposed of according to University Standards upon return.**

**△ PPE required are heat resistant gloves and safety glasses**

- If battery is believed to be damaged, approach with caution, as it should be considered an exploding hazard. PPE must be worn when handling the defective battery.
- Battery should be handled with care, and held away from face and body.
- Place battery in fireproof battery disposal bag.
- Bring battery to qualified and authorized disposal site.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

#### 6.4.6 Motor Preparation



### STANDARD LAUNCH PROCEDURE

### VEHICLE DEMONSTRATION CHECKLIST

### MOTOR PREPARATION

**Required Personnel:** Safety Officer, Launch Manager

**Required PPE:** Nitrile gloves, Safety glasses

#### INSPECTION

LM: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps could result in the following failure modes: L.1, VE.11, VE.13, VFM.1, VFM.3, VFM.4, VFM.5, VS.1, VS.2, VS.3, VS.5, VS.7, VS.8, or an unidentified failure mode and thus a mission failure**

- Remove the motor from its packaging.
- Check that the motor is properly assembled according to manufacturer's instructions and inspect the motor for defects.
- Acquire approval of motor inspection from Launch Manager. LM: \_\_\_\_\_

#### PRE-FLIGHT CHECKLIST

LM: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps in order could result in the following failure modes: L.1, VE.11, VE.13, VFM.1, VFM.3, VFM.4, VFM.5, VS.1, VS.2, VS.3, VS.5, VS.7, VS.8, or an unidentified failure mode and thus a failed launch**

**△ The next steps should ONLY be performed by the Launch Manager Dave Brunsting. Gloves and safety glasses must be worn.**

**Motor Preparation**

LM: \_\_\_\_\_

- Insert the propellant into the casing, ensuring that the two spacers precede the propellant.
- Screw on the rear closure.
- Insert the motor into the motor mount, ensuring proper motor direction.
- Attach the motor retainer ring.
- Check motor for a secure fit.

**⚠ This concludes the steps that must be performed by the Launch Manager.**

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

**6.4.7 Setup on Launch Pad****STANDARD LAUNCH PROCEDURE****VEHICLE DEMONSTRATION CHECKLIST****SETUP ON LAUNCH PAD**

**Required Personnel:** Vehicles Lead, Recovery Lead, ACS Lead, PLS Lead, Safety Officer, Project Manager, Launch Manager, Range Safety Officer (RSO), Launch Control Officer (LCO)

**Required PPE:** Leather gloves, Nitrile gloves, Safety glasses

**INSPECTION**

RL: \_\_\_\_\_ SO: \_\_\_\_\_

**⚠ Failure to complete the following steps could result in the following failure modes: L.2, L.3, L.4, L.5, L.9, LE.1, LE.2, VFM.1, VFM.2, VFM.3, VFM.5 or an unidentified failure mode and thus a failed launch.**

- Walk on ground adjacent where launch pad will be located to ensure it is hard and stable. If soft or muddy, move launch pad location with approval from RSO.
- Make sure launch rail is clear of dirt or debris that would inhibit vehicle launch.
- Inspect vehicle rail buttons to ensure there is no damage.
- Inspect screws and knobs on launch rail structure to ensure they are adjustable are secure, and not loose. If loose, alert RSO immediately.
- Confirm with RSO the launch controller is satisfactory for the launch. PM: \_\_\_\_\_

**LAUNCH SITE EVALUATION**

SO: \_\_\_\_\_

**⚠ Failure to complete the following steps could result in the following failure modes: L.2,**

**L.3, L.4, L.5, L.9, LE.1, LE.2, VFM.1, VFM.2, VFM.3, VFM.5 or an unidentified failure mode and thus a failed launch.**

**△ Before leaving the team workshop, ensure weather is suitable for launch. If any of the following conditions are expected, launch will not be possible: precipitation, low cloud cover, high winds over 20 mph, temperature below 0 degrees F, tornado warning. Immediately Call Launch Manager if weather is in question prior to launch.**

If weather is acceptable, proceed with launch operations.

**△ Inspect launch site for wildlife. Consult RSO, LCO, and Launch Manager to ensure no wildlife will be affected by launch operations.**

### LAUNCH EQUIPMENT SETUP

RL: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps could result in the following failure modes: L.2, L.3, L.4, L.5, L.9, LE.1, LE.2, VFM.1, VFM.2, VFM.3, VFM.5 or an unidentified failure mode and thus a failed launch.**

Register with LCO and RSO at the launch site PM: \_\_\_\_\_

Set up launch pad from trailer on hard, flat ground in designated area.

Using wrenches in toolbox to install the launch pad according to Launch Manager's instructions

Position launch block such that the vehicle is able to propel off the block without damaging the motor.

Double check the launch rail is clear such that the rail buttons will not be obstructed.

**△ Next step must be repeated before every launch.**

Use a level and protractor to ensure launch angle is within 5 degrees from vertical.

### PRE-FLIGHT CHECKLIST

LM: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps could result in the following failure modes: L.2, L.3, L.4, L.5, L.9, LE.1, LE.2, VFM.1, VFM.2, VFM.3, VFM.5 or an unidentified failure mode and thus a failed launch.**

With RSO approval, at least 4 team members must transport vehicle to launch pad.

Place Vehicle on Launch Rail. VL: \_\_\_\_\_

Lower the launch rail such that it is parallel to the ground.

Align the rail buttons with the rail and gently slide the vehicle onto the rail with the fin can towards the ground. Figure ?? depicts this step during a previous launch.

Use a wooden block or metal rail platform to provide vehicle an offset on launch. This step ensures the motor has air to successfully ignite and has a surface to push off at the beginning of motor burn.

**△ Failure to complete the next step could result in serious personnel injury and potential hospitalization.**

Once the vehicle is in position, lift the rail and vehicle to vertical position.



**Figure 79:** Slide Vehicle onto Launch Rail

- Using a ladder, access the recovery electronics using the power key and pin switches.
- Activate Recovery Electronics. RL: \_\_\_\_\_
- Recovery Lead arms recovery electronics using power keys and pin switches. There should be 3 LEDs visible on the CRAS-M and 2 LEDs visible on the CRAS-S through the LED holes after arming the power switches. Figure 80 depicts altimeters being armed while the vehicle is vertical. **If less than 5 Recovery LEDs are visible through LED holes, see "Troubleshooting", below.**



**Figure 80:** Arming Recovery Electronics

- Verify ACS Power. AL: \_\_\_\_\_
- ACS Lead ensures power LED is not in launched state through barometric hole. **If LED indicates the vehicle is in launched state vehicle must be taken off launch pad, disassembled, and team must revisit "ACS Preparation".**
- Ensure all electronics are prepared for launch one additional time. SO: \_\_\_\_\_

- Continue Aligning Vehicle on Launch Rail.
  - Use air holes to ensure PLS and ACS power is on while on ladder.
  - Once all electronics are on and confirmed, choose a launch rail angle with 10 degrees and set the rail at this angle. Check the angle of the rail on the bottom of the rail.
  - Lock rail in position using adjustable knobs and wrenches.
- Proceed to "Igniter Installation" to complete next steps.

**TROUBLESHOOTING**

RL: \_\_\_\_\_ SO: \_\_\_\_\_

- The Raven altimeter performs a continuity check before flight to ensure that all ejection charges are properly connected. Should the altimeter fail this check on the launch pad, the altimeters may need to be removed and examined.
- ⚠️ Ensure that the battery box switches are in the "off" position. Failure to turn off the altimeters could result in unintentional black powder ignition.**
  - Take the rocket off of the launch pad and back to the preparation table.
  - Remove the shear pins from the rocket and separate the sections.
  - Remove the parachute, Nomex protector and shock cords from the rocket.
  - Separate the fin can and recovery tube.
  - Unbolt the CRAS-M from the aft recovery bulkhead.
  - Slide the CRAS-M out of the rocket.
- ⚠️ Recheck to ensure that the battery box switches are in the "off" position. Failure to do so could result in unintentional black powder ignition.**
  - Disconnect the black powder charges from the lever nut wire connections.
  - Unbolt and remove the CRAS-M upper bulkhead and filler.
  - Remove the CRAS-M core and examine the altimeter wire connections for defects. If none are detected, plug the Raven altimeters into a computer for diagnostics. Consult the user's manual for more information.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

**6.4.8 Igniter Installation****STANDARD LAUNCH PROCEDURE****VEHICLE DEMONSTRATION CHECKLIST****IGNITER INSTALLATION**

**Required Personnel:** Safety Officer, Launch Manager

**Required PPE:** Nitrile gloves, Safety glasses

**INSPECTION**

LM: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps in order could result in the following failure modes: LE.3, VFM.1, VFM.3, VFM.5 or an unidentified failure mode and thus a failed launch**

- Remove the motor from its packaging.
- Check that the motor is properly assembled according to manufacturer's instructions and inspect the motor for defects.
- Acquire approval of motor inspection from Launch Manager. LM: \_\_\_\_\_

**PRE-FLIGHT CHECKLIST**

LM: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps in order could result in the following failure modes: LE.3, VFM.1, VFM.3, VFM.5 or an unidentified failure mode and thus a failed launch**

**△ The next steps should ONLY be performed by the Launch Manager Dave Brunsting. Heat resistant gloves and safety glasses should be worn.**

- Clear all personnel from launch pad area except for the Launch Manager. All personnel must return to RSO-designated viewing area.
- Check that the ignition wires, connected to the launch control system, do not have a live voltage across them. This can be done by lightly touching the clips to each other while away from the vehicle, watching for sparks. If no sparks are thrown it is safe to proceed.
- Remove the igniter clips from the igniter.
- Ensure that the igniter has properly exposed ends which are split apart for at least 3 inches in length.
- Insert the igniter into the motor.
- Attach the clips to the igniter, ensuring sufficient contact.
- Launch Manager must clear the launch area and return to the viewing area.
- Alert RSO that igniter is live and launch vehicle is prepared for launch.
- Proceed to "Vehicle Flight" for next steps.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

### 6.4.9 Launch Procedures



## STANDARD LAUNCH PROCEDURE

## VEHICLE DEMONSTRATION CHECKLIST

## LAUNCH PROCEDURES

**Required Personnel:** Launch Manager, RSO

**Required PPE:** Nitrile gloves, Safety glasses

### FLIGHT INITIATION CHECKLIST

LM: \_\_\_\_\_ SO: \_\_\_\_\_

**△ Failure to complete the following steps could result in the following failure modes: LE.1, LE.3, or an unidentified failure mode and thus a failed launch.**

**△ Confirm the following procedures have been completed before proceeding: Vehicle Preparation, Recovery Preparation, PLS Preparation, ACS Preparation, Motor Preparation, Setup on Launch Pad, Igniter Installation. If any step was not approved, vehicle must be disarmed and removed from launch pad. Assembly must restart from that point.**

Confirm with LCO once again the launch controller is satisfactory for the intended launch. PM: \_\_\_\_\_

Launch Manager confirms successful launch preparations with LCO.

LCO must make an announcement over the rocketry-club set up loudspeaker to alert all personnel in the area that a launch is occurring.

LCO commences launch countdown over loudspeaker.

One member of the team presses the ignition button on the launch controller.

**△ If there is no ignition, See "Troubleshooting" below.**

**△ If any component other than the igniter is malfunctioning, the LCO may give permission to team personnel to remove vehicle from launch rail only after the Launch Manager disarms the igniter.**

All personnel must remain in designated viewing area until LCO and RSO allows personnel into launch field.

Proceed to "Post-Flight Recovery and Analysis" once vehicle lands and RSO allows personnel to enter the launch field.

### TROUBLESHOOTING

RL: \_\_\_\_\_ SO: \_\_\_\_\_

Occasionally, a rocket motor will fail to ignite on the pad. This can be caused by numerous issues, such as faulty igniters, incorrect installation, faulty launch equipment, and damaged motor.

- After a failed ignition, the LCO of a launch range will typically attempt another ignition. If this fails, proceed to the next step.

**△ The remaining steps should only be performed by the Launch Manager.**

- Disconnect the igniter from the ignition clips.
- Carefully remove the igniter from the motor.
- Install another igniter, paying careful attention to standard procedure, and attempt another ignition.
- If this ignition fails, take the rocket off the pad, take the motor out and inspect it for damage or incorrect assembly.
- If the motor appears in good condition and properly assembled, inspect the launch system to ensure that it is properly set up, in good condition, and has a charged battery. The range LCO should perform this inspection.
- Put the rocket back on the pad and attempt another ignition with a fresh igniter. If this fails, consult the Launch Manager for further troubleshooting.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

#### 6.4.10 Post-Flight Recovery and Analysis



### STANDARD LAUNCH PROCEDURE

### VEHICLE DEMONSTRATION CHECKLIST

### POST-FLIGHT RECOVERY AND ANALYSIS

**Required Personnel:** Vehicles Lead, Recovery Lead, ACS Lead, PLS Lead, Safety Officer, Launch Manager

**Required PPE:** Leather gloves, Heat resistant gloves, Safety glasses

#### INSPECTION

SO: \_\_\_\_\_

- △ Failure to complete the following steps could result in the following failure modes: L.6, PV.9, or an unidentified failure mode and thus a failed launch.**
- △ Personnel may only enter launch area when given permission by RSO.**
- △ Black powder charges may still be live upon landing. Do not approach until Launch Manager verifies all charges have gone off.**
- △ Motor is still hot upon landing. Do not touch until the checklist specifically mentions to.**

- Using cameras, take photos of all vehicle sections and PLS vehicle before touching anything.
- Document on phones or paper the final positions of components and any visible damage.

**POST-FLIGHT RECOVERY CHECKLIST**

RL: \_\_\_\_\_ SO: \_\_\_\_\_

- △ Failure to complete the following steps could result in the following failure modes: L.6, PV.9, or an unidentified failure mode and thus a failed launch.**
- △ Personnel may only enter launch area when given permission by RSO.**
- △ Black powder charges may still be live upon landing. Do not approach until Launch Manager verifies all charges have gone off.**
- △ Motor is still hot upon landing. Do not touch until the checklist specifically mentions to.**
- △ Do not touch PLS until told to do so.**
  - Verify team ground station received panoramic image transmission before recovering.
  - After pictures have been taken from a distance, the Launch Manager must ensure that all 8 black powder charges successfully ejected. This can be done visually by confirming the tape seals are ripped or gone entirely. Figure 81 depicts charges that have successfully deployed and one charge that did not, for visual reference. **If any black powder charges have not successfully fired, see "Troubleshooting" below for safe procedures.**



(a) 3 Successful Charges



(b) 1 Failed Charge

**Figure 81:** Post-Launch Black Powder Images

- △ Recovery Lead must verify all black powder charges have gone off before proceeding.**
- △ Recovery Lead turns all power keys to be OFF before proceeding.**
  - Continue to take pictures of all components until Project Manager deems the quantity acceptable for report writing and team media.
  - Begin Collecting Vehicle Sections SO: \_\_\_\_\_
  - Disconnect quicklinks for all parachutes. At least one team member will be responsible

for returning all 5 parachutes to the team staging area.

- Disconnect CRAS-S from nose cone by undoing the quicklink. One team member will be responsible for returning the CRAS-S to the team staging area.
- One team member will be responsible for returning the nose cone to the team staging area.
- Disconnect the quicklink attaching the drogue recovery harness from the ACS eyebolt.
- Remove nomex blankets and parachute bags. One team member will be responsible for returning the 2 parachute deployment bags to the team staging area. An additional one team member will be responsible for returning the 3 nomex blankets to the team staging area.
- Two team members will be responsible for transporting the payload tube and connected drogue and main recovery harnesses to the team staging area.

**⚠ The next step requires Heat Resistant Gloves to prevent burns.**

- Two team members will be responsible for transporting the fin can to the team staging area. One member must hold the end nearer to the ACS. One team member must hold the end nearer to the fins and motor. **The individual closer to the motor must wear Heat Resistant Gloves while completing this step.**
- Measure angle of bulkhead on PLS with respect to the ground. Do so using a level and protractor. **Record this angle for mission success evaluation.** PL: \_\_\_\_\_

**⚠ A team member may not touch the PLS after mission completion.**

- One team member will be responsible for returning the PLS to the team staging area.
- Three remaining team members will ensure the landing area is free of any debris, disconnected parts, or team-created waste.
- Proceed to Post-Flight Analysis Checklist.
- If team has available time and resources, another flight can occur on the same day. Repeat all steps from beginning to properly launch twice on the same day. This is unlikely due to availability and time restraints, however.
- Pack up all equipment and disassemble all components.
- Disconnect batteries and return to fire-proof battery bag.
- Perform a sweep of the area with entire team to ensure all trash and parts are taken back to team workshop in trash bags.
- Return all tools to proper storage locations in team workshop.
- Dispose of all trash and recycling appropriately in team workshop

**POST-FLIGHT ANALYSIS CHECKLIST**

SO: \_\_\_\_\_

**⚠ Failure to complete the following steps could result in the following failure modes: L.6, PV.9, or an unidentified failure mode and thus a failed launch.**

**△ The Launch Manager is the ONLY individual permitted to complete the next step.**

- Wait 10 minutes for the motor casing to cool before removing motor casing.
- PLS Image Transmission** PL: \_\_\_\_\_
  - Verify team ground station received panoramic image transmission before recovering
  - Ensure image is sufficient in quality and contains 360 degrees of view.
- ACS Data Evaluation** AL: \_\_\_\_\_
  - Download data from microcontroller and compare to expected data.
  - Verify controller extended tabs electronically.
- Altitude Evaluation** RL: \_\_\_\_\_
  - Recovery Lead connects the 5 altimeters in the CRAS-M and 2 altimeters in the CRAS-S to a laptop with the proper software installed.
  - Record the apogee from each altimeter. Calculate the average and standard deviation.
  - Compare highest apogee to target apogee of 5,300 ft.
- Camera Video Evaluation** VL: \_\_\_\_\_
  - After removing camera from camera shroud, eject micro SD card.
  - Download the recorded video onto a team member's laptop.
  - Verify ACS drag tabs successfully extended during flight.
  - Distribute video to team for personal and team media use.

**TROUBLESHOOTING**

SO: \_\_\_\_\_

In the unlikely event that a black powder charge remains intact during descent, the charge must be removed before regular post-launch procedures can commence.

- Ensure that all altimeters are fully powered off by flipping the switches on the attached battery boxes into the "off" position. Failure to do so could result in an unintentional ignition.**
- These next steps should only be performed by the Launch Manager.**
  - Separate the fin can and recovery tube.
  - Unbolt the CRAM from the aft recovery bulkhead.
  - Remove the CRAM from the body tube.
- Re-check to ensure that the battery box switches are in the "off" position.**
  - Unhook the black powder charges from the level nut wire connections. Remove the charges from the charge wells.
  - Dispose of the charges through University Hazardous Waste procedures.

I certify and attest that the above checklists have been fully and properly completed

Safety Officer: \_\_\_\_\_ Date: \_\_\_\_\_

## 7 Project Plan

### 7.1 Testing

NDRT has completed 26 tests prior to competition to ensure systems can complete the mission as designed. Table 65 outlines all 26 completed tests and relevant requirements, including those provided by NASA and team-derived. To date, 23 tests have passed success criteria. 3 tests require a re-test prior to competition flight to demonstrate functionality. Sections 6.1.1-6.1.4 contain all testing procedures, success criteria, results, and next steps upon completion.

**Table 65:** Complete Testing Overview

System	Test ID	Title	Requirements Satisfied	Result
Vehicle	TV.1	Bulkhead Assembly Strength Test	2.4, VF.2	Pass
	TV.2	Demonstration Flight Test	2.1, 2.4, 2.6, 2.8, 2.9, 2.16, 2.18.1, 2.22.6, VF.1	Pass
	TV.3	Fins Impact Test	2.4	Pass
	TV.4	Nose Cone Impact Test	2.4	Pass
	TV.5	Shake Test	2.4, 3.7	Pass
	TV.6	Subscale Flight Test	2.17	Pass
ACS	TA.1	Demonstration Flight Test	AF1, AD.4	Failed, Pending Re-test
	TA.2	Flip Test	AF1	Pass
	TA.3	Sample Data Control Algorithm Test	AF1	Pass
	TA.4	Sample Data Servo Motor Actuation Test	AF4	Pass
	TA.5	Shake Test	2.4	Pass
	TA.6	Subscale Data Filter Test	AF1	Pass
	TR.1	Altimeter Simulated Flight Test	3.4, 3.8, RF.5, RF.6, PF.6	Pass

	TR.2	Battery Life Test	2.7, RE.2	Pass
	TR.3	Black Powder Separation Ground Test	3.2, VD.2, AF4, RE.2, RE.3, RD.4, PF.7	Pass
	TR.4	Demonstration Flight Test	3.1, 3.3, 3.11, 3.13, RE.1, RE.4	Pass
	TR.5	Deployment Charge Disarm Test	3.6, RD.5, RD.6	Pass
	TR.6	GPS Transmitter Test	3.12	Pass
	TR.7	Parachute Open Test	3.1.1	Pass
PLS	TP1	Demonstration Flight	2.18.2, 4.3.1, 4.3.2, 4.3.3, 4.3.4, PF.10	Failed, Pending Re-test
	TP2	Ejection Detection Test	4.3.2 PF.9	Pass
	TP3	Image Transmission Test	4.3.4, PF.5	Failed, Pending Re-test
	TP4	Landing Detection Test	4.3.2	Pass
	TP5	Leg Deployment Test	4.3.2, PF.11	Pass
	TP6	Orientation Test	4.3.3, PF.8, PF.14	Pass
	TP7	Retention Test	PF.3	Pass

### 7.1.1 Vehicles Testing



## LAUNCH VEHICLE: BULKHEAD ASSEMBLY STRENGTH TEST

Test ID: TV.1

Responsible Individual: Notre Dame Vehicle Design Lead

### Required PPE

- Safety Glasses
- Protective gloves

### Materials and Equipment

- Payload tube structural assembly test article
- Recovery eyebolt secured to bulkhead with nut and washer
- Recovery quicklink
- Recovery parachute chord

- Weight suspension platform with eyebolt attachments
- Four 70lb bags of concrete
- Pine 1x4 wood plank

### Objective

The objective is to validate the structural integrity of the payload bay bulkhead assembly under worst-case main parachute loading conditions.

### Motivation

A major concern for the bulkhead assembly was its capability to sustain the force produced by the parachute when deployed, as it experiences the greatest total force of any component during flight. If the parachute was to open instantaneously, it was predicted to produce a force of 287.3 lbs. In order to ensure the bulkhead assembly can withstand this force, a strength test was conducted on a test article replicating the payload tube bulkhead assembly.

### Success Criteria

Test ID	Success Description	Result
TV.1	The payload bay bulkhead can withstand the worst case loading scenario from the parachute without sustaining damage and is therefore recoverable and reusable.	Pass

### Test Setup

1. The payload tube structural assembly test article is created as a replica of the relevant components of the payload tube bulkhead assembly. The test article is shown in Figure 82
2. The test article is mounted between two level, stable structures with a gap in the middle, using a pine 1x4 wood plank.
3. A parachute chord is attached to the eyebolt via quicklink.
4. The parachute chord is looped through the eyebolts secured to the weight suspension platform so that it is suspended from the test article.



(a) View into the test article from the top showing the bulkhead



(b) Bottom view of the test article with quicklink attached to eyebolt

**Figure 82:** Replica of the payload tube bulkhead assembly for strength testing

### Test Procedure

1. 70 lb concrete bags are placed one-by-one onto the suspended platform until four bags are suspended, as shown in Figure 83.
2. The test article is visually inspected for damage or structural failure.
3. Weights are removed and the test stand is disassembled
4. The test article is closely inspected for cracking or permanent deformation.



**Figure 83:** Bulkhead assembly strength test with 310 lb suspended from the test article

## Results

The bulkhead assembly strength test was successfully completed on February 12th, 2021. The total weight held by the bulkhead assembly test article reached 310 lbs without any damage or plastic deformations. This load is larger than the worst-case force of 287.3 lb predicted to occur during main parachute deployment, meaning the bulkhead assembly was successful in demonstrating structural integrity under the main parachute deployment force. The predicted and tested forces on the payload bulkhead assembly are summarized in Table 66 for reference.

**Table 66:** Comparison of predicted and tested force on the payload tube bulkhead assembly

Scenario	Force (lb)
Predicted main parachute deployment	287.3
Bulkhead strength test	310.0

## Next Steps

Proceed to Test TV.3 to continue clearing vehicle structures for the demonstration flight.



## LAUNCH VEHICLE: DEMONSTRATION FLIGHT TEST

Test ID: TV.2

Responsible Individual: Notre Dame Vehicle Design Lead

**Required PPE**

- Safety Glasses

**Materials and Equipment**

- Nose cone
- Body tube assembly
- Fin can assembly
- Cesaroni L-1395 Blue Streak motor
- Motor retainer cap
- CRAS-M
- CRAS-S
- Recovery parachutes
- PLS
- ACS
- Screws and shear pins
- Drill drill bits
- Phillips head screwdriver
- Two wood mounts
- Tape measure
- Sharpie
- Folding table
- 12-foot, 1515 Launch rail

**Objective**

The objective is to ensure a safe and fully operational full-scale flight and flight profile predictions. Additionally, this test is motivated by the intent to ensure ACS, recovery, and PLS functionality.

**Motivation**

The motivation of the demonstration flight is to validate the stability and structural integrity of the launch vehicle design through all stages of flight. The launch vehicle must be able to undergo all stages of a nominal flight without posing any danger to onlookers, and without incurring any damage so that no repairs or replacements are necessary prior to a re-flight. Additionally, the test flight is intended to ensure accurate implementation of launch, payload subsystem, apogee control system, and recovery processes, and to verify flight profile predictions through all flight stages.

**Success Criteria**

Test ID	Success Description	Result
TV.2	The launch vehicle completes flight successfully with appropriately timed separations and parachute deployments. All internal components are retained without damage after visual inspection.	Pass

### Test Setup

1. See Launch Checklists for step-by-step instructions for launch.
2. Launch Manager secures and prepares motor before conducting final launch vehicle checks.

### Test Procedure

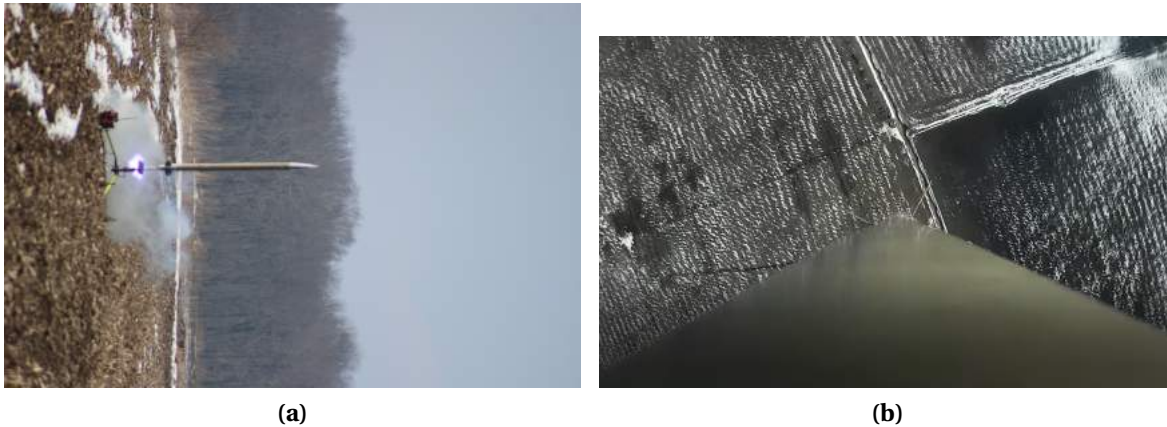
1. The launch vehicle is balanced on a single wood mount, and the CG is marked using a Sharpie.
2. The separation between the CP and CG is measured using a tape measure to ensure the correct static stability margin is achieved.
3. The vehicle is mounted on the launch rail.
4. The recovery lead activates the recovery system and verifies that it is ready for launch.
5. With permission from the RSO, the motor is ignited and the full-scale demonstration flight is conducted.
6. Upon landing, all components are recovered and inspected for damage.
7. All systems are removed and lithium polymer batteries are stored in a battery bag.

### Results

The first full-scale demonstration flight took place on February 27th, 2021 at the launch site in Three Oaks, Michigan. An image of the launch vehicle at lift-off alongside a screenshot from the on-board camera is shown in Figure 84.

An overview of flight conditions is provided in Section 5.1. As a launch vehicle control flight, the launch was successful and all stability, trajectory, and recovery parameters observed were nominal. The average altitude reading from the recovery altimeters showed an apogee altitude of 4,472 ft. The separation events and parachute deployments occurred at their appropriate times, ensuring that components landed at a kinetic energy below 75 lb-ft. All internal components and subsystems were successfully retained without damage as intended. A plot of the altimeter data from the flight is provided in Section 5.2.

Although the ACS was flown in its active state, drag tabs did not deploy other than a brief, short extension near apogee that did not impact the launch vehicle speed in a measurable way. This



**Figure 84:** Photos taken from full-scale demonstration flight

accounts for the overshoot compared to the target apogee altitude of 5,300 ft. The bug in the ACS code that caused the issue will be accounted for in the upcoming Payload demonstration flight.

Additionally, the CRAS-S and PLS did not jettison from the payload tube as intended. While this was not detrimental to the mission success from a control flight perspective, an additional Payload demonstration flight will be necessary to verify the payload success criteria.

### Next Steps

As the launch vehicle passed the TV.2 success criteria, it is prepared for competition flight. An additional Payload Demonstration Flight will be performed prior to the competition flight to verify the ACS, CRAS-S, and PLS subsystems.

Additionally, after the drag analysis performed in Section 5.5, it was determined that the launch vehicle would be painted to provide a smoother surface finish. Painting will be done professional before the upcoming Payload Demonstration Flight and Competition Flight.



## LAUNCH VEHICLE: FINS IMPACT TEST

Test ID: TV.3

Responsible Individual: Notre Dame Vehicle Design Lead

### Required PPE

- Safety Glasses
- Close-toed shoes

### Materials and Equipment

- Full fin can structural assembly
- Added weight equivalent to ACS and empty motor casing

- Tape measure

### Objective

The objective is to ensure the fins are able to sustain the impact load if the launch vehicle were to land directly on any fin.

### Motivation

During recovery, the fin can will come down under the main parachute. It is crucial that the fins remain structurally intact upon landing to ensure that the launch vehicle can be re-flown without repairs. If the launch vehicle were to land on the fins and the fins were not strong enough to withstand the impact load, the fiberglass would shatter, posing a safety hazard to those nearby. In addition, a failure of a fin during landing would require a new fin to be manufactured and attached to the launch vehicle.

### Success Criteria

Test ID	Success Description	Result
TV.3	The fins can withstand the impact test without sustaining damage that would require repairs or modifications for the launch vehicle to be reused.	Pass

### Test Setup

1. The speed the fin can is predicted to impact the ground at was calculated to be 16.8 ft/s under main parachute. Using basic kinematic equations, a drop height of 4.39 ft was calculated to achieve a speed of 16.8 ft/s upon landing.
2. Ballast weight was added to the fin can assembly until achieving a total weight of 270 oz, the predicted weight of the assembly at landing.
3. A patch of soft ground is chosen outside to conduct the drop test on.
4. A vehicles member uses a tape measure to locate a height of 4.38 ft above the ground.
5. Another vehicles member holds the fin can assembly at a slight angle with one fin pointed at the ground, because during the real flight, the parachute would create an angled fall.
6. The fin can assembly is held up to the tape measure so that the tip of the bottom fin is 4.38 ft above the ground.

### Test Procedure

1. The member holding the fin can assembly drops it in an orientation such that the lowest fin contacts the ground first, taking care to keep their feet clear of the landing spot.
2. Vehicles members inspect the fins and fin can assembly to ensure that no part is damaged. Special attention is paid to the epoxy fillets at the interface between fin and

boattail to look for cracking.

3. The fin is given a firm push and tug to ensure that it has not come loose from the assembly.

**Results** The fins impact test was successfully completed on February 11th, 2021. The test proved that the fins can withstand a direct impact with the ground upon landing at the predicted speed under main parachute. The fin impacted directly with the ground and after inspection, no damage was observed on the fins, epoxy fillets, or anywhere else on the assembly. A firm push and tug on the fin also verified that it did not come loose from the assembly at the internal motor mount tube. Images taken during the drop test are provided in Figure 85. It was concluded that the fin impact test results were successful and the fins are durable enough to be launched. The design and material choice of the fins, and their assembly within the fin can, demonstrated suitable structural integrity to withstand the predicted impact loading upon landing.



(a) Fin can assembly ready to drop



(b) Fin can assembly after drop test

**Figure 85:** Fins impact test

### Next Steps

Proceed to Test TV.4 to continue clearing vehicle structures for demonstration flight.



## LAUNCH VEHICLE: NOSE CONE IMPACT TEST

Test ID: TV.4

Responsible Individual: Notre Dame Vehicle Design Lead

### Required PPE

- Safety Glasses
- Long Sleeves
- Long Pants
- Close-Toed Shoes
- Gloves

### Materials and Equipment

- Nose cone
- Stable elevated structure
- Tape measure

### Objective

Verify that the FNC-6.0 nose cone can withstand the predicted impact loads acting on it during landing.

### Motivation

The nose cone will be recovered separately from the rest of the launch vehicle, under its own parachute. It is crucial that the nose cone remains structurally intact upon landing to ensure that the launch vehicle can be reflown without repairs. Furthermore, the payload recovery system is stored inside the nose cone. Consequently, if the nose cone fails, damage to the payload recovery system is likely to occur. For these reasons, the nose cone impact test was performed.

### Success Criteria

Test ID	Success Description	Result
TV.4	No cracks or any damages are visible on the nose cone after the impact test.	Pass

### Test Setup

1. The speed the nose cone is predicted to impact the ground at was calculated to be 24.4 ft/s under its parachute. Using basic kinematic equations, a drop height of 9.24 ft was calculated to achieve a speed of 24.4 ft/s upon landing.
2. A patch of soft ground is chosen outside, next to an elevated structure, to conduct the drop test on.

3. A vehicles member uses a tape measure to locate a height of 9.24 ft above the ground.
4. Another vehicles member stands on the elevated structure to bring the bottom-most surface of the nose cone to a height of 9.24 ft.
5. A third vehicles member ensures the one holding the nose cone is stable on top of the elevated structure.

### Test Procedure

1. Drop the nose cone such that the tip of the nose cone lands first. Be careful not to provide any additional kinetic energy to it as it is released.
2. Visually inspect the interior and exterior for dents, cracks, missing fragments, and deformations.
3. Repeat with the nose cone in a side-landing orientation

### Results

The test was performed outdoors on February 10, 2020. The conditions outside were snowy and 23 °F. Under these conditions, the nose cone material was more stiff, and thus more likely to incur damage as a result of the drop test. A patch of snow was removed from the ground such that the nose cone would land on soft ground, as it would during launch. The nose cone was dropped from a height of 9.24 ft. such that its velocity at landing would be equivalent to its velocity when falling under the parachute, 24.4 ft/s. The nose cone was first dropped such that the tip impacted the ground first. Images from this drop test are shown in Figure 86.



**Figure 86:** Photos of the nose cone tip-first drop test

There was no visible physical damage to the nose cone after the first test. The nose cone landed smoothly, and left a mark in the ground where it landed. The test was then repeated such that the nose cone landed on its side. Images from this drop test are shown in Figure 87.



(a) Nose cone ready to drop

(b) Nose cone mid-fall

(c) Nose cone after drop test

**Figure 87:** Photos of the nose cone side-first drop test

There was no visible damage to the nose cone after the test. Thus, the nose cone incurred no damage in either of the two successive tests, and passed the nose cone impact test. Due to the fact that the cold weather made it more likely that the nose cone would fail, the fact that it did not provides additional confidence that the nose cone will have a safe landing during the full-scale flight.

### Next Steps

Proceed to Test TV.5 to continue clearing vehicle structures for demonstration flight.



## LAUNCH VEHICLE: SHAKE TEST

Test ID: TV.5

Responsible Individual: Notre Dame Vehicle Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Fin can and boattail assembly
- Payload tube assembly

- Recovery tube assembly
- Nose cone
- Assembled ACS
- Assembled PLS
- Assembled CRAS-M
- Assembled CRAS-S
- Parachutes and shock cords

### Objective

The shake test is done in order to ensure that all components of the launch vehicle are secured as intended.

### Motivation

The shake test is done to simulate the vibrations of an actual launch.

### Success Criteria

Test ID	Success Description	Result
TV.5	No components of the vehicle are audibly loose or damaged after shaking vehicle.	Pass

### Test Setup

1. Several members of the team hold the entire launch vehicle above the ground. In order to not directly pull apart any component of the launch vehicle, the members will hold onto the body tubes.

### Test Procedure

1. The members who are holding the launch vehicle start to shake the launch vehicle lightly, simulating the vibrations of an actual launch.
2. After shaking the launch vehicle for around thirty seconds, the team will verify that all components are still secured.
3. If all components are still properly secured, the members will then shake the launch vehicle more vigorously to simulate the vibrations and disturbances of a real flight.
4. After shaking the launch vehicle again for around thirty seconds, the team will verify that all components are still secured.

### Results

There were no unexpected noises during the shake. Specifically, only quicklinks rattling together made noise during the test, which were expected. Upon visual inspection of each body part, there were no damages or potential problematic areas. As a result, the launch vehicle and interior systems demonstrated sufficient structural integrity for flight.

## Next Steps

Vehicle structures are fully cleared, proceed to Test TV.2 for demonstration flight.



## LAUNCH VEHICLE: SUBSCALE FLIGHT TEST

Test ID: TV.6

Responsible Individual: Notre Dame Vehicle Design Lead

## Required PPE

- Safety Glasses

## Materials and Equipment

- Subscale nose cone
- Subscale body tubes with coupler and bulkhead epoxied
- Subscale boattail assembly with affixed fins and motor mount tube
- Motor retainer cap
- (3) Aerotech G80T-10 motors
- (3) Motor igniters
- Subscale parachute
- 3D printed ACS drag tabs
- ACS and Recovery sensor sled with all sensors and batteries attached
- (2) 8 screws
- Phillips head screwdriver
- 5 oz Ballast bag
- Tape measure
- Sharpie
- Wood mount

## Objective

Demonstrate that a 42.3% scale model of the launch vehicle can successfully perform a full flight and recovery, and that the ACS drag tabs are able to lower the apogee altitude.

## Motivation

Verify performance predictions and properties of the launch vehicle design by flying a scale model with accurate dimensions and CG/CP locations. The validity of the simulation models is tested by comparing their results to the subscale flight data. The stability and structural integrity of the design is verified by observation of the flight and analysis of the flight data. The drag coefficient of the full-scale design can be updated based on the result. Verify the ability of the ACS drag tabs to decrease the apogee altitude, and estimate an incompressible drag coefficient for the tabs.

**Success Criteria**

Test ID	Success Description	Result
TV.6	The team successfully launches and recovers a subscale model of the launch vehicle prior to CDR.	Complete

**Test Setup**

1. Pass the body tube assembly to the Recovery Lead to pack the parachute.
2. With the parachute packed inside, insert the main body tube coupler into the body tube portion of the boattail assembly.
3. Plug the batteries into the required sensors on the sensor sled to initiate data collection or ready configuration.
4. Insert the sensor sled into the forward end of the main body tube assembly.
5. Ensure that the sensor sled is resting on top of the bulkhead.
6. Screw a 8 screw through the threaded hole in the main body tube to secure the sensor sled in place.
7. Insert the nose cone shoulder into the forward opening of the main body tube.
8. Align the threaded holes in the nose cone shoulder and the main body tube, and screw a 8 screw through them to secure the nose cone.
9. Insert an Aerotech G80T-10 motor into the motor mount tube.
10. Secure the motor by screwing on the motor retainer cap.
11. Secure an igniter in the opening of the motor using masking tape.
12. Balance the launch vehicle on the wood mount until it does not tip in either direction.
13. Mark the point at which the launch vehicle balances with a Sharpie as the CG.
14. Use the tape measure to measure the location of the CG from the nose cone, and verify that the measurement agrees with the OpenRocket simulated CG.
15. If necessary, add ballast to move the CG and repeat steps 12-14 until the CG is measured in the correct location.
16. Mount the launch vehicle on the launch rail by sliding the rail buttons down the 1010 slots.
17. Set the launch rail to a desired rail cant angle, and record the angle.
18. Attach the ignition leads to the motor igniter.

**Test Procedure**

1. Record the wind speed, temperature, and humidity.
2. With the launch vehicle properly mounted on the launch rail, ignite the motor.
3. Observe the entire flight from ignition to landing, checking off predicted flight events as they occur, and noting any anomalies.

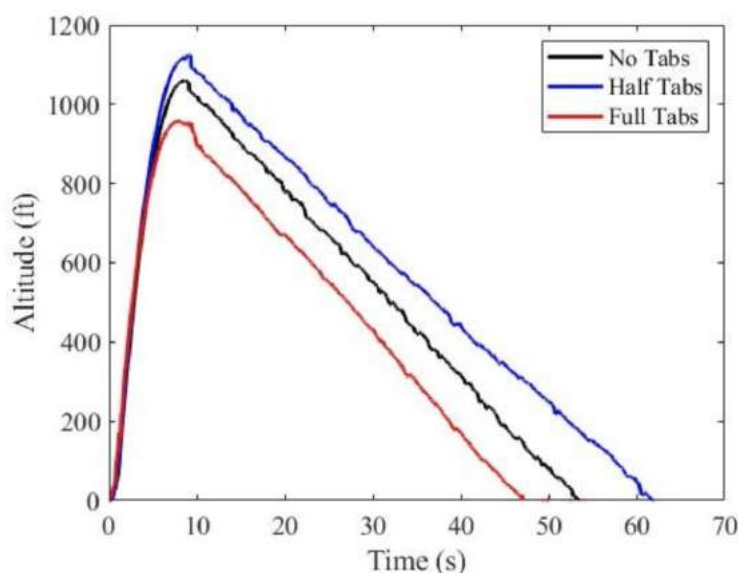
4. Inspect the launch vehicle at the landing site for any damage.
5. Listen to the Recovery Stratologger for beeps indicating the apogee altitude, and record the result.
6. Disassemble the launch vehicle and inspect once again for damage. If all components are intact, another launch may be conducted.
7. Download and save all sensor data from the previous flight.
8. Insert the 3D printed ACS half-extension drag tab configuration onto the coupler.
9. Repeat the test setup procedure.
10. Repeat steps 1-7 for the second test flight.
11. Repeat the entire process for a third test flight, instead with the full-extension drag tab configuration attached to the coupler .

## Results

Passed. The team successfully conducted three launches and recoveries of the 42.3% scale launch vehicle on November 13th, 2020 at the launch field in Three Oaks, MI. The first flight did not include 3D printed drag tabs, while the second and third flights included the half-extension and full-extension drag tab configurations. The apogee results from these flights are shown in Table 73, and plots of the flight data are shown in Figure 73.

ACS Configuration	Apogee Altitude (ft)
No Tabs	1060
Half Tabs	1124
Full Tabs	957

**Table 67:** Subscale Flight Test Apogee's



**Figure 88:** Subscale Flight Test Data

The apogee result of the configuration with no drag tabs was impacted by early weathercocking that occurred at the launch rail exit, and the results of the following two flights yielded higher apogee altitudes because a longer launch rail was used to ensure that the rail exit speed was high enough to yield stability

### Next Steps

Proceed to Test TV.1 to begin clearing vehicle structures for demonstration flight.

## 7.1.2 Apogee Control System Testing



### APOGEE CONTROL SYSTEM: DEMONSTRATION FLIGHT TEST

Test ID: TA.1

Responsible Individual: Notre Dame Apogee Control System Design Lead

#### Required PPE

- Safety Glasses

#### Materials and Equipment

- Launch Vehicle
- Assembled ACS Structure
- Charged Laptop
- Sensor Computer Connection Wires

#### Objective

The goal of this test is to ensure that the system is able to perform as desired and induce an appropriate amount of drag such that the vehicle arrives at the team apogee target of 5,300 ft.

#### Motivation

A demonstration flight allows for the complete system to be tested prior to final adjustments before the Flight Readiness Review and the competition flight.

#### Success Criteria

Test ID	Success Description	Result
TA.1	The control algorithm successfully deploys tab extensions to induce drag and reduce vehicle velocity to the target of 5,300 ft. Additionally, tabs deploy at appropriate times but do not extend and retract in an oscillatory motion.	Failed, pending re-test

#### Test Setup

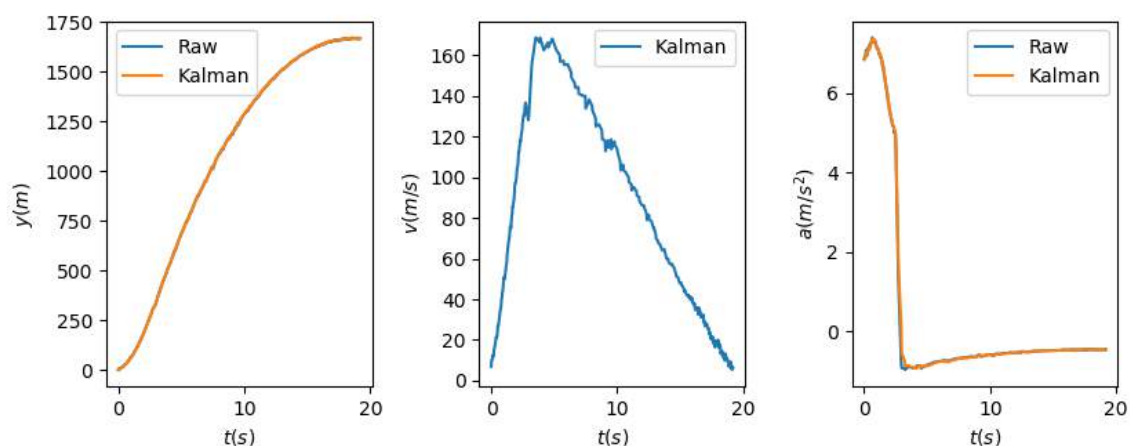
1. See Launch Checklist: Apogee Control System Preparation for instructions on setting up the ACS before the demonstration flight.
2. See Launch Checklist: Vehicle Preparation for instructions to integrate the ACS into the vehicle before the demonstration flight.
3. Power ON all electronics. Ensure battery is fully charged for up to two hours of use.

### Test Procedure

1. Make sure ACS is integrated into vehicle properly, according to launch checklists.
2. Verify ACS power LED is on while vehicle is on launch pad. Similarly, verify ACS stage LED indicates a "pre-flight" condition.
3. Proceed with flight and recovery per Launch Checklist: Launch Procedures
4. Remove ACS from vehicle after post-flight recovery.
5. Connect Raspberry Pi to laptop with SSH
6. Download data and inspect for 1) Kalman filtered data, 2) vehicle apogee, and 3) tab extension points.

### Results

Partially complete. The team was able to demonstrate the Kalman filter, control algorithm, and drag tab actuation during the first vehicle demonstration flight. Despite this, the team was not able to verify full system performance due to a bug in the state transition code. The issue has been addressed, and the team will complete a further demonstration flight to verify full system functionality. Figure 89 depicts ACS data collected during the vehicle demonstration flight.



**Figure 89:** Vehicle Demonstration Flight Position, Velocity, and Acceleration ACS Data

### Next Steps

An additional Demonstration Flight is required to complete Test TA.1. A comprehensive software review has occurred and the ACS system has been deemed ready for a Demonstration Flight to occur during the Payload Demonstration Flight.



## APOGEE CONTROL SYSTEM: FLIP TEST

Test ID: TA.2

Responsible Individual: Notre Dame Apogee Control System Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled ACS Structure
- Charged Laptop
- Sensor Computer Connection wires
- Protractor

### Objective

The goal of this test is to ensure that the accelerometer and IMU both give accurate readings while also certifying secure ACS assembly.

### Motivation

This test ensures that the accelerometer and IMU are calibrated correctly and give accurate readings when orientation of the structure changes. Additionally, verifying structural integrity will ensure no loose parts damage the vehicle body during flight.

### Success Criteria

Test ID	Success Description	Result
TA.2	Sensors accurately detect orientation and acceleration data during rotation to within 10% of expected values. No parts are visually or audibly loose after rotations.	Pass

### Test Setup

1. Assemble full ACS structure.
2. Power ON all electronics. Ensure battery is sufficiently charged for at least 20 minutes of use.
3. Connect sensors to laptop for live sensor readings. Check that sensors are transmitting data to the laptop.

## Test Procedure

1. Ensure all sensors are on and connected to laptop prior to dropping.
2. Hold ACS structure with two hands above the table. Ensure wires are not tangling.
3. Slowly rotate ACS clock-wise, with respect to the personnel's line of vision.
4. A second member must verify sensors are transmitting changes in data in the correct direction.
5. Do not proceed until sensors data transmission is operating.
6. Re-orient ACS in starting position.
7. Rotate ACS end-over-end and repeat step 4.
8. Re-orient ACS in starting position.
9. Position ACS at an angle and use the protractor to record the value.
10. Compare this value to the sensor-detected angle.
11. Calculate error between expected and recorded values.

## Results

Passed. This test allowed the team to calibrate the accelerometer and the IMU so that the Kalman filter was able to receive the correct component of acceleration in its filtering. The sensors were able to appropriately respond to rotations of the system, and the vertical component of acceleration was consistently read by the Kalman filter.

## Next Steps

Proceed to Test TA.3 to continue clearing ACS sensors and electronics for demonstration flight. Additionally, proceed to Test TA.5 to continue clearing ACS structure.



## APOGEE CONTROL SYSTEM: SAMPLE DATA CONTROL ALGORITHM TEST

Test ID: TA.3

Responsible Individual: Notre Dame Apogee Control System Design Lead

## Required PPE

- Safety Glasses

## Materials and Equipment

- ACS Sensor Sled
- Charged Laptop
- Sensor Computer Connection Wires

## Objective

The goal of this test is to demonstrate that the data filter and control algorithm function well together, and that the control algorithm gives realistic indications for tab extensions.

### Motivation

The data test will verify the software aspect of the apogee control system design in advance of testing the actual servo movements and tab extensions.

### Success Criteria

Test ID	Success Description	Result
TA.3	The control algorithm correctly identifies flight data and initiates necessary adjustments by indicating tab extensions with 0.5 second of data transmission.	Pass

### Test Setup

1. Assemble the ACS system
2. Connect the laptop to the Raspberry Pi through SSH
3. Create a program to simulate sensor readings from a spreadsheet
4. Construct simulated flight data

### Test Procedure

1. Run the test data into the data filtering algorithm.
2. Save control algorithm output.
3. Using a coding program of choice (i.e. MATLAB, Python, etc.) compare the provided data and control algorithm output.
4. Mark all expected tab extensions and the actual simulated extensions from the algorithm output.
5. Verify all tab extensions occur within 0.5 seconds of the expected extension, and that all expected extensions occur.

### Results

Passed. This allowed the team to debug the control and data filtering code, and also to tune the parameters of the Kalman filter and proportional control algorithm. The team was able to attain reasonable simulated extension given the tab dimensions and flight conditions simulated under. The team performed simulations with both the data gathered from the sub-scale flight and a computer simulation.

### Next Steps

Proceed to Test TA.4 to continue clearing ACS sensors and electronics for demonstration flight.



## APOGEE CONTROL SYSTEM: SAMPLE DATA SERVO MOTOR ACTUATION TEST

Test ID: TA.4

Responsible Individual: Notre Dame Apogee Control System Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled ACS Structure
- Charged Laptop
- Sensor Computer Connection Wires
- Video Camera (i.e. Phone camera with video capabilities)

### Objective

The goal of this test is to demonstrate that the control electronics are able to accurately interface with the servo motor.

### Motivation

A servo actuation test will be able to verify that the servo operates and can be controlled by the electronics as expected.

### Success Criteria

Test ID	Success Description	Result
TA.4	The drag tabs extend at the specific times programmed into the sample data, to within 0.5 seconds.	Pass

### Test Setup

1. Assemble the ACS system
2. Connect the laptop to the Raspberry Pi through SSH
3. Create a program to simulate sensor readings from a spreadsheet
4. Construct simulated flight data
5. Place ACS upright on a table

### Test Procedure

1. Run the test data into the data filtering algorithm.

2. Take a video of the tab extensions as the sample data is run.
3. Compare tab extensions in the video with expected tab extensions in the sample data.

### Results

Passed. The test was carried out as specified, and the servo was able to actuate the drag tabs. The team was able to compare the extension of the tabs with the ideal extension of tabs designated by the control algorithm and confirm that the two were in agreement.

### Next Steps

Proceed to Test TA.1 for demonstration flight criteria.



## APOGEE CONTROL SYSTEM: SHAKE TEST

Test ID: TA.5

Responsible Individual: Notre Dame Apogee Control System Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled ACS Structure
- Charged Laptop
- Sensor Computer Connection Wires

### Objective

The objective of the shake test is to ensure that the system is resilient to perturbation, and also to ensure that accelerometers accurately respond to an external stimulus.

### Motivation

A shake test allows the complete sensor array to be tested, specifically in response to a simulated flight environment. Additionally, verifying structural integrity will ensure no loose parts damage the vehicle body during flight.

### Success Criteria

Test ID	Success Description	Result
TA.5	Sensors detect orientation and acceleration data during shakes. No parts are damaged after thorough visual inspection following shakes.	Pass

### Test Setup

1. Assemble full ACS structure.
2. Power ON all electronics. Ensure battery is sufficiently charged for at least 20 minutes of use.
3. Connect sensors to laptop for live sensor readings. Check that sensors are transmitting data to the laptop.

### Test Procedure

1. Ensure all sensors are on and connected prior to shaking.
2. Hold ACS structure with two hands above the table. Ensure wires are not tangled.
3. Slowly shake ACS vertically.
4. A second member must verify sensors are transmitting changes in data in the correct direction.
5. Do not proceed until sensors data transmission is operating.
6. Open a metronome on the internet using the laptop. Turn the volume up.
7. Start a metronome at 200 bpm.
8. Perform 10 vertical shakes to the metronome clicks, including both upward and downward motions in the same shake.
9. Re-orient ACS to starting position.
10. Perform 10 horizontal shakes to the same metronome clicks, including both motions, right and left, in the same shake.
11. Confirm sensors detected motion on laptop. If data anomalies are identified, return to Test TA.3 to confirm sensor accuracy.
12. Inspect ACS structure visually. Take special note of locations of possible stress concentrations, such as corners or edges of parts.

### Results

Passed. This allowed the team to gauge the sensitivity of the accelerometers. By shaking the system in different directions, the team was able to verify the functionality of each axis of the accelerometer data, and confirm that they were able to respond to sudden accelerations of large magnitude.

### Next Steps

Proceed to Test TA.1 for demonstration flight criteria.



## APOGEE CONTROL SYSTEM: SUBSCALE DATA FILTER TEST

Test ID: TA.6

Responsible Individual: Notre Dame Apogee Control System Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Subscale Sensor Sled
- Charged Laptop
- Sensor Computer Connection Wires

### Objective

The objective of the subscale flight is to collect data while testing sensors and electronics, and then test the filtering algorithm to ensure data can be cleaned for use in the demonstration flight.

### Motivation

This subscale flight provides the opportunity to adjust underlying assumptions and filtering programming in the control algorithm if necessary, as well as ensure the sensors are able to detect motor burnout and apogee. Additionally, the subscale data filtering test allows for the ACS team to better filter data to provide clean data to the servo motor.

### Success Criteria

Test ID	Success Description	Result
TA.6	ACS sensors are able to capture a full flight. Data filtering algorithm is able to smooth provided subscale data for effective servo motor actuation.	Pass

### Test Setup

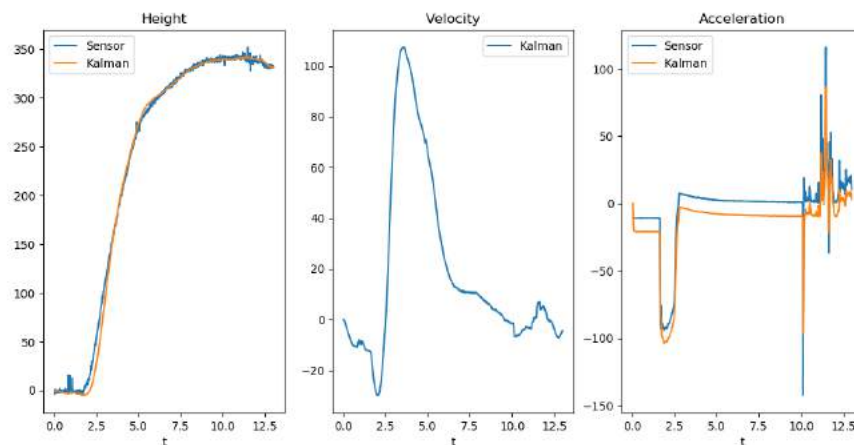
1. See Subscale Launch Procedures for instructions on performing three subscale flights.
2. Power ON all electronics.
3. Connect Raspberry Pi to laptop using the SSH

### Test Procedure

1. Download subscale data from all subscale flights.
2. Save a duplicate of each data set for testing.
3. Open Kalman filter program from coding software of choice.
4. Apply filter to each subscale data set.
5. Visually confirm the filter does not affect algorithm before burnout or after apogee.
6. Visually note drastic changes in provided data and compare to smoothed data. Adjust filter if filtered data will cause control algorithm to act incorrectly.

### Results

Passed. Three subscale flights were performed and the chosen Kalman filter is able to smooth all data, detect burnout and apogee. The sensors were able to capture accurate data for each flight as well, confirmed with recovery electronics on the same sensor sled. Figure 90 depicts both the raw and filtered subscale flight data to show the smoothed curve.



**Figure 90:** Kalman Filtered Subscale Data

### Next Steps

Proceed to Test TA.2 to begin clearing final ACS sensors and electronics assembly for demonstration flight.

### 7.1.3 Recovery Testing



#### RECOVERY: ALTIMETER SIMULATED FLIGHT TEST

Test ID: TR.1

Responsible Individual: Notre Dame Recovery Design Lead

#### Required PPE

- Safety Glasses

#### Materials and Equipment

- Altimeters used in CRAS-M and CRAS-S: 2 Perfectflite Stratologger SL100's, 2 Perfectflite StratologgerCF's, and 1 Featherweight Raven3
- 5 LiPo batteries
- 10 Small LEDs
- Charged Laptop

- USB connector cable

### Objective

The objective of this test is to ensure that the altimeters will ignite the black powder charges at apogee (with respective delays, if necessary) and 575 ft (again, with respective delays) for the altimeters in the CRAS-M and 525 ft (with respective delays) for the altimeters used by the CRAS-S.

### Motivation

This test is important to ensure that the launch vehicle is safely recovered and completes its mission, contingent on the successful operation of the altimeters. Performing a simulated flight allows for the entire system to be tested before use in a real launch.

### Success Criteria

Test ID	Success Description	Result
TR.1	Altimeter lights illuminate at the correct points during a simulated flight created in a computer program.	Pass

### Test Setup

1. Attach lights to the drogue and main ejection output terminal blocks of 1 Perfectflite Stratologger SL100, 1 Perfectflite Stratologger CF, and the Featherweight Raven3. Attach a light to each of the main ejection output terminal blocks of 1 Perfectflite Stratologger SL100 and 1 Perfectflite Stratologger CF.
2. Connect a battery to the battery terminal block on each altimeter.

### Test Procedure

1. Connect the first altimeter to be tested to the laptop with the proper software to running the altimeter through a simulated flight test using the data I/O connector on the altimeter.
2. Run the altimeter through a simulated flight using the computer generated flight data.
3. Record the height at which the altimeter light(s) illuminate and compare with the expected height of illumination in the simulated flight code.
4. Repeat steps 1-3 for all 5 altimeters.

### Results

Test TR.1 was successful. Each altimeter was tested using a simulated flight software and small LED lights attached to the drogue and main ejection output terminal blocks. The drogue

output lights of the CRAS-M altimeters lit up as expected at apogee with respective delays. At 575 feet, the lights connected to the main ejection output terminals became lit as expected, again with respective delays. The CRAS-S altimeters also responded to the simulated test correctly, with the LED lights illuminating at 525 feet with respective delays.

**Next Steps** Proceed to Test TR.2 to continue clearing recovery electronics for demonstration flight.



## RECOVERY: BATTERY LIFE TEST

Test ID: TR.2

Responsible Individual: Notre Dame Recovery Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Altimeters: Stratologger SL100, Stratologger CF, and Raven4
- Eggfinder Mini
- 1S Lithium polymer battery and charger
- 2S Lithium polymer battery and charger
- 4 small LED lights
- Timer

### Objective

The goal of this test is to ensure that the batteries for the altimeter and GPS transmitters can provide sufficient power to the electronics for at least 2 hours on the pad before launch.

### Motivation

This test is being performed to verify the battery life calculations completed in Section (battery life section) and to ensure that requirement RE.3 is met.

### Success Criteria

Test ID	Success Description	Result
TR.2	The altimeters and GPS transmitters remain on and powered for at least 2 hours on one battery charge.	Pass

### Test Setup

1. Completely charge 1S lithium polymer batteries for altimeters and 2S lithium polymer batteries for Eggfinders

### Test Procedure

1. Plug batteries into various electronics and start a separate timer for each battery.
2. When the electronic device powers down, stop the timer and record the time elapsed.
3. Ensure all batteries are tested for the applicable sensors or electronics as the configuration would be during demonstration flight.

### Results

The Lithium polymer batteries were connected to the various electronics and LED lights utilized in the CRAS-M and CRAS-S and placed outside in a box with the temperature reading 13°F to simulate launch conditions. The batteries held charge for the entire 2 hours and continued to light the LEDs and power the electronics throughout the duration of the time. Figure 91 shows the set up of the successful battery life test.



**Figure 91:** Battery Testing Set Up

### Next Steps

Proceed to Test TR.6 to continue clearing recovery electronics for demonstration flight.

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## RECOVERY: BLACK POWDER SEPARATION GROUND TEST

Test ID: TR.3

Responsible Individual: Notre Dame Recovery Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled Launch Vehicle
- Black powder (provided by Launch Manager)
- Vehicle supports
- E-matches
- Long wires
- 9V battery

### Objective

The objective of this test is to ensure that the calculated amount of black powder is sufficient to separate the vehicle sections and allow for parachute deployment, as well as to ensure that the recovery hardware, parachutes, and electronics will be sufficiently protected from ejection gasses or debris. The test will also serve as a test of the CRAS-S and payload jettison.

### Motivation

This test is performed to verify the calculations detailed Appendix 7.3 before the system is launched.

### Success Criteria

Test ID	Success Description	Result
TR.3	For each separation point, both sections of the vehicle fully separate. No structural damage to vehicle, recovery hardware, parachutes, or electronics results from black powder charges.	Pass

### Test Setup

1. Set altimeter to eject at a specified time.
2. Launch Manager prepared CRAS-M and CRAS-S charges as stated in Launch Checklist:  
Recovery Preparation

3. Place vehicle supports in launch area.

### Test Procedure

1. Start by testing the CRAS-M at the main parachute ejection point
2. Allow the mentor to assemble the black powder charge and place it in the charge well.  
Connect the wires to each end of the e-match.
3. Verify amount of black powder at the selected separation point with the Launch Manager and record for evaluation.
4. Assemble launch vehicle.
5. Once everyone is clear of the testing site, allow the mentor to place the leads of the long wires on each terminal of the 9V battery and watch as the black powder ignites.
6. If no ejection, consult with Launch Manager. Safely disarm vehicle and increase amount of black powder by 0.5 g.
7. If ejection is a success, move on to next separation point.
8. For the nose ejection point, once the sections are fully separated, carefully flip the payload bay into a vertical configuration and allow for CRAS-S and PLS to slide out.

### Results

Ground testing was a success for each of the three separation points. Figure 92 shows the successful ground test for the main parachute deployment.



(a) CRAS-M ground testing set up



(b) Configuration during test



(c) Configuration just after test

**Figure 92:** CRAS-M black powder ground testing

Similarly, Figure 93 shows the successful ground testing of the nose jettison.



**Figure 93:** CRAS-S black powder ground testing

All of the recovery hardware, parachutes, and electronics were inspected after each ground test and found undamaged. Figure 94 shows the undamaged nose parachute and harness after ground testing.



**Figure 94:** Undamaged Nose Parachute and Harness After Ground Testing

The ground testing also validated the general functionality of the nose recovery system. While the CRAS-S did not jettison from the payload tube during the ejection process, when the payload bay was tipped downward, the CRAS-S deployed from the vehicle without difficulty. This test serves as preliminary validation that the CRAS-S and payload will jettison from the rocket upon separation and the nose cone parachute will fully deploy. Table 68 shows the charge masses used in the successful ground testing.

**Table 68:** Black Powder Used in Ground Testing

Event	Mass (g)
Drogue	2.0
Main	4.5
Nose	2.0

### Next Steps

Despite the sections completely separating when using 2.0 g for the drogue ground testing, the team's mentor advised using 3.0 g for the drogue ejection and this advice was heeded. Proceed to Test TR.5 to test deployment charge disarm capability.



## RECOVERY: DEMONSTRATION FLIGHT TEST

Test ID: TR.4

Responsible Individual: Notre Dame Recovery Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled CRAS-M
- Assembled CRAS-S
- Assembled Launch Vehicle
- E-matches

### Objective

The goal of this test is to ensure that the recovery system is working properly and will allow for successful vehicle recovery on competition day.

### Motivation

Testing the entire system in similar conditions to the competition launch is the most accurate way to determine if the system will work.

### Success Criteria

Test ID	Success Description	Result
TR.3	For each separation point, both sections of the vehicle fully separate. All parachutes deploy successfully. No structural damage to CRAS-M or CRAS-S.	Pass

### Test Setup

1. Complete Launch Checklist: Recovery Preparation
2. Complete Launch Checklist: Launch Vehicle Preparation
3. Complete Launch Checklist: Launch Setup

### Test Procedure

1. Complete Launch Checklist: Launch Procedure
2. Complete Launch Checklist: Post-Flight Recovery and Analysis
3. Inspect CRAS-M and CRAS-S for any damages. Take pictures of all systems for further inspection.

### Results

The recovery system performed successfully during the demonstration flight test. The drogue, main, and nose cone parachutes deployed and safely recovered the launch vehicle with a drift radius within NASA requirements with no structural damage to the CRAS-M or CRAS-S.

### Next Steps

The recovery subsystem is cleared for competition launch.



## RECOVERY: DEPLOYMENT CHARGE DISARM TEST

Test ID: TR.5

Responsible Individual: Notre Dame Recovery Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Fully mounted and assembled recovery avionics
- Flathead Screwdriver
- Small Incandescent Lights

### Objective

The objective of this test is to ensure that any ejection charges that were not set off during the flight for any reason can be safely disarmed on the ground.

### Motivation

This test is performed to ensure that the most dangerous part of the system can be safely deactivated before the vehicle is launched.

**Success Criteria**

Test ID	Success Description	Result
TR.5	The light, a substitute for the e-match, does not illuminate at any point during the disarming of deployment charge disarming.	Pass

**Test Setup**

1. Replace the e-matches with small lights at the e-match connection slot.
2. Ensure that the batteries used to power the altimeters are fully charged and the electronics are fully assembled and ready to operate.

**Test Procedure**

1. With the e-match substitutes in place, power on all three recovery altimeters.
2. Listen through the start up sequence of a the altimeters, ensuring proper start up.
3. One at a time, turn off the altimeters using the power key.
4. Look for any illumination from light bulbs.
5. Record if any lights illuminate.

**Results**

Test TR.5 was successful. All altimeters were disarmed without the lights illuminating during the process.

**Next Steps**

Proceed to Test TR.4 for the demonstration flight.

**RECOVERY: GPS TRANSMITTER FIELD TEST**

Test ID: TR.6

Responsible Individual: Notre Dame Recovery Design Lead

**Required PPE**

- Safety Glasses

**Materials and Equipment**

- Eggfinder RX GPS receiver
- Eggfinder Mini GPS transmitter
- Windows computer with VisualGPS installed
- USB cable

**Objective**

The objective of this test is to confirm that the GPS Transmitter is functioning correctly before demonstration launch.

### Motivation

The motivation of this test is to ensure the GPS transmitter can transmit data on vehicle location after descent so the team can find and recover the landed vehicle.

### Success Criteria

Test ID	Success Description	Result
TR.6	The VisualGPS computer program is able to receive data from the GPS transmitter through the Eggfinder RX receiver and correctly plots the location of the Eggfinder Mini transmitter to within 10 yards.	Pass

### Test Setup

1. The Eggfinder RX GPS receiver and the Eggfinder Mini GPS transmitter are assembled following the instructions in the assembly manuals.
2. Power up the Eggfinder Mini GPS transmitter. A red LED light should begin blinking about once per second on the Eggfinder Mini transmitter's RF board.
3. Plug the USB cable of the Eggfinder RX into the Windows computer. The red light should immediately come on, indicating that the receiver is receiving power. After one or two seconds, the green light on the RF board of the Eggfinder RX should begin blinking in sync with the light on the Eggfinder Mini, indicating that it is receiving data from the Eggfinder Mini.

### Test Procedure

1. Open the program VisualGPS on the windows computer. The program should begin plotting the approximate locations of the Eggfinder Mini transmitter on a grid system and displaying the satellite strength.
2. After confirming everything is functioning correctly, turn off the Eggfinder Mini transmitter by unplugging the battery. The green light on the Eggfinder RX receiver should stop blinking.
3. Unplug the USB cable. The test is complete.
4. If any complications occur or if any of the requirements for each step are not met, refer to the troubleshooting sections of the assembly manuals for the Eggfinder TX or Mini transmitter and Eggfinder RX receiver.

### Results

Test TR.6 was successful. Figure 95 shows the outputs from both the Eggfinder TX (left) and the Eggfinder Mini (right). The latitudes and longitudes given by both of the GPS devices were within the acceptable range of accuracy, indicating a success.

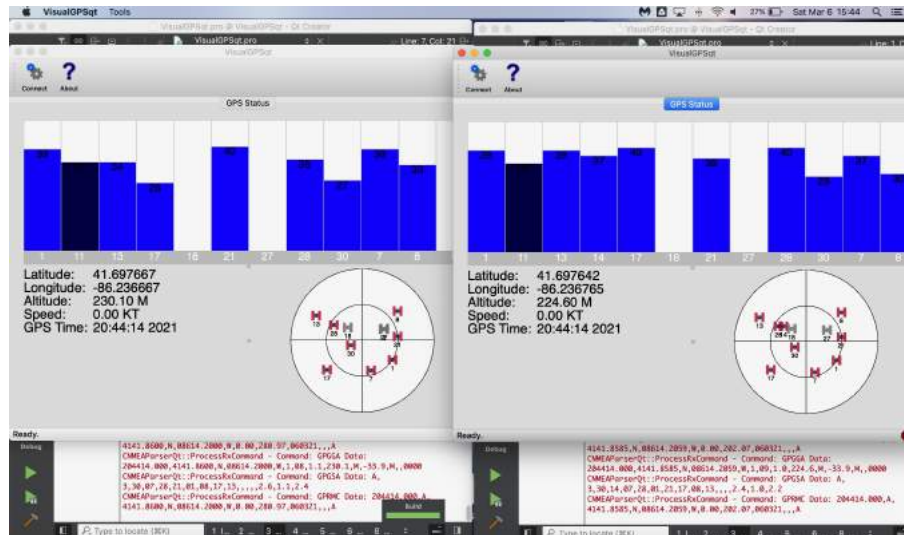


Figure 95: GPS Outputs

## Next Steps

Recovery electronics are completely tested and prepared for demonstration flight. Proceed to Test TR.4 for the demonstration flight.



## RECOVERY: PARACHUTE OPEN TEST

Test ID: TR.7

Responsible Individual: Notre Dame Recovery Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled drogue parachute system
- Assembled main parachute system
- Assembled nose parachute system

### Objective

The goal of this test is to ensure that the parachutes can fully open in their planned configurations

### Motivation

The successful opening of the parachutes, especially of the main parachutes release from the deployment bag, is critical to a successful recovery and must be ensured before a full scale launch.

### Success Criteria

Test ID	Success Description	Result
TR.3	Parachute fully opens before reaching the ground from a height of more than 35 ft.	Pass

### Test Setup

1. Take all assembled parachute configurations to the 4th floor balcony of the Jordan Hall of Science on University of Notre Dame's campus. This is roughly 40 ft above the first floor.

### Test Procedure

1. Hold parachute closed while a second member holds the recovery structure beneath the parachute.
2. Drop each parachute system from the balcony and watch for the parachute to open as it descends.
3. Ensure parachute fully opens prior to landing on the ground of the 1st floor.

### Results

The parachute systems were dropped from the balcony of Jordan Hall of Science with successful results. The main parachute exited the deployment bag and was completely clear of the bag when it hit the ground. The parachute's shroud lines were also completely untangled. The test ensures that the parachute systems will deploy as expected when the sections of the launch vehicle separate. Figure 96 shows the main parachute extended on the ground after the successful parachute drop test.



**Figure 96:** Image taken after completion of balcony drop testing of the main parachute.

### Next Steps

Proceed to Test TR.4 for the demonstration flight.

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#### 7.1.4 Planetary Landing System Testing



### PLANETARY LANDING SYSTEM: DEMONSTRATION FLIGHT TEST

Test ID: TP.1

Responsible Individual: Notre Dame Experimental Payload Design Lead

#### Required PPE

- Safety Glasses

#### Materials and Equipment

- Full vehicle
- Complete PLS system
- Fully charged batteries
- Charged laptop capable of receiving image transmission

### Objective

The objective is to verify that the PLS can be retained in the vehicle, jettison at 525 ft, land on the ground safely, orient to within 5 degrees from vertical, take a panoramic image, and transmit to a team computer.

### Motivation

Testing the complete PLS system prior to competition enables the team to make necessary adjustments before competition launch day arrives.

### Success Criteria

Test ID	Success Description	Result
TP.1	The PLS suffers no damages during jettison, descent under parachute, landing or orientation, determined by a visual inspection following the mission. The PLS is able to transmit a full panoramic image of acceptable quality to receiver after landing, before team recovery.	Failed, pending re-test

### Test Setup

1. Follow step-by-step instructions in Launch Checklist: Planetary Landing System Preparation to prepare the PLS and PLS parachute for integration into the launch vehicle.
2. Ensure all batteries are fully charged for at least 2 hours of use and electronics are powered ON before inserting into vehicle.
3. Follow step-by-step instructions in Launch Checklist: Launch Vehicle Preparation to properly integrate PLS into vehicle and secure the retention system
4. Follow step-by-step instructions in Launch Checklist: Recovery Preparation to have Launch Manager safely arm the CRAS-S with black powder for separation.
5. Power ON laptop and ensure image receiving software program is active.

### Test Procedure

1. Follow step-by-step instructions in Launch Checklist: Launch Procedures to commence the demonstration flight test.
2. Allow mission to proceed without interruption from Notre Dame personnel.

3. Wait for orientation and image to be transmitted to laptop before recovery.
4. If no image is transmitted after 15 minutes, recover vehicle.
5. If image is transmitted within 15 minutes, recover vehicle.
6. Use level and protractor to determine final PLS angle from vertical. Record this value for data analysis.
7. Use camera to record PLS parachute final location relative to PLS structure.
8. Evaluate transmitted image quality on laptop and ensure landscape is appropriately depicted in image compared to a simple look around the landing area. Image must not be significantly obstructed by parachute or
9. Compare PLS end state angle to angle detected in PLS computer.

### Results

Failed test, pending re-test. The PLS failed to deploy from the payload tube following nosecone ejection, as it was blocked by the CRAS-S. The PLS impacted the ground on its side while still in the payload tube, and did not have the opportunity to demonstrate ejection detection, leg deployment, landing detection, orientation, or data transmission. The unusual impact scenario caused two of the cameras to become dislodged. No permanent damage was done.

### Next Steps

Repeat Test TP.1 and discuss an alternative testing strategy with Safety Officer and Chief Engineer until success criteria is met. A repeat of TP.1 as written will require another scheduled demonstration flight and relevant FAA waiver.



## PLANETARY LANDING SYSTEM: EJECTION DETECTION TEST

Test ID: TP.2

Responsible Individual: Notre Dame Experimental Payload Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled PLS
- Payload Tube of Vehicle Body
- Jumper Cable
- Several Cushions or Pillows
- Small LED Light

### Objective

The objective is to verify that the PLS ejection detection system can accurately and quickly determine if the PLS has ejected from the payload tube.

### Motivation

The PLS must be able to verify ejection so that the legs can begin to deploy during descent. If ejection is not detected, PLS is unlikely to orient within 5 degrees from the vertical after landing.

### Success Criteria

Test ID	Success Description	Result
TP.2	The landing legs move to their deployed state within three seconds of the PLS exiting the payload tube and detachment of the jumper pin.	Pass

### Test Setup

1. Configure PLS with landing legs closed.
2. Attach LED to Raspberry Pi.
3. Install Raspberry Pi and jumper pins to PLS.
4. Install PLS into retention system in the payload bay.
5. Place padded cushions directly below the payload bay.
6. Position a video camera such that the payload bay and LED can be captured in the same shot.

### Test Procedure

1. Lift payload bay about 1 foot in the air. Keep cushions directly below the payload bay.
2. As you lift, the PLS should slide out and the jumper cable should detach.
3. Inspect PLS for any damages.
4. Stop video.
5. In slo-motion view, determine how long the LED took to illuminate after the jumper cable released.
6. Compare this value to the 3 second limit specified in the success criteria.

### Results

The PLS moved its legs to the deployed state reliably upon detachment of the jumper pin. The average ejection detection time was under 1 second, therefore the test has been passed.

### Next Steps

If Test TP.2 results passes success criteria, proceed to Test TP.5 to continue clearing PLS deployment system for demonstration flight.

If Test TP.2 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate ejection detection system design and repeat Test TP.2 until success criteria is met.



## PLANETARY LANDING SYSTEM: IMAGE TRANSMISSION TEST

Test ID: TP.3

Responsible Individual: Notre Dame Experimental Payload Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled PLS system
- Fully charged battery
- Charged laptop capable of receiving image transmission

### Objective

To objective is to confirm that the PLS can transfer an image from the maximum allowable drift distance of 2,500 ft. Additionally, this test will verify that the PLS camera and data transmission system can transmit an image of acceptable quality.

### Motivation

The PLS should be able to transmit an acceptable image from anywhere within the allowable drift radius, such that the PL image can be scored for competition.

### Success Criteria

Test ID	Success Description	Result
TP.3	The PLS can transmit all packages to complete a panoramic images, without obstruction, from a distance of at 2,500 ft or more.	Failed, pending re-test

### Test Setup

1. Go to an open field with at least 0.5 miles of uninterrupted landscape.
2. At least one member place PLS on the ground, powered ON with legs deployed.
3. Attach parachute to eyebolt and hold up in the air.
4. Release parachute to simulate a natural landing position of the parachute.
5. Call other members to confirm laptop is powered on with image receiving software active.

### Test Procedure

1. Initiate the PLS imaging process while PLS is on ground. Orientation is not critical for this test, but PLS should be upright.
2. Wait for a maximum of 5 minutes from initiation to image reception.
3. Download full panoramic image onto laptop and view.
4. Perform a visual scan of the area and confirm the transmitted image matches the landscape.
5. Evaluate quality of image and ensure the image is unobstructed, clear, and the landscape is easily identifiable.

### Results

Failed test, pending re-test. PLS image transmission system often produced error that caused loss of one of four images.

### Next Steps

If Test TP3 results passes success criteria, imaging and transmission systems are cleared. Proceed to Test TP1 for demonstration flight.

If Test TP3 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate image transmission software or camera selection and repeat Test TP3 until success criteria is met.



## PLANETARY LANDING SYSTEM: LANDING DETECTION TEST

Test ID: TP4

Responsible Individual: Notre Dame Experimental Payload Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Assembled ACS Structure
- Small LED Light
- Shock Cord or Rope
- Timer
- Measuring Tape

### Objective

To objective is to verify that the PLS can identify ground impact and initiate the orientation process.

### Motivation

To meet mission criteria, the PLS must orient and transmit the image, which it will not be able to do if the PLS does not transition to the orientation process after identifying landing.

### Success Criteria

Test ID	Success Description	Result
TP.4	LED illuminates when PLS lands on the ground, and the calculated kinetic energy on impact is lower than the actual expected kinetic energy on impact under parachute.	Pass

### Test Setup

1. Attach shock cord to the PLS eyebolt.
2. Attach LED to Raspberry Pi to indicate landing sequence detection.
3. Power ACS on and set legs to descent configuration, with legs perpendicular to the PLS structure.

### Test Procedure

1. Raise PLS up at least 4 ft, holding onto the cord, not the ACS structure itself.
2. Measure starting height with a measuring tape.
3. Start timer when ACS descent begins.
4. Lower ACS to the ground slowly until impact. Stop timer.
5. Observe if LED illuminates or not.
6. Calculate descent kinetic energy of ACS using timer calculations.
7. If LED illuminated, verify descent kinetic energy is less than the expected descent kinetic energy. This would result in test success.
8. If LED does not illuminate, first inspect LED and replace if necessary. If LED is good, allow PLS to descend lightly faster than the previous trial.
9. Repeat Step 8 until LED illumination or maximum possible descent kinetic energy is reached. This would result in test failure.

### Results

Test completed successfully. The PLS is able to differentiate parachute descent from landing and calculates a average maximum kinetic energy of 18.63 ft-lb.

### Next Steps

If Test TP.4 results passes success criteria, proceed to Test TP.6 to begin clearing PLS orientation system for demonstration flight.

If Test TP.4 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate bulkhead design and material selection. Repeat Test TP.4 until success criteria is met.



## PLANETARY LANDING SYSTEM: LEG DEPLOYMENT TEST

Test ID: TP.5

Responsible Individual: Notre Dame Experimental Payload Design Lead

### Required PPE

- Safety Glasses
- Anti-static glove

### Materials and Equipment

- Assembled PLS
- Jumper Cable Ejection Detection System
- Timer
- Camera
- Protractor
- Shock Cord or Rope

### Objective

The objective is to validate the structural integrity of the payload bay bulkhead assembly under worst-case parachute loading conditions.

### Motivation

To verify the payload bay bulkhead assembly design and failure calculations To ensure the successful recovery of the launch vehicle.

### Success Criteria

Test ID	Success Description	Result
TP.5	When the jumper cable is released, the legs rotate to a 90 degree angle within 25 seconds.	Pass

### Test Setup

1. Attach shock cord to the PLS eyebolt.
2. Place PLS in ejection configuration, such that the legs are parallel to the length of the body.
3. Insert jumper cable.
4. Power all system on.
5. Set up camera to record leg deployment.

### Test Procedure

1. Raise PLS up by cord to about chest-height of the holder.

2. Turn camera on.
3. Pull jumper cable pin out while wearing an anti-static glove.
4. Start timer at the same time as jumper cable pin removal.
5. Stop timer when legs stop moving.
6. Verify time is under 25 seconds.
7. While PLS is still in the air, use a protractor to measure the angle between the PLS body and the legs.
8. Verify the angle is 90 degrees, rounding to the nearest whole degree.

### Results

Upon removal of the jumper pin, the legs deploy reliably to a 90 degree angle within 25 seconds.

### Next Steps

If Test TP.5 results passes success criteria, proceed to Test TP.4 to continue clearing vehicle structures for demonstration flight.

If Test TP.5 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate leg design, servo motor selection, or Raspberry Pi code, depending on origin of failure. Repeat Test TP.5 until success criteria is met.



## PLANETARY LANDING SYSTEM: ORIENTATION TEST

Test ID: TP.6

Responsible Individual: Notre Dame Experimental Payload Design Lead

### Required PPE

- Safety Glasses

### Materials and Equipment

- Fully Assembled Planetary Landing System
- Inclined surface
- Boxes Level

### Objective

To objective is to ensure the PLS is able to orient to within 5 degrees from vertical open landing on an uneven surface.

### Motivation

The PLS mission requires an orientation to within 5 degrees of vertical, so testing this system before competition is crucial.

**Success Criteria**

Test ID	Success Description	Result
TP6	System can maintain vertical orientation within 5 degrees from vertical on a 20 degree or greater incline from the horizontal.	Pass

**Test Setup**

1. Identify or create an inclined or uneven surface for use. (To create an uneven surface stack boxes to make one area of a raised height)
2. Place PLS in descent configuration, with legs perpendicular to the PLS structure.

**Test Procedure**

1. Use the floor jack to set the plywood to a 10 degree angle. Record this exact angle
2. Place PLS inclined surface, or with one leg resting on top of stacked boxes.
3. Record starting angle using level of the top bulkhead of the PLS.
4. Allow PLS to detect the surface and begin orientation.
5. Repeat Steps 1-4 multiple times, on various setups. Stop after PLS fails or initial angle is greater than 30 degrees.
6. Record maximum possible starting angle for a 5 degree from vertical orientation.
7. If possible, repeat test using a textured surfaces, or in random locations with lots of obstacles and re-test with same criteria.

**Results**

PLS was able to reliably detect landing, and was able to successfully orient to within 5 degrees of vertical on all surfaces tested.

**Next Steps**

If Test TP.6 results passes success criteria, proceed to Test TP.7 to clear the PLS retention system for demonstration flight.

If Test TP.6 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate leg design, servo motor selection, Raspberry Pi code, or material selection depending on origin of failure. and material selection. Repeat Test TP.6 until success criteria is met.

**PLANETARY LANDING SYSTEM: RETENTION TEST**

Test ID: TP.7

Responsible Individual: Notre Dame Experimental Payload Design Lead

**Required PPE**

- Safety Glasses

## Materials and Equipment

- Payload Tube
- Full Assembled PLS structure
- CRAS-S

## Objective

To objective is to ensure the PLS retention system can restrict PLS movement during flight.

## Motivation

The PLS cannot complete the mission if it is damaged during flight or is too restricted by the retention system that it does not eject.

## Success Criteria

Test ID	Success Description	Result
TP.7	No components move visually or audibly during the duration of the test. No components are damaged during test.	Pass

## Test Setup

1. Insert the PLS retention system into the payload bay and screw it in place.
2. Get the PLS to the flight configuration and connect the jumper pins.
3. Slide the PLS it into the payload bay, make sure the retention dowels fit into the PLS bulkhead holes.
4. Place the CRAS-S over the PLS legs.
5. Attach the nose cone and insert the shear pins.

## Test Procedure

1. Hold payload tube and nose cone assembly with two hands such that the nose cone is pointing upwards.
2. Quiet everyone in the room. Listen closely for any noises during next steps.
3. Shake for a minute the payload bay to simulate vibrations during flight.
4. Disconnect nose cone and inspect the PLS for any damage.
5. Repeat test setup and slowly flip assembly 180 degrees so that the nose cone is pointing to the ground.
6. inspect PLS for any damage.
7. Repeat Test Setup again and repeat 180 flip test, but flip quickly this time.
8. Inspect the PLS again for any damages.

## Results

The PLS and retention system did not make any rattling noises during motion, indicating everything is staying securely in place. Upon inspection after each stage of testing, the PLS remained undamaged and nothing was out of place from the original setup.

**Next Steps**

If Test TP.7 results passes success criteria, proceed to Test TP.8 to continue clearing the PLS structure for demonstration flight.

If Test TP.7 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate retention structure design and material selection. Repeat Test TP.7 until success criteria is met.

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## 7.2 Requirements Compliance

Tables 69-72 show the requirements, both NASA provided and NDRT derived, that drove the design and logistical approach of the project. The tables define a unique requirement ID, provide a short description of the requirement, and the compliance plan the team has or will follow (where applicable). The tables also define the verification method used for each requirement (I for inspection, D for Demonstration, T for Testing, and A for Analysis) and a short description of the verification plan, as well as a status marker. Requirements verified through Demonstration or Testing list the relevant Test IDs as well.

### 7.2.1 NASA Requirements Compliance

#### 7.2.1.1 General

**Table 69: NASA General Requirements**

Requirement		Verification Method				Verification Plan	Status
ID	Description	I	D	T	A		
1.1	Students on the team will 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 will submit new work. Excessive use of past work will merit penalties.	x				The current design is entirely independent from previous years designs, an has been entirely designed and reported by undergraduate team members. All construction and flight operations so far conducted have been performed by undergraduate team members, aside from motor assembly and handling of black powder. Future flight and test operations are expected to be performed by undergraduate team members.	In Progress
1.2	The team will 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.	x				The current project plan, containing project timelines and budget through the end of the project, can be found in Section 7.3, while risks and mitigations can be found in Section 6.	In Progress
1.3	Foreign National (FN) team members must 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.	x				All Foreign National team members that may attend launch week have been identified in the appropriate forms submitted to NASA.	Complete
1.4	The team must identify all team members attending launch week activities by the Critical Design Review (CDR). Team members will include: Students actively engaged in the project throughout the entire year, one mentor, and no more than two adult educators.	x				All team members that may attend launch week have been identified in the appropriate forms submitted to NASA.	Complete

ID	Requirement Description	Verification Method				Verification Plan	Status
		I	D	T	A		
1.5	The team will engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities, as defined in the STEM Engagement Activity Report, by FRR. To satisfy this requirement, all events must occur between project acceptance and the FRR due date and the STEM Engagement Activity Report must be submitted via email within two weeks of the completion of the event.	x				The team has engaged with 271 community members over the course of 5 major educational outreach events with the St. Joseph County Boys and Girls Club, St. Pius Middle School, Children's Dispensary, and the Charles Black Center, with at least one more event expected before the conclusion of the project.	Complete
1.6	The team will establish a social media presence to inform the public about team activities.	x				The team has established its own website, along with Facebook, Twitter, and Instagram accounts, and a LinkedIn group.	Complete
1.7	Teams will 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.	x				At this time, the team's Proposal, PDR, CDR, and FRR documents have been successfully emailed to NASA. The FRR Addendum and PLAR documents will be submitted in the future.	In Progress
1.8	All deliverables must be in PDF format.	x				All documents so far submitted have been in PDF format.	In Progress
1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.	x				All documents so far submitted have contained an accurate table of contents.	In Progress
1.10	In every report, the team will include the page number at the bottom of the page.	x				All documents so far submitted have contained an accurate page number at the bottom of each page.	In Progress
1.11	The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.	x				The team currently join review presentations remotely, with every individual using their own computer equipment. This is expected to continue for the FRR presentation.	In Progress
1.12	All teams will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted on the launch field. At launch, 8-foot 1010 rails and 12-foot 1515 rails will be provided. The launch rails will be canted 5 to 10 degrees away from the crowd on launch day. The exact cant will depend on launch day wind conditions.	x				The team expects to use a 12-foot 1515 rail during the competition launch at our home launch field.	Complete
1.13	Each team must identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The mentor must maintain a current certification, and be in good standing, through the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to launch week.	x				The team's mentor is Dave Brunsting, who currently possesses Level 3 HPR certification from the NAR and TRA. He is currently expected to be capable of launching with us during our home field competition launch.	Complete
1.14	Teams will track and report the number of hours spent working on each milestone.	x				The team has kept track of the hours spent working on this project, and hours can be found reported in Section 1. Hours will continue to be tracked as the project progresses.	In Progress

### 7.2.1.2 Launch Vehicle

**Table 70: NASA Launch Vehicle Requirements**

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
2.1	The vehicle will deliver the payload to an apogee altitude between 3,500 and 5,500 ft AGL.	The launch vehicle has been designed to have a maximum apogee of 5765 ft, and a minimum apogee of 5299 ft, both of which are within the qualifying altitude range.			TV.2	x	Simulations of the launch vehicle have been performed in OpenRocket and RocketSim, and have verified those simulations using data from the successful Vehicle Demonstration Flight. Analysis of the demonstration flight data can be found in Section 5.5.	Complete
2.2	Teams shall identify their target altitude goal at the PDR milestone.	The team has chosen a target apogee of 5300 ft.	x				The team's PDR document was read through prior to submission, to ensure that the team's target apogee was clearly declared.	Complete
2.3	The vehicle will carry one commercially available, barometric altimeter.	The vehicle will carry a number of commercial barometric altimeters for recovery purposes, including 2 Stratolgger CFs, 2 Stratolgger SL100s, and a Featherweight Raven 4. The exact scoring altimeter will be selected and marked prior to the competition launch.			TV.2		During the Vehicle Demonstration Flight, all 5 barometric altimeters successfully took data. Analysis of the demonstration flight data can be found in Section 5.5.	Complete
2.4	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.	The vehicle is designed with a recovery system capable of bringing the vehicle from apogee to the ground without significant damage. The vehicle will be capable of reflight within 2 hours.		TV.1, TV.2, TV.3, TV.4, TV.5			The vehicle successfully completed a series of strength and impact tests, as well as its Vehicle Demonstration Flight, and did not receive any damage. It is expected to be capable of reuse for the Payload Demonstration flight without repair.	Complete
2.5	The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.	The vehicle is designed to have 4 independent sections: the nosecone, payload bay, recovery tube, and fin can.	x				The constructed vehicle has a total of 4 independent sections during descent, as counted after construction.	Complete
2.5.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.	The couplers at the bottom of the payload bay and bottom of the recovery tube, which separate in flight, are designed to be at least 6 in long.	x				All couplers on the vehicle have been measured, and are greater than 6 in in length.	Complete
2.5.2	Nosecone shoulders which are located at in-flight separation points will be at least ½ body diameter in length.	The nosecone shoulder is currently designed to be 3 in long.	x				The nosecone shoulder has been measured, and is approximately 5in in length.	Complete
2.6	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens.	Detailed launch procedures have been prepared that will allow the team to prepare the vehicle for launch in less than 2 hours. These launch procedures can be found in Section 6.3.		TV.2			After recovery deployment testing was completed, the vehicle was assembled and launched in less than 2 hours.	Complete
2.7	The launch vehicle and payload will 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.	All electrical subsystems of the vehicle will be powered by batteries sufficiently large to allow them to remain functional for at least 2 hours.		TR.2		x	The expected power draw of vehicle electrical components have been assessed, and the minimum required battery sizes have been calculated. Battery life tests on all critical hardware have been performed, and showed that all critical electronics are capable of lasting greater than 2 hours, even in cold weather.	Complete
2.8	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system.	The team will use a Cessaroni L1395-BS, and will use the included motor igniter, which is designed to be fired using a standard 12 VDC system.		TV.2			A standard 12 VDC firing system was used successfully during the Vehicle Demonstration Flight.	Complete

Requirement		Verification Method				Verification Plan	Status	
ID	Description	Compliance Plan	I	D	T			A
2.9	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).	All vehicle, recovery, and payload electronics are fully internal to the vehicle, aside from the standard motor ignition circuit.		TV.2			No external circuitry or special ground support equipment was used during the successful Vehicle Demonstration Flight.	Complete
2.10	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).	The team will use a Cessaroni L1395-BS, which utilizes an APCP propellant and has been certified by the Canadian Association of Rocketry.	x				Prior to motor selection, the motor letter of certification was found through the CAR website.	Complete
2.10.1	Final motor choices will be declared by the Critical Design Review (CDR) milestone.	The team has selected the Cessaroni L1395-BS as its flight motor. The team currently owns several of these motors and does not anticipate any motor change.	x				The team's CDR document has been read through prior to submission, to ensure that the final motor choice has been clearly declared.	Complete
2.11	The launch vehicle will be limited to a single stage.	The vehicle is currently designed with a single rocket motor, and is not designed to separate before apogee.	x				The design has been checked for additional motor mounts or staging mechanisms.	Complete
2.12	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).	The vehicle is currently designed to use a single rocket motor with a total impulse of 4895.4 Newton-seconds.	x				The total impulse of the motor to be used was checked prior to selection.	Complete
2.13	Pressure vessels on the vehicle will be approved by the RSO and will meet a number of safety criteria.	None of the vehicle subsystems or payloads feature pressure vessels, aside from the certified rocket motor casing.	x				The design of the vehicle and all subsystems have been checked for pressure vessels.	Complete
2.14	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	The vehicle is currently designed with a minimum static stability margin of 2.26 at rail exit.				x	The location of the vehicle center of pressure at rail exit has been calculated using OpenRocket, which can be found in Section 3.6.2. The location of the vehicle center of gravity has been estimated using OpenRocket, as well as a full CAD model of the vehicle and its subsystems. The Center of Gravity was measured before flight, and was found to be within .05 in of the simulated location.	Complete
2.15	Any structural protuberance on the rocket will be located aft of the burnout center of gravity.	The vehicle is currently designed with 2 rail buttons, both of which are located aft of the vehicle's burnout center of gravity. There are no other structural protuberances on the vehicle.	x			x	The location of the vehicle's burnout center of gravity has been estimated using OpenRocket, found in Section 3.6.2 as well as a full CAD model of the vehicle and its subsystems. This location was marked on the vehicle after construction, and the rail buttons were placed aft of this location.	Complete
2.16	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	The vehicle is currently designed to reach a minimum velocity of 68.1 ft/s at rail exit.			TV.2	x	The vehicle's velocity at rail exit has been calculated using OpenRocket and further qualified using RockSim. Acceleration data from the Vehicle Demonstration flight (5.5 was used to determine a measured off-rail velocity of 71.9 ft/s.	Complete
2.17	All teams will successfully launch and recover a subscale model of their rocket prior to CDR. Subscale are not required to be high power rockets.	The team successfully completed three launches of its subscale model on November 13.		TV.6			Data taken from altimeters on board the subscale vehicle during its flights show altitude data indicative of a successful launch, and can be found in Section ?? and Test number TV.6.	Complete
2.17.1	The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.	The subscale vehicle was designed to be a 42.3% scale model of the full scale vehicle.	x				The components of the subscale vehicle were measured prior to assembly to ensure that they were constructed to the proper dimensions.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
2.17.2	The subscale model will carry an altimeter capable of recording the model's apogee altitude.	A Stratolgger CF on board the subscale vehicle recorded altitude data from all three flights, showing apogees of 1060 ft, 1124 ft, and 957 ft.		TV6, TA.7			In addition to the commercial altimeters, a team-built data recording system was on board, recording average apogees of 1063 ft, 1118 ft, and 956 ft.	Complete
2.17.3	The subscale rocket must be a newly constructed rocket, designed and built specifically for this year's project.	The vehicle has been designed and built solely by this year's team.	x				All design decisions and construction activities for the subscale vehicle have been documented and presented in the team's PDR and CDR reports.	Complete
2.17.4	Proof of a successful flight shall be supplied in the CDR report. Altimeter data output may be used to meet this requirement.	Data from the onboard Stratolgger CF can be found in the team's CDR.	x				The team's CDR document was read through prior to submission, to ensure that the subscale flight data was clearly displayed.	Complete
2.18	<b>All teams will complete demonstration flights as outlined below:</b>	See Requirements 2.18.1-2.18.2					N/A	N/A
2.18.1	Vehicle Demonstration Flight - All teams will successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The following criteria must be met during the full-scale demonstration flight:	See Requirements 2.18.1.1-2.18.1.9		TV.2			N/A	Complete
2.18.1.1	The vehicle and recovery system will have functioned as designed.	The vehicle has been designed to reach an apogee of at least 5300 ft, recover within NASA requirements, and be capable of reflight without repair.			TV.2		Data taken from onboard altimeters during the Vehicle Demonstration Flight has been analyzed, and is within the expected performance range of the vehicle. The vehicle and all subsystems were inspected after flight, and no permanent damage was found.	Complete
2.18.1.2	The full-scale rocket must be a newly constructed rocket, designed and built specifically for this year's project.	The vehicle has been designed and built solely by this year's team.	x				All design decisions and construction activities have been documented and presented in the team's PDR, CDR, and FRR reports.	Complete
2.18.1.3	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. The following requirements still apply:	See Requirements 2.18.1.3.1-2.18.1.3.2					The full payload was flown during the Vehicle Demonstration flight.	Complete
2.18.1.4	If the payload changes the external surfaces of the rocket (such as with camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight.	The vehicle flew its Vehicle Demonstration flight with all its components onboard, including any camera housings or airbraking systems.		TV.2			The vehicle demonstration flight was completed with both the camera and airbraking system onboard and active.	Complete
2.18.1.5	Teams shall fly the launch day motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance if the home launch field cannot support the full impulse of the launch day motor or in other extenuating circumstances (such as weather).	The team flew the vehicle using a CTI L1395 during the Vehicle Demonstration flight.	x				The motor was inspected prior to installation to ensure that it was the correct motor type.	Complete
2.18.1.6	The vehicle must be flown in its fully ballasted configuration during the full-scale test flight.	All subsystems used the same amount of ballast during the Vehicle Demonstration flight that they will during the competition launch.	x				The vehicle was inspected prior to Demonstration flight, and contained the maximum amount of ballast that it will be flown with.	Complete
2.18.1.7	After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA Range Safety Officer (RSO).	The team has launched vehicle in its fully completed form, with no modifications planned after the vehicle demonstration flight.	x				No major modifications to the vehicle will be permitted by any subteams.	Complete

Requirement		Verification Method				Verification Plan	Status	
ID	Description	Compliance Plan	I	D	T			A
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.	A number of commercial barometric altimeters were active during the vehicle demonstration flight. Data from these altimeters can be found in Section 5.2.	x				The team's FRR has been read through prior to submission to ensure that vehicle demonstration flight data is present.	Complete
2.18.1.9	Vehicle Demonstration flights must be completed by the FRR submission deadline.	The team's vehicle demonstration flight was performed on February 27, which is before the FRR submission deadline of March 8.		TV.2			Data from the Vehicle Demonstration Flight can be found in Section 5.2.	Complete
2.18.2	Payload Demonstration Flight - All teams will successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline.	The team plans to fly the final, fully active payload on March 13, which is prior to the Payload Demonstration deadline.		TP.1			The payload and all retention systems will be inspected after payload demonstration to ensure that no permanent deformation or damage was caused during flight or deployment, as well as inspected for proper function, including self-leveling and data transmission.	In Progress
2.18.2.1	The payload must be fully retained until the intended point of deployment (if applicable), all retention mechanisms must function as designed, and the retention mechanism must not sustain damage requiring repair.	The retention system succeeded in retaining the payload during the Vehicle Demonstration Flight.		TP.1			The retention system was inspected after the Vehicle Demonstration Flight, and did not take any permanent damage.	Complete
2.18.2.2	The payload flown must be the final, active version.	The payload flown during the Vehicle Demonstration was the full, active payload. This will be reflown during the Payload Demonstration Flight.		TP.1			The payload was inspected, and did not take any significant damage during the Vehicle Demonstration Flight.	Complete
2.18.2.3	If the above criteria are met during the original Vehicle Demonstration Flight, occurring prior to the FRR deadline and the information is included in the FRR package, the additional flight and FRR Addendum are not required.	During the Vehicle Demonstration flight, the payload did not fully deploy, and therefore a separate Payload Demonstration Flight will be required. This flight is planned for March 13.		TP.1			The payload will be inspected after flight to ensure proper deployment and operation.	In Progress
2.19	An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASA required Vehicle Demonstration Re-flight after the submission of the FRR Report.	The team currently plans to complete the Payload Demonstration on March 13, prior to the FRR Addendum submission date.	x				N/A	In Progress
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's name and contact information will be present on the inside of the nosecone, the inside of the payload bay, and the payload itself.	x				Prior to Vehicle Demonstration flight, the vehicle was inspected to ensure that team contact information is present and easily readable on all separately descending elements of the vehicle.	Complete
2.21	All Lithium Polymer batteries will be sufficiently protected from impact with the ground and will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other payload hardware.	All Lithium Polymer batteries used on the recovery, ACS, and payload systems have been clearly marked with brightly colored tape to differentiate them from other hardware.	x				Prior to Vehicle Demonstration flight, all systems with batteries were inspected to ensure that the LiPo batteries are easily distinguishable from the rest of the hardware.	Complete
2.22	<b>Vehicle Prohibitions</b>	See Requirements 2.22.1-2.22.10					N/A	N/A
2.22.1	The launch vehicle will not utilize forward firing motors.	The current design does not feature forward-firing rocket motors.	x				The design of the vehicle and all subsystems have been checked for forward-firing motors.	Complete
2.22.2	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)	The design currently features a CTI L1395, which does not expel titanium sponge.	x				The design of the vehicle and all subsystems have been checked for titanium-expelling motors.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
2.22.3	The launch vehicle will not utilize hybrid motors.	The design currently features a CTI L1395, which does not utilize hybrid propellant.	x				The design of the vehicle and all subsystems have been checked for hybrid rocket motors.	Complete
2.22.4	The launch vehicle will not utilize a cluster of motors.	The design currently features a single rocket motor.	x				The design of the vehicle and all subsystems have been checked for additional rocket motors.	Complete
2.22.5	The launch vehicle will not utilize friction fitting for motors.	The design currently uses a screw-on Aeropack motor retainer to retain the motor during flight.	x				The vehicle retained the motor using an Aeropack motor retainer during the Vehicle Demonstration Flight.	Complete
2.22.6	The launch vehicle will not exceed Mach 1 at any point during flight.	The vehicle is currently designed to reach a maximum Mach number of 0.6.			TV.2	x	The maximum expected velocity has been determined through analysis conducted in OpenRocket, and was verified through velocity data gathered through onboard altimeters during the Vehicle Demonstration Flight.	Complete
2.22.7	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad	The vehicle is expected to use a maximum of 36.7 oz lbs of ballast, which is 4.62% of the full vehicle mass.	x				During the Vehicle Demonstration flight, the vehicle was flown with 36.7 oz of ballast, which is the maximum it is expected to need to use.	Complete
2.22.8	Transmissions from onboard transmitters will not exceed 250 mW of power (per transmitter).	The transmitters onboard the vehicle are expected to transmit at a maximum of 100 mW of power each.	x				Documentation accompanying the selected transmitters have been read to ensure that the transmission power does not exceed 250 mW.	Complete
2.22.9	Transmitters will not create excessive interference. Teams will utilize unique frequencies, handshake/passcode systems, or other means to mitigate interference caused to or received from other teams.	All active transmitters on the vehicle will use unique frequencies to mitigate interference with other transmitters.	x				Documentation accompanying the selected transmitters have been read to ensure that the transmitters all use different, unique frequencies.	Complete
2.22.10	Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses.	The vehicle design utilizes a limited amount of aluminum in structural bulkheads and standoffs, and a small amount of steel in small structural elements like screws, eyebolts and quicklinks.	x				The design has been checked by the team, and does not feature what the team has determined to be an excessive amount of metal.	Complete

### 7.2.1.3 Recovery System

**Table 71: NASA Recovery Requirements**

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
3.1	The launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee, and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue stage descent is reasonable, as deemed by the RSO.	The recovery system is currently designed to deploy a 2 ft drogue parachute at the vehicle's apogee, and a 12 ft main parachute at 575 ft AGL.		TR.4			The full functionality of the recovery system has been demonstrated during the Vehicle Demonstration flight, as described in Section 5.1.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
3.1.1	The main parachute shall be deployed no lower than 500 feet.	The recovery system is currently designed to deploy its main parachute at 575 ft AGL.		TR.7	TR.4		A drop test (Test TR.7) was performed on the main parachute to ensure that they open within 35 ft of deployment. The data from the onboard barometric altimeters, taken during the Vehicle Demonstration Flight, was analyzed, and confirmed that the main parachute opened before 500 ft.	Complete
3.1.2	The apogee event may contain a delay of no more than 2 seconds.	The recovery system is currently designed to deploy its drogue parachute at the vehicle's apogee.			TR.4		The data from the onboard barometric altimeters has been analyzed after the Vehicle Demonstration flight and confirms that the drogue parachute was deployed less than 2 seconds after apogee.	Complete
3.1.3	Motor ejection is not a permissible form of primary or secondary deployment.	The recovery system currently uses electrically triggered ejection charges.		TR.4			Proper ignition of the parachute ejection charges has been demonstrated during the Vehicle Demonstration Flight.	Complete
3.2	Each team must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full-scale launches.	Successful ground separation demonstrations were performed prior to the Vehicle Demonstration Flight.		TR.3			Procedures and results for ground separation tests can be found at Test number TR.3.	Complete
3.3	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.	The maximum terminal kinetic energy of the heaviest vehicle section is expected to be 62.5 ft-lbf, based on hand calculations.			TR.4	x	Analysis of the descent kinetic energy was performed in OpenRocket, as well as a team developed MATLAB code and hand calculations, as described in Section 3.6.3.	Complete
3.4	The recovery system will contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers.	The recovery system is designed to feature three redundant commercial altimeters, each capable of deploying both the main and drogue parachutes.		TR.1			Altimeter testing was performed, the results of which can be found in Test TR.1.	Complete
3.5	Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.	Each of the recovery altimeters is powered by its own commercially-available battery.	x				Prior to assembly, the recovery altimeters was visually inspected to ensure that they are electrically isolated and independently powered.	Complete
3.6	Each altimeter will 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.	Each recovery altimeter features a keyed, locking rotary switch for arming.		TR.5			Accessibility of the recovery arming switches was demonstrated during the Ejection Charge Disarming test, Test TR.5.	Complete
3.7	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).	Each recovery arming switch locks in position with the removal of the arming key.		TV.5			A shake demonstration was performed to simulate vibrations in the recovery system during launch, verifying that the switches will not be knocked out of place. The altimeters remained powered for the duration of the flight.	Complete
3.8	The recovery system electrical circuits will be completely independent of any payload electrical circuits.	The recovery system is currently designed to be completely electrically isolated from the payload.		TR.1			Procedures and results for altimeter testing, performed prior to the Vehicle Demonstration flight, can be found at Test TR.1.	Complete
3.9	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	The main parachute compartment is held together using 4 2 nylon shear pins, and the drogue compartment is held together with 2 2 nylon shear pins.	x				Prior to launch, the vehicle was visually inspected to ensure the presence of the appropriate number of shear pins holding the vehicle together. Launch procedures can be found in Section 6.3.	Complete
3.10	The recovery area will be limited to a 2,500 ft. radius from the launch pads.	The vehicle is expected to drift a maximum of 2369 ft from the launch pad in worst-case conditions.				x	Analysis of the vehicle drift has been performed in a custom MATLAB program, OpenRocket, and through hand calculations, as described in Section 3.6.3.	Complete
3.11	Descent time will be limited to 90 seconds (apogee to touch down).	The vehicle is expected to take a maximum of 80.4 seconds to descend from apogee to the ground.			TR.4	x	Analysis of the vehicle descent time has been performed in OpenRocket as well as a team-built MATLAB script and hand calculations, as described in Section 3.6.3. The descent time was further verified using altitude data taken during the Vehicle Demonstration flight.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
3.12	An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver.	An Eggfinder Mini and Eggfinder TX is used to track the independently descending vehicle and nosecone.	x	TR.6			The vehicle was visually inspected prior to launch to ensure that the GPS trackers were present and active prior to launch. Function of the transmitters were verified during Test TR.6.	Complete
3.13	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	All recovery electronics are shielded from electromagnetic interference through the use of copper-taped boxes.		TR.4			All transmitters and recovery electronics were active during the Vehicle Demonstration flight, with no evidence of interference.	Complete

### 7.2.1.4 Payload Experiment

**Table 72: NASA Payload Requirements**

Requirement		Verification Method					Verification Plan	Status	
ID	Description	Compliance Plan	I	D	T	A			
4.3	<b>Primary Landing System Mission Requirements:</b>	See Requirements 4.3.1-4.3.4					N/A	N/A	
4.3.1	The landing system will be completely jettisoned from the rocket at an altitude between 500 and 1,000 ft. AGL. The landing system will not be subject to the maximum descent time requirement (Requirement 3.11) but must land within the external borders of the launch field. The landing system will not be tethered to the launch vehicle upon landing.	The payload will eject from the vehicle at 525 ft AGL, and descend from the altitude under a 48 in parachute. It is expected to drift a maximum of 831 ft from the launch pad.		TP1			x	Using hand calculations, analysis of the lander's drift during descent has been performed and determined to be within the 2500 ft launch field radius, as described in Section 3.6.4. The deployment system will be demonstrated in full during the the Payload Demonstration Flight, as described in Test TP1.	In Progress
4.3.2	The landing system will land in an upright orientation or will be capable of reorienting itself to an upright configuration after landing. Any system designed to reorient the lander must be completely autonomous.	The payload legs automatically deploy on ejection, using three servos attached to leadscrews. After landing, the onboard microcontroller will use input from an IMU to adjust the angle of the landing legs, reorienting the lander to be vertical.		TP1, TP1, TP2, TP4, TP5			x	Kinematic analysis on the landing legs have been performed, and they have been determined to be capable of fully deploying before the payload lands. The speed of leg deployment was demonstrated on the ground in Test TP5, detection of landing was demonstrated in Test TP4, and detection of ejection was in Test TP2. Full functionality will be verified during the Payload Demonstration flight on March 13.	In Progress
4.3.3	The landing system will self-level to within a five-degree tolerance from vertical.	After landing, the onboard microcontroller will use input from an IMU to adjust the angle of the landing legs, reorienting the lander to be within 5 degrees of vertical.			TP6			The reorientation of the lander was tested on the ground for inclines up to 20 degrees, with data from the onboard IMU confirming the initial and final orientation of the lander.	Complete
4.3.3.1	Any system designed to level the lander must be completely autonomous.	The payload will eject from the vehicle, land, and reorient without any external input.		TP6				The reorientation of the lander was tested on the ground (Test TP6) for inclines up to 20 degrees, with data from the onboard IMU confirming the initial and final orientation of the lander. No communication to the lander occurred during reorientation testing.	Complete
4.3.3.2	The landing system must record the initial angle after landing, relative to vertical, as well as the final angle, after reorientation and self-leveling. This data should be reported in the Post Launch Assessment Report (PLAR).	The orientation of the lander, both before and after landing and leveling, will be measured by an onboard IMU and recovered after successful recovery of the payload. This data will be included in the PLAR after competition launch.		TP6				Acquisition of orientation data was demonstrated during orientation ground testing, described in Test TP6. The orientation data from the competition flight will be included in PLAR.	In Progress

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
4.3.4	Upon completion of reorientation and self-leveling, the lander will produce a 360-degree panoramic image of the landing site and transmit it to the team.	The payload holds 4 cameras, offset by 90 degrees, each of which takes a picture of the environment. These pictures are then stitched into a single panoramic picture, and transmitted to the team's ground station using the onboard radio transceiver.		TP1, TP3			The imaging and transmission ability of the payload has been assessed through imaging transmission tests, Test TP3, and will be further verified during Payload Demonstration Flight.	In Progress
4.3.4.1	The hardware receiving the image must be located within the team's assigned prep area or the designated viewing area.	The ground station receiving the transmitted panorama will be located in the launch viewing area.	x				Prior to launch, the ground station will be checked to ensure that it is active and within the correct area.	In Progress
4.3.4.2	Only transmitters that were onboard the vehicle during launch will be permitted to operate outside of the viewing or prep areas.	All active transmitters will be contained either within the vehicle, or within the launch viewing area.	x				Prior to launch, the ground station will be checked to ensure that it is active and within the correct area.	In Progress
4.3.4.3	Onboard payload transmitters are 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 must be approved by NASA during the design process.	The payload transmitters operate at an RF power of 100 mW.	x				The documentation associated with the commercial transmitters used for the payload was read, and the power emitted by the transmitters was found to be under 250 mW.	Complete
4.3.4.4	The image should be included in your PLAR.	The panoramic image produced by the payload will be included in the team's PLAR.	x				Prior to submission, the team's PLAR will be inspected to ensure that the panoramic image produced by the payload is included.	Incomplete
4.4	<b>General Payload Requirements</b>	See Requirements 4.4.1-4.4.6					N/A	N/A
4.4.1	Black Powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Energetics will not be permitted for any surface operations.	Black powder ejection charges are planned for in-flight payload/nose cone ejection only.	x				The has been thoroughly inspected, and does not contain surface-ignited energetics.	Complete
4.4.2	Teams must abide by all FAA and NAR rules and regulations.	The current design does not violate any FAA or NAR regulations.	x				Applicable regulations, including the NAR High Power Rocketry Safety Code and FAA regulation 14 CFR 101.22-101.29, have been read, and the design has been determined to be in compliance with these regulations.	Complete
4.4.3	Any experiment element that is jettisoned, except for planetary lander experiments, during the recovery phase will receive real-time RSO permission prior to initiating the jettison event.	The only experiment element to be jettisoned in flight is the planetary lander.					N/A	Complete
4.4.4	Unmanned aircraft system (UAS) payloads, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAS.	The planetary lander, as designed, is not considered an Unmanned Aerial System (UAS).					N/A	Complete
4.4.5	Teams flying UASs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112-95 Section 336; see <a href="https://www.faa.gov/uas/faqs">https://www.faa.gov/uas/faqs</a> ).	The planetary lander, as designed, is not considered an Unmanned Aerial System (UAS).					N/A	Complete
4.4.6	Any UAS weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.	The planetary lander, as designed, is not considered an Unmanned Aerial System (UAS).					N/A	Complete

## 7.2.1.5 Safety

**Table 73: NASA Safety Requirements**

ID	Requirement Description	Verification Method				Verification Plan	Status
		I	D	T	A		
5.1	Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.	x				The team's FRR will be thoroughly inspected prior to submission to ensure the presence of final launch procedures. Current procedures, to be used in the Vehicle Demonstration and Payload Demonstration flights can be found in Section 6.3.	In Progress
5.2	Each team must identify a student safety officer who will be responsible for all items in section 5.3.	x				The team's Safety Officer for this project is Jake Shapiro.	Complete
5.3	<b>The role and responsibilities of the safety officer will include, but are not limited to:</b>					N/A	N/A
5.3.1	The safety officer shall monitor team activities with an emphasis on safety during design of vehicle and payload, construction of vehicle and payload components, assembly of vehicle and payload, ground testing of vehicle and payload, full-scale launch test(s), subscale launch test(s), launch day, recovery activities, and STEM engagement activities.	x				The team has developed and implemented a team Safety Handbook and series of Standard Operating procedures to aid in team safety. Members of the team's safety sub-team are present during all construction, assembly, and testing operations, to monitor activities and ensure compliance.	In Progress
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	x				Standard procedures and checklists have been developed for construction, test and launch activities. Members of the safety team were present during all these activities so far, and will continue to be present during the Payload Demonstration flight and Competition flight, to ensure compliance.	In Progress
5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	x				Current versions of the team's hazard analysis FMEA, procedures, and SDS data have been compiled and can be found in Sections 6 and 6.3. These are not expected to change significantly for the rest of the competition.	Complete
5.3.4	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	x				Current versions of the team's hazard analysis, FMEA, and procedures, have been compiled and can be found in Sections 6 and 6.3. These are not expected to change significantly for the rest of the competition.	Complete
5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.	x				The team works closely with the Michiana Rocketry Club to ensure that all launch operations are conducted in a safe and legal manner.	In Progress
5.5	Teams will abide by all rules set forth by the FAA.	x				The team works closely with the Michiana Rocketry Club to ensure that all launch operations are conducted in accordance with FAA CFR 14 101.21-101.29.	In Progress

**7.2.1.6 Final Flight**

**Table 74: NASA Final Flight Requirements**

Requirement		Verification Method				Verification Plan	Status
ID	Description	I	D	T	A		
<b>Commercial Spaceport Launch Site Requirements</b>						N/A	N/A
6.2.1	The launch must occur at a NAR or TRA sanctioned and insured club launch. Exceptions may be approved for launch clubs who are not affiliated with NAR or TRA but provide their own insurance, such as the Friends of Amateur Rocketry. Approval for such exceptions must be granted by NASA prior to the launch.	x				The team expects to complete the competition flight at Michiana Rocketry club, NAR # 721.	Incomplete
6.2.2	Teams must submit their rocket and payload to the launch site Range Safety Officer (RSO) prior to flying the rocket. The RSO will inspect the rocket and payload for flightworthiness and determine if the project is approved for flight. The local RSO will have final authority on whether the team's rocket and payload may be flown.	x				The team will submit the rocket and payload to the local RSO prior to flight.	Incomplete
6.2.3	The team mentor must be present and oversee rocket preparation and launch activities.	x				The team mentor, Dave Brunsting, is expected to be present at the competition flight at Michiana Rocketry.	Incomplete
6.2.4	BOTH the team mentor and the Launch Control Officer shall observe the flight and report any off-nominal events during ascent or recovery on the Launch Certification and Observations Report.	x				The team mentor, Dave Brunsting, as well as the local LCO, are expected to be present at the competition flight at Michiana Rocketry and capable of reporting on the status of the competition launch.	Incomplete
6.2.5	The scoring altimeter must be presented to BOTH the team's mentor and the Range Safety Officer.	x				The team mentor, Dave Brunsting, as well as the local RSO, will be presented the scoring altimeter after competition flight to verify the official altitude.	Incomplete
6.2.6	The mentor, the Range Safety Officer, and the Launch Control Officer must ALL complete the applicable sections of the Launch Certification and Observations Report. The Launch Certification and Observations Report document will be provided by NASA upon completion of the FRR milestone and must be returned to NASA by the team mentor upon completion of the launch.	x				The team mentor, Dave Brunsting, as well as the local RSO and LCO, will be given the Launch Certification and Observations Report to complete.	Incomplete
6.2.7	The Range Safety Officer and Launch Control Officer certifying the team's flight shall be impartial observers and must not be affiliated with the team, individual team members, or the team's academic institution.	x				The RSO and LCO at the competition launch are not currently known by any members of the team, and are not affiliated with the university in any way.	Incomplete
6.2.8	Teams may launch only once. Any launch attempt resulting in the rocket exiting the launch pad, regardless of the success of the flight, will be considered a launch. Additional flights beyond the initial launch will not be scored and will not be considered for awards.	x				The team expects to launch only once on the day of the competition flight.	Incomplete

## 7.2.2 NDRT Requirements Compliance

### 7.2.2.1 Launch Vehicle

**Table 75: NDRT Launch Vehicle Requirements**

Requirement		Verification Method				Verification Plan	Status
ID	Description	Compliance Plan	I	D	T		
FUNCTIONAL REQUIREMENTS							

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
VE1	The launch vehicle shall reach an apogee at or above 5300 ft in all NASA-defined flight conditions, including winds up to 20 mph and launch rail angles of up to 10 degrees from vertical.	As currently designed, the vehicle is predicted to reach an apogee between 5765 ft and 5299 ft, in all expected flight conditions.			TV.2	x	The predicted apogee of the vehicle has been analyzed using models in OpenRocket and Rocksim to produce the current apogee predictions, as described in Section 3.6.1. The models have been further verified using data taken during the Vehicle Demonstration Flight, as described in Section 5.5.	Complete
VE2	The bottom of the payload bay shall have an aft-facing shock cord connection point, capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 1.5.	The current design features a bulkhead epoxied near the bottom of the payload bay, with an embedded eyebolt as a shock cord connection. This connection is capable of sustaining the maximum flight loads with a factor of safety of 2.55.				x	The strength of the payload bay bulkhead was assessed via finite-element analysis, while the eyebolt strength was taken from manufacturer ratings.	Complete
VE3	The fin can shall be constructed to be capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 1.5.	The current fin can is designed to sustain flight loads to a factor of safety of 7.9.				x	The strength of the fin can has been assessed through a combination of hand-shear calculations and finite-element analysis.	Complete
<b>DESIGN REQUIREMENTS</b>								
VD.1	The launch vehicle shall have a minimum of 3 in-flight separation points.	The current design features 3 in-flight separation points: at the bottom of the recovery tube, the top of the recovery tube, and the nosecone.	x				After construction, the number of separation points was counted to ensure that there are three.	Complete
VD.2	The nose cone shall contain space sufficient for the placement of a parachute capable of slowing the nosecone below 20 ft/s, along with associated shock cord and thermal protection.	The current nosecone selection features a hollow interior, with more than sufficient to contain the parachute, shock cord and thermal protection required to recover the nosecone.		TR.3			Prior to launch, the nosecone recovery hardware was packed into the nose for the nosecone separation demonstration, Test TR.3.	Complete
VD.3	The recovery tube of the vehicle shall have a minimum length of 30 in, and a maximum length of 48 in.	The recovery tube is currently designed to be 33in in length.	x				After construction, the recovery tube was measured, and has been cut to the appropriate length.	Complete
VD.4	The vehicle fin can shall have a minimum of 10 inches of length available to house the ACS.	The vehicle is currently designed with 11 inches of space above the motor mount to accommodate the ACS.	x				After construction, the fin can was measured to ensure that it was cut to the appropriate length to accommodate the ACS.	Complete
VD.5	The vehicle fin can shall have a maximum length of 48 in.	The vehicle is currently designed with a fin can length of 45.75 in, including the aft boattail.	x				After construction, the fin can was measured to ensure that it had been cut to the appropriate length.	Complete
VD.6	The payload bay of the vehicle shall have a minimum internal diameter of 6 in.	The vehicle is currently designed with an inner diameter of 6 in.	x				Prior to construction, the diameter of the payload bay was measured to ensure that it was the appropriate diameter.	Complete
VD.7	The off-rail stability of the fully loaded vehicle shall be between 2 and 3 calibers.	The vehicle is currently designed with an off-rail stability of 2.26 calibers.				x	The location of the vehicle center of pressure at rail exit has been calculated using OpenRocket, as well as Ansys Fluent, as described in Sections 3.6.2. The location of the vehicle center of gravity has been estimated using OpenRocket, as well as a full CAD model of the vehicle and its subsystems, and was within 0.05 in of the measured CG prior to the Vehicle Demonstration Flight	Complete
VD.8	The payload bay shall be constructed of EM-transparent material.	The payload bay was constructed of a fiberglass-Kevlar composite, which is EM-transparent.	x				Research into the fiberglass composite used for the body tubes has confirmed that it is RF transparent.	Complete
VD.9	The payload bay shall have a minimum length of 21 in, and a maximum length of 48 in.	The payload bay is currently designed with a total length of 30.5 in.	x				After construction, the payload bay was measured to ensure that it has been cut to the appropriate length.	Complete
<b>ENVIRONMENTAL REQUIREMENTS</b>								

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
VE.1	All airframe components shall be capable of sustaining a minimum of 54 Gs of axial acceleration.	All current airframe components are expected to be capable of sustaining a minimum of 87.5 Gs of axial acceleration.				x	A combination of and calculation and finite element analysis has been performed on all load-bearing components of the vehicle, confirming factors of safety.	Complete

### 7.2.2.2 Apogee Control System

**Table 76: NDRT ACS Requirements**

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
<b>FUNCTIONAL REQUIREMENTS</b>								
AE1	The ACS shall be capable of recording vehicle altitude (via barometric pressure) and vehicle acceleration.	The ACS uses a BMP388 for barometric altitude measurement and an ADXL 345 for acceleration measurement.			TA.1, TA.2, TA.3, TA.4, TA.7		A number of tests of the various sensors on the ACS have been performed, as described in Tests TA.2, TA.3, TA.4, and TA.7. Test TA.1 will be redone during the Payload Demonstration Flight.	In Progress
AE2	ACS shall provide a connection for a recovery harness, capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 1.5.	The ACS is currently designed with an eyebolt mounted in the center of its top bulkhead as a connection point, capable of sustaining flight loads with a factor of safety of 8.4.				x	A combination of hand-calculations and finite-elements analysis has been performed to verify the structural integrity of the recovery attachment point.	Complete
AE3	The ACS shall be capable of continuously actuating its control surfaces for a minimum of one minute.	The ACS is capable of continuously actuating its control surfaces for approximately 12.5 minutes.		x		x	Hand calculations of the theoretical maximum run time of the ACS have been performed, and an actuation demonstration was performed in Test TA.4 confirm that the system is capable of one minute of actuation.	Complete
AE4	The ACS shall create a pneumatic seal with the vehicle body tube at the fore end of the system.	The ACS to bulkhead has been carefully tolerated to seal the ACS from the black powder ejection charges in the recovery tube.		TR.3			Parachute separation demonstrations have been performed to confirm proper separation of the vehicle without damage, as described in Test TR.3	Complete
<b>DESIGN REQUIREMENTS</b>								
AD.1	ACS shall have a maximum allowable weight of 80 oz.	The ACS currently weighs 60.0 oz, and has been ballasted up to its allowable weight.	x				The ACS was weighed prior to installation in the vehicle, to verify that it is under 80 oz.	Complete
AD.2	ACS shall have a maximum length of 10 in.	The ACS is currently designed to have a length of 10 in.	x				The ACS length has been measured prior to installation in the vehicle to verify its length.	Complete
AD.3	ACS shall have a maximum diameter of 6 inches, with all external control surfaces retracted.	The ACS is currently designed to have a diameter of 5.9 in.	x				The ACS diameter was measured prior to installation in the vehicle to verify its construction.	Complete
AD.4	The ACS shall be capable of installation and removal from the vehicle without the use of power tools.	The ACS shall be oriented within the vehicle with a twist-in mechanism at the bottom of the system, and secured into the vehicle using screws.		TA.2			Prior to the vehicle demonstration flight, the ACS was fully installed in the vehicle without the use of power tools, as described in Test TA.2.	Complete
AD.5	All control surfaces extending from the exterior of the vehicle shall be a minimum of 2 calibers aft of the vehicle's on-pad Center of Mass.	The ACS drag tabs are currently designed to be 2.3 calibers behind the vehicle center of mass.	x				The distance between the vehicle center of mass and drag tabs were measured after construction to ensure their relative location.	Complete
<b>ENVIRONMENTAL REQUIREMENTS</b>								
AE.1	All ACS components shall be capable of sustaining a minimum of 54 Gs of axial acceleration.	All current components of the ACS are expected to be capable of sustaining 91 Gs of axial acceleration.	x				A combination of hand calculations and finite element analysis have been performed on all significant load-bearing components of the ACS.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
AE.2	The ACS shall be capable of remaining on the launch pad for a minimum of 2 hours prior to launch.	The ACS is expected to be capable of remaining on the launch pad for a total of 20 hours.				x	Hand calculations have been performed estimating the wait time the ACS is capable of, in addition to battery life tests.	Complete

### 7.2.2.3 Recovery System

**Table 77: NDRT Recovery Requirements**

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
<b>FUNCTIONAL REQUIREMENTS</b>								
RE1	All recovery altimeters shall store recorded data on local memory or removable storage which can readily be downloaded to a laptop computer at the launch field via a commercially available cable or adapter.	The design currently features three different models of altimeters, all of which are capable of storing and transferring altitude data to a laptop computer in the field.		TR.4			After the vehicle demonstration flight, altitude data from all the onboard altimeters were downloaded for further analysis, as shown in Section 5.2.	Complete
RE2	All recovery parachutes and shock cords shall be thermally protected from black powder ejection charges.	The design currently features Nomex blankets that are used to protect the parachutes and shock cords from the black powder ejection charges.		TR.3			The parachutes and shock cords were visually inspected after the ground parachute ejection demonstrations to ensure that no damage was done to the recovery components.	Complete
RE3	All recovery avionics shall be pneumatically sealed from vehicle compartments with ejection charges.	The design currently features closely toleranced bulkheads, separating the electronics from the black powder charges.		TR.3			The recovery avionics were visually inspected after the ground parachute ejection demonstrations to ensure that they were still powered and functional.	Complete
RE4	The vehicle nosecone shall be recovered independently from the rest of the vehicle.	The current design features a separate parachute and shock cord for the nosecone, which descends separately from the main vehicle.		TR.4			The function of the nosecone ejection and recovery system will be demonstrated during the Payload Demonstration flight.	In Progress
RE5	The main vehicle recovery system shall have a minimum of 3 electrically isolated systems for deploying both the main and drogue parachute.	The current design features 2 Stratologger CFs and a Raven3 altimeter for main vehicle recovery, all of which are electrically isolated from each other and capable of deploying both the main and drogue parachutes of the vehicle.		TR.1			The ability of these altimeters to independently ignite e-matches was tested on the ground prior to flight, and full function was demonstrated during the Vehicle Demonstration flight.	Complete
RE6	The nosecone recovery system shall have a minimum of 2 electrically isolated systems for deploying its parachute.	The current design features 2 Stratologger SL100 altimeters for nosecone recovery, both of which are electrically isolated from each other and capable of ejecting the nosecone and deploying the nosecone parachute.		TR.1			The ability of these altimeters to independently ignite e-matches was tested on the ground prior to flight, and full function was demonstrated during the Vehicle Demonstration flight.	Complete
RE7	The avionics bay shall contain 2 parachute connections, both capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 1.5.	The current design features steel eyebolt connected to an aluminum bulkhead, with a minimum factor of safety of 1.5.				x	A combination of hand calculations and FEA have been performed to confirm the structural integrity of the parachute connection.	Complete
<b>DESIGN REQUIREMENTS</b>								
RD.1	The recovery system for the main vehicle shall have a maximum allowable mass of 160 oz.	The main recovery system currently weighs 145 oz.	x				All components of the main recovery system were weighed prior to installation, to ensure that they were under the required maximum.	Complete
RD.2	All recovery components shall have a maximum diameter of 6 in.	The diameter of the main recovery system is currently designed to have a diameter of 5.9 in.	x				The diameter of the main recovery module was measured prior to installation, to ensure that it was under the maximum allowable diameter.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
RD.3	The recovery system for the nosecone shall have a maximum allowable mass of 25 oz.	The nosecone recovery system, as currently measured, weighs 23.2 oz.	x				All components of the nosecone recovery system were weighed prior to installation, to ensure that they were under the required maximum.	Complete
RD.4	All recovery avionics shall be removable from the launch vehicle without the use of power tools.	The main recovery module is to be retained in the vehicle with externally accessible screws.		TR.3			During parachute ejection ground testing, installation and removal of the avionics module without power tools was demonstrated.	Complete
RD.5	All arming switches used for main vehicle recovery shall be accessible from one location on the rocket body.	The key switches for arming the main vehicle altimeters are vertically aligned, and externally accessible from a single location on the exterior of the vehicle.	x				The vehicle was visually inspected after recovery installation to ensure that the main recovery arming switches are accessible from one location on the rocket body.	Complete
RD.6	All arming switches used for nosecone recovery shall be accessible from one location on the rocket body.	The key switches for arming the nosecone altimeters are vertically aligned, and externally accessible from a single location on the exterior of the vehicle.	x				The vehicle was visually inspected after recovery installation to ensure that the nosecone recovery arming switches are accessible from one location on the rocket body.	Complete
ENVIRONMENTAL REQUIREMENTS								
RE.1	The recovery systems shall be capable of sustaining a minimum of 54 Gs of axial acceleration.	All current components of the recovery system are expected to be capable of sustaining 56 Gs of axial acceleration.				x	A combination of hand calculations and finite element analysis have been performed on all significant load-bearing components of the recovery system.	Complete
RE.2	The recovery system shall be capable of remaining on the launch pad for a minimum of 2 hours prior to launch.	The recovery system is expected to be capable of remaining on the launch pad for a total of 17 hours.				x	Hand calculations have been performed estimating the wait time the recovery system is capable of.	Complete

### 7.2.2.4 Payload Experiment

**Table 78: NDRT Payload Requirements**

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
FUNCTIONAL REQUIREMENTS								
PE1	The PLS shall descend with a maximum terminal velocity of 20 ft/s.	The lander parachute has been sized such that the lander descends at a velocity of 17.5 ft/s.				x	The descent velocity of the lander has been calculated using hand calculations, as described in Section 3.6.4.	Complete
PE2	The PLS shall have a drift radius of less than 2500 ft from the launch pad.	The lander is expected to drift a maximum of 831 ft from the launch pad.				x	The descent velocity of the lander has been found using simple hand calculations, as described in Section 3.6.4.	Complete
PE3	All moving elements of the PLS shall be locked in place during flight.	The lander legs are to be locked in place through the stall torque of the leg deployment servos.		TP.7			A shake demonstration was performed on the PLS, to ensure that all elements were properly secured when in flight configuration.	Complete
PE4	The PLS shall be capable of withstanding an impact with the ground at a minimum of 20 ft/s.	The lander is expected to be capable of sustaining the expected ground impact with a factor of safety of 3.3.				x	The hinges connecting the lander legs to the body have been analyzed using finite-element analysis.	Complete
PE5	The PLS shall be capable of transmitting data to a minimum distance of 2 km.	The lander radio transceiver has been selected to be capable of transmission to at least 2 km.		TP.3			A range demonstration will be performed using the integrated lander electronics during the Payload Demonstration flight, to ensure that all they are capable of transmission to the required distance.	In Progress
PE6	The PLS shall contain minimum of 2 electrically isolated systems for deployment from the vehicle.	The lander will be jettisoned from the vehicle by black powder ejection charges initiated by an independent pair of Stratollogger SL100s.		TR.1, TP.1			The ability of these altimeters to independently ignite e-matches was tested on the ground prior to flight, and full function was demonstrated during the Vehicle Demonstration flight.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
PE7	PLS legs shall be capable of sustaining forces associated with nosecone ejection.	The payload legs will be constructed of 1/8th in carbon fiber plate, supported on the bottom by an epoxied-in centering ring.		TR.3			The strength of the payload legs was be verified through the nosecone ejection ground tests, described in Test TR.3	Complete
PE8	PLS leg servos shall have sufficient torque to reorient the PLS after landing.	The leg servos have a stall torque of 75 oz-in, capable reorienting the payload.		TP6		x	The required reorientation torque was calculated using hand calculations. The system was be further verified through ground demonstrations of the orientation system, Test TP6.	Complete
PE9	PLS shall be capable of detecting ejection from the vehicle.	The lander has jumper wires connected to the inside of the payload bay, which will separate as the lander is jettisoned. This separation will be detected by the lander's microcontroller.		TP2			A ground release demonstration was be performed, verifying that the lander's mirocontroller can detect jettison from the payload bay, Test TP2.	Complete
PE10	PLS shall be capable of deploying from the vehicle without interference from the nose cone or any other vehicle elements.	The nose cone is to be fully ejected from the vehicle as the payload is jettisoned, clearing the way for payload deployment.		TP1, TP2			A ground release demonstration was be performed (Test TP2), verifying the ability of the lander to release from the payload bay. This will be further verified during the Payload Demonstration flight, where the lander will be ejected in a representative flight environment (Test TP1).	In Progress
PE11	PLS shall be capable of fully deploying its legs within 25 seconds of ejection.	As currently designed, the lander legs are capable of deployment within 4.2 seconds of jettison from the vehicle.		TP5		x	Analysis of the leg deployment speed has been through hand calculations. The deployment time of the lander legs was further tested through timing of the lander legs on the ground (Test TP5).	Complete
PE12	The PLS shall contain a GPS module and method of transmitting GPS data to the team.	The PLS microcontroller has an attached standalone GPS module, and transmits the GPS data through the Adafruit LoRa radio bonnet.		TP3			A range demonstration will be performed using the integrated lander electronics to ensure that they are capable of transmission of GPS data to the team's ground station during the Payload Demonstration Flight.	In Progress
PE13	The PLS ground station electrical components shall be powered via commercially available batteries or a USB connector.	The ground station is powered by a USB connector, connected to a laptop.		TP3			All functional tests of the lander's transmission systems have so far been done with the ground station only connected to a laptop computer.	Complete
PE14	The PLS shall be capable of orienting on a slope less than 20 degrees.	As currently designed, the lander has leg travel sufficient to reorient on inclines of up to 20 degrees.		TP6			The orientation system of the lander was be tested on the ground on inclines of up to 20 degrees.	Complete
DESIGN REQUIREMENTS								
PD.1	The PLS shall have a maximum weight of 80 oz, including the lander, retention, deployment and descent hardware.	The payload has been measured to weigh a total of 79.5 oz, including retention.	x				The payload components were weighed prior to installation in the vehicle, to verify that they were under 80 oz.	Complete
PD.2	The PLS shall have a maximum length of 21 in.	The payload is currently designed to have a length of 15.5 in.	x				The payload length was measured prior to installation in the vehicle to verify its length.	Complete
ENVIRONMENTAL REQUIREMENTS								
PE.1	The PLS shall be capable of sustaining a minimum of 54 Gs of axial acceleration.	All current components of the payload are expected to be capable of sustaining 56 Gs of axial acceleration.				x	A combination of hand calculations and finite element analysis have been performed on all significant load-bearing components of the payload.	Complete
PE.2	PLS shall be capable of remaining on the launch pad for a minimum of 2 hours.	The payload is expected to be capable of remaining on the launch pad for a total of 4 hours.				x	Hand calculations have been performed estimating the pad time the PLS is capable of.	Complete
PE.3	Ground station power supply shall be capable of powering the system for a minimum of 2 hours.	The ground station is expected to be capable of remaining on the launch pad for a total of X hours.				x	Hand calculations have been performed estimating the operation time the ground station is capable of.	Complete

### 7.3 Budgeting and Funding Summary

Some additions to the budgeting plan include a donation from one of the team's sponsors Pratt & Whitney and an increase in the Recovery allocation to allow for the purchase of a new GPS transmitter. Also, since the team will not be traveling to Huntsville this year for competition, the team will save funds that would have been spent on travel.

**Table 79: NDRT 2020/2021 Revenue**

Source	Amount
Carryover (2019/2020)	\$9,297
Team Merchandise	\$82.05
NDRT Alumni	\$1,000
ND Day Fundraising	\$940
Collins Aerospace	\$5,000
Pratt & Whitney	\$10,000
<b>Total</b>	<b>\$23,319.05</b>

**Table 80: Budget allocation and funds spent to date.**

Item	Allocation	Funds Spent
Vehicle Design	\$4,000.00	\$2,273.69
Apogee Control System	\$1,000.00	\$906.61
Recovery System	\$1,400.00	\$1,399.58
Planetary Landing System	\$1,700.00	\$1,576.39
<b>Vehicle Subtotal</b>	<b>\$8,100.00</b>	<b>\$6,188.26</b>
Safety	\$300.00	\$31.99
STEM Engagement	\$100.00	\$0.00
Competition Travel	\$0.00	\$0.00
<b>Total Expenses</b>	<b>\$8,500.00</b>	<b>\$6,188.26</b>
Total Revenue	\$26,319.05	\$26,319.05
Remaining Funds	\$17,819.05	\$20,130.79

**Table 81:** Vehicles budget summary

Item	Vendor	Qty	Unit Price	Tax & Ship.	Total Cost
Rocksim v10 Licenses	Apogee Components	3	\$21.25	\$0.00	\$63.75
Standard Rail Button (fits 1" Rail - 1010) - 2 Per Pack	Apogee Components	1	\$3.48	\$0.00	\$3.48
Motor Mount Tubing - 29mm x 12" Motor Mount Tube	LOC Precision	2	\$1.99	\$0.00	\$3.98
Aerotech G80 Blue Thunder 29 mm - Single Use	BuyRocketMotors.com	3	\$26.99	\$0.00	\$80.97
Aerotech 29mm Aluminum Motor Retainer	BuyRocketMotors.com	1	\$14.39	\$0.00	\$14.39
UPS HAZMAT Shipping Fee	BuyRocketMotors.com	1	\$37.00	\$0.00	\$37.00
BTL-2.5-1.5	Public Missiles, Ltd.	1	\$31.95	\$0.00	\$31.95
2.6" Tube Coupler. 5" Long for Bays	Rocketarium	2	\$2.75	\$0.00	\$5.50
2.6" Phenolic Tube. 36" Long	Rocketarium	3	\$19.95	\$0.00	\$59.85
Shipping of all subscale parts	Subscale Shipping	1	\$57.16	\$0.00	\$57.16
Spray Paint	Home Depot	1	\$5.33	\$0.00	\$5.33
(K)Frame Airframe 6" Body Tubes	Giant Leap Rocketry	3	\$169.99	\$65.10	\$575.07
G12 Fiberglass Coupler	Apogee Components	2	\$64.29	\$17.57	\$146.15
FNC-6.0 Nosecone	Wildman Rocketry	1	\$109.95	\$14.70	\$124.65
Fiberglass Boattail	Public Missiles, Ltd.	1	\$132.95	\$14.95	\$147.90
Rail Buttons	Apogee Components	1	\$11.17	\$0.00	\$11.17
Motor Retainer	Apogee Components	1	\$56.67	\$5.08	\$61.75
.187" Fiberglass	Curbell Plastics	1	\$181.68	\$30.83	\$212.51
JB Weld Epoxy	eRockets	1	\$7.99	\$3.23	\$11.22
RocketPoxy	BuyRocketMotors.com	1	\$39.38	\$14.95	\$54.33
1/8" Fiberglass	McMaster Carr	2	\$44.64	\$15.91	\$105.19
3" Phenolic Airframe	Giant Leap Rocketry	1	\$18.99	\$9.69	\$28.68
L1395 Blue Streak Rocket Motor	Chris' Rocket Supplies, LLC	1	\$292.99	\$58.65	\$351.64
9x9" Tarp	Home Depot	1	\$14.27	\$0.00	\$14.27
70lbs Quickrete	Home Depot	4	\$12.15	\$0.00	\$48.60
Handwarmers	Home Depot	2	\$5.98	\$5.24	\$17.20
				<b>Total Cost</b>	<b>\$2,273.69</b>
				Allocation	\$4,000.00
				Margin	\$1,726.31

**Table 82:** ACS budget summary

<b>Apogee Control System Components</b>	<b>Vendor</b>	<b>Qty</b>	<b>Unit Price</b>	<b>Tax &amp; Ship.</b>	<b>Total Cost</b>
Raspberry Pi Zero W	Adafruit	1	\$10.00	\$0.00	\$10.00
Adafruit ADXL345	Adafruit	1	\$17.50	\$0.00	\$17.50
Adafruit MPL3115A2	Adafruit	1	\$9.95	\$0.00	\$9.95
HiLetgo MPU9250/6500	Amazon	2	\$8.99	\$0.00	\$17.98
SanDisk 32GB Ultra microSDHC	Amazon	1	\$8.49	\$0.00	\$8.49
Turnigy 2000mAh LiPo Battery	Hobby King	2	\$4.53	\$0.00	\$9.06
Zippy 1300mAh Compact LiPo Pack	Hobby King	2	\$7.95	\$9.60	\$25.50
D980TW Servo	Servo City	2	\$169.99	\$6.99	\$346.97
Adafruit Powerboost	Adafruit	1	\$14.95	\$10.42	\$25.37
3/8" Aluminum Sheet	McMaster Carr	1	\$26.99	\$0.00	\$26.99
3/8"-16 Steel Threaded Rod	McMaster Carr	1	\$11.45	\$0.00	\$11.45
3/16" HDPE Sheet	McMaster Carr	2	\$6.23	\$0.00	\$12.46
1/2" 6/6 Nylon	McMaster Carr	1	\$58.26	\$0.00	\$58.26
1/4" 6/6 Nylon	McMaster Carr	1	\$38.87	\$0.00	\$38.87
PCB	OshPark	1	\$82.60	\$5.50	\$88.10
1/2" ID Ball Bearing	McMaster Carr	1	\$6.27	\$0.00	\$6.27
1/2" MDS Nylon	McMaster Carr	1	\$55.76	\$0.00	\$55.76
1/4" MDS Nylon	McMaster Carr	1	\$30.31	\$0.00	\$30.31
Nylon Washers	McMaster Carr	1	\$7.29	\$15.90	\$23.19
Servo coupler	Servo City	1	\$12.98	\$0.00	\$12.98
No. 10 Socket Head Screw	McMaster Carr	1	\$6.68	\$0.00	\$6.68
18-8 Steel Button Head Screws	McMaster Carr	1	\$5.99	\$7.66	\$13.65
1/4" Nylon Washers	McMaster Carr	1	\$7.80	\$7.97	\$15.77
ADXL345 Accelerometer	Adafruit	1	\$17.50	\$0.00	\$17.50
2S Lipo Battery	Hobby King	1	\$7.95	\$9.60	\$17.55
<b>Total Cost</b>					<b>\$906.61</b>
Allocation					\$1,000.00
Margin					\$93.39

**Table 83:** Recovery budget summary

Recovery System Components	Vendor	Qty	Unit Price	Tax & Ship.	Total Cost
Keylock Switch (KO117A125)	Digi-Key	5	\$8.19	\$8.21	\$49.16
StratologgerCF Altimeter	PerfectFlite Direct	2	\$54.95	\$9.70	\$119.60
Eggfinder Starter Set	Eggtimer Rocketry	2	\$80.75	\$8.00	\$169.50
25Ft. Lg. 1/4" Tubular Kevlar with 2 Loops	OneBadHawk Recovery	1	\$28.00	\$0.00	\$28.00
35Ft. Lg. 3/4" Tubular Nylon with 2 Loops	OneBadHawk Recovery	2	\$31.00	\$10.00	\$72.00
12 Ft. Standard Parachute	Rocketman	1	\$139.50	\$0.00	\$139.50
2 Ff. Standard Parachute	Rocketman	1	\$25.65	\$0.00	\$25.65
Square-Profile Buna-N O-Ring (No. 256)	McMaster-Carr	1	\$9.30	\$0.00	\$9.30
Multipurpose 6061 Aluminum (1/4"x8"x8")	McMaster-Carr	2	\$18.31	\$0.00	\$36.62
Multipurpose 6061 Aluminum (3/8"x2"x12")	McMaster-Carr	1	\$7.26	\$0.00	\$7.26
Flame-Retardant Garolite G-10/FR4 Sheet 1/16"	McMaster-Carr	1	\$10.75	\$0.00	\$10.75
Turnigy 2S Lipo	Hobby King	2	\$7.15	\$0.00	\$14.30
4-40 3/4" Lg Screws, 18-8 Steel, 100 Pack	McMaster-Carr	1	\$4.20	\$0.00	\$4.20
4-40 1/2" Lg Screws, nylon	McMaster-Carr	1	\$7.13	\$0.00	\$7.13
4-40 Washers	McMaster-Carr	1	\$1.43	\$0.00	\$1.43
4-40 Low Strength Nuts	McMaster-Carr	1	\$0.89	\$0.00	\$0.89
6-32 3/4" Lg Screws	McMaster-Carr	1	\$3.43	\$0.00	\$3.43
3000 lb Swivel	Fruity Chutes	1	\$9.00	\$0.00	\$9.00
1S Lipo Batteries	Amazon	1	\$19.99	\$0.00	\$19.99
6-32 1-1/2" Lg. Steel Standoffs	McMaster-Carr	4	\$3.61	\$0.00	\$14.44
6-32 3" Lg. Aluminum Standoffs	McMaster-Carr	3	\$2.09	\$0.00	\$6.27
12-24 3/4" Lg. Alloy Steel Screws	McMaster-Carr	1	\$10.60	\$0.00	\$10.60
General purpose tap 12-24	McMaster-Carr	1	\$5.50	\$0.00	\$5.50
Raven 4 Altimeter	Featherweight Altimeters	1	\$160.00	\$10.00	\$170.00
Copper Tape	McMaster-Carr	1	\$18.81	\$8.58	\$27.39

**Table 84:** Recovery budget summary continued

Recovery System Components	Vendor	Qty	Unit Price	Tax & Ship.	Total Cost
2S Lipo Batteries	Hobby King	2	\$14.30	\$9.60	\$38.20
1S Lipo Batteries (6)	Amazon	1	\$19.99	\$0.00	\$19.99
Command Strips	Amazon	1	\$12.24	\$0.00	\$12.24
Wire Connectors	Amazon	1	\$6.99	\$0.00	\$6.99
Pin switches	LabRat Rocketry	3	\$6.95	\$5.50	\$26.35
BRB900 Transmitter	BigRedBee	1	\$324.00	\$9.90	\$333.90
<b>Total Cost</b>					<b>\$1,399.58</b>
Allocation					\$1,400.00
Margin					\$0.42

**Table 85:** PLS budget summary

Planetary Landing System Components	Vendor	Qty	Unit Price	Tax & Ship.	Total Cost
3102 Servo Programmer	Servo City	1	\$6.49	\$0.00	\$6.49
2000 Series Dual Mode Servo	Servo City	1	\$23.99	\$6.99	\$30.98
Turnigy 2200mAh 2S LiPo	Hobby King	1	\$10.95	\$9.60	\$20.55
Kevlar Shock Cord 1/4"	Fruity Chutes	1	\$3.00	\$0.00	\$3.00
36" Elliptical Parachute	Fruity Chutes	1	\$95.62	\$0.00	\$95.62
3" Deployment Bag	Fruity Chutes	1	\$40.85	\$15.64	\$56.49
Shaft Coupler	Servo City	3	\$6.99	\$0.00	\$20.97
Dual Mode Servo	Servo City	3	\$31.99	\$6.99	\$102.96
1/8" Fiberglass Sheet	McMaster Carr	3	\$10.69	\$0.00	\$32.07
Unthreaded Spacers	McMaster Carr	2	\$4.44	\$0.00	\$8.88
Nylon Unthreaded Spacers	McMaster Carr	1	\$12.70	\$0.00	\$12.70
1/4" Nylon Sheet	McMaster Carr	1	\$9.81	\$0.00	\$9.81
Nylon Sleeve Bearing	McMaster Carr	3	\$4.52	\$0.00	\$13.56
1/8" Carbon Fiber Sheet	McMaster Carr	1	\$183.76	\$0.00	\$183.76
1/4" Lead Screw	McMaster Carr	3	\$19.98	\$0.00	\$59.94

Table 86: PLS budget summary continued

Planetary Landing System Components	Vendor	Qty	Unit Price	Tax & Ship.	Total Cost
1/4" Bronze Nut	McMaster Carr	3	\$32.41	\$0.00	\$97.23
Steel Eyebolt	McMaster Carr	1	\$3.21	\$54.85	\$58.06
Zinc Corner Bracket	McMaster Carr	20	\$0.71	\$0.00	\$14.20
3/16" Shoulder Screw	McMaster Carr	8	\$1.86	\$0.00	\$14.88
18-8 Stainless Steel Nylon-Insert Locknut	McMaster Carr	1	\$5.16	\$0.00	\$5.16
PET Plastic Precision Acme Lead Round Nut,	McMaster Carr	3	\$29.38	\$0.00	\$88.14
18-8 Stainless Steel Shoulder Screw	McMaster Carr	8	\$4.33	\$18.24	\$52.88
6-40 Socket Head Screw	McMaster Carr	1	\$13.14	\$0.00	\$13.14
Aluminum Unthreaded Spacer	McMaster Carr	4	\$2.59	\$0.00	\$10.36
1/8" HDPE Sheet	McMaster Carr	1	\$4.44	\$0.00	\$4.44
8-32 Shoulder Screw	McMaster Carr	15	\$1.72	\$12.69	\$38.49
1/8" Nylon	McMaster Carr	1	\$5.42	\$7.62	\$13.04
Adafruit 9 DOF Breakout Board	Adafruit	1	\$14.95	\$10.84	\$25.79
Adafruit Camera	Adafruit	4	\$29.95	\$18.18	\$137.98
8-32 Shoulder Screws	McMaster Carr	10	\$1.72	\$9.69	\$26.89
1-1/4" Socket Head Screw	McMaster Carr	1	\$8.55	\$0.00	\$8.55
M2 Socket Head Screws	McMaster Carr	1	\$12.05	\$0.00	\$12.05
1/4" D., 36" L Wooden Dowel	McMaster Carr	1	\$1.08	\$0.00	\$1.08
M2 Steel Hex Nut	McMaster Carr	1	\$1.59	\$23.21	\$24.80
Pi Camera Lens	Amazon	2	\$24.99	\$0.00	\$49.98
LoRa Radio Bonnet	Adafruit	2	\$32.50	\$0.00	\$65.00
Male Header Pins	Adafruit	2	\$3.00	\$18.54	\$24.54
2000 Series Dual Mode Servos	Servo City	3	\$31.99	\$6.99	\$102.96
Female Header Pins	Amazon	1	\$13.98	\$0.00	\$13.98
Wire Spool	Amazon	1	\$14.99	\$0.00	\$14.99
<b>Total Cost</b>					<b>\$1,576.39</b>
Allocation					\$1,700.00
Margin					\$123.61

**Table 87:** Safety budget summary

<b>Item</b>	<b>Vendor</b>	<b>Qty</b>	<b>Unit Price</b>	<b>Tax &amp; Ship.</b>	<b>Total Cost</b>
Solder Smoke Absorber	Kulannder Direct	1	\$31.99	\$0.00	\$31.99
<b>Total Cost</b>					<b>\$31.99</b>
Allocation					\$300.00
Margin					\$268.01

## Appendix A: Complete Black Powder Calculations

Variables:

- $\tau$ : shear strength of shear pin
- $d$ : shear pin diameter
- $n_1$ : number of shear pins used
- $b$ : bulkhead diameter
- $n_2$ : moles of gas needed
- $V$ : chamber volume
- $R$ : gas constant
- $T$ : ignition temperature

### Primary Separation Event: Drogue Deployment

Force needed to break shear pins:

$$F = \frac{\pi}{4} \tau d^2 n_1$$

$$F = \frac{\pi}{4} (10,000 \text{ psi}) (0.106 \text{ in})^2 (2) = \boxed{116 \text{ lbf}}$$

Convert to pressure:

$$P = \frac{F}{\frac{\pi}{4} b^2}$$

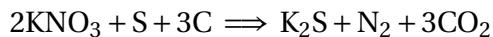
$$P = \frac{176 \text{ lbf}}{\frac{\pi}{4} (6 \text{ in})^2} = 6.24 \text{ psi} = \boxed{0.42 \text{ atm}}$$

Calculate moles of gas needed:

$$n_2 = \frac{PV}{RT}$$

$$F = \frac{(0.42 \text{ atm})(6.95 \text{ L})}{(0.082 \frac{\text{Latm}}{\text{molK}})(1837 \text{ K})} = \boxed{0.0196 \text{ moles gas}}$$

Calculate black powder needed:



$$\frac{0.0196 \text{ moles gas}}{1} \times \frac{2 \text{ mol KNO}_3}{4 \text{ mol gas}} \times \frac{101.1 \text{ g KNO}_3}{1 \text{ mol KNO}_3} = 0.990 \text{ g KNO}_3$$

$$\frac{0.0196 \text{ moles gas}}{1} \times \frac{1 \text{ mol S}}{4 \text{ mol gas}} \times \frac{32.1 \text{ g S}}{1 \text{ mol S}} = .157 \text{ g S}$$

$$\frac{0.0196 \text{ moles gas}}{1} \times \frac{3 \text{ mol C}}{4 \text{ mol gas}} \times \frac{12.0 \text{ g C}}{1 \text{ mol C}} = 0.176 \text{ g C}$$

$$0.990 \text{ g KNO}_3 + .157 \text{ g S} + 0.176 \text{ g C} = \boxed{0.1.323 \text{ g Black Powder}}$$

To account for the imperfect seal and to aid measurement in the field, this will be rounded up to  $\boxed{2.0 \text{ g}}$  of black powder is needed for the separation event.

### Secondary Separation Event: Main Deployment

Force needed to break shear pins:

$$F = \frac{\pi}{4} \tau d^2 n_1$$

$$F = \frac{\pi}{4} (10,000 \text{ psi}) (0.106 \text{ in})^2 (4) = \boxed{353 \text{ lbf}}$$

Convert to pressure:

$$P = \frac{F}{\frac{\pi}{4} b^2}$$

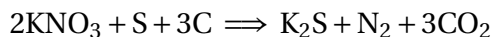
$$P = \frac{353 \text{ lbf}}{\frac{\pi}{4} (6 \text{ in})^2} = 12.48 \text{ psi} = \boxed{0.85 \text{ atm}}$$

Calculate moles of gas needed:

$$n_2 = \frac{PV}{RT}$$

$$F = \frac{(0.85 \text{ atm})(10.66 \text{ L})}{(0.082 \frac{\text{Latm}}{\text{molK}})(1837 \text{ K})} = \boxed{0.0600 \text{ moles gas}}$$

Calculate black powder needed:



$$\frac{0.0600 \text{ moles gas}}{1} \times \frac{2 \text{ mol KNO}_3}{4 \text{ mol gas}} \times \frac{101.1 \text{ g KNO}_3}{1 \text{ mol KNO}_3} = 3.035 \text{ g KNO}_3$$

$$\frac{0.0600 \text{ moles gas}}{1} \times \frac{1 \text{ mol S}}{4 \text{ mol gas}} \times \frac{32.1 \text{ g S}}{1 \text{ mol S}} = 0.482 \text{ g S}$$

$$\frac{0.0600 \text{ moles gas}}{1} \times \frac{3 \text{ mol C}}{4 \text{ mol gas}} \times \frac{12.0 \text{ g C}}{1 \text{ mol C}} = 0.540 \text{ g C}$$

$$3.035 \text{ g KNO}_3 + 0.482 \text{ g S} + 0.540 \text{ g C} = \boxed{4.058 \text{ g Black Powder}}$$

To account for the imperfect seal and to aid measurement in the field, this will be rounded up to  $\boxed{4.5 \text{ g}}$  of black powder is needed for the separation event.

### Tertiary Separation Event: Nosecone Jettison

Force needed to break shear pins:

$$F = \frac{\pi}{4} \tau d^2 n_1$$

$$F = \frac{\pi}{4} (10,000 \text{ psi})(0.083 \text{ in})^2 (2) = \boxed{232 \text{ lbf}}$$

Convert to pressure:

$$P = \frac{F}{\frac{\pi}{4}b^2}$$

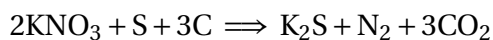
$$P = \frac{108.2 \text{ lbf}}{\frac{\pi}{4}(6 \text{ in})^2} = 3.83 \text{ psi} = \boxed{0.26 \text{ atm}}$$

Calculate moles of gas needed:

$$n_2 = \frac{PV}{RT}$$

$$F = \frac{(0.26 \text{ atm})(5.93 \text{ L})}{(0.082 \frac{\text{Latm}}{\text{molK}})(1837 \text{ K})} = \boxed{0.0102 \text{ moles gas}}$$

Calculate black powder needed:



$$\frac{0.0102 \text{ moles gas}}{1} \times \frac{2 \text{ mol KNO}_3}{4 \text{ mol gas}} \times \frac{101.1 \text{ g KNO}_3}{1 \text{ mol KNO}_3} = 0.518 \text{ g KNO}_3$$

$$\frac{0.0102 \text{ moles gas}}{1} \times \frac{1 \text{ mol S}}{4 \text{ mol gas}} \times \frac{32.1 \text{ g S}}{1 \text{ mol S}} = 0.082 \text{ g S}$$

$$\frac{0.0102 \text{ moles gas}}{1} \times \frac{3 \text{ mol C}}{4 \text{ mol gas}} \times \frac{12.0 \text{ g C}}{1 \text{ mol C}} = 0.092 \text{ g C}$$

$$0.518 \text{ g KNO}_3 + 0.082 \text{ g S} + 0.092 \text{ g C} = \boxed{0.692 \text{ g Black Powder}}$$

Though only about 1 g of black powder is needed to eject the nose, the payload jettison depends on the CRAS-S ejecting with the nose. To ensure this, and to aid measuring in the field,  $\boxed{2 \text{ g}}$  of black powder will be used.