University of Notre Dame

2022-2023

NOTRE DAME ROCKETRY TEAM
CRITICAL DESIGN REVIEW

NASA STUDENT LAUNCH 2023

360° ROTATING OPTICAL IMAGER AND APOGEE CONTROL SYSTEM

Submitted September 17, 2023

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Contents

Table 1: Commonly-Used Acronyms

Acronym	Meaning
ABS	Acrylonitrile Butadiene Styrene
ACS	Apogee Control System
AGL	Above Ground Level
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CNC	Computer Numerical Control
CP	Center of Pressure
FED	Fin Can Energetic Device
GPIO	General-Purpose Input/Output
I^2C	Inter-Integrated Circuit
IMU	Inertial Measurement Unit
LiPo	Lithium Polymer
NED	Nose Cone Energetic Device
OR	OpenRocket
PCB	Printed Circuit Board
PDF	Payload Demonstration Flight
PDR	Preliminary Design Review
PED	Payload Energetic Device
PWM	Pulse Width Modulation
RAM	Random Access Memory
RF	Radio Frequency
RS	RockSim
SPDT	Single Pole, Double Throw
SSH	Secure Shell
TROI	360° Rotating Optical Imager
VDF	Vehicle Demonstration Flight

1 Summary of Report

1.1 Team Summary

Team Info:	Notre Dame Rocketry Team (NDRT) University of Notre Dame 365 Fitzpatrick Hall of Eng. Notre Dame, IN 46556
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CDR Hours:	1472
Final Launch Plan:	Huntsville, AL April 15, 2023

1.2 Launch Vehicle Summary

Table 2 summarizes the launch vehicle design. The launch vehicle will have three separation events and deploy two parachutes to minimize the kinetic energy of sections upon landing. The FED deploys the drogue parachute, a 2 ft diameter, 1.6 C_d Rocketman elliptical parachute at apogee. At 900 ft AGL, the nose cone (containing the NED) will eject from the payload tube, remaining tethered to the launch vehicle via a kevlar shock cord. The PED will deploy the main parachute at 548 ft AGL. The main parachute is a 12.8 ft diameter, 2.92 C_d SkyAngle XXL parachute, which is connected to a 25 ft tubular nylon shock cord rated for 4,400 lbs. The main parachute will be housed in a deployment bag and assisted by a 2 ft, C_d 1.6 FruityChutes pilot parachute.

Table 2: Launch Vehicle Summary

Feature	Value				
Target Apogee (ft.)	4600				
Selected Motor	Aerotech L2200G-P				
Outer Diameter (in.)	6.17				
Rail Size	12 ft, 1515				
Dry Mass (w/o Ballast) (oz)	809.0				
Dry Mass (w/ Ballast) (oz)	809.0				
Wet Mass (oz)	898.2				
Burnout Mass (oz)	809.0				
Landing Mass (oz)	658.2				
Feature	**Nose Cone**	**Payload Bay**	**ACS Tube**	**Fin Can**	**Total**
Length (in.)	27.0	27.0	39.0	38.5	**131.5**
Mass (oz)	82.7	203.2	318.5	293.9	**898.2**

1.3 Payload Summary

The **360° Rotating Optical Imager** (**TROI**) utilizes an actuating lead screw to deploy and orient a camera subassembly with multiple degrees of freedom outside the payload body tube (NASA Reqs. 4.2.1.1., 4.2.1.2., 4.2.4., 4.3.1.). TROI will remain fixed throughout flight and will receive commands via APRS to take and store images on an onboard ESP32 microcontroller once landed (NASA Req. 4.2.2.).

A secondary non-scoring payload, the Apogee Control System (ACS), is included within the launch vehicle, behind its burnout CG in compliance with NASA Req. 2.16. The ACS actuates a set of four drag flaps that deploy between burnout and apogee and lower the launch vehicle's apogee to within 25 ft of the 4600 ft target apogee.

2 Changes Made Since PDR

2.1 Changes To Vehicle Criteria

Since PDR, some of the body tube lengths have changed. Additionally, the "removable bulkhead" mechanics, which were previously discussed in PDR, have been described in greater detail. There are two parts to the mechanism of primary importance: the bulkhead that is fixed to the body tube and the removable wall that is removed. The "fixed" bulkhead will be made out of aluminum, 0.25 in. thick, and screwed into the Payload Bay section for every launch. Aluminum was chosen because of its high strength, easy machinability, and the need for TROI to be able to send transmissions. The removable wall will be made out of carbon fiber and will be mounted attached to the bulkhead during flight but will be removed from the tube with the nose cone as it ejects via the NED. For more information on this setup, see Section 4.4.3.

Another major change since PDR is the use of a Nose Cone Ring. This ring will be 3.0 in. long. It serves to provide both a sufficient volume within the body tubes for the shock cords during black powder ignition and shorten the distance the TROI has to extend to reach out of the Payload Bay. In short, adding the ring allows the TROI to have to extend 3.0 in. less out of the body tube. This simplifies the device without adding too many complications to the system in relation to recovery; the nose cone section was and still is the lightest section. For more information on this change, see Section 3.3.2.

2.2 Changes To Recovery Criteria

Several notable changes have been made to the recovery system following feedback from the team's PDR presentation, advice from the team mentor, and the team's own additional research. The first significant change is that only six total altimeters will now be used on the launch vehicle with each separation event triggered by two altimeters. The team identified several reasons for this change including a lack of altimeters available for purchase that matched the team's PDR specifications. Furthermore, the additional altimeters were deemed to be somewhat over-redundant as two altimeters could still be wired to three total black powder charges per module. This change also resulted in a beneficial weight reduction as it will require less wiring and one fewer switch and battery per module.

A larger, 12.8 ft SkyAngle XXL parachute has now been selected instead of the previously selected 9 ft Rocketman High-Performance parachute. The need for a larger parachute was initially identified during PDR feedback but was further substantiated using previous years' flight data which showed Rocketman main parachutes often underperform. A full analysis of this change can be viewed in Section 4.4.1. Within this main parachute and drogue parachute assembly, thicker tubular nylon shock cords have also been selected to reduce the possibility of zippering the body tube during the drogue and main parachute deployments. Details of these shock cords can be found in Sections 4.4.1 and 4.4.2. The last major change is that multiple e-matches will now be wired to each charge for events that deploy a parachute. This will reduce the chance that a charge does not detonate due to a faulty e-match and will thus improve the likelihood the events occur correctly.

2.3 Changes To Payload Criteria

The length of the payload body tube increased to properly integrate the PED, shock cord, and removable bulkhead system required to protect the TROI from recovery deployment. Hence, the length of the lead screw increased in order to allow the camera subsystem to have sufficient deployment clearance, in turn increasing the total length of the TROI. The tiered bulkhead design was modified to reduce the payload length, and the main stepper motor and lead screw deployment system is now attached to the aft bulkhead. For electronics, the system has been partitioned into two subsystems: the ESP32 main subsystem and the ESP32-CAM subsystem. The ESP32 main subsystem connects to the sensor suite and the RF communications, while the ESP32-CAM subsystem is attached to the moving camera arm and is thus free to rotate with the camera. There are two wooden mounting boards for electronics between the tiered bulkheads, and the ESP32 main subsystem and the main sensor suite are stored there.

2.4 Changes To Project Plan

The project plan remains largely consistent with the one proposed during the preliminary design phase. A $500 addition to the overall team funds has been recognized due to the sale of old team merchandise that was previously in inventory. However, the competition travel budget was also increased by $500 after assessing inflated travel costs during trip planning. Overall, the funds allocated for this year's competition will remain sufficient for the full-scale construction of the vehicle and team travel. The acquisition of components remains on schedule and no lead times are expected to delay progress. The first full-scale Vehicle Demonstration Flight is scheduled for February 4 with additional dates available to launch on February 11 and February 25. These launch opportunities will allow completion of the Vehicle Demonstration flight before the FRR submission deadline. The project plan is more thoroughly detailed in Sections 9.4 and 9.5.

3 Technical Design: Launch Vehicle

3.1 Mission Statement

The main responsibility of the launch vehicle is to complete the mission goals of the 2023 launch competition safely and reliably. To accomplish this goal, the vehicle design is driven by NASA-specified and team-derived requirements deemed necessary for mission success. The main NASA requirements driving the vehicle design are: an apogee between 4,000 and 6,000 feet above ground level (NASA Req. 2.1), a maximum motor impulse of 5,120 Newton-seconds (NASA Req. 2.12), a minimum velocity of 52 feet per second after rail exit (NASA Req. 2.17); a static stability margin of at least 2.0 at the exit of the launch rail (NASA Req. 2.14); and a minimum thrust to weight ratio of 5:1 (NASA Req. 2.15).

The scoring payload requires that the launch vehicle allow the system to take unobstructed 360° images. The non-scoring payload, the apogee control system (ACS), requires the launch vehicle to reach an altitude that exceeds the target apogee. The ACS can then actively control the final vehicle apogee by increasing form drag around the launch vehicle. Additionally, all vehicle components must be designed to withstand all other forces experienced throughout all portions of the mission.

3.1.1 Mission Success Criteria

The following criteria will be used to determine the success of the launch vehicle:

- The launch vehicle shall achieve the desired stability during flight.
- The launch vehicle shall achieve the desired exit-rail velocity.
- The trajectory of the launch vehicle shall be above the target apogee.
- The vehicle sections shall separate during recovery events.

- The vehicle shall land undamaged and is able to be relaunched.

3.2 Launch Vehicle Design Overview

The final launch vehicle design has four independent sections: the nosecone, the payload bay, the ACS body tube, and the fin can. All three separation events are accomplished with the use of black powder. The first separation point during flight occurs between the ACS body tube and fin can via the FED: a drogue parachute is deployed at apogee. The second separation point during flight occurs between the nosecone and the payload bay via the NED: a shock cord tethers the sections together at 900 ft. The final separation point during flight occurs between the payload bay and the ACS body tube via the PED: a main parachute is deployed at 584 ft.

The launch vehicle has an outer diameter of 6.17 in. and a total length of 131.5 in. The motor used for the launch vehicle is the AeroTech L2200G-P motor. There are no pressure vessels on the launch vehicle, so all NASA Requirements on pressure vessels (2.13, 2.13.1, 2.13.2, and 2.13.3) are followed. Figures 1 and 2 display a detailed breakdown of the launch vehicles design, highlighting the independent sections, separation points, and internal components. Additionally, Table 3 lists many of the key specifications of the launch vehicle.

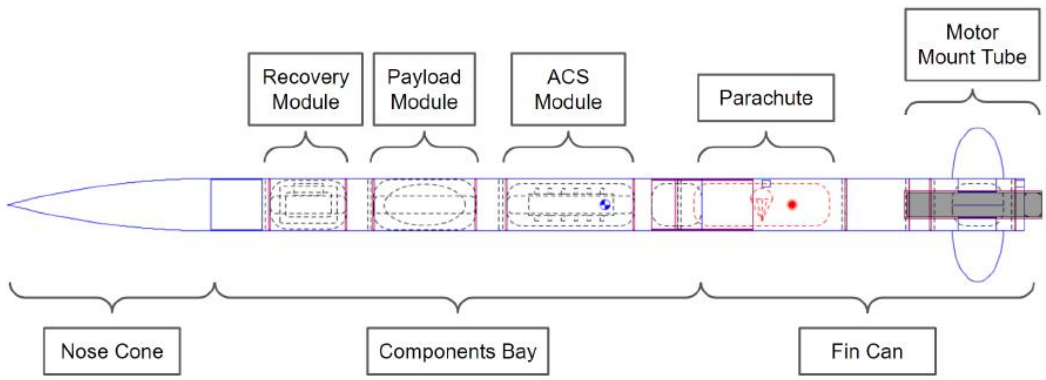


Figure 1: Launch Vehicle Design Breakdown of Sections and Separation Points

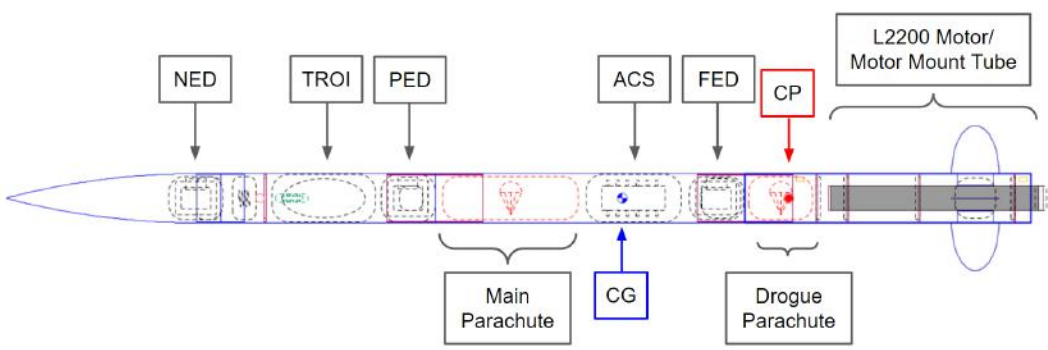


Figure 2: Launch Vehicle Design Breakdown of Internal Components

Table 3: Launch Vehicle Design Overview

Parameter	Value
CG Location (in)	98.51
CP Location (in)	76.465
Static Stability Margin (cal)	3.57
Rail Exit Stability Margin (cal)	2.772
Overall Length (in)	131.5
Thrust-to-Weight Ratio	8.99:1
Rail Exit Velocity (ft/s)	85.82
Overall Predicted Mass (oz)	898.246

3.3 Vehicle Component Analysis

3.3.1 Nose Cone

A fiberglass ogive nose cone was chosen for the launch vehicle. The design requirement, NASA Req. 2.4.2, dictates the shoulder be at least half of the body diameter in length. The shoulder diameter and the length will be 6 inches. In practice, the 3.00 in. G12 fiberglass "ring" that will by epoxied onto the shoulder will make the shoulder length 3.0 in. The major criteria used to determine the nosecone design included durability and mass so that the nose cone can withstand the forces that act upon the vehicle during landing. The team chose to purchase a 6.00 in. filament wound 4:1 ogive nosecone with a metal tip from Composite Warehouse. A metal tip was chosen for increased durability and because it allows for the fiberglass to be wound to a sharper point, increasing aerodynamic performance. The dimensions and CAD model of the nose cone can be seen below in Table 4 and Figure 3.

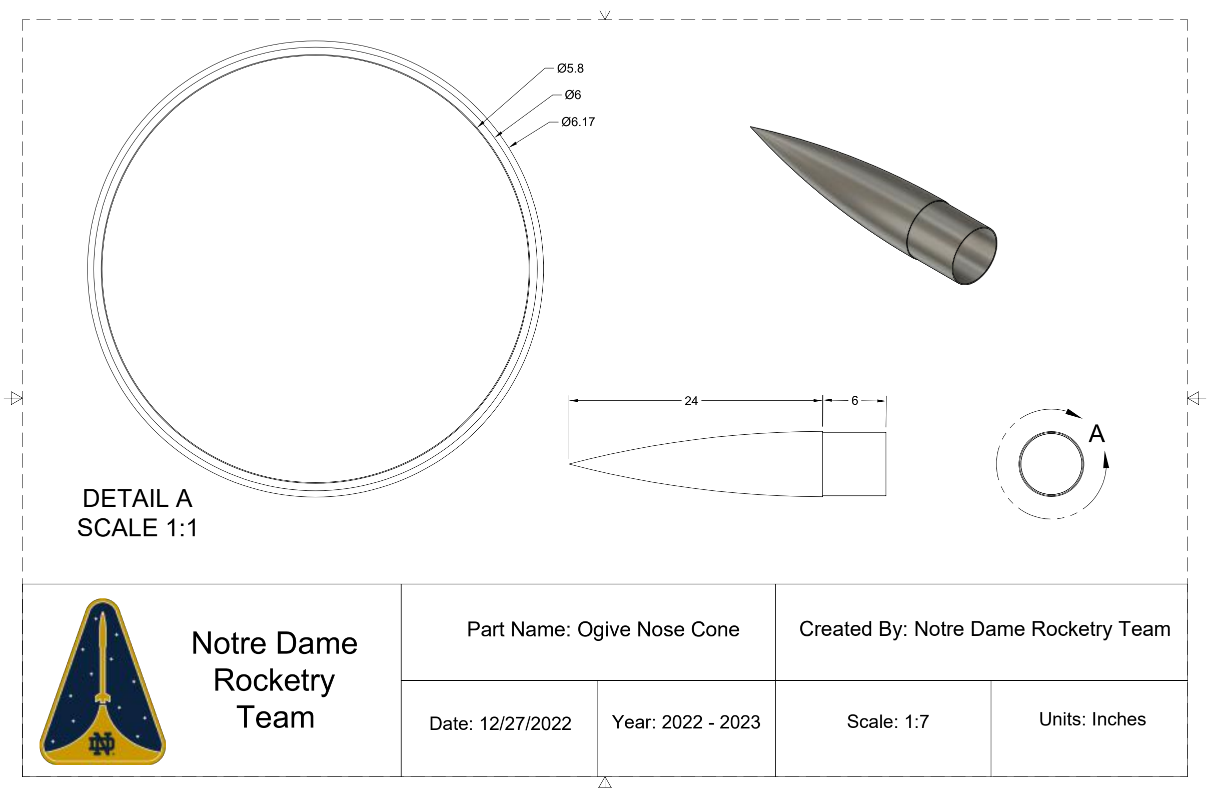


Figure 3: CAD Drawing of Nose Cone

Table 4: Nose Cone Dimensions

Dimensions	Value
Nose Cone Length	24.0 in.
Nose Cone Base Diameter	6.17 in.
Shoulder Length	3.0 in exposed (6.0 in total)
Shoulder Outer Diameter	6.00 in.
Total Length	30 in.
Shape	Ogive
Nose Cone Ratio	4:1
Material	Fiberglass
Predicted Mass	24.44 oz

3.3.2 Nose Cone "Ring"

A 3.00 in. long cylinder of G12 Fiberglass will be epoxied onto the nose cone shoulder to allow the shock cord to have sufficient volume within the body tube for black powder ignition and distribute some of the launch vehicle's mass to the nose cone section, the lightest independent section of the launch vehicle. Attaching a 3.00 in. body tube "ring" allows the nose cone shoulder to still have 3.00 in. of length, given a shoulder diameter of 6.00 in., the shoulder length is still one half the shoulder diameter. Figure 4 displays the CAD drawing for the nose cone and nose cone ring assembly. Table 5 lists the specifications of the nose cone ring.

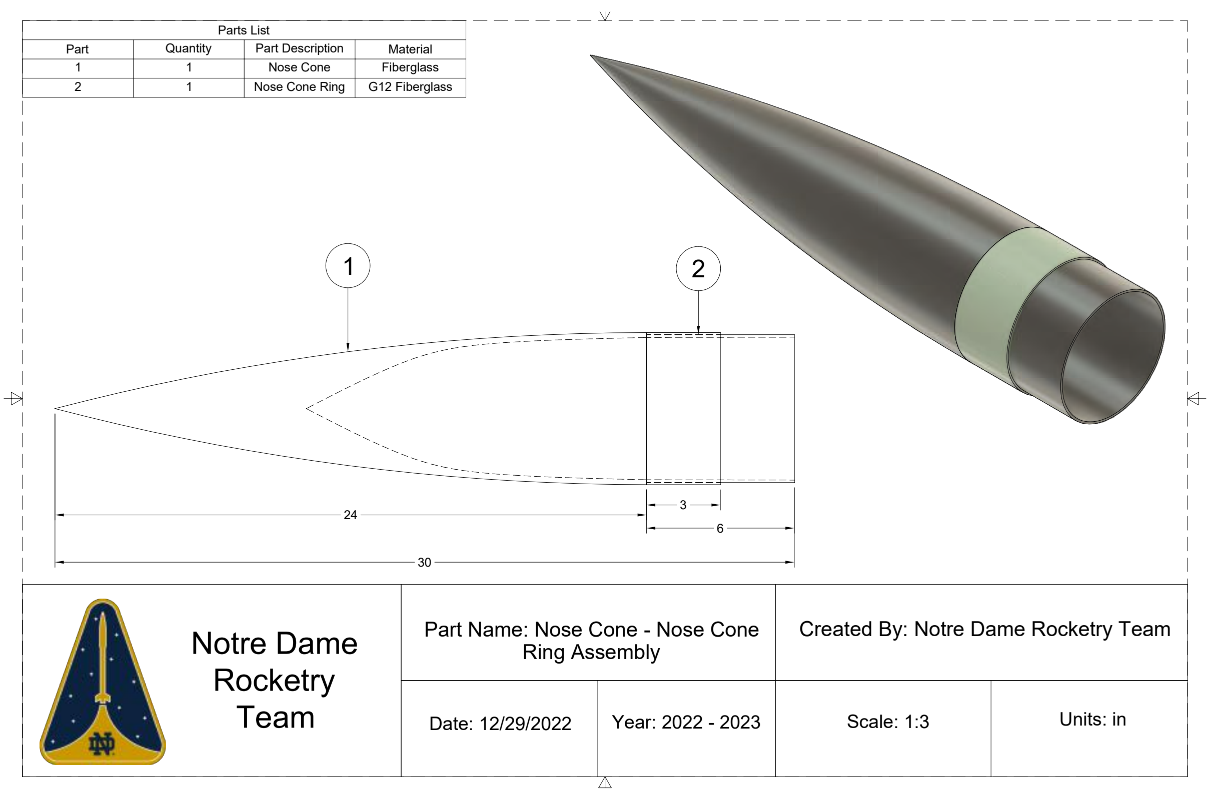


Figure 4: CAD Drawing of Nose Cone/Nose Cone Ring Assembly

Table 5: Nose Cone Ring Dimensions

Dimensions	Value
Ring Length	3.00 in.
Ring Outer Diameter	6.17 in.
Ring Inner Diameter	6.00 in
Material	G12 Fiberglass
Predicted Mass	6.682 oz

3.3.3 Airframe

Two materials were chosen for the launch vehicle airframe. For the Payload Bay, G12 Fiberglass was chosen. This decision was made based on its transmission ability — a requirement for the payload's complete operation — high strength, and durability. For the Payload Bay's coupler, G12 Fiberglass was also chosen for the same reasons. For the ACS Body Tube and the Fin Can Body Tube, carbon fiber was chosen. This decision was made based on its extremely high strength, durability, and the lack of internal components' need for transmissibility. Furthermore, the ACS Body Tube and Fin Can body Tube both have carbon fiber couplers. All couplers, both G12 Fiberglass and carbon fiber, are 12.00 in. in length total, with 6.0 inches inside the body tube and 6.0 inches extending out of the body tube. Given a coupler outer diameter of 6.00 inches, the coupler lengths satisfy NASA Req. 2.4.1. Figure 5 displays the CAD drawing for the Payload Bay, including the body tube, coupler, and aluminium bulkhead. Table 6 lists the specifications of the independent section.

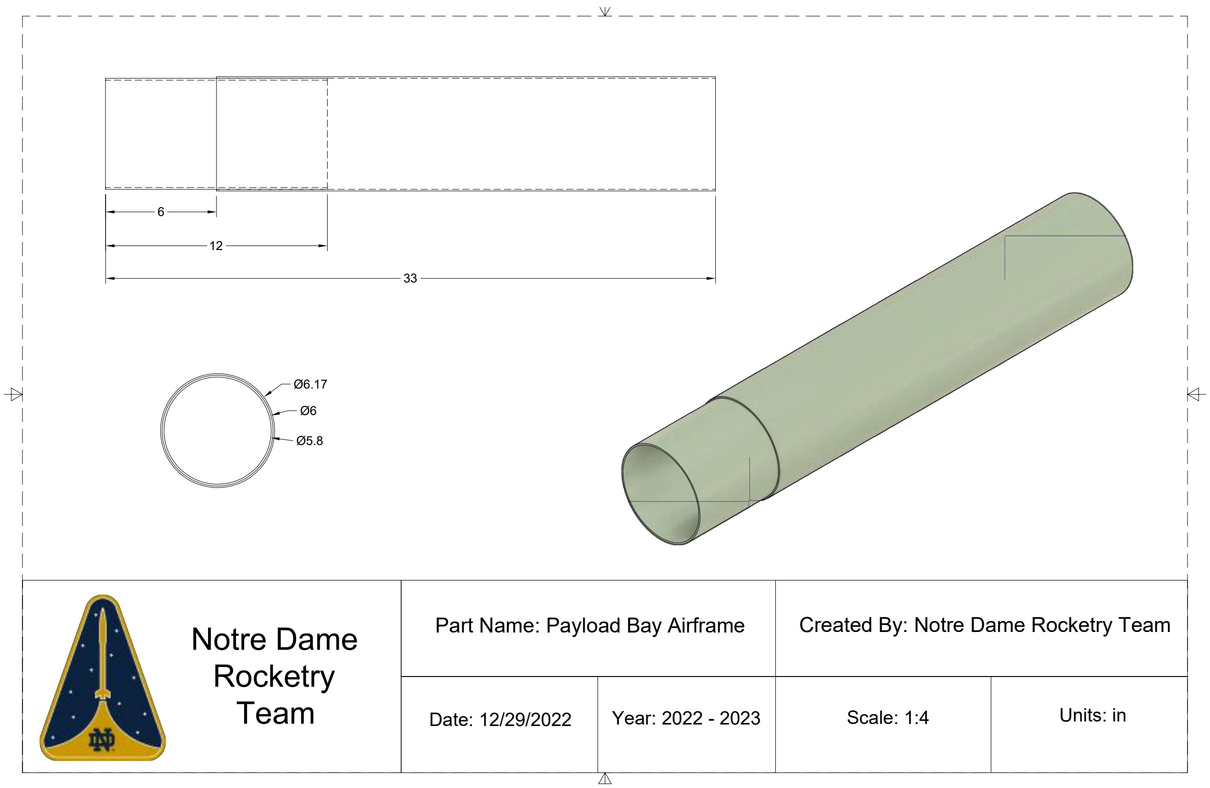


Figure 5: CAD Drawing of Payload Bay Airframe

Figure 6 displays the CAD drawing for the ACS Tube Airframe, including the body tube, coupler, and ACS flap holes. Table 7 lists the specifications of the independent section. Note that the ACS flaps are included in the mass of the

Table 6: Payload Bay Dimensions

Dimensions	Value
Payload Bay Body Tube Length	27.0 in
Payload Bay Body Tube Outer Diameter	6.17 in
Payload Bay Body Tube Inner Diameter	6.00 in
Payload Bay Body Tube Material	G12 Fiberglass
Payload Bay Body Tube Predicted Mass	60.138 oz
Payload Bay Coupler Total Length	12.0 in
Payload Bay Coupler Outer Diameter	6.00 in
Payload Bay Coupler Inner Diameter	5.80 in
Payload Bay Coupler Material	G12 Fiberglass
Payload Bay Coupler Predicted Mass	25.806 oz

ACS body tube for simplicity; in practice, the mass of the flaps and the body tube should be equivalent. As well, the flaps cover the holes during flight, as if the holes were never even cut.

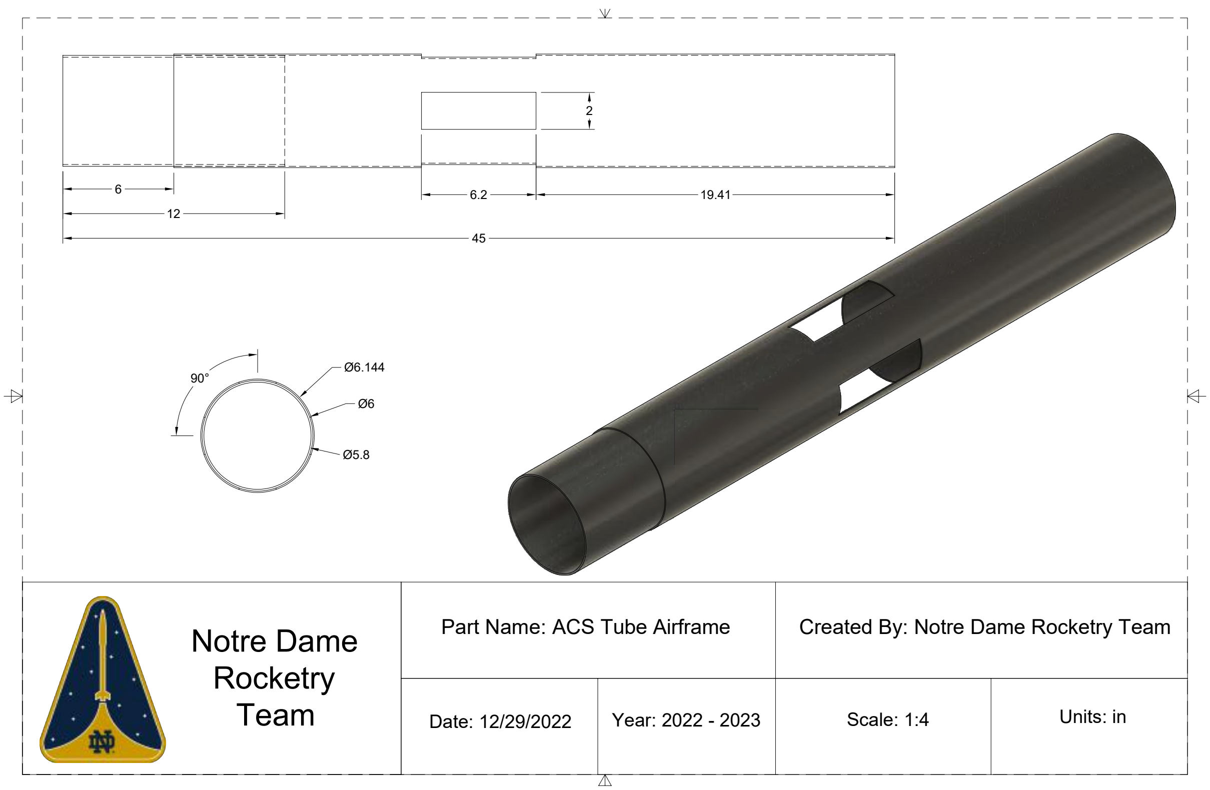


Figure 6: CAD Drawing of ACS Tube Airframe

Figure 7 displays the CAD drawing for the Fin Can Body Tube. Table 8 lists the specifications of the independent section.

Table 7: ACS Body Tube Dimensions

Dimensions	Value
ACS Body Tube Body Tube Length	39.0 in
ACS Body Tube Body Tube Outer Diameter	6.144 in
ACS Body Tube Body Tube Inner Diameter	6.00 in
ACS Flap Length	6.20 in
ACS Flap width	2.00 in
ACS Flap Quantity	4
ACS Body Tube Body Tube Material	Carbon Fiber
ACS Body Tube Body Tube Predicted Mass (Includes ACS Flap Mass)	53.04 oz
ACS Body Tube Coupler Total Length	12.0 in
ACS Body Tube Coupler Outer Diameter	6.00 in
ACS Body Tube Coupler Inner Diameter	5.80 in
ACS Body Tube Coupler Material	Carbon Fiber
ACS Body Tube Coupler Predicted Mass	9.282 oz

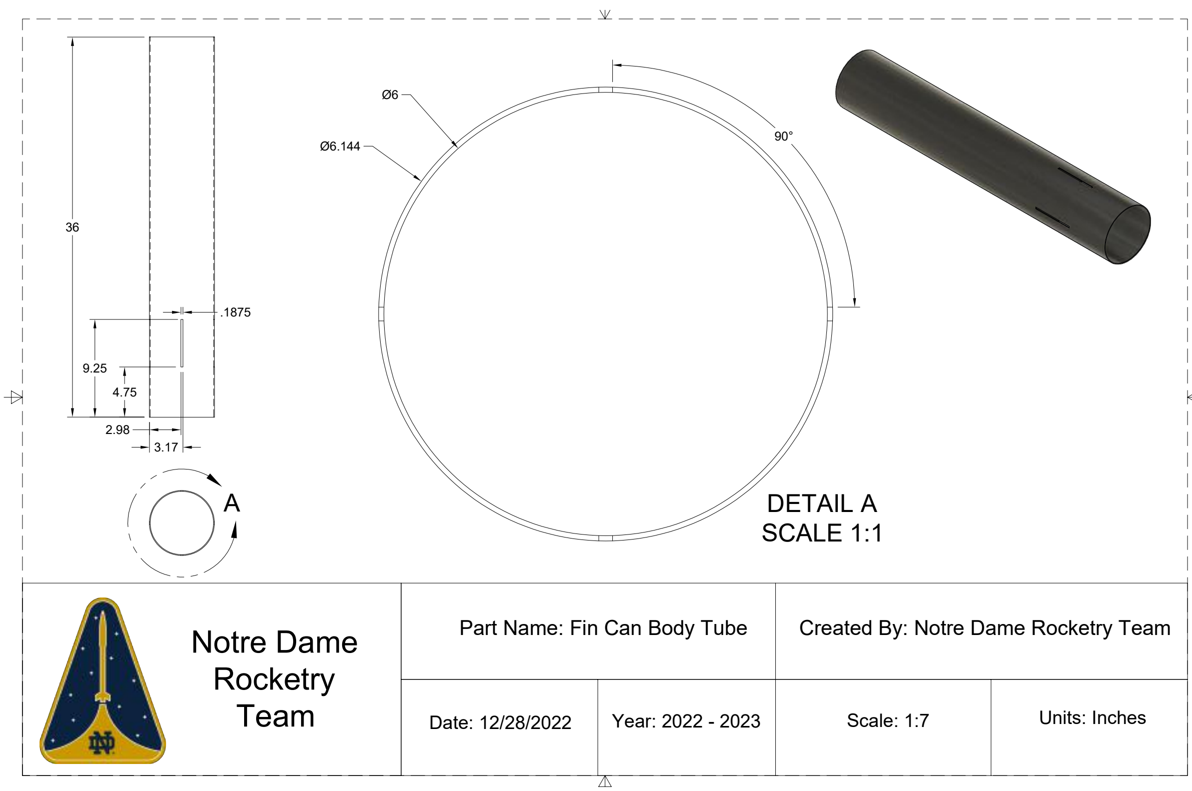


Figure 7: CAD Drawing of Fin Can Body Tube

3.3.4 Camera Shroud

The camera shroud will contain the designated camera during flights to record high quality video of the launch. The camera shroud must attach to the launch vehicle, securely hold the camera, allow access to the camera's buttons, and have a negligible effect on the aerodynamics and weight of the vehicle. The selected camera is the Mobius2 Actioncam. The camera can film a video of 1080p quality at 60 frames per second, with a field of view of 130°. The video will be saved onto a microSD memory card. The camera weighs approximately 1.587 oz and is 2.52 in. by 1.40

Table 8: Fin Can Body Tube Dimensions

Dimensions	Value
Fin Can Body Tube Length	36.0 in
Fin Can Body Tube Outer Diameter	6.144 in
Fin Can Body Tube Inner Diameter	6.00 in
Fin Slot Length	4.50 in
Fin Slot Width	0.1875 in
Fin Can Body Tube Material	Carbon Fiber
Fin Can Body Tube Predicted Mass	46.384 oz

in. by 0.709 in. The shroud is predicted to weigh 1.413 oz.

The camera shroud consists of two parts. The larger piece will hold the camera and is epoxied to the exterior of the payload bay body tube. The second piece covers the rear of the camera and uses a teardrop shape to reduce the impact of the shroud on flight performance. This piece will bolt onto the initial piece using two side-mounted bolts. The placement of the shroud on the payload bay allows the camera to see the deployment of the ACS flaps, drogue parachute, and main parachute. The camera shroud drawing can be seen in Figure 8

The camera will face toward the aft end of the launch vehicle and is at an angle of 3° relative to the body tube for better access when placing the camera in the shroud, and to maximize the field of view. The camera shroud will be 3D printed with ABS plastic. CFD was analyzed to confirm the camera shroud will not create aerodynamic instability during flight and thus it abides by NASA Req. 2.16. Section 5.4 shows the camera shroud's minimal effect on the overall aerodynamics of the launch vehicle.

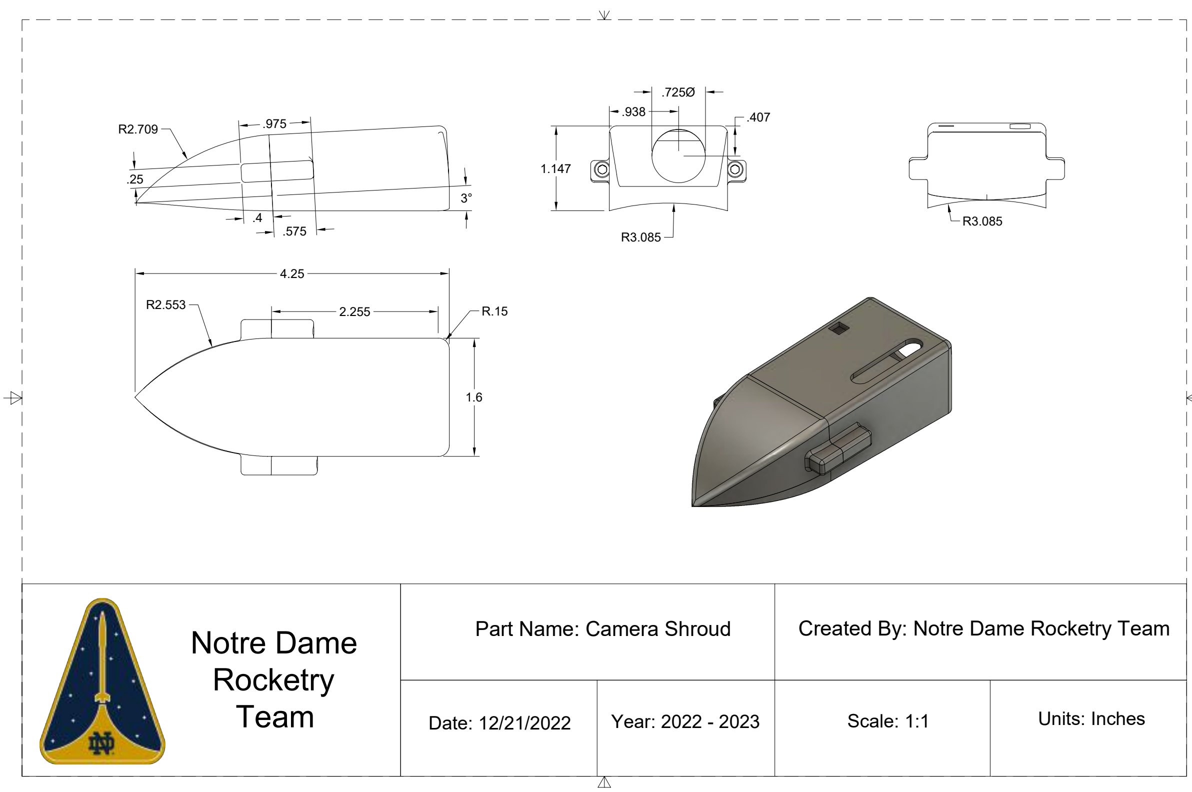


Figure 8: Camera Shroud Drawing

3.3.5 Fixed Bulkhead

The launch vehicle will have a fixed bulkhead located in the fin can. The bulkhead serves as the aft pressure wall for the pressurized section during the FED separation event. Figure 9 displays the bulkhead CAD drawing and its dimensions. An eye bolt will be mounted on this bulkhead that serves as the recovery harness mount for the drogue parachute. Figure 10 displays the CAD drawing of the bulkhead-eyebolt assembly. Table 9 lists all the critical dimensions of the bulkhead and eyebolt. The team analyzed the bulkhead using FEA and simulated the forces experienced during the deployment of the drogue parachute. It was determined that the bulkhead and eye bolt exceed the required strength and performed well under expected conditions. See Section 5.3 for all the information on the bulkhead FEA results.

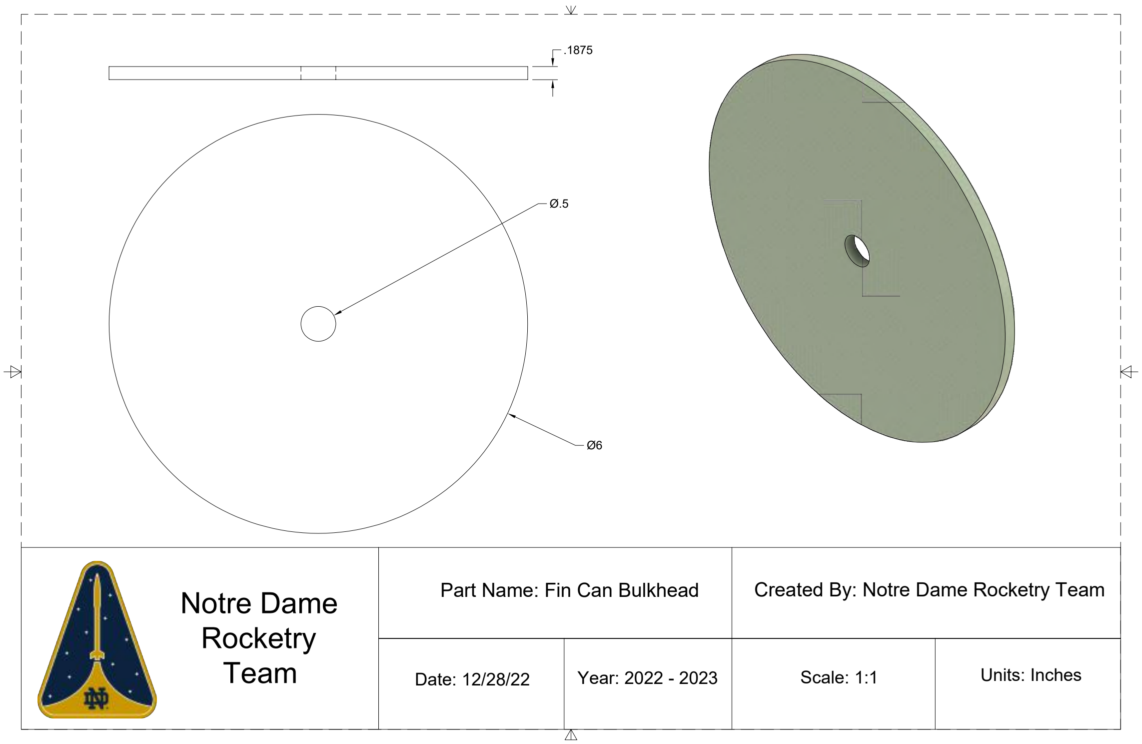


Figure 9: CAD Drawing of the Fin Can Fixed Bulkhead

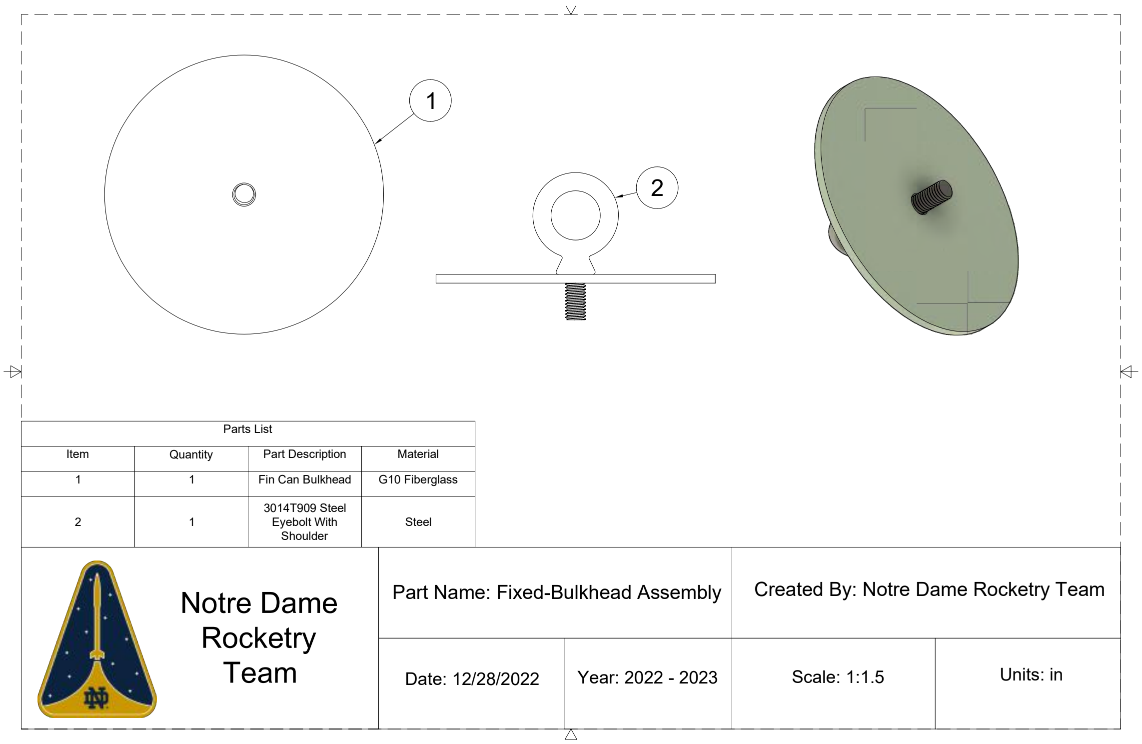


Figure 10: CAD Drawing of the Bulkhead-Eyebolt Assembly

Table 9: Bulkhead-Eyebolt Dimensions

Dimensions	Value
Bulkhead Outer Diameter	6.00 in.
Bulkhead Inner Diameter	0.50 in.
Bulkhead Thickness	0.1875 in.
Bulkhead Material	G10 Fiberglass
Bulkhead Prodicted Mass	5.283 oz
Eyebolt Diameter	1.0625 in.
Eyebolt Shank Diameter	0.4375 in.
Eyebolt Shank Length	3.00 in.
Eyebolt Material	Steel
Eyebolt Predicted Mass	3.12 oz

3.3.6 Fins

Four elliptical fins will be used for the full-scale launch vehicle. The elliptical shape was chosen based on an analysis between different shapes: for various shapes with the same area, the elliptical fins were able to provide the greatest center of pressure value. Additionally, the elliptical fins were chosen based on the principle that curved surfaces are, in general, stronger than edged surfaces. The fins will be made out of G10 Fiberglass due to it's high compressive strength, flexural strength, rigidity, and relatively lower cost than carbon fiber. Figure 11 displays the CAD drawing of one elliptical fin. The four elliptical fins will be set 90° apart from each other on the fin can. Table 10 lists all the specifications of the fins. Additionally, see Section 5.3.3 for a detailed breakdown of the fin flutter analysis.

Table 10: Bulkhead-Eyebolt Dimensions

Dimensions	Value
Shape	Elliptical
Root Chord	6.00 in.
Fin Height	6.00 in.
Tab Length	4.50 in.
Tab Height	1.50 in.
Thickness	0.1875 in.
Quantity	4
Offset Angle	90°
Material	G10 Fiberglass
Singular Fin Predicted Mass	7.358 oz
Predicted Mass of All 4 Fins	29.432 oz

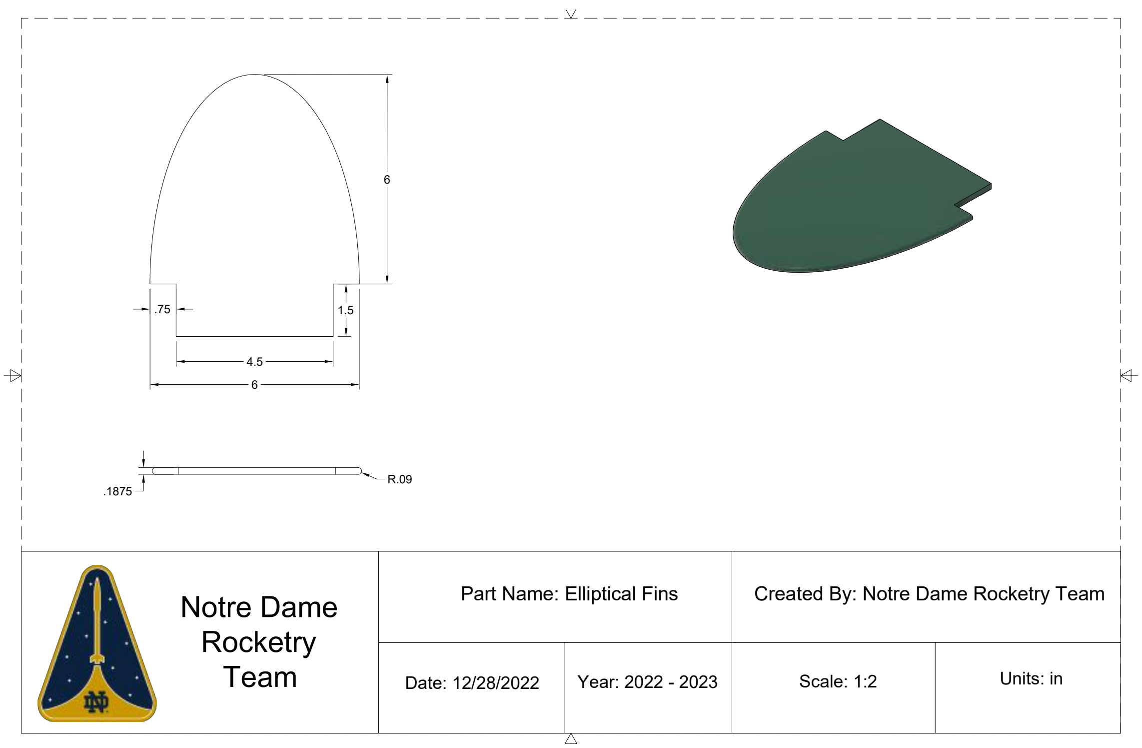


Figure 11: CAD Drawing of the Elliptical Fins

3.3.7 Motor Retention

The motor retention system consists of the motor mount tube, centering rings, and motor retainer ring. The motor mount tube contains the motor and directly experiences the thrust of the motor. The motor mount tube will be made of carbon fiber due to its high yield strength, light weight, and heat resistance. The centering rings distribute the thrust force of the motor to the airframe and secure the motor mount tube within the airframe. The centering rings will be cut from G10 fiberglass due to its ease of manufacturing and high yield strength. Figure 12 displays the CAD drawing of the centering rings. The purpose of a motor retainer is to secure the motor within the motor mount tube after burnout. The motor retainer will be an Aeropack 75mm retainer. Figure 13 displays the CAD drawing of the motor retainer ring. Figure 14 shows the entire motor retention assembly. The specifications for the motor retention components can be seen in Table 11.

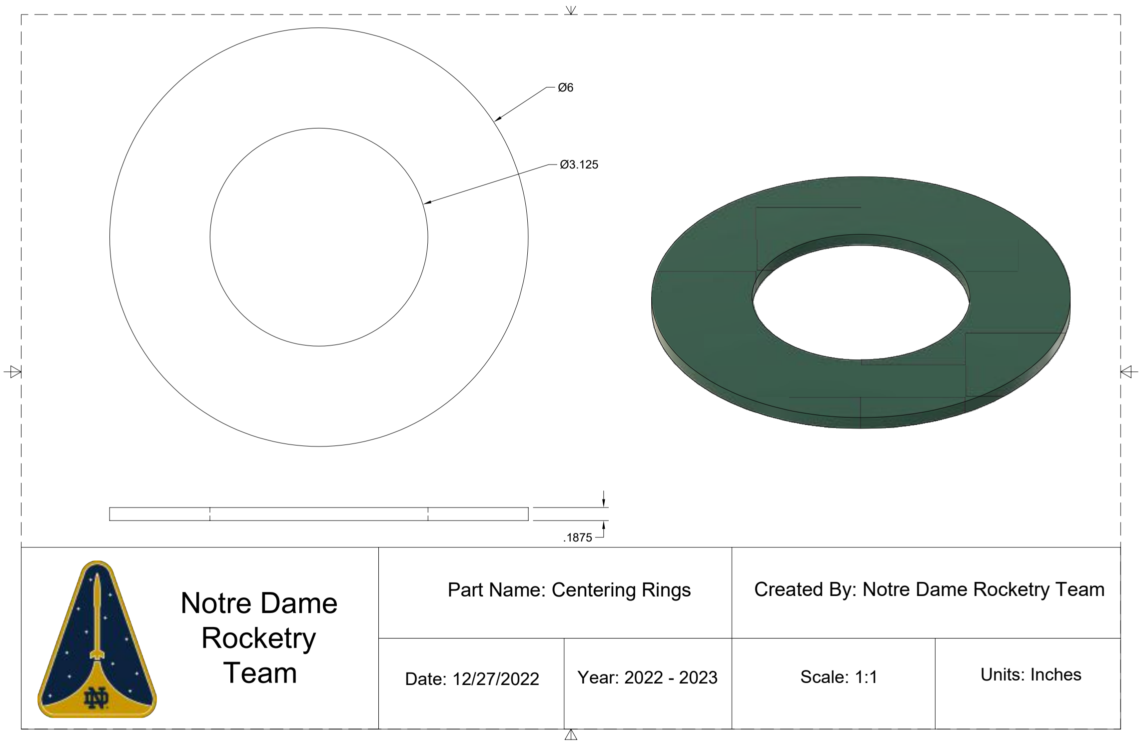


Figure 12: CAD Drawing of the Centering Rings

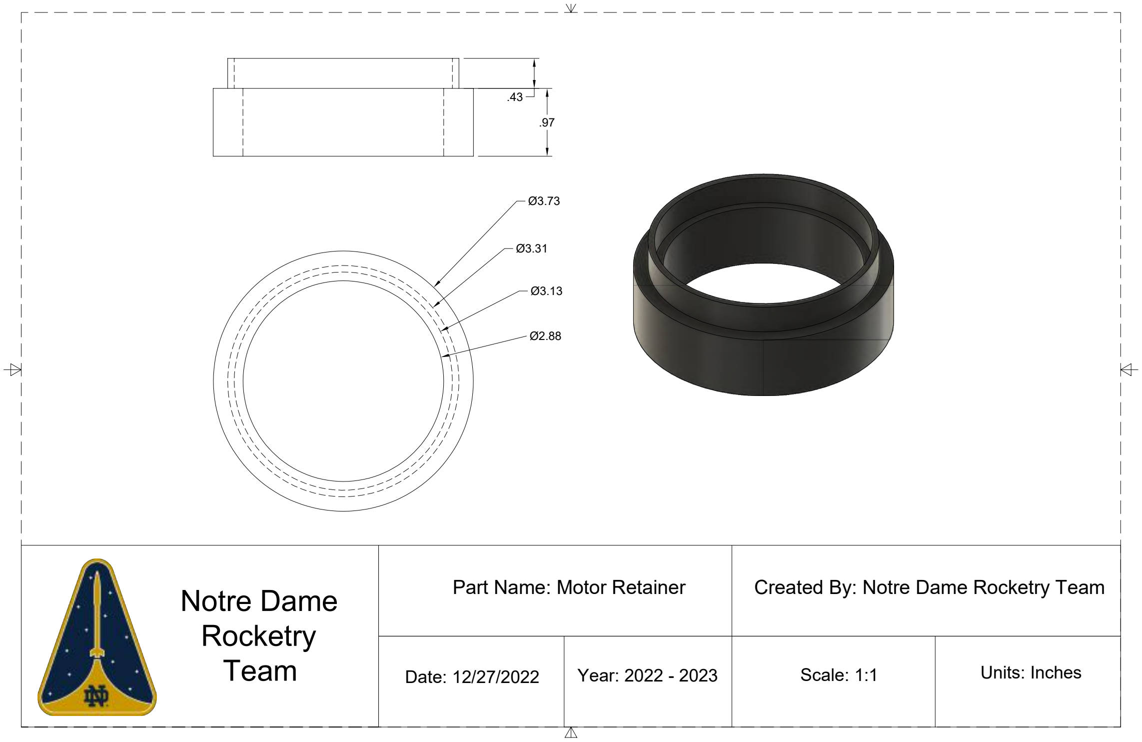
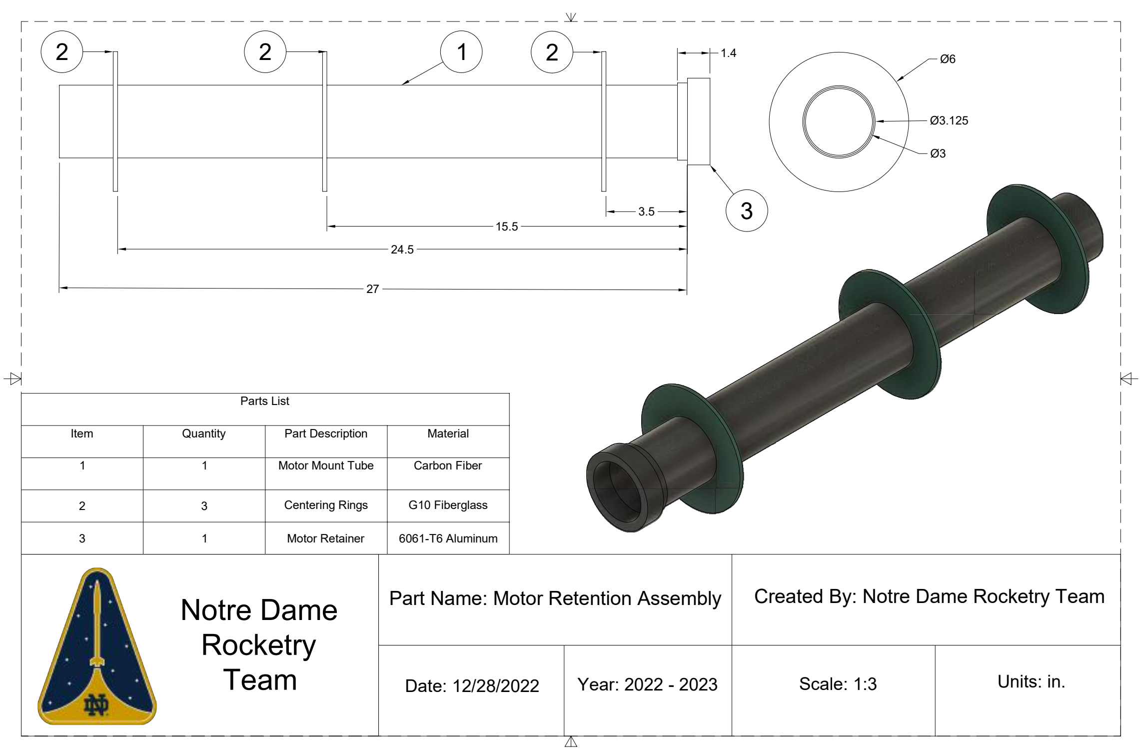


Figure 13: CAD Drawing of the Motor Retainer



Parts List

Item	Quantity	Part Description	Material
1	1	Motor Mount Tube	Carbon Fiber
2	3	Centering Rings	G10 Fiberglass
3	1	Motor Retainer	6061-T6 Aluminum

Figure 14: CAD Drawing of the Motor Retention Assembly

Table 11: Motor Retention Components Specifications

Dimensions	Value
Motor Mount Tube Inner Diameter	3.00 in.
Motor Mount Tube Outer Diameter	3.125 in.
Motor Mount Tube Length	27.0 in.
Motor Mount Tube Material	Carbon Fiber
Motor Mount Tube Predicted Mass	15.912 oz
Centering Ring Inner Diameter	3.125 in.
Centering Ring Outer Diameter	6.00 in.
Centering Ring Thickness	0.1875 in.
Distance to First Centering Ring	3.50 in from aft
Distance to Second Centering Ring	15.50 in from aft
Distance to Third Centering Ring	24.50 in from aft
Centering Ring Material	G10 Fiberglass
Singular Centering Ring Predicted Mass	4.628 oz
Predicted Mass of All 3 Centering Rings	13.884 oz
Motor Retainer Inner Diameter	3.125 in.
Motor Retainer Material	6061-T6 Aluminum
Motor Retainer Prediced Mass	4.16 oz

3.3.8 Rail Buttons

For the full-scale launch vehicle, airfoil-shaped rail buttons will be used. This design was chosen based on its minimal drag on the launch vehicle, According to the producer, airfoil-shaped rail buttons offer 47.3% less drag than their circular counterparts. Additionally, the producer further claims that if one was to fillet the top round edge, the drag can be reduced up to 20% more. Figure 15 displays a CAD drawing of the rail button with the screw attached to it. Furthermore, Figure 16 shows the locations of where the two launch rail buttons will be located. There is sufficient space between the two rail buttons, allowing the launch vehicle to have a stable and direct trajectory while on the rail. Each rail button is predicted to weigh 0.1734 oz.

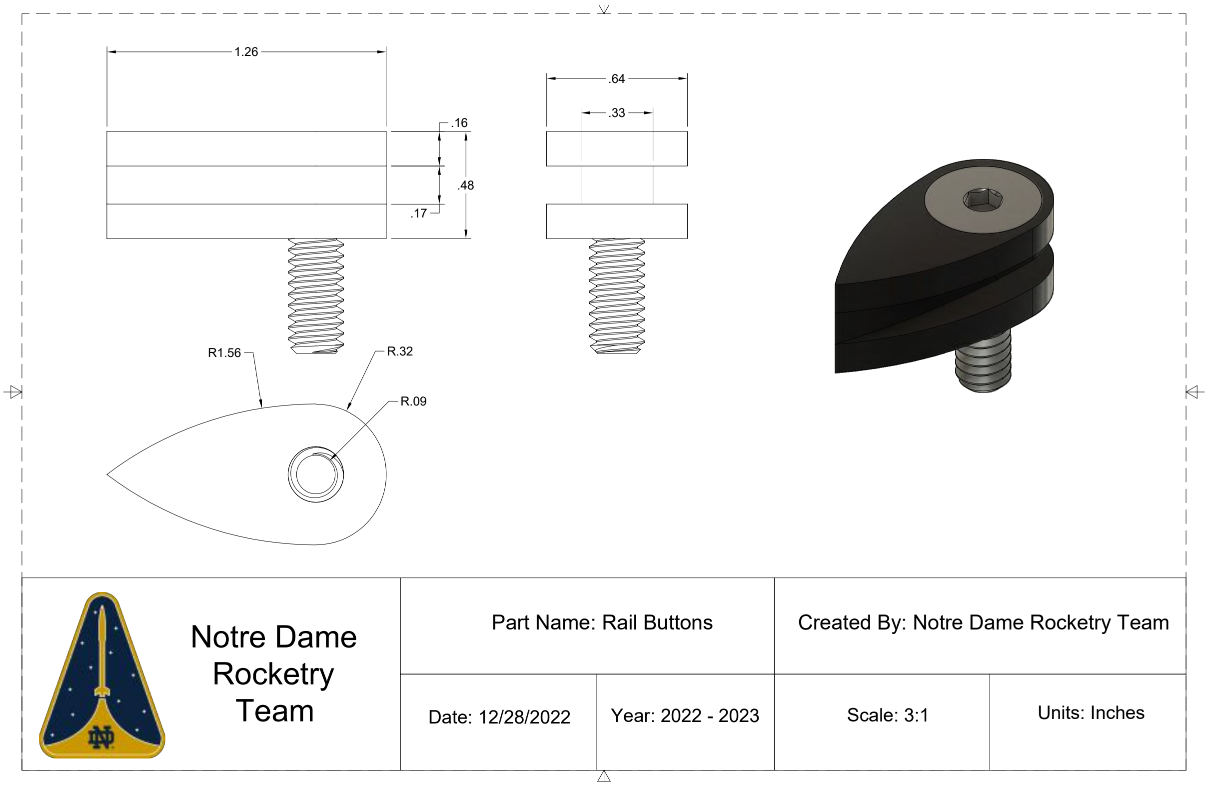


Figure 15: CAD Drawing of the Rail Button

Figure 16: Location of the Rail Buttons on the Launch Vehicle

3.4 Launch Vehicle Integrated Design

The team finalized the overall design for the fullscale launch vehicle after ensuring all component placements will result in a safe balance of vehicle stability, drag, thrust-to-weight ratio, and overall mass of each section.

3.4.1 Vehicle Layout and Design Summary

The nose cone and ACS body tube have been summarized in Sections 3.3.1 and 3.3.3, respectively. Before going over the overall launch vehicle, the two remaining sections will be outlined. Figure 17 displays the fully assembled

Payload Bay section. Included in this section is the payload bay body tube, coupler, aluminum bulkhead, eyebolt, and the camera shroud. For more information on the aluminum bulkhead, see Section 4.4.3.

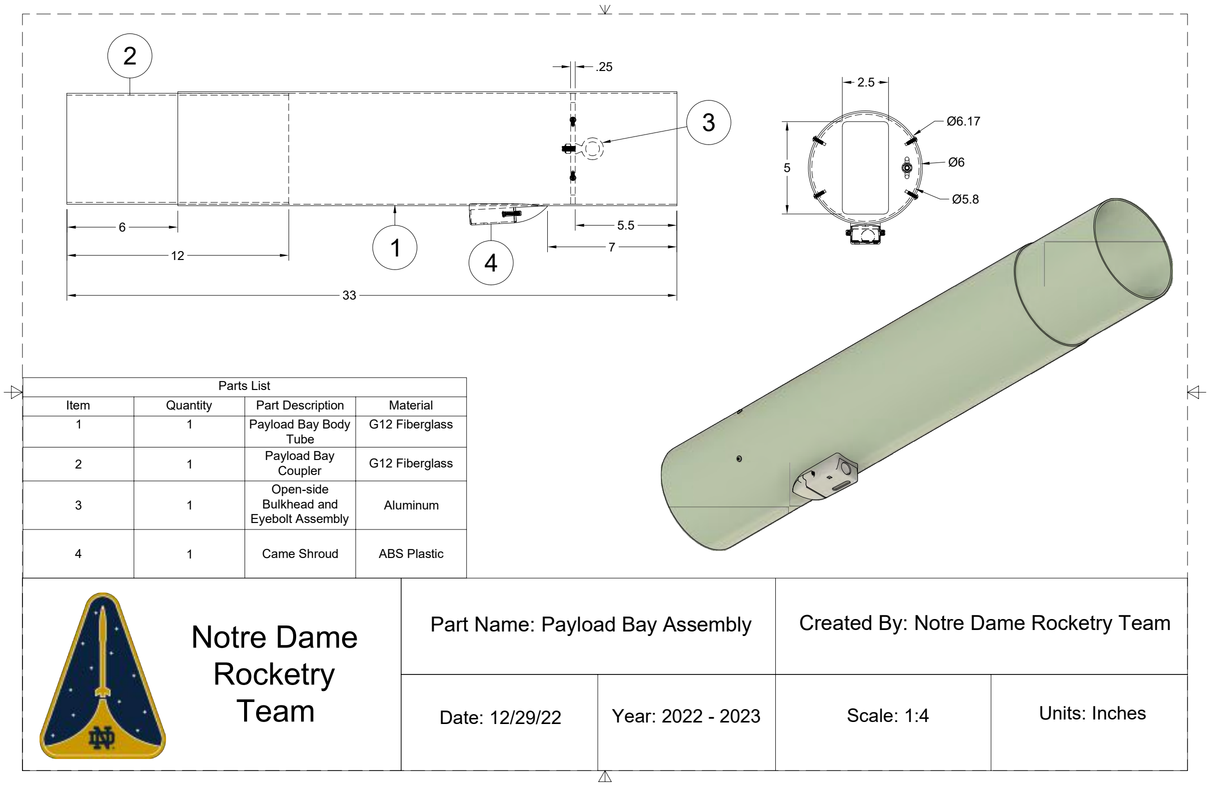
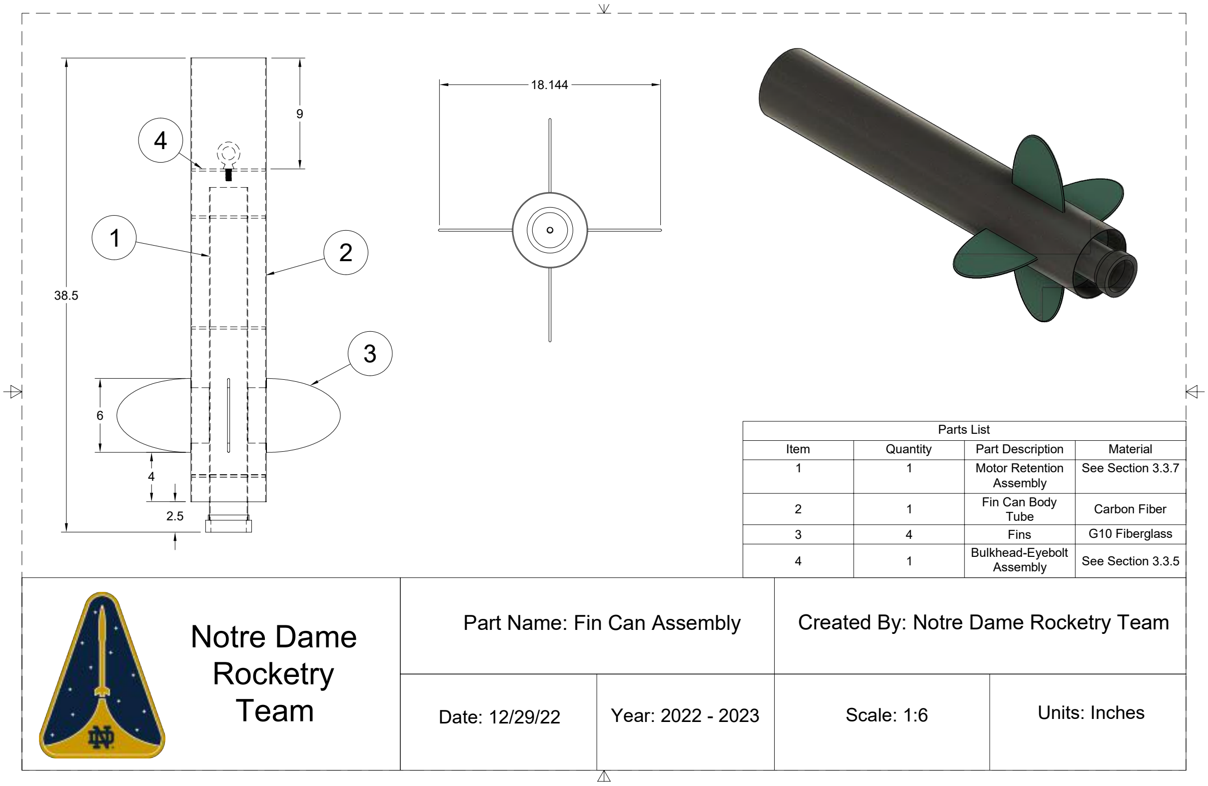


Figure 17: CAD Drawing of the Payload Bay Entire Assembly

Figure 18 displays the fully assembled Fin Can section. Included in this section is the fin can body tube, motor mount tube, 4 elliptical fins, 3 centering rings, motor retainer, fixed bulkhead, and an eyebolt.



Parts List			
Item	Quantity	Part Description	Material
1	1	Motor Retention Assembly	See Section 3.3.7
2	1	Fin Can Body Tube	Carbon Fiber
3	4	Fins	G10 Fiberglass
4	1	Bulkhead-Eyebolt Assembly	See Section 3.3.5

Figure 18: CAD Drawing of the Fin Can Assembly

Figure 19 displays the CAD drawing of the fully constructed launch vehicle. Figure 20 displays all the independent sections and internal electronics, and separation points.

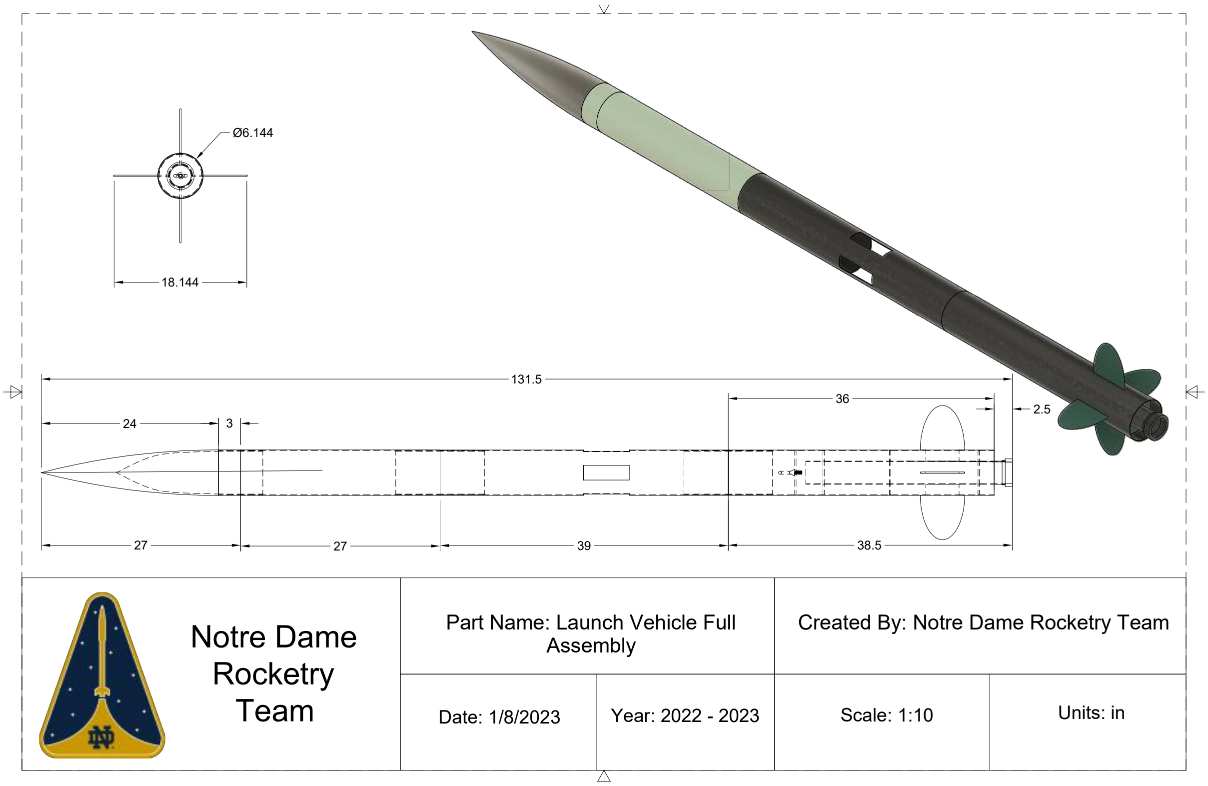


Figure 19: CAD Drawing of the Full NDRT Launch Vehicle

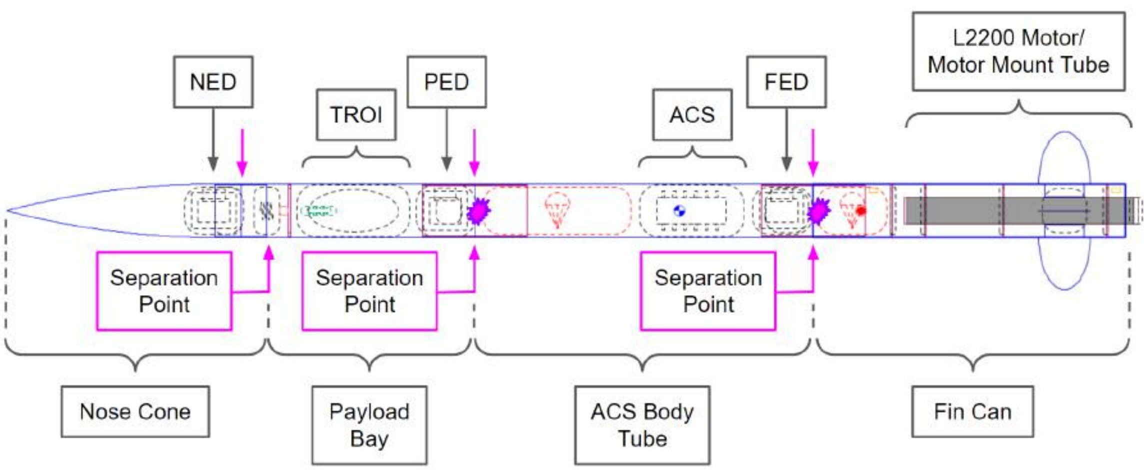


Figure 20: Launch Vehicle Sections and Internal Electronics

There will be three separation points in the launch vehicle. The nose cone will separate from the Payload Bay via the NED, the Payload Bay and ACS Body Tube will separate via the PED, and the Fin Can and the ACS Body Tube will separate via the FED. All three separation points will occur with the use of black powder. Table 12 lists exactly where the separation points occur on the launch vehicle.

Figure 21 displays all the internal structures, parachutes, and shock cord inside the launch vehicle.

Table 12: Fullscale Launch Vehicle Separation Information

Sections Separating	Separation Location (in)	Black Powder Location (in)
Nose Cone/Payload Bay	30.0	27.30
Payload Bay/ACS Body Tube	54.0	54.0
ACS Body Tube/Fin Can	93.0	92.8

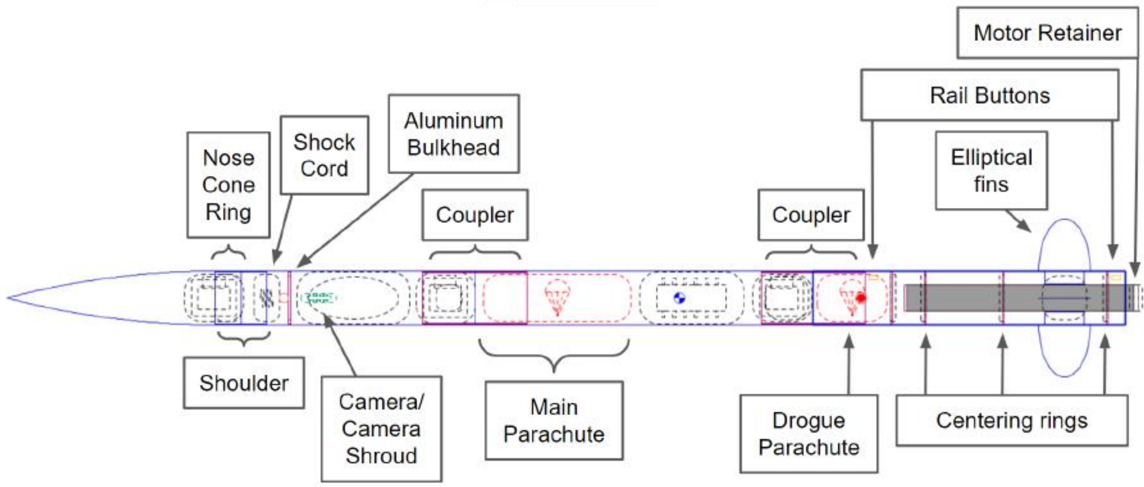


Figure 21: Launch Vehicle Internal Structures, Parachutes, and Shock Cord

Finally, there are a multitude of components and materials for the launch vehicle design. Table 13 lists all the key launch vehicle components and their respective material.

Table 13: Fullscale Launch Vehicle Material Breakdown

Component	Material
Nose Cone	Fiberglass
Nose Cone Ring	G12 Fiberglass
Payload Bay Body Tube	G12 Fiberglass
Payload Bay Coupler	G12 Fiberglass
Camera Shroud	ABS Plastic
Payload Bay Aluminum Bulkhead	Aluminum
ACS Body Tube Body Tube	Carbon Fiber
ACS Body Tube Coupler	Carbon Fiber
Fin Can Body Tube	Carbon Fiber
Motor Mount Tube	Carbon Fiber
Centering Rings	G10 Fiberglass
Fixed Bulkhead	G10 Fiberglass
Fins	G10 Fiberglass
Motor Retainer	6061-T6 Aluminum

3.4.2 Detailed Mass Statement

Table 14 lists the basic, predicted, and allowable mass and the mass margin percentage. The basic mass is the current design's mass. The predicted mass utilizes the ASNI S-120A-201X American National Standard for mass growth allowance (some of the growth percentages were modified to reflect the expected mass growth on the component). For more information on the theory behind the predicted mass, see Appendix Section B.

Table 15 lists the mass breakdown for each independent section of the launch vehicle, including all internal components during ascent and descent. Table 15 also shows that the launch vehicle's mass is less than the allowable mass. And, while the margin of the main parachute and shock cord is negative, all other sections have a positive margin, and the total margin is also positive.

Table 14: Launch Vehicle Mass Breakdown

<table>
<tr><th>Component</th><th>Basic Mass Estimate (oz)</th><th colspan="2">Predicted Mass (oz)</th><th>Allowable Mass (oz)</th><th>Margin (%)</th></tr>
<tr><td>Launch Vehicle</td><td>475.120</td><td colspan="2">483.109</td><td>485.00</td><td>0.390</td></tr>
<tr><td>Recovery Device (PED)</td><td>33.932</td><td>35.713</td><td rowspan="3">112.280</td><td rowspan="3">115.00</td><td rowspan="3">2.365</td></tr>
<tr><td>Recovery Device (FED)</td><td>33.932</td><td>35.713</td></tr>
<tr><td>Recovery Device (NED)</td><td>38.764</td><td>40.854</td></tr>
<tr><td>Shock Cord</td><td>10.00</td><td colspan="2">10.20</td><td>10.00</td><td>-2.029</td></tr>
<tr><td>Main Parachute</td><td>119.08</td><td colspan="2">121.46</td><td>115.00</td><td>-5.619</td></tr>
<tr><td>Drogue Parachute</td><td>18.83</td><td colspan="2">19.21</td><td>20.000</td><td>3.967</td></tr>
<tr><td>ACS</td><td>76.733</td><td colspan="2">79.731</td><td>80.000</td><td>0.336</td></tr>
<tr><td>Payload</td><td>68.863</td><td colspan="2">72.255</td><td>75.000</td><td>3.659</td></tr>
<tr><td>Total</td><td>875.257</td><td colspan="2">898.246</td><td>900.00</td><td>0.195</td></tr>
</table>

Table 15: Launch Vehicle Independent Section Mass Breakdown

Section	Basic Ascent Mass Estimate (oz)	Predicted Ascent Mass (oz)	Basic Descent Mass Estimate* (oz)	Predicted Descent Mass* (oz)
Nose cone	79.691	82.650	69.689	72.447
Payload Bay	195.920	203.212	195.920	203.212
ACS Bay	309.676	318.485	171.766	177.816
Fin Can	289.970	293.899	200.770	204.699
Total	875.257	898.246	638.144	658.175

*

Main Parachute, Drogue Parachute, Shock Cord, and Motor Propellant are not Included in Section Mass

The sudden increase in mass from PDR is primary due to the need for thicker shock cords and a new main parachute. The new shock cords (0.5 inch thick) are almost twice as thick as the previously used shock cords (5/16 inch thick), resulting in additional mass. The need for thicker shock cords was communicated to the team by NASA during the PDR presentation; there was a fear that the carbon fiber body tubes of thickness 0.072 inches would be at a high risk of zippering if the shock cords were not made thicker. Also, the main parachute was changed to strike a balance between drift radius, descent time, and landing kinetic energy. The chosen main parachute is almost twice as heavy as the previous one. For more information on the shock cord and parachute changes, see Section 4.4. While there is a great increase in launch vehicle weight, shock cord, and parachute masses do not impact the independent section mass at landing so, a sudden increase in mass has no negative impact on recovery requirements. For ascent requirements, the increase in mass will not affect the team's ability to reach the target apogee, off-rail stability, off-rail velocity, or the thrust-to-weight ratio requirements as shown in Section 5.

3.4.3 Motor Selection

The L2200 motor remains the optimal motor for competition. It offers the best range of apogees for all launch scenarios, is readily available, and is cost-effective. The thrust curve is shown below in Figure 22, and the L2200's specifications are shown in Table 16.

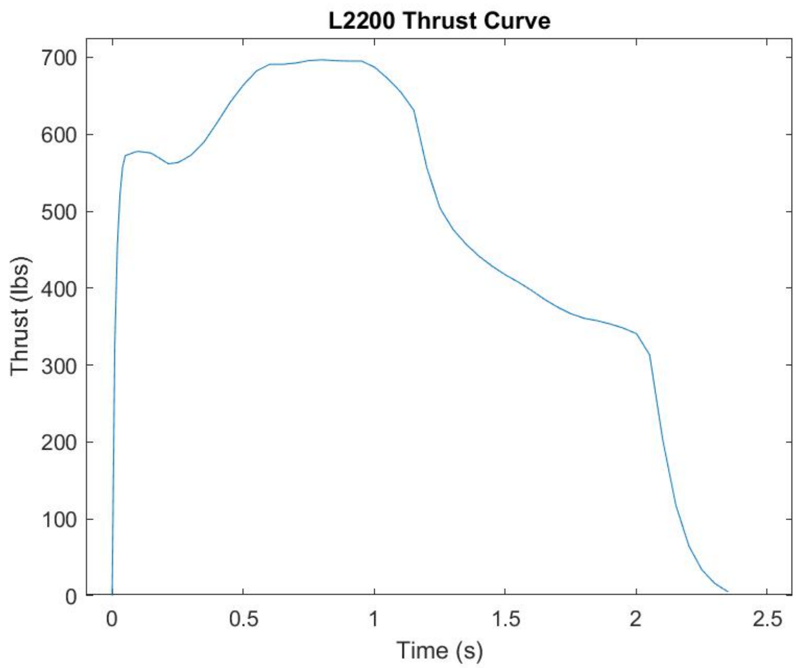


Figure 22: L2200 Thrust Curve, Taken from OpenRocket Data

Table 16 outlines the various characteristic of the L2200 solid rocket motor, including size, weight, cost, and thrust.

Table 16: L2200 Motor Specifications, Taken from OpenRocket

L2200	
Dimension	**Value**
Diameter	2.95 in.
Length	26.2 in.
Loaded Weight	168 oz
Propellant Weight	89.2 oz
Burnout Weight	78.8 oz
Total Impulse	1147 lb-sec
Average Thrust	504 lb
Maximum Thrust	697 lb
Burn Time	2.27 sec
Cost	$371.00
Thrust-to-Weight	8.99:1

3.5 Subscale Flight Results

3.5.1 Construction Process

The subscale construction process was recorded in great detail to demonstrate the team's ability to construct a launch vehicle and to carefully document construction methods for implementation in the full scale construction process. Safety protocol was properly adhered to by all team members when using machinery or handling potentially harmful materials.

3.5.1.1 Nose Cone Construction of the subscale launch vehicle began with the nosecone. The nose cone was modeled in Fusion360 and 3D printed using ABS filament in the Notre Dame Engineering Innovation Hub (EIH). The nose cone shoulder was drilled and tapped for 8-32 screws that will secure the nose cone to the fore body tube.

Figure 23: Nose cone

3.5.1.2 Fiberglass Tubing Both body tube sections, the coupler, and the motor mount tube are made of G12 fiberglass. They were cut on the bandsaw in the EIH.

3.5.1.3 Internal Structural Components The fins, bulkheads, baffle, and centering rings are made of G10 fiberglass. These were all cut on the water jet in the EIH. The baffle holes as well as the eyebolt mounting holes were drilled using the drill press in the NDRT workshop. The fins were sanded to achieve an airfoil profile in order to reduce drag.

Figure 24: Drill Press

Figure 25: Water Jet Cutting Submerged G10 Fiberglass Sheet

Figure 26: Baffle and bulkhead

3.5.1.4 Sleds The mounting blocks as well as the sled walls for the ACS, Recovery, and Payload sleds are made of G10 fiberglass and were cut on the water jet in the EIH. The airframe mounting blocks were machined from aluminum, and then tapped for an 8-32 bolt. An eyebolt was screwed into the top of each sled for ease of integration on the day of launch.

Figure 27: Individual components cut to size

3.5.1.5 Assembly The coupler was attached to the fore body tube using epoxy. The recovery bulkhead was attached to the fore body tube, and the baffle was attached to the aft body tube using epoxy as well. The three centering rings were attached to the motor mount tube using JB Weld, since this area experiences high temperatures due to the proximity of the motor, and JB Weld retains its strength at higher temperatures. The fins were secured to the motor mount tube and the aft body tube with JB Weld, which was also used to secure the motor retaining ring to the motor mount tube. All components were prepared by sanding the joint areas to ensure that the epoxy adhered properly. All team members working with epoxy wore gloves and safety glasses. Holes were drilled in the fin can for two rail buttons. These were both attached using a screw and round base T-nut.

Figure 28: Fore body tube and coupler

Figure 29: Fin can with rail buttons

3.5.2 Subscale Test Priorities and Flight Summary

To fulfill NASA Req. 2.18, the team designed and successfully launched and recovered a subscale model of the launch vehicle. This year's subscale flights were completed on November 20, 2022 and December 4, 2022 at the Three Oaks, MI launch site, with one launch occurring on each day.

The main priorities for the subscale launch were to match the manufacturing techniques, relative structure, thrust-to-weight ratio, and static stability of the full scale vehicle in order to both practice critical skills before the construction of the full scale vehicle and to abide by NASA Req. 2.18.1. Per NASA Req. 2.18.2, the vehicle carried several altimeters in order to collect flight data and determine apogee. The results of the altimeter data can be found in Section 3.5.4.2. Beyond just launching the subscale launch vehicle, many measurement devices were placed inside the vehicle to compare and improve flight simulator models to benefit the design of the full-scale launch vehicle.

The subscale launch vehicle carried recovery, ACS, and TROI test modules; all threee modules collected flight data from altitude to acceleration to orientation. In order to deploy the parachute, an 8 second delay charge was placed at the end of the subscale's I357 motor. Table 17 lists all the main conditions of the launch site at the time of flight.

Table 17: Subscale Launch Vehicle Launch Site Conditions

Condition	Value
Temperature	27° F (270K)
Pressure	1.024 (14.9 psi)
Wind Speeds	12 mph
Altitude	692 ft
Latitude	41.8°
Longitude	-86.6°
Clouds	Clear skies
Weather	No precipitation

The first flight was partially successful. The sections separated and the parachute deployed; however, it did not fully slow the descent of the vehicle as predicted. Reviewing the launch, the team determined that tangled shock cords prevented the parachute from opening fully. Still, the subscale vehicle landed undamaged. The second flight was fully successful as the parachute deployed correctly and the subscale vehicle returned to the ground at the expected speed. All data used in the subscale launch analysis section was taken from the successful flight. Figure 30 displays the subscale launch vehicle on the ground after landing for the successful flight on December 4th, fulfilling NASA Req. 2.18.4.2.

Figure 30: Entire Subscale Landing Orientation

3.5.3 Scaling Factor and Dimensions

For the subscale launch vehicle, a scaling factor of 50% was applied to most areas of the design. However, since its creation, dimensions of the full-scale launch vehicle have changed. Table 18 lists all the main components of the launch vehicle, their full-scale dimension, the subscale dimension, and the scaling factor used to scale them. Despite full-scale changes, the subscale launch vehicle is scaled no larger than 75 %, abiding by NASA Req. 2.18.5.

The stability margin and thrust-to-weight ratio were the only two variables of the design that were intentionally kept as close as possible to the full-scale values. They both impact the performance of the subscale and full-scale vehicles in the same way, a goal of the team and the entire purpose behind NASA Req. 2.18.1. To clarify, these values should have a scaling factor of 100 % because they are the characteristics of the vehicle and are unitless.

Not all variables needed to be scaled to the intended goal of 50 %, as long as they weren't over 75 %. For example, the inner diameter of all body tubes had no impact on the flight performance besides affecting the mass. As well, the motor mount tube length, inner diameter, and outer diameter were based on the motor selected, and the motors do not necessarily scale linearly. Finally, the fin tab length and height were scaled down to 50 %, but that was not necessarily important because it had no bearing on the flight; all that mattered was that the tab length and height were suitable to support the fins.

Table 18: Scaling of the Full-scale Launch Vehicle to the Subscale Launch Vehicle

Variable	Fullscale Dimension	Subscale Dimension	Scaling Factor
Nose Cone Length	24.0 in	12.0 in	50.0 %
Nose Cone Base Diameter	6.17 in	3.086	50.02 %
Body Tube Total Length	100.5 in	48.0 in	47.76 %
Body Tube Outer Diameter	6.17	3.08 in	49.92 %
Fin Root Chord	6.00 in	3.00 in	50.0 %
Fin Height	6.00 in	3.00 in	50.0 %
Total Length	131.5 in	61.0 in	46.39 %
Stability Margin	3.57 cal	3.58 cal	100.3 %
Thrust-to-Weight Ratio	8.99:1	9.34:1	103.9 %

Figure 31 shows the subscale launch vehicle CAD drawing, with some critical dimensions listed. Figures 32 and 33 shows the subscale launch vehicle component and section breakdown.

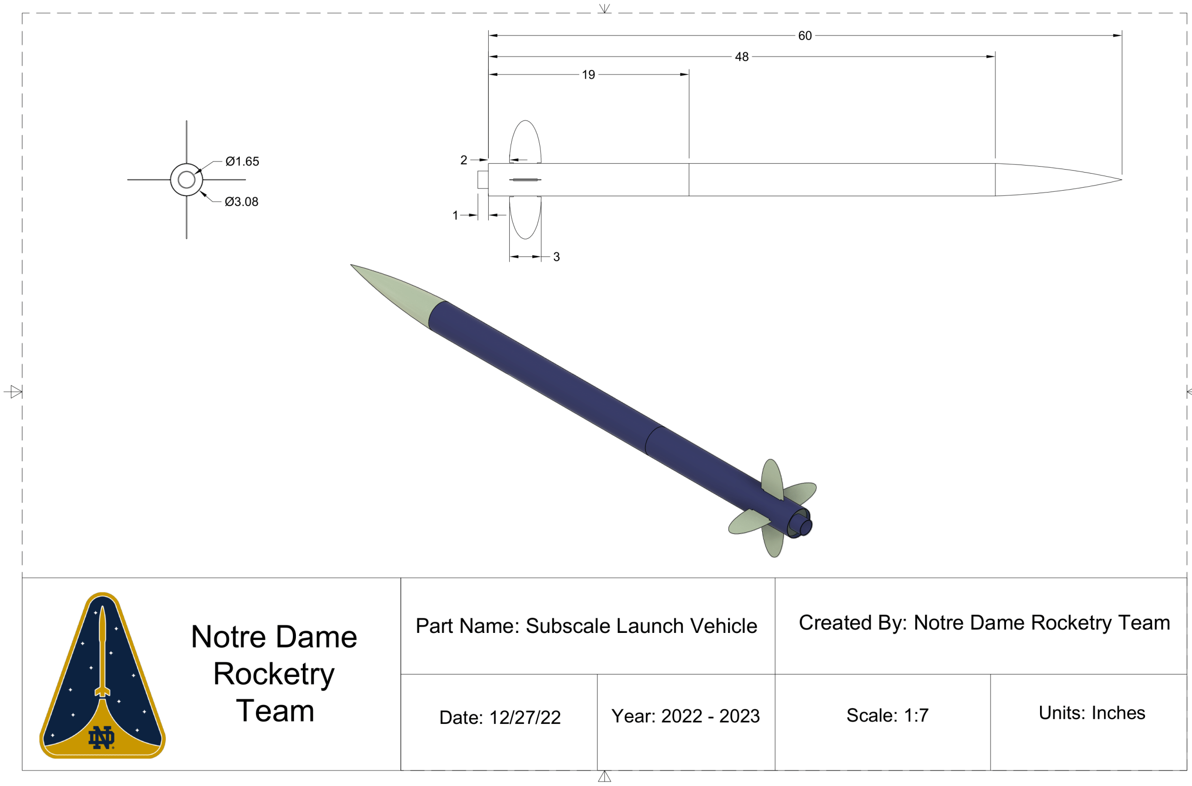


Figure 31: Subscale Launch Vehicle CAD Drawing

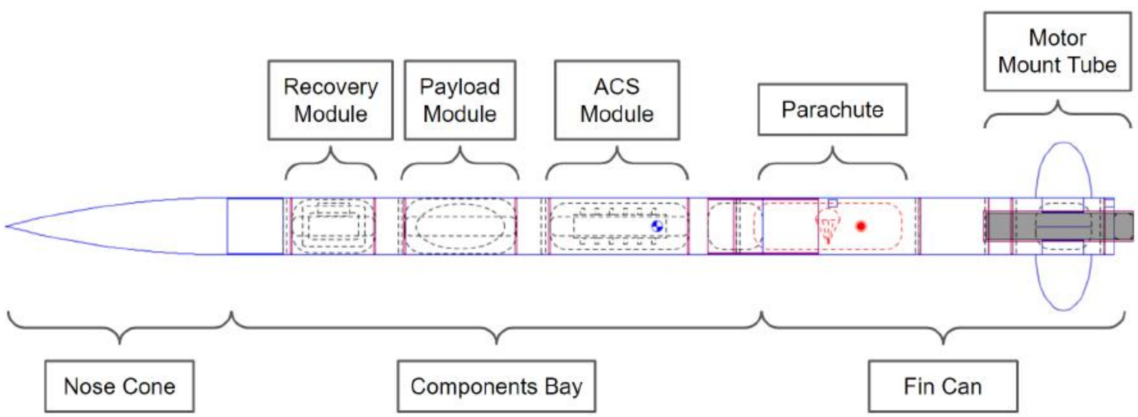


Figure 32: Subscale Launch Section Breakdown

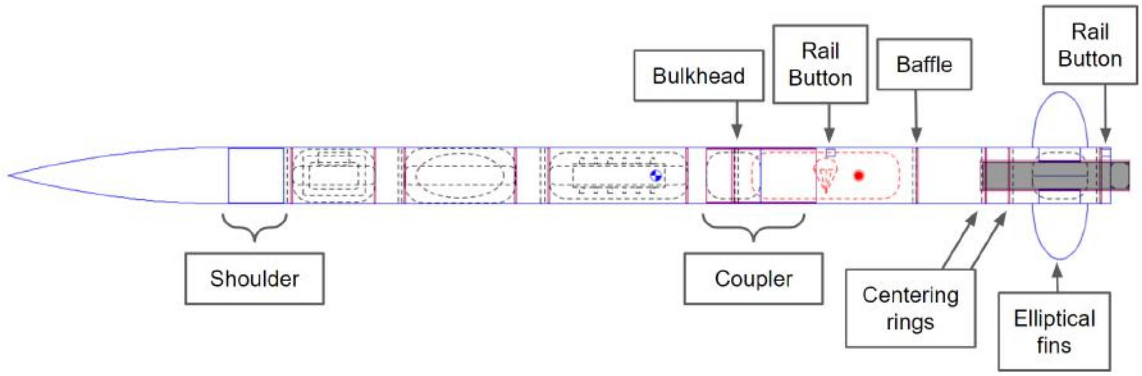


Figure 33: Subscale Launch Component Breakdown

Table 19 lists the section mass breakdown of the subscale launch vehicle.

Table 19: Subscale Launch Vehicle Mass Breakdown

Section	Mass (oz)
Nose Cone & Components Bay	70.87
Fin Can	53.73
Total	124.60

3.5.4 Subscale Launch Analysis

3.5.4.1 Prelude: Initializing Flight Simulation Software Before the discussion of flight analysis can start, it is important to lay out the steps taken to simulate the launch conditions. Appendix Section B.1 lists all the steps taken to simulate the subscale launch vehicle on OpenRocket, and Appendix Section B.2 lists all the steps taken to simulate the subscale launch vehicle on RockSim.

3.5.4.2 Altitude Results Figure 34 displays both the measured altitude data and the simulated profile of the subscale flight. Figure 34 shows both the measured altitude data and the predicted data from simulations. The red line labeled "Altimeter" is altitude data collected using an altimeter, directly during flight from the Recovery Module (satisfying NASA Req. 2.18.2). The blue "Accelerometer + Kalman" line is altitude data collected by a separate altimeter located in the ACS module and processed using a Kalman filter. The Kalman filter was applied to the data in order to remove outliers and reduce noise. The noise that exists in the data is a byproduct of the data collected; a MATLAB "smooth" command could have been used on the data, but it was thought that keeping it as is would demonstrate better the type of data collected in flight. The yellow and purple lines are the OpenRocket simulated data and the RockSim simulated data, respectively.

At apogee, the actual parachute deployment took longer than that in the simulation, resulting in a slight difference between the post-apogee simulation results and the flight data. Regardless, the flight data clearly indicates that the parachute successfully opened and assisted in reducing the descent velocity, with a total descent time of 29.1 seconds. Thus, NASA Req. 2.18.4.1 is satisfied.

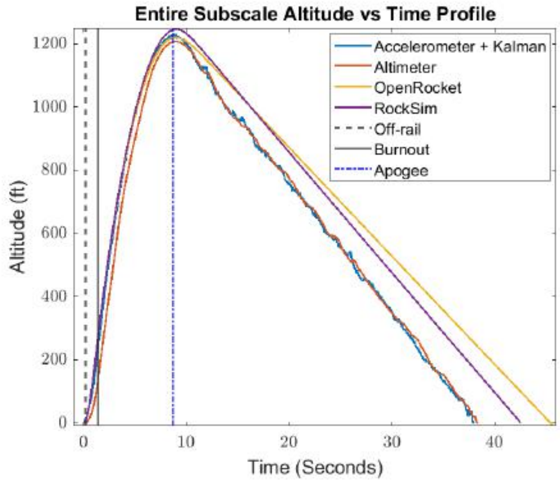


Figure 34: Entire Profile Subscale Simulation and Flight Altitude Data

Figure 34 displays the measured data agreed well with simulation data, but showed better agreement for ascent than descent. The precision of ascent, compared to descent is due to the differences in the coefficient of drag, the timing of the parachute not being exactly at the time as the flight simulators' predicted, and the tumbling of the launch vehicle during descent resulting in inconsistent data, both in terms of the measurement devices and the simulators.

The following analysis will focus primarily on the ascent portion of the flight because the main purpose of the subscale vehicle is to "resemble and perform as similarly as possible to the full-scale mode" (NASA Req. 2.18.1). The descent will be different for full-scale due to the use of the three unique recovery modules. For the subscale launch vehicle, the recovery deployment was executed with the use of a simple 8 second delay charge built into the I357 motor.

Figure 35 shows both the measured altitude data and the predicted data from simulations with the flight data being collected in the same method as in Figure 34. Table 20 list all the apogees for the different subscale simulation and flight data results, and also lists the simulations' percent error in relation to the flight measured apogee.

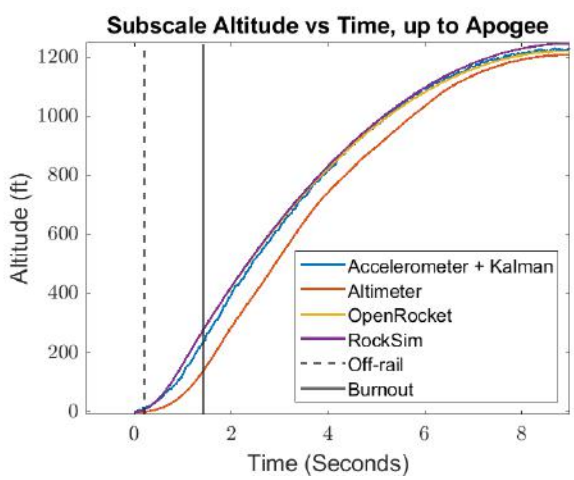


Figure 35: Subscale Simulation and Flight Altitude Data, Collected up to Apogee

Figure 35 and Table 20 show the flight simulators were more accurate at predicting the data from the "Accelerometer + Kalman" data, especially OpenRocket. It is important to highlight that the "Accelerometer + Kalman" data was ACS-measured data, and the ACS for the full-scale launch vehicle will need to accurately predict and redirect the

Table 20: Apogee Values for Subscale Simulation and Flight Data

Method	Apogee (ft)	Percent Difference to Accelerometer + Klaman	Percent Difference to Altimeter
Accelerometer + Kalman	1230.657	N/A	1.896 %
Altimeter	1207.7524	1.861 %	N/A
OpenRocket	1239.1	0.686 %	2.596 %
RockSim	1245.734	1.225 % .	3.145 %

altitude towards the target apogee during launch ascent. Moving forward, the proven precision of flight simulators for predicting ACS's data ensures that the OpenRocket and RockSim altitude simulations will be close to the actual altitude on launch day.

The "Altimeter" data, taken from the recovery module altimeter were predicted well by the flight simulations closely but was not as precise as the "Accelerometer + Kalman" data. A majority of the measured data error may be the result of the altimeters' slight manufactured inaccuracy, or potentially inconsistent hole sizing in the launch vehicle airframe for the altimeters to receive pressure. The two altimeters were purchased from different vendors.

The holes drilled were less than 1/8 in. thick. For the full-scale design, an extremely detailed understanding of the body tube hole sizings necessary for altimeter pressure readings will be undertaken to ensure that this will never be a potential factor of error again. Nevertheless, it can be deduced from the altitude data that both altimeters are precise, and the flight simulators were able to accurately predict the results.

3.5.4.3 Velocity Results Figure 36 shows the velocity measured during the subscale launch and that predicted by the flight simulation methods. The "Accelerometer + Kalman" data was collected by combining accelerometer and altimeter data. The accelerometer data was integrated and the altimeter data was differentiated, and both data sets were put through a algorithm to output the most accurate result. Additionally, a Kalman filter was applied to the data in order to reduce any outliers and heavy noise. For the subscale launch, the team tested how accurate the algorithms were in integrating and differentiating data to output velocity data. Tables 21 and 22 list all the maximum and off-rail velocities, respectively, for the flight data and subscale simulation total velocity data. These tables also list the simulations' percent error in relation to the flight measured values.

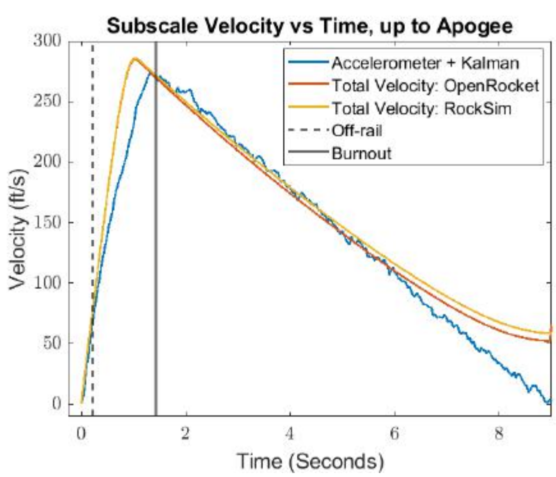


Figure 36: Subscale Simulation and Flight Total Velocity Data

Table 21: Maximum Velocity (Burnout) Values for Flight Data and Flight Simulators' Total Velocity Data

Method	Velocity (ft/s)	Percent Difference to Accelerometer + Kalman
Accelerometer + Kalman	274.0648	N/A
OpenRocket	287.6	4.939 %
RockSim	285.627	4.219 %

Table 22: Offrail Velocity Values for Flight Data and Flight Simulators' Total Velocity Data

Method	Velocity (ft/s)	Percent Difference to Accelerometer + Kalman
Accelerometer + Kalman	65.2966	N/A
OpenRocket	73.01	11.813 %
RockSim	69.193	5.967 %

Figure 36 and Tables 21 and 22 show the flight simulations does not match the measured total velocity data. This is to be somewhat expected, given that it is not measured data but derived data. One possible solution was to highlight that the velocity is mainly based off of the +z axis (vertical) acceleration of the accelerometer. Thus, the measured velocity becomes less and less accurate to the total velocity as the zenith angle of the launch vehicle increases, as proven in Section 3.5.4.7.3. As a remedy, the measured data was plotted against the flight simulated vertical velocity data. Figure 37 displays the velocity of the subscale measured data and the vertical velocity of the flight simulation methods. Tables 23 and 24 list all the maximum and offrail velocities, respectively, for the flight data and subscale simulation vertical velocity data. These tables also lists the flight data's percent error in relation to the simulations' values.

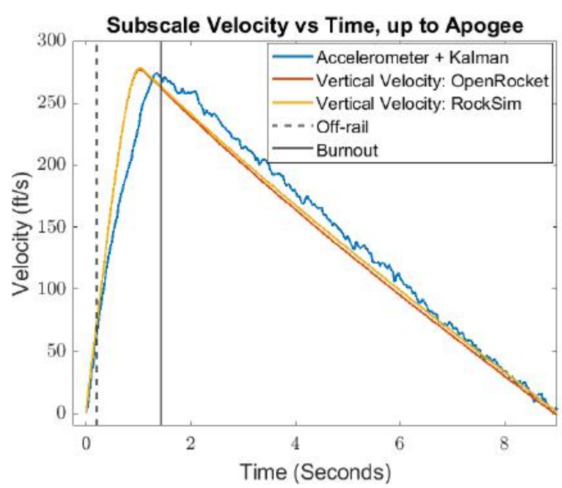


Figure 37: Subscale Simulation and Flight Vertical Velocity Data

Table 23: Maximum Velocity Values for Flight Data and Flight Simulators' Vertical Velocity Data

Method	Velocity (ft/s)	Percent Difference to Accelerometer + Kalman
Accelerometer + Kalman	274.0648	N/A
OpenRocket	279.85	2.111 %
RockSim	277.794	1.361 %

Table 24: Offrail Velocity (Burnout) Values for Flight Data and Flight Simulators' Vertical Velocity Data

Method	Velocity (ft/s)	Percent Difference to Accelerometer + Kalman
Accelerometer + Kalman	65.2966	N/A
OpenRocket	72.208	10.585 %
RockSim	68.433	4.803 %

From the figure and tables, it is evident that the simulated data for vertical velocity better resembles the measured velocity. Still, the error in measured data increases as it reaches apogee, which can be credited to the change in zenith angle. For more information on this phenomena, see Section 3.5.4.7.3.

Additional error in the measured data is due to the fact that this is derived data, not directly measured data. To determine the level of error, the uncertainly was analysed. The uncertainty analysis for the accelerometer was based on a Signal to Noise Ratio (SNR) analysis of the raw accelerometer data. The signal to noise ratio was estimated by creating a clean data set by filtering the data using a moving average and a threshold filter. The clean data set was subtracted from the raw data and the average noise was divided by the average signal level to produce a relative uncertainty of 0.93%. The uncertainty from noise is significantly higher than the uncertainty due to equipment resolution, which was neglected for this analysis. Because the accelerometer data is integrated to determine the altitude and velocity, the uncertainty in the measurement grows continuously. However, it was assumed that the Kalman filter reduced propagation error, and so for the purposes of this analysis, the maximum relative error in the altitude measurement was assumed to be on the same order of magnitude as the accelerometer uncertainty. This results in a maximum uncertainty of approximately 12ft. Based on the specification sheet of the StratoLogger, typical calibration and altitude uncertainty contribute to an overall relative uncertainty of approximately 0.1 % for the sensor. Thus, the maximum uncertainty in the altitude measurement from the altimeters is approximately 2ft. These uncertainty estimations explain some of the differences between the altimeter and the accelerometer results as well as differences between the experimentally measured data and that of the simulation. However, there are also a number of physical factors that contribute to differences between simulation and the subscale launch trajectory. These include differences between simulated and actual motor burn and performance, limitations in turbulence modelling and simulation estimation of skin friction, and nonuniformities in the atmosphere, including wind gusts. Despite these differences, the simulation results show good agreement with the experimentally measured flight trajectory, indicating the ability of the team to accurately predict the flight path of the launch vehicle.

3.5.4.4 Acceleration Results Figure 38 shows the acceleration of the subscale measured data and the vertical acceleration of the flight simulation methods. The flight simulator data used was the vertical component of acceleration, not acceleration magnitude, due to the reasons outlined in Section 3.5.4.3. The data is titled "Vertical Acceleration" but is the absolute value of the vertical acceleration component. This is because RockSim only outputs positive values for the vertical acceleration; everything post burnout should be negative. Table 25 list all the maximum acceleration for the flight data and subscale simulation vertical acceleration data. This table also lists the simulations' percent error in relation to the flight data values.

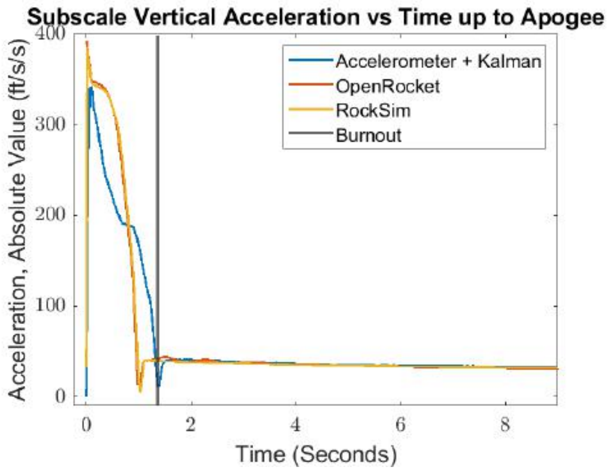


Figure 38: Subscale Simulation and Flight Total Acceleration Data

Table 25: Maximum Acceleration Values for Flight Data and Flight Simulators' Vertical Acceleration Data

Method	Acceleration (ft/s^2)	Percent Difference to Accelerometer + Kalman
Accelerometer + Kalman	341.9983	N/A
OpenRocket	392.42	14.743 %
RockSim	384.929	12.553 %

Figure 38 and Table 25 show the measured and simulated data are in relative agreement. However, there are discrepancies during motor burn. After burnout, the measured acceleration matches the simulated vertical acceleration due to the only acceleration being from gravity, 32.17 ft/s^2, and drag. In fact, the drag and gravity accelerations are acting in the same direction, resulting in the measured data accelerating after burnout to be greater than 32.17ft/s^2, as seen in Table 26, which lists the accelerations of the measured data and the flight simulated vertical acceleration data at 8 seconds. 8 seconds was chosen as a point where the acceleration is only based on gravity and drag.

Table 26: Acceleration Values for Flight Data and Flight Simulators' Vertical Acceleration Data at 8 Seconds During Flight

Method	Acceleration (ft/s^2)	Percent Difference to Accelerometer + Kalman
Accelerometer + Kalman	33.3659	N/A
OpenRocket	32.004	4.082 %
RockSim	32.609	2.268 %

Table 26 shows the simulated data agrees with the measured data, with a slight margin of error that is believed to come from a few places. First, the accelerometer used during flight could have some slight manufactured inaccuracies. Second, as mentioned previously, the error in measured data naturally increases as it reaches apogee, which can be credited to the change in zenith angle. Third, the drag force component of the acceleration was based on the C_d and velocity from flight, and both values may have some existing discrepancies. Fourth, the simulated data in itself may utilize certain assumptions when determining the acceleration, and such assumptions will result in inaccurate data. It should never be assumed that the simulations are always collecting perfect data. Still, the simulations are good predictors of mission performance.

3.5.4.5 Static Stability The static stability margin of the subscale launch vehicle was designed to be the same as that of the full-scale. Equation 1 was used to calculate static stability:

$$\text{Stability} = \frac{CP - CG}{d_{outer}} \tag{1}$$

Where the outer diameter, d_{outer}, of the subscale launch vehicle is 3.08 in. Table 27 lists the locations of the Center of Gravity, CG, and the Center of Pressure, CP, and stability margins for the subscale launch vehicle, the OpenRocket modeled subscale launch vehicle, and the RockSim modeled subscale launch vehicle. This table also lists the percent error of the simulations' launch vehicle values in relation to the constructed launch vehicle's stability margin. The CG of the constructed subscale launch vehicle was taken to an approximation at the hundredth mark given the limited resolution of the tape measure.

Table 27: Static Stability Margin for Flight Simulated Launch Vehicle and Actual Subscale Launch Vehicle

Method	CG Location (in.)	CP Location (in.)	Static Stability Margin (cal.)	Stability Percent Difference to Constructed
Subscale Launch Vehicle	35.28	46.226*	3.554	N/A
OpenRocket	35.258	46.296	3.58	0.732 %
RockSim	35.256	46.155	3.55	0.113 %

*On the day of launch, the Subscale Launch Vehicle CP was assumed to be the average of the OpenRocket and RockSim values.

Table 27 proves the team was successful in constructing the launch vehicle with a stability margin that was extremely close to the simulated one. A stability greater than 2.0 cal satisfies NASA Req. 2.14. The CG of the simulation and subscale launch vehicle are slightly different as motor masses, parachute postions, and other component masses vary.

3.5.4.6 Drag Coefficient The understanding of drag on the launch vehicle is essential for estimating apogee. The drag coefficient was calculated based on the data collected during the ascent of the launch vehicle. Equation 2 was used to calculate the drag force

$$F_d = \frac{1}{2}\rho C_d V^2 A, \tag{2}$$

where F_d is the drag force, ρ is the air density, C_d is the drag coefficient, V is the vehicle's vertical velocity, and A is the vehicle's cross sectional area. For the purposes of determining altitude, only the force in the vertical direction is considered, and so only the vertical component of velocity was used. The ideal gas law, shown in Equation 3 was used to calculated the density of air.

$$\rho = \frac{P}{RT} \tag{3}$$

Here, P is the static pressure, R is the gas constant for air, and T is the temperature. For determining the air density, the gas constant set to 287.05 $\frac{J}{kgK}$. Equations 4 and 5 were used to determine the pressure and temperature. These equations are taken from the NASA Earth atmosphere model.

$$T = 59 - 0.00356 \times h \tag{4}$$

$$P = \frac{2116}{144} \times \left(\frac{T + 459.7}{518,6}\right)^{5.256} \tag{5}$$

where h is the height. Note, the value of pressure must be converted to Pascals from psi. Section 5.3.3 confirms that such temperature and pressure calculations performed here will result in reliable data to the standard atmospheric model, especially for ground conditions. The density equation used in the Earth atmosphere model was ignored, and instead the ideal gas assumption was used. Figure 39 demonstrates that the use of the ideal gas equation for finding the air density will result in air density values that are very precise to the OpenRocket and RockSim simulated values, utilizing subscale measured altitude data for the h value for Equation 4. "RockSim:Simulated" refers to the air density values taken directly from the flight simulator. "RockSim: Ideal Gas" and "OpenRocket: Ideal Gas" refer to the use of the simulators' temperature and pressure values in the ideal gas equation to find the air density. "Calculated: Idea Gas" refers to the use of Equations 4 and 5 for finding temperature and pressure, respectively, and then the found values were put in the ideas gas equation. Notice how the "RockSim: Simulated" and "RockSim: Ideal Gas" directly overlap with eachother, and the "Calculated" value is a good balance between the two simulators.

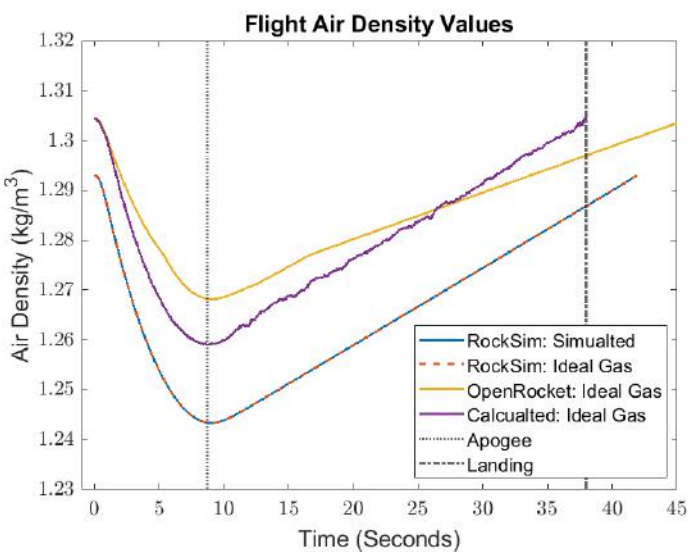


Figure 39: Air Denstiy Values for the Subscale Launch Vehicle, Utilizng different methods

Equation 6 was used as the basis for determining the drag force on the vehicle. Given the discoveries in Section 3.5.4.3 that only the vertical direction of data is precise to the simulated data, Newton's 2nd Law, Equation 6, for the vertical direction can be used:

$$\sum F_v = ma_v = T - F_d - mg \tag{6}$$

where $\sum F_v$ is the sum of the forces on the system in the vertical direction, m is the mass of the launch vehicle, a_v is the acceleration in the vertical direction, and g is the universal gravitational constant. Only data from burnout to apogee is considered so the span of flight where the motor is producing thrust is ignored. If only this section of the flight is considered, the only affects on the vertical acceleration is the gravitational force and drag force. Thus, Equation 7 can be used.

$$\sum F_v = ma_v = -F_d - mg \tag{7}$$

With Equation 8 rearranged, the equation to find the drag force is now:

$$F_d = -m(a_v + g) \tag{8}$$

A combination of Equations 3,6, and 8 were used to find the drag coefficient, as seen in Equation 9:

$$c_d = \frac{2F_d}{\rho V^2 A} = \frac{-2m(a_v + g)}{\rho V^2 A} = \frac{-2mRT(a_v + g)}{PV^2 A} \tag{9}$$

The drag coefficients can now be determined. Figure 40 displays the drag coefficient as a function of time. Figure 41 displays the drag coefficient as a function of velocity, from burnout to apogee. In the figures, the blue "Estimated C_d" utilizes the measured data by the subscale's accelerometer and filtered through the Kalman filter. Additionally, Table 28 lists the C_d values at burnout for both the measured estimations and the flight simulators' values and the percent error of the simulated launch vehicle's C_d in relation to the constructed launch vehicle's C_d. Table 29 lists the average C_d values, looking at burnout to 4 seconds, for both the measured estimations and the flight simulators' values. 4 seconds is the point when the estimated C_d values start to greatly diverge from the simulated values, due to the limitation of the measured data. This table also lists the percent error of the simulated launch vehicle's C_d in relation to the constructed launch vehicle's.

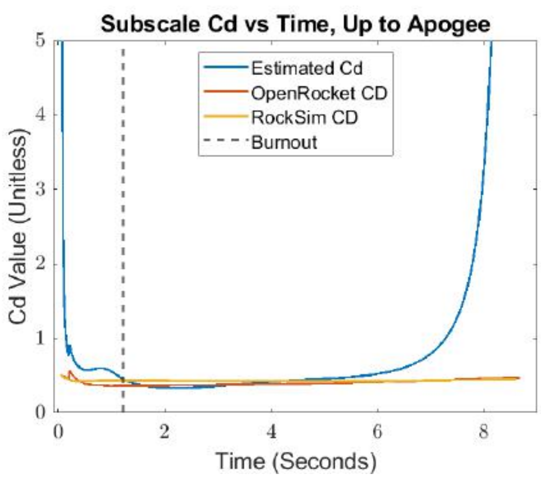


Figure 40: Coefficient of Drag as a Function of Time, up to Apogee

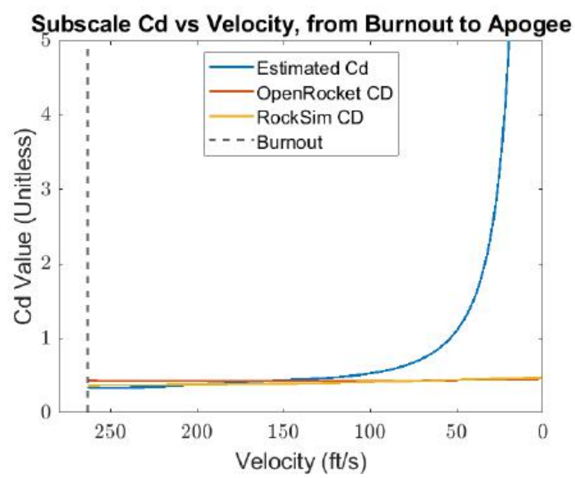


Figure 41: Coefficient of Drag as a Function of Velocity, From Burnout to Apogee

Table 28: Drag Coefficient Values for Flight Data and Flight Simulators' Cd Data at Burnout (Maximum Velocity)

Method	Cd	Percent Difference to Estimated Cd
Estimated Cd	0.3540	N/A
OpenRocket Cd	0.4357	23.079 %
RockSim Cd	0.3661	3.418 %

Table 29: Drag Coefficient Average Values for Flight Data and Flight Simulators' Cd Data from Burnout to 4 seconds

Method	Cd	Percent Difference to Estimated Cd
Estimated Cd	0.37432	N/A
OpenRocket Cd	0.43231	15.492 %
RockSim Cd	0.37647	0.574 %

In Figure 40, the data to the left of the burnout time shows why assumption 5 was made; it is very inaccurate. Tables 28 and 29's values indicate that the C_d value estimated from the RockSim simulation is precise to the subscale's instrumentation data, but the OpenRocket simulation data is extremely imprecise when compared to the subscale's instrumentation data. This error in flight simulator C_d values is due to the different ways the flight simulators compute temperate, pressure, and air density compared to how the estimated C_d computed such values. The notion that pressure is calculated differently between flight simulators supports the conclusions found in Section 3.5.4.5 that CP is different between the OpenRocket and RockSim models, despite the exact same vehicle airframe. Additionally, the plots of temperature, pressure, and air density for the fullscale launch vehicle flight can be found in Section 5, and this is a clear indication that there are differences in the ways they are calculated.

There is a small fraction of time in the ascent of flight where the measured Cd data is precise to the flight simulators, and that is right at the point of burnout. As the vehicle approaches the apogee, the C_d becomes increasingly imprecise. Ignoring the differences in pressure, temperature, and air density which were previously discussed, the increasing error comes from the measured vertical velocity and acceleration values. First, as mentioned prior in the velocity section, the error in measured velocity data increases greatly as it reaches apogee, which can be credited to the change in zenith angle. For more information on this phenomena, see Section 3.5.4.7.3. It appears that the C_d precision found at burnout is a due to the zenith angle of flight not being great enough yet to result in major amounts of error. Second, the error in data is due to the fact that velocity is derived from integrating the acceleration data and differentiating the altitude data, and any discrepancies in those data sets is intensified with the velocity data set.

Based on what was stated above, the best location to determine the estimated C_d is at burnout. The average of the two measured C_d values at burnout was be taken to determine the subscale's estimated C_d value. The estimated C_d value for the subscale launch vehicle was 0.37432. This exact method will be reciprocated once the vehicle demonstration flight is performed during the FRR period. This C_d value cannot be used on the full-scale launch vehicle due to different materials on some of the components.

3.5.4.7 Flight Angle The zenith angle, or flight angle, of the launch vehicle is critical to many aspects of flight. For the subscale launch, all flight angle measurements were determined based on the IMU data collected within the ACS module.

3.5.4.7.1 Flight Zenith Angle Figure 42 displays the flight zenith angle as a function of time, up to apogee. The real flight data is the "IMU Data," as explained earlier that the IMU collected all orientation data during the subscale flight, and the "OpenRocket" and "RockSim" data is the orientation of the simulated launch vehicle. The measured angle was precise throughout the entire duration of time from ignition to apogee.

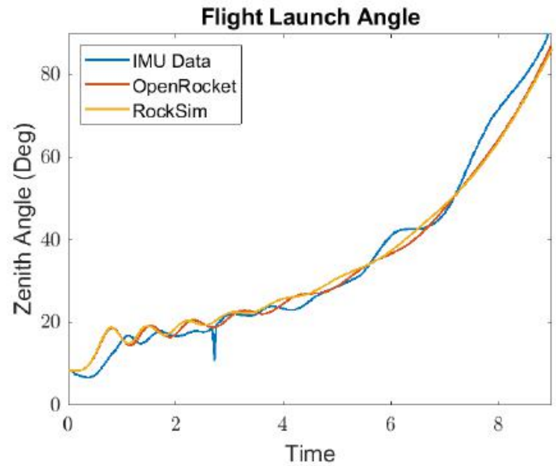


Figure 42: Flight Zenith Angle as a Function of Time, up to Apogee

3.5.4.7.2 Weather-Cocking According to RockSim, weather-cocking becomes an issue of consideration in the design as if the launch vehicle exceeds a flight angle of 40 degrees before apogee. Figure 43 displays the flight angle as a function of time, with the 40 degree weather-cocking location emphasized, which shows, the launch vehicle does exceed 40 degrees before apogee.

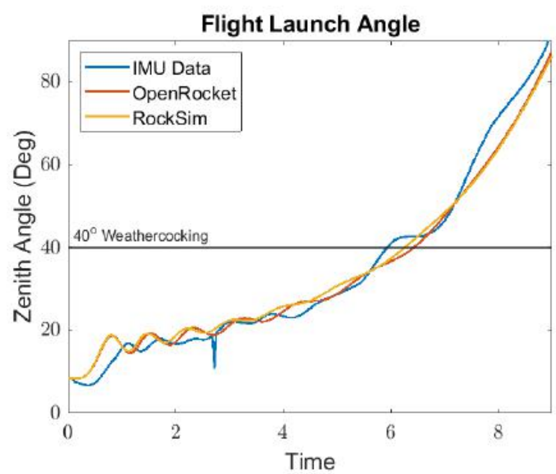


Figure 43: Flight Zenith Angle as a Function of Time, in reference to the 40 Degree Weather-Cocking Cone

Figures 44 and 45 display the flight zenith angle plotted against the altitude and vertical velocity as a function of time, up to apogee. The red circles on the two figures display where the flight zenith angle, altitude, and vertical velocity align as the flight zenith angle crosses the 40 degree weather-cocking cone. Table 30 lists these exact values.

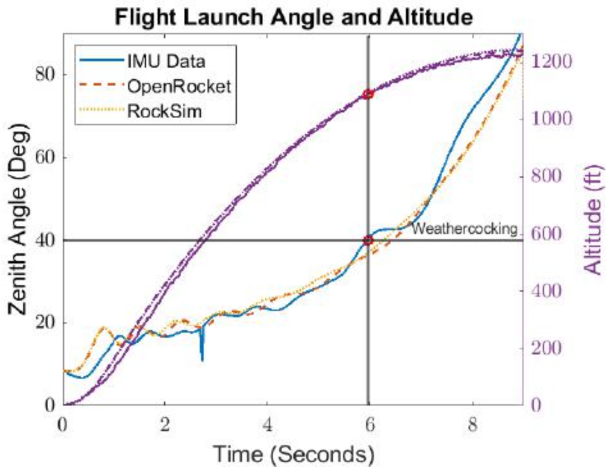


Figure 44: Flight Zenith Angle vs Time Plotted in Reference to the Altitude vs Time, up to Apogee

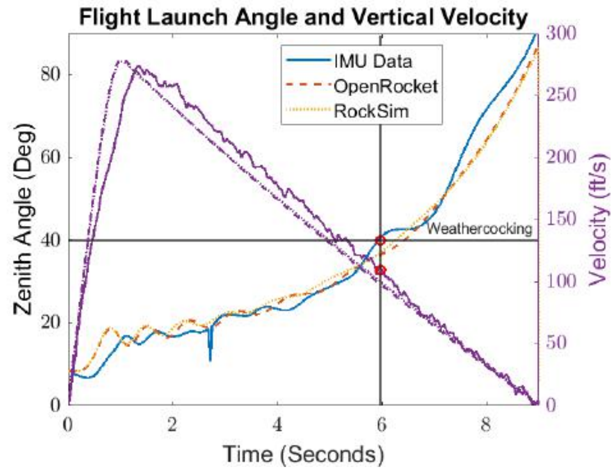


Figure 45: Flight Zenith Angle vs Time Plotted in Reference to the Vertical Velocity vs Time, up to Apogee

Table 30: Flight Measured Values as the Subscale Launch Vehicle crosses the 40 Degree Weather-Cocking Cone

Method	Variable	Value	Apogee's Value	Difference to Apogee's Value	Percent Difference to Apogee's Value
Accelerometer + Kalman	Altitude	1095.3137 ft	1230.657 ft	135.34 ft	10.997 %
Accelerometer + Kalman	Vertical Velocity	113.237 ft/s	15.7943 ft/s	97.44 ft/s	616.95 %

From the figures, it is evident that the altitude and vertical velocity are nearing apogee as the flight zenith angle crosses the 40 degree weather-cocking cone. While the velocity may seem like a substantial value at the 40 degree weather-cocking cone, the altitude difference shows that the launch vehicle isn't traveling much farther, and the acceleration at this moment is large enough (32.17 ft/s^2) that the vehicle will slow down before any major influential weather-cocking affect could ever happen.

3.5.4.7.3 Evidence that Velocity Error Increases as Zenith Angle Increases Figure 46 displays the velocity of the subscale measured data and the total velocity of the flight simulation methods. Figure 47 displays the percent difference in the measured velocity and the simulated total velocity of the launch vehicle.

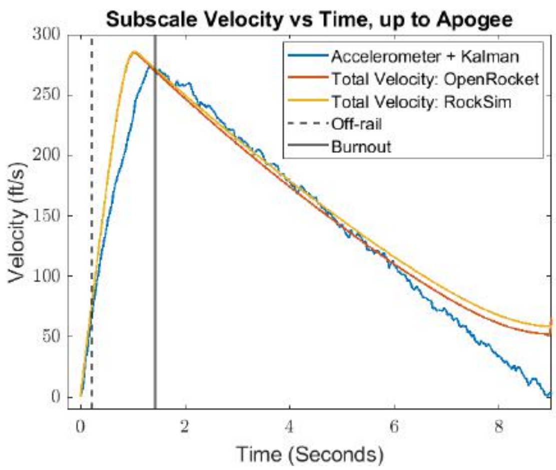


Figure 46: Measured Subscale Velocity and Simulated Total Velocity vs Time, up to Apogee

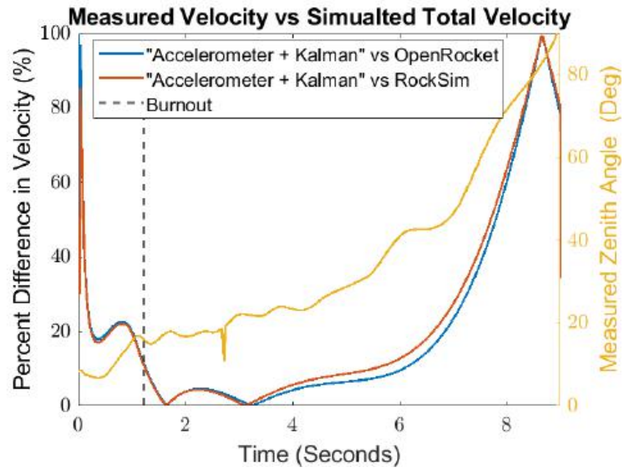


Figure 47: Percent Difference in Measured Velocity and Simulated Total Velocity vs Time Plotted in Reference to the Flight Zenith Angle vs Time, up to Apogee

From the figures, there is a near-direct relationship between the flight zenith angle and the percent error in the total velocity after burnout. The distinction is made with "after burnout" because the acceleration data from ignition to burnout was already deduced to be difficult to make accurate in Section 3.5.4.4. In order to determine if the issue was total velocity, the flight zenith angle, or both, the measured velocity was also plotted against the simulated vertical velocity, as seen in Figure 48. As well, Figure 49 displays the percent difference in the measured velocity and the simulated vertical velocity of the launch vehicle.

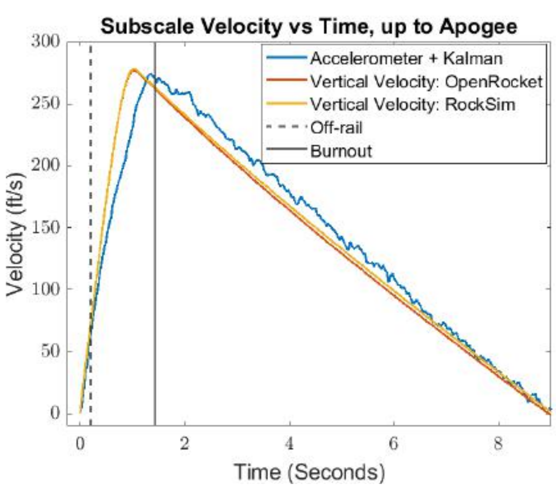


Figure 48: Measured Subscale Velocity and Simulated Vertical Velocity vs Time, up to Apogee

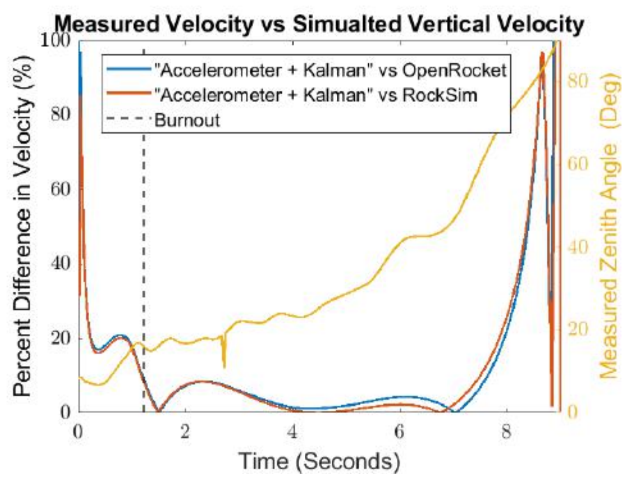


Figure 49: Percent Difference in Measured Velocity and Simulated Total Velocity vs Time Plotted in Reference to the Flight Zenith Angle vs Time, up to Apogee

Figure 48 shows the percent error is substantially less during a majority of the ascent time after burnout. However, the percent difference still spikes up as the flight zenith angle greatly increases around the 7 second mark. Therefore, the issue wasn't just due to the incorrect use of simulated total velocity, but the issue was still nevertheless greatly impacted by the launch vehicle's zenith angle during flight. For such large flight zenith angles, the measured data becomes more and more inaccurate, confirming the general theory mentioned in Section 3.5.4.7. Justifying this theory helps to explain the discrepancies in the results in Sections 3.5.4.3, 3.5.4.4, and3.5.4.6.

3.5.5 Implications for Full Scale Design

3.5.5.1 Implications From Altitude Data As discussed in Section 3.5.4.2, the flight simulated data was very precise to the measured altimeter data; the two altimeters gave relatively similar readings. In particular, it was found that the ACS module, located on top of the CG, was better predicted by the flight simulated data than the recovery altimeter data. Given this, the team will be using the altitude data collected within the ACS for full-scale. More importantly, the altitude results confirm that the flight simulators can be used to predict the altitude, which allows all altitude mission performance results in Section 5 to be trusted.

3.5.5.2 Implications From Velocity Data As discussed in Section 3.5.4.3, the velocity data measured from flight was the vertical velocity and the flight simulators were very successful in predicting the subscale launch vehicle's vertical velocity. These discoveries make sense, given how the data was collected. However, there is a realization that the team cannot accurately measure total velocity from just one sensor during flight but, the only velocity that affects the apogee is the vertical velocity. Therefore, the ACS's ability to only measure vertical velocity during competition flight will not hinder the ACS's ability to both predict and maneuver the launch vehicle towards the target apogee.

3.5.5.3 Implications From Acceleration Data As discussed in Section 3.5.4.4, it is extremely difficult to understand the vertical acceleration from ignition to burnout before launch, given the rapid changes in the thrust force and mass. To get a better sense on how rapid the change in thrust is, see Figure 50. A change in 100 lbs in one second is extremely intense, and given the time step of the measurement devices it is not shocking that the simulations data is slight off from the measured data. For full-scale, the team expects that the actual full-scale acceleration to be slightly less than the simulated acceleration.

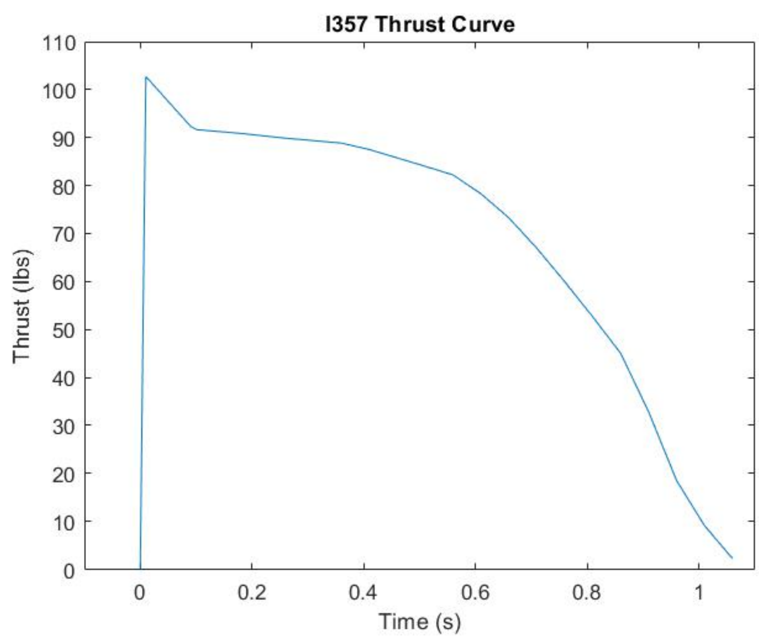


Figure 50: I357 Thrust Curve, Taken from OpenRocket Data

3.5.5.4 Implications From Stability Data Form the discussion in Section 3.5.4.5, the data is a good indication in the team's expertise to model the launch vehicle on the flight simulation software. As well, the precision of the CG value is an indication that the team was able to construct the launch vehicle with a high level of accuracy and detail.

Finally, the similarity in the CP values for OpenRocket and RockSim is an indication of good redundancy. Overall, the stability of the subscale — which will become the full-scale launch vehicle because this was not scaled down whatsoever — is safe and will not hinder the flight trajectory

3.5.5.5 Implications From Drag Coefficient Data With the estimated drag coefficient of the launch vehicle calculated in Section 3.5.4.6, the team can now better predict how the launch vehicle, especially the ACS flaps, will act during ascent. This will improve the level of accuracy of the ACS system in reaching the target apogee.

3.5.5.6 Implications From Flight Zenith Angle Data From the data in Section 3.5.4.7. The team was able to confirm that the measured data aligns closely with the simulated orientation during flight. This will benefit the team during the mission performance analysis in confirming that the weather-cocking of the launch vehicle — given a larger stability margin — will not hinder the flight trajectory greatly. The subscale launch vehicle flight confirmed that for wind speeds of 12 mph and a launch angle of 8.5 degrees, the large stability does not negatively impact the flight, and the flight trajectory is safe. These are very similar conditions to those expected in Huntsville, Alabama in April. As well, this section helped to explain a majority of the error in the flight data, especially when it comes to why the data appears to become more inaccurate as it approaches apogee. This newfound understanding of the data's errors will assist the team in deciding the types of measurement devices placed in the full-scale, the quantity of measurement devices, and the orientation of measurement deices in the launch vehicle. It will also assist the team in the expectations of data collection and overall data optimization so all data is collected in more realistic methods.

4 Technical Design: Vehicle Recovery System

4.1 Mission Statement and Success Criteria

The primary goal of the recovery system is to ensure no damage occurs to the launch vehicle, the payload, or any spectators near the vehicle upon landing. The reusability of the vehicle required by NASA Req. 2.3. is only possible if the recovery system performs flawlessly and slows the descent rate of the vehicle to a reasonable speed. The following list of criteria will be used to determine if the recovery of the vehicle after any given launch was successful:

- The vehicle is in the condition to be relaunched on the same day without repairs (NASA Req. 2.3.)
- Each section of the vehicle lands with less than 65 ft-lb of kinetic energy (NASA Req. 3.3.)
- The vehicle does not exit the launch area by drifting more than 2500 ft (NASA Req. 3.10.)
- The vehicle does not take more than 80 seconds to descend from apogee (NASA Req. 3.11.)
- The vehicle actively transmits its position to the team to facilitate a safe recovery (NASA Req. 3.12.)
- The on-board altimeters collect altitude and velocity data to be plotted and submitted to NASA (NASA Req. 2.19.1.8.1.)
- The vehicle does not injure or damage anyone or anything upon landing

4.2 Design Overview

Three independent modules will make up the recovery system: the FED, NED, and PED. Each module is made up of carbon fiber bulkheads, altimeters, LiPo batteries, key switches, charge wells, and an eye bolt. Two redundant altimeters will be used in each energetic device, which will be separate from the altimeters used by the ACS and TROI systems. The NED will include a GPS to track the vehicle's location in real time. The FED is designed to deploy the drogue parachute when the vehicle reaches apogee. The NED is designed to separate the nosecone from the payload tube at 900 ft AGL. This separation event opens the end of the body tube for the sole purpose of allowing the payload to deploy. No parachutes will deploy during this event. A shock cord connecting the NED to an eye bolt mounted to an aluminum ring within the payload tube will keep the nosecone tethered while allowing the payload to deploy. A removable carbon fiber wall connected to the NED eyebolt via a second, shorter shock cord is placed between the payload and NED to protect the payload from ejection gasses from the NED's charges. These components will be pulled out of the payload body tube after the nose cone is ejected (see 4.4.3). The PED is designed to begin the deployment process for the main parachute at an altitude of 584 ft AGL. This module is located in the aft Payload Bay. Shock cords, quick links, and eye bolts attach the main and drogue parachutes to the launch vehicle. A deployment bag is used to protect the main parachute from ejection gasses and deploy it in an orderly manner. A pilot parachute will be used to ensure the main parachute exits the deployment bag. The full overview of the entire recovery system, from pre-launch preparations at the team's home base all the way to post-flight analysis, can be viewed in the Concept of Operations diagram in Figure 51, below.

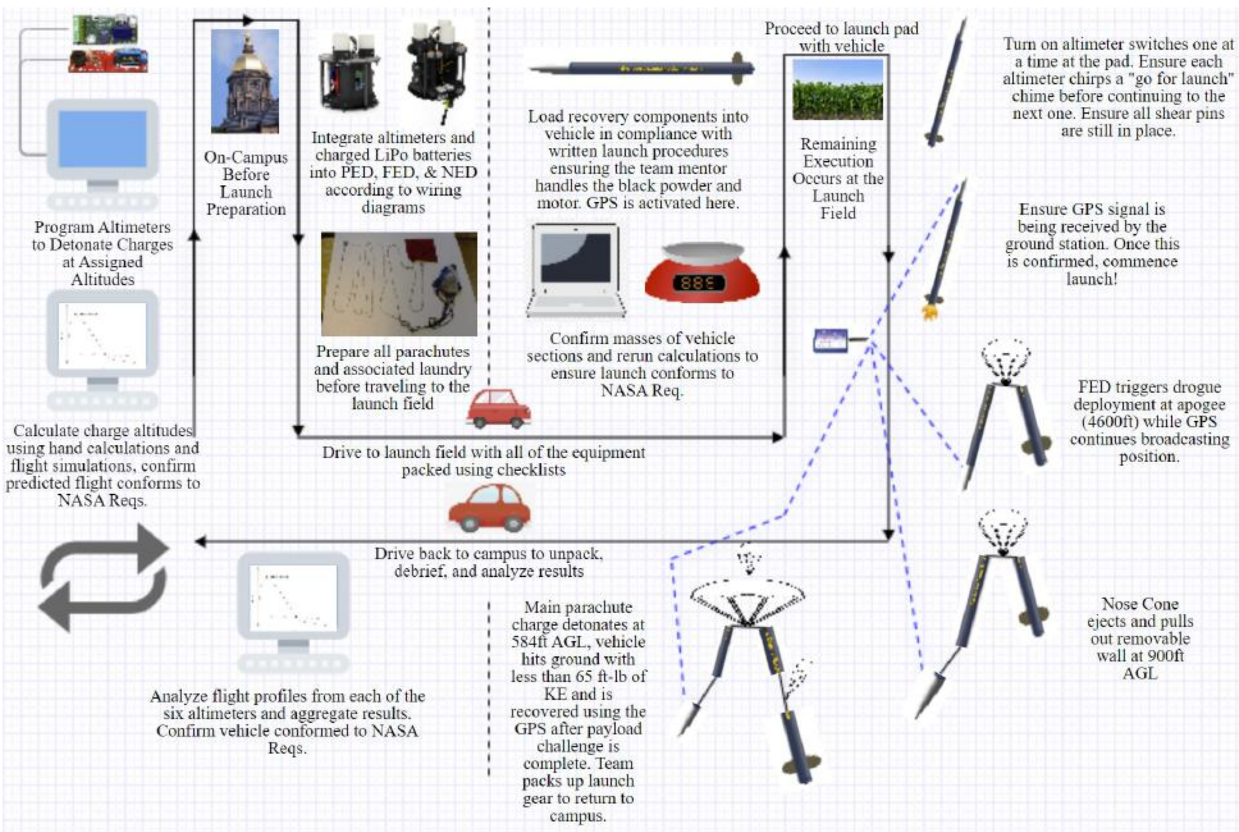


Figure 51: Concept of Operations Diagram

4.3 Separation and Deployment

The recovery system will stage the deployment of all of the recovery devices and the nosecone ejection. Black powder charges will provide the pressure to separate the sections needed to catalyze these events. Motor ejection will not be used for any of these events (NASA Req. 3.1.3.). Black powder continues to be used instead of alternatives explored during the PDR phase such as ammonium phosphate and CO_2 due to its low cost and strong reliability.

4.3.1 Recovery Event Sequence

The first separation event will feature a drogue parachute that the FED will deploy at apogee. This event will be triggered by a primary ejection charge at apogee, with two backup charges occurring at 1 s delays thereafter not to exceed two seconds after apogee (NASA Req. 3.1.2.).

Next, the NED will eject the nosecone at 900 ft AGL. This event will not deploy a parachute as the nosecone will remain attached to the body tube by a shock cord in order to allow the payload to deploy upon landing. This event will be triggered by a primary ejection charge at 900 ft AGL, followed by two charges occurring at 816 ft and 733 ft (calculated using 1 s delays thereafter).

Finally, the PED will trigger the deployment of the SkyAngle XXL main parachute at 584 ft AGL. This event will be triggered by a primary ejection charge at 584 ft AGL, followed by two backup charges occurring at 542 ft and 500 ft (calculated using 0.5 s delays after the primary charge). Figure 52 shows the separation sequence of events along the flight path.

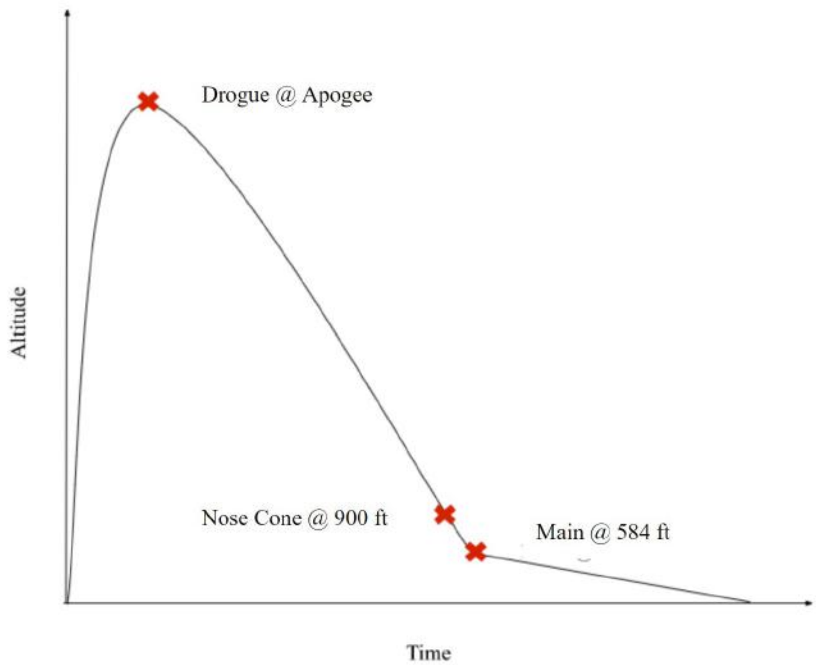


Figure 52: Separation Events Along Flight Path

4.3.2 Ejection Charge Sizing

Figure 53 shows the location of the separation events inside the launch vehicle and corresponding pressurized sections. The dimensions of each section are specified in Table 31.

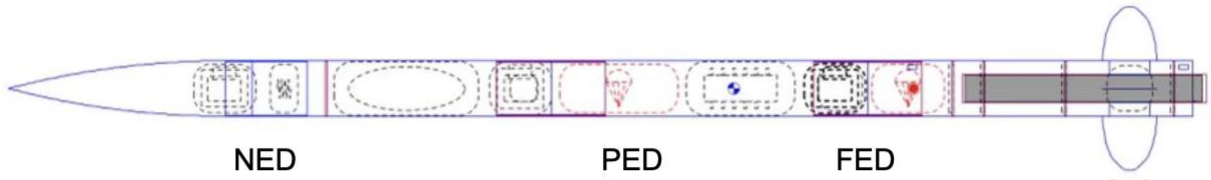


Figure 53: Launch Vehicle Separation Points

Table 31: Dimensions of Pressurized Sections

Section	Length (in)	Cross-Sectional Area (in^2)	Volume (in^3)
NED (Fore)	7.7	28.27	217.68
PED (Middle)	19.5	28.27	551.33
FED (Aft)	12	28.27	339.28

Per (NASA Req. 3.9.), five 4-40 shear pins will be used at each separation point to hold the vehicles' sections in place. The ACS will produce a maximum force of 180 lb and the size and quantity of shear pins were determined using a factor of safety of 2 so as to not be affected by ACS actuation. The size of the ejection charges was selected using the following calculations:

$$\text{Force to Break Shear Pins: } \mathrm{F_{shear}} = \tau_{\mathrm{max}}\mathrm{A_{pin}N_{pins}} = 360 \text{ lbf}$$

$$\text{Pressure to Break Shear Pins: } \mathrm{P_{shear}} = \frac{F_{\text{shear}}}{A_{\text{bh}}}$$

$$\text{Moles of Gas Needed: } n_{\text{gas}} = \frac{P_{\text{shear}}A_{\text{bh}}L_{\text{sect}}}{\mathrm{RT}}$$

$$\text{Grams of Carbon Needed: } g_{\mathrm{C}} = \frac{3}{4}n_{\text{gas}} \times \frac{12\text{g C}}{\text{mol C}}$$

$$\text{Grams of Sulfur Needed: } g_{\mathrm{S}} = \frac{1}{4}n_{\text{gas}} \times \frac{32.1\text{g S}}{\text{mol S}}$$

$$\text{Grams of Potassium Nitrate Needed: } \mathrm{g_{KNO_3}} = \frac{1}{2}n_{\text{gas}} \times \frac{101.1\text{g KNO}_3}{\text{mol KNO}_3}$$

$$\text{Grams of Black Powder Needed: } g_{pb} = g_C + g_S + g_{KNO_3}$$

where τ_{max} is the shear strength of nylon, A_{pin} is the cross-sectional area of one 4-40 shear pin, N_{pins} is the number of pins at each separation point, A_{bh} is the cross-sectional area of the bulkhead, L_{sect} is the length of each pressurized section and T is the ignition point of black powder. A factor of safety of 1.25 is added for the primary charges. An extra 0.5 g of black powder is added to the secondary and tertiary charges. Table 32 shows the ejection charges for each separation event.

Table 32: Summary of Separation Events

Separation Event	Altimeter Location	Parachute Deployment	Ejection Altitude	Ejection Charge Size (g)
Nose Cone Separation	NED	No	900	1.75
			816	2.25
			733	2.25
Main Deployment	PED	Yes	584 ft	4.4
			542 ft	4.9
			500 ft	4.9
Drogue Deployment	FED	Yes	Apogee	2.7
			Apogee + 1 s	3.2
			Apogee + 2 s	3.2

4.4 Recovery Laundry

Two different parachutes will be used during the recovery process: the main parachute and the drogue parachute. The main parachute was selected based on its ability to slow the vehicle section with the most mass to a descent velocity that would yield a kinetic energy under 65 ft-lb without excessive drift. The drogue parachute was selected based on its ability to slow the descent vehicle to a reasonable descent velocity at which the main parachute could open without excessive drift. After thorough simulations and hand calculations, a 12.8ft SkyAngle XXL parachute was selected as the main parachute and a 2ft Rocketman Elliptical Parachute with a drag coefficient of 1.6 was selected as the drogue parachute. Details on these assemblies, a recap of the selection process utilized during PDR, and new considerations since PDR will be discussed in this section.

4.4.1 Main Parachute Assembly

In order to meet NASA Req. 3.3., a main parachute will be used to decelerate the launch vehicle before impact. The minimum drag parameter, $C_d A$, used for sizing the main parachute was found using the masses of the separated sections (excluding laundry) and the total descent mass (including laundry) as shown in Table 33 below.

Table 33: Vehicle Section Masses

Section	Weight (oz)
Nose Cone (Separated)	72.447
Payload Bay (Separated)	203.212
ACS Bay (Separated)	177.816
Fin Can (Separated)	204.699
Total Mass of Separated Sections	658.175
Mass of Laundry (Between Sections)	150.871
Total Mass of Vehicle During Descent	809.046

The separated section mass values are crucial for determining the max descent velocity of the main parachute as they must adhere to the kinetic energy requirement outlined in (NASA Req. 3.3.). The total mass of the vehicle during descent is essential for calculating the descent velocity as well considering that the whole vehicle contributes to the force of gravity pulling the vehicle toward earth. After solving for the $C_d A$ term in a force balance between the drag of a parachute and the vehicle's weight, the $(C_d A)_{\text{min}}$ for the entire vehicle during main descent is given by

$$(C_d A)_{\text{min}} = \frac{2 m_{\text{tot}} g}{\rho \sqrt{\frac{2KE_{\text{max}}}{m_{\text{max}}}}} = 120.96 \text{ ft}^2$$

where m_{tot} is the total vehicle mass after burnout, KE_{max} is the max kinetic energy given by NASA Req. 3.3., and m_{max} is the mass of the heaviest separated section from Table 33. The team will attempt the extra challenge and land with a kinetic energy of less than 65 lb-ft.

After feedback from NASA mentors at the team's PDR presentation suggested large parachutes from Rocketman typically underperform their advertised descent rates, the team further analyzed last year's Rocketman main parachute performance. The investigation found that altimeter data from several flights showed the 12ft Rocketman Standard parachute consistently underperformed its expected descent rates. With this discovery and several small changes in our expected mass after burnout, the team decided to reevaluate the main parachute selection to ensure each section would stay below the kinetic energy limit. After consultation with our team mentor, the team was informed SkyAngle parachutes typically perform closer to their advertised descent rates. This, paired with the fact that the company uses an independent authority on aerodynamic decelerators to rate its parachutes per its website, made the team confident parachutes from this company would likely perform closer to expected. After testing various SkyAngle parachutes with the `full_vehicle_descent_calcs.m` script that calculates the descent rate of the main parachute (see Section 5.2 for more), the SkyAngle XXL was selected. The script predicts that even if the parachute underperforms by as much as 35%, the parachute would still provide sufficient drag to slow the vehicle to a speed that yields no section kinetic energies above 75 ft-lb. A deployment bag will be used to deploy the main parachute and will be packed in an organized manner before launch. A pilot parachute will be used to ensure the main parachute exits the deployment bag. Table 34 lists the parameters for both the main and pilot parachutes. Both parachutes will be protected with one 24" square Dino Chutes Nomex Blanket. It is worth noting that the reference area used to determine the C_d of the parachute is *not* the entire surface area of the parachute calculated purely using the full parachute diameter.

Table 34: Main and Pilot Parachute Parameters

Parameter	Main	Pilot
Brand	SkyAngle	FruityChutes
Shape	Parabolic	Classic Elliptical
Canopy Material	1.9 oz Silicon Coated Balloon Cloth	1.1 oz Ripstop Nylon
No. Shroud Lines	4	8
C_d	2.92	1.6
Diameter (ft)	12.8	2
Weight (oz)	64	2.2
Packing Volume (in^3)	452	12.2

Table 35 describes the specifications of the shock cords connected using a quick link that act as one long shock cord used to connect the parachutes to the rest of the launch vehicle.

Table 35: Main Recovery Shock Cord

Parameter	Cord 1	Cord 2
Brand	Rocketman	Rocketman
Material	Tubular Nylon	Tubular Nylon
Width (in)	1.25	1.25
Length (ft)	15	10
No. Loops	2	2
Breaking Strength (lbs)	4400	4400
Weight (oz)	10.5	7

Table 36 describes the specifications of the Nomex blanket that will be used to protect the parachutes and shock cord from ejection gas and debris in order to meet NDRT Req. R.1.

Table 36: Main Parachute Protection Parameters

Parameter	Value
Brand	Dino Chutes
Material	Nomex-equivalent
Size	24 in. Square
Weight (oz)	4.06

The assembly and connections of the main and pilot parachutes to the rest of the launch vehicle are shown in Figure 54. These components are structurally analyzed in Section 5.3.

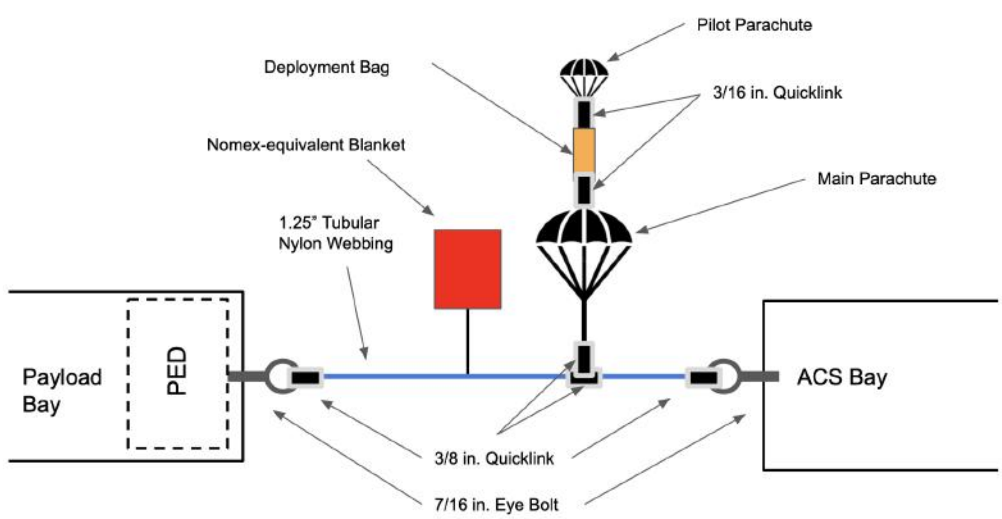


Figure 54: PED Deployment Diagram

4.4.2 Drogue Parachute Assembly

In order to control the descent from apogee until the main parachute deploys, a properly-sized drogue parachute must be fitted to the launch vehicle and deployed at apogee. The drogue parachute must be sized large enough so that the acceleration caused by the deployment of the main parachute does not exceed the limitations of the hardware and bulkheads that are load-bearing. However, the parachute also cannot be too large as this could result in excessive descent time and drift which could make the vehicle violate NASA Req. 3.10. and 3.11.

The drogue parachute selected during the PDR, a Rocketman Elliptical 2 ft parachute, was then reassessed using the `full_vehicle_descent_calcs.m` hand calculation script. Since the main parachute was increased in size from the PDR, the team's primary concern was a potentially unacceptably-large increase in global acceleration and thus forces applied to various components through the vehicle. Therefore, the hand calculations focused on determining the global acceleration of the vehicle with the updated main parachute and vehicle mass. As is further explored in Section 5.3.2, the existing drogue parachute selection resulted in a global acceleration of 24.78gs. Since this value was below the team's self-imposed acceptable acceleration of 30gs set in the PDR report, the drogue parachute was determined to be acceptable. Furthermore, the descent time and drift calculations outlined in Sections 5.2.2 and 5.2.3 confirm the drogue parachute is small enough to keep the descent time and drift radius within those required by NASA Req. 3.10. and 3.11. Furthermore, the selected drogue parachute is identical to the one used on the team's full-scale vehicle last year and subscale vehicle this year which not only eliminates the need to purchase a new parachute but also means the team has existing data on this exact parachute's performance. As is further explored in Section 5.2, this parachute has been determined to provide roughly 87% of its advertised drag on last year's full-scale flights which is sufficient for the vehicle's needs this year. The details of the drogue parachute can be viewed in Table 37, below.

Table 37: Drogue Parachute Parameters

Parameter	Main
Brand	Rocketman
Shape	Elliptical
Canopy Material	1.1 oz Ripstop Nylon
No. Shroud Lines	8
C_d	1.6
Outer Diameter (ft)	2
Spillhole Diameter (in)	4.33
Weight (oz)	2.1
Packing Volume (in^3)	12.2

The parachute will be connected to the vehicle using a tubular nylon shock cord. The specifications for this shock cord can be viewed in Table 38, below.

Table 38: Drogue Recovery Shock Cord

Parameter	Cord 1	Cord 2
Brand	Rocketman	Rocketman
Material	Tubular Nylon	Tubular Nylon
Width (in)	0.625	0.625
Length (ft)	15	10
No. Loops	2	2
Breaking Strength (lbs)	3200	3200
Weight (oz)	2.46	3.69

The drogue parachute and shock cord will be folded and wrapped in a Nomex blanket to protect them from the hot gases produced by the FED's black powder charges. This folding will be conducted in accordance with the steps outlined in Section 8.2.2.2 that were successfully implemented for the same parachute on the subscale vehicle. The Nomex blanket to be used is square in shape with full specifications viewable in Table 39, below.

Table 39: Drogue Parachute Protection Parameters

Parameter	Value
Brand	Rocketman
Material	Nomex-equivalent
Size	12 in. Square
Weight (oz)	0.95

Quick links will be used to attach the drogue shock cord to the eye bolts and the parachute itself. The full drogue deployment assembly can be viewed in Figure 55, below.

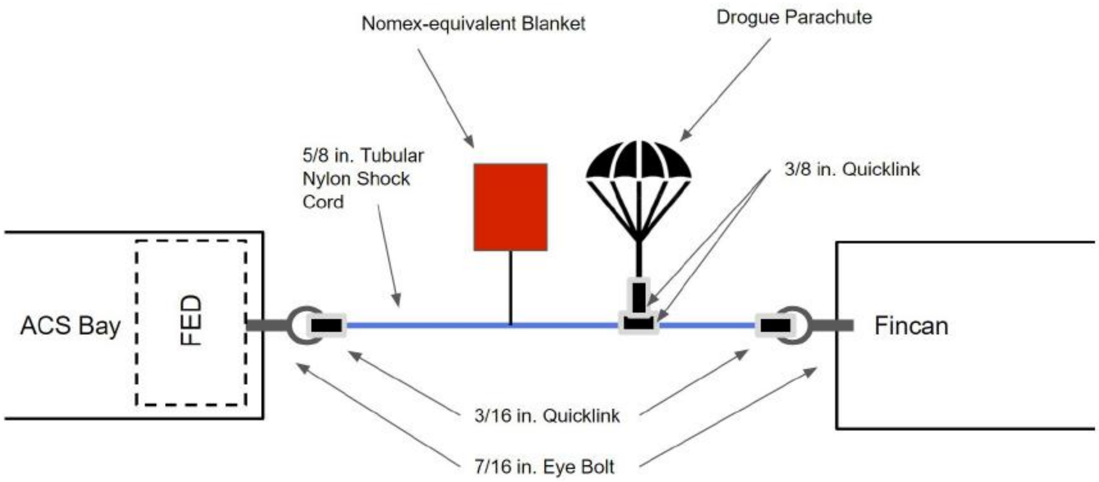


Figure 55: FED Deployment Diagram

4.4.3 Nose Cone Ejection Assembly

The primary purpose of the nose cone ejection event is to provide a hole for the TROI payload system to deploy through. In order to accomplish this, the nose cone will be ejected from the Payload Bay using black powder charges. The nose cone will remain tethered to the remainder of the vehicle by a 25 ft kevlar shock cord from the NED to a 1/4 in. eye bolt on an aluminum ring mounted in the Payload Bay. This custom-machined aluminum ring will be mounted to the body tube using 8-32 stainless steel screws identical to those used with the airframe interfacing blocks throughout the rest of the vehicle. Holes will be tapped in the ring to allow this mounting to occur. A rendering of this ring assembly can be viewed in Figure 56.

Figure 56: Aluminum Ring Assembly Rendering

Additionally, drawings for the aluminum ring can be viewed in Figure 57, below.

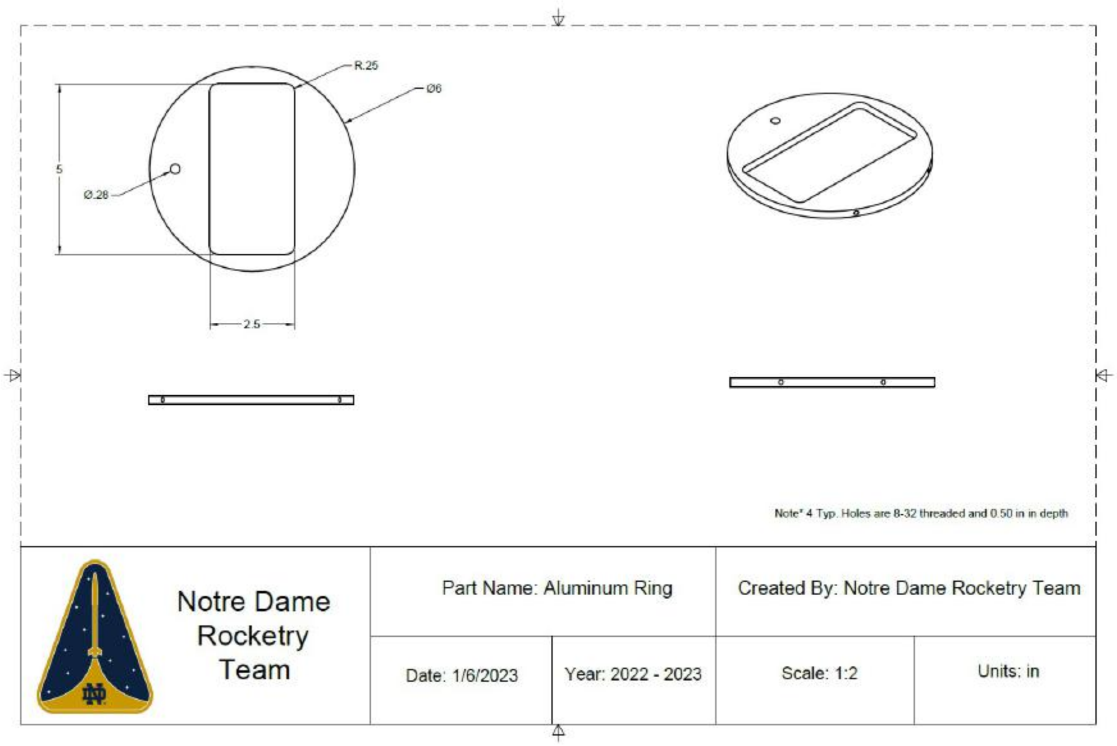
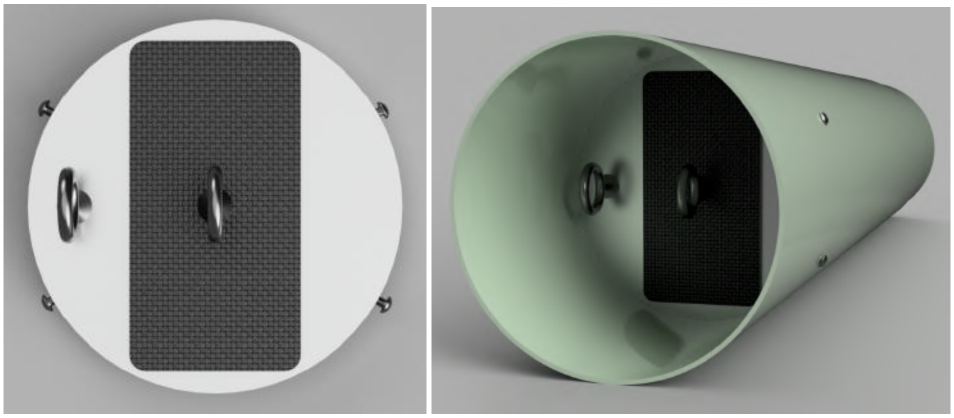


Figure 57: Aluminum Ring Drawing

During flight, the hole on this aluminum ring will be covered by a removable carbon fiber wall. This will ensure that the only section pressurized by the charges on NED will be the area between the removable wall and the aft bulkhead of NED thus keeping the payload safe. The removable wall will loosely fit into the hole and will be secured to the ring during flight by masking tape. Once the nose cone ejects from the body tube, it will pull the removable wall with it using a shorter, 5 ft long kevlar shock cord. Before the first demonstration flight, the strength of the masking tape will be tested to ensure it can withstand the vibrations of in-flight forces and the deployment of the drogue parachute while keeping the wall in place. If a stronger tape is deemed necessary this will be pursued; however, stronger tapes threaten to keep the removable wall attached to the ring even after the nose cone ejects which would prevent the payload from deploying. Renderings of the full assembly from the top view and the full assembly in the Payload Bay can be seen in Figure 58. A drawing for the removable wall can be seen in Figure 59, below.



(a) Aluminum Ring and Wall Isolated (b) Aluminum Ring and Wall Isolated in Payload Bay

Figure 58: Aluminum Ring and Wall Full Assembly Renderings

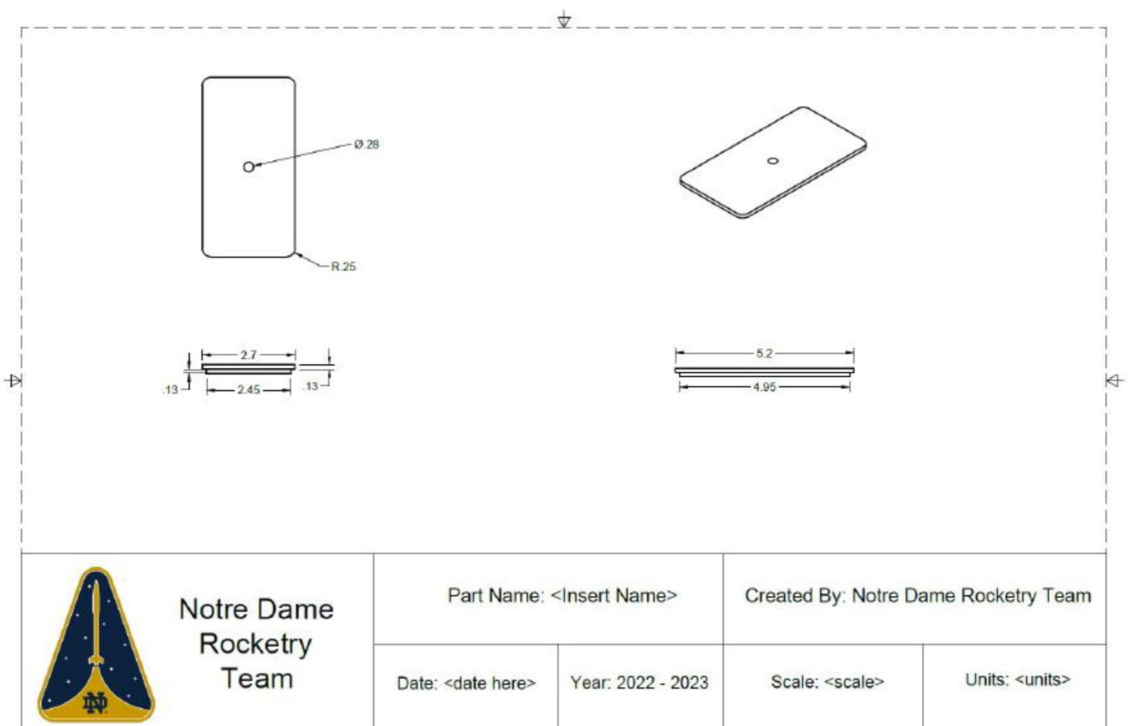


Figure 59: Removeable Wall Drawing

The details for the two shock cords that will be used can be viewed in Table 40, below. The team was comfortable choosing smaller-diameter shock cords for this application as zippering is much less of a concern due to the fact that no parachute is deployed during this event.

Table 40: Nose Cone Recovery Shock Cords

Parameter	Cord 1	Cord 2
Brand	Rocketman	Rocketman
Material	Kevlar	Kevlar
Diameter (in)	0.19	0.19
Length (ft)	25	5
Breaking Strength (lbs)	5300	5300
Weight (oz)	6.17	1.27

The full deployment diagram for the nose cone event can be viewed in Figure 60, below. A detailed breakdown of the full recovery interaction with the TROI payload, along with an additional diagram, can be viewed in Section 6.8.

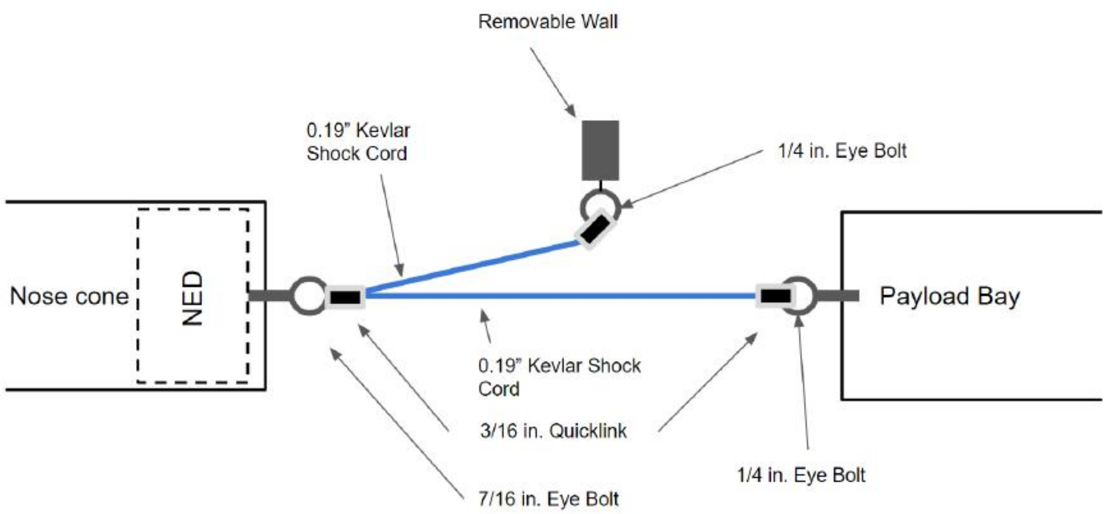


Figure 60: NED Deployment Diagram

4.5 Recovery Modules

The three recovery modules (FED, NED, and PED) will be responsible for both triggering recovery events through the detonation of onboard black powder charges and transferring the load from the parachute deployments to the full vehicle. This load transfer occurs through a path that enters the modules via 2000 lb eye bolts and exits the modules at airframe interfacing blocks located on bulkheads. The FED and PED are identical in every respect with the NED differing slightly in bulkhead size and equipped altimeters. The bulkhead size on the NED is slightly smaller than the FED and PED so that it can fit inside the shoulder of the nose cone. The structural elements and design of the modules will be explored in this section.

4.5.1 Primary Structural Elements

A 7/16"-14 eyebolt will be fastened to the top of a single bulkhead on each module to transmit the primary load of the drag force from the parachutes to the remainder of the vehicle. The properties of the eye bolt used on each module are shown in Table 41.

Table 41: Eye Bolt Properties

Parameter	Value
Brand	McMaster Carr
Material	Steel
Thread	7/16"-14
Breaking Strength (lbs)	2000

The eye bolts will be attached to 1/8 in. carbon fiber bulkheads. A trade study was conducted to determine the material of the bulkheads. Carbon fiber was chosen due to its strength and RF shielding capabilities. The RF shielding capabilities of carbon fiber are necessary to protect the altimeters from interference and ensure that the ejection charges go off according to accurate recovery altimeter data. FEA was used to determine the bulkhead thickness, which will be further explained in Section 5.3. All three recovery modules have the same bulkhead thickness. Four airframe interfacing blocks will be used to connect the recovery modules to the body tube. In the FED and PED, the load will be passed from the eye bolt through the bulkhead to these blocks, which will be manufactured from 6061 aluminum to the specifications shown in Figure 61.

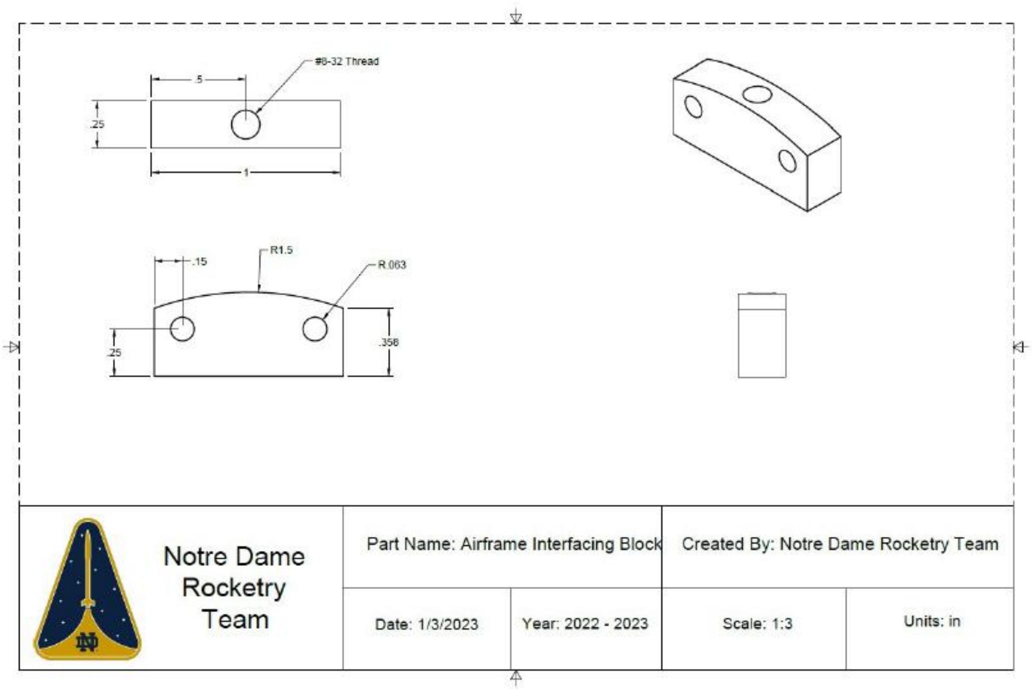


Figure 61: Airframe Interfacing Blocks Drawing

Two 4-40 screws are used to attach the airframe interfacing blocks to the bulkhead, and two 8-32 screws are used to attach the airframe interfacing blocks to the body tube. In The NED, the airframe interface blocks are not on the same bulkhead as the eye bolt. Therefore, the load in the NED will travel through the eye bolt to the aft bulkhead and then on to the three aluminum turnbuckle standoffs that connect both bulkheads. From these standoffs, the load will be further transferred to the fore bulkhead before finally exiting the module through four airframe interface blocks. Figure 62 shows the rendered images of the full NED and PED/FED assemblies. Figures 63 and 64 show the exploded assembly view of the NED and PED/FED.

(a) PED/FED Rendered View (b) NED Rendered View

Figure 62: PED/FED and NED Rendered Views

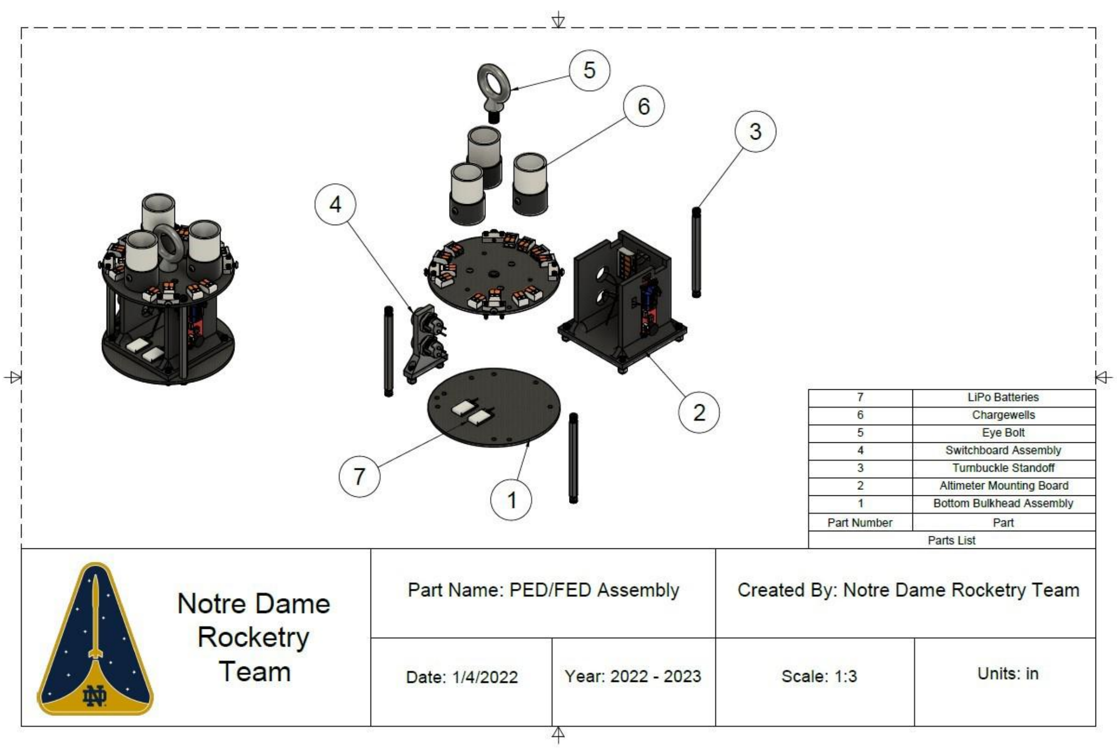


Figure 63: PED/FED Exploded View

Figure 64: NED Exploded View

4.5.2 Secondary Structural Elements

The NED, PED, and FED contain several minimally load-bearing components along with the primary structural elements described in Section 4.5.1. Each module will contain three charge well assemblies to house the black powder charges, shown in Figure 65, that will be mounted on the face of the modules' aft bulkheads that face the separation end of the body tube. The charge wells will be made of PVC and will be fixed to 3D-printed ABS end caps using 8-32 stainless steel screws that run horizontally through the diameter of the assembly with nuts. Epoxy will also be added between the PVC and end caps to further ensure a strong connection. The assemblies will be attached to the aft bulkhead by bolting the end caps to the bulkhead with additional 8-32 stainless steel screws, nuts, and washers.

The two bulkheads, altimeter mounting board, and switchboard are enclosed within three aluminum turnbuckle standoffs that connect the fore and aft bulkheads in each recovery module. In the FED and PED, these standoffs are minimally load-bearing as the airframe interface blocks are on the same bulkhead as the eye bolt. These standoffs were placed in a triangular arrangement to allow for the switchboard to be accessed more easily. All of the mounting boards will be 3D printed with ABS plastic and have flange bases that allow for them to be attached to the fore bulkheads with 11/16 in. 8-32 stainless steel socket head screws. Screws will be used instead of epoxy to allow for simple assembly and disassembly of the recovery modules. The top of the mounting board is free and not attached to the aft bulkhead to prevent unnecessary loads from the aft bulkhead accidentally passing through the piece. The altimeter mounting board is U-shaped from above, like a rectangular prism missing one side and the top. This will allow it to better resist any moments created at the base of the mounting board, above the flange, by vibrations during flight. The mounting board in previous years was shaped as a thin rectangle and broke above the flange base during flight due to an inability to resist vibrations. The switchboard will not be U-shaped, but will instead have chamfered walls near the flange better resist vibrations that occur during flight. The switchboard is shown in Figure

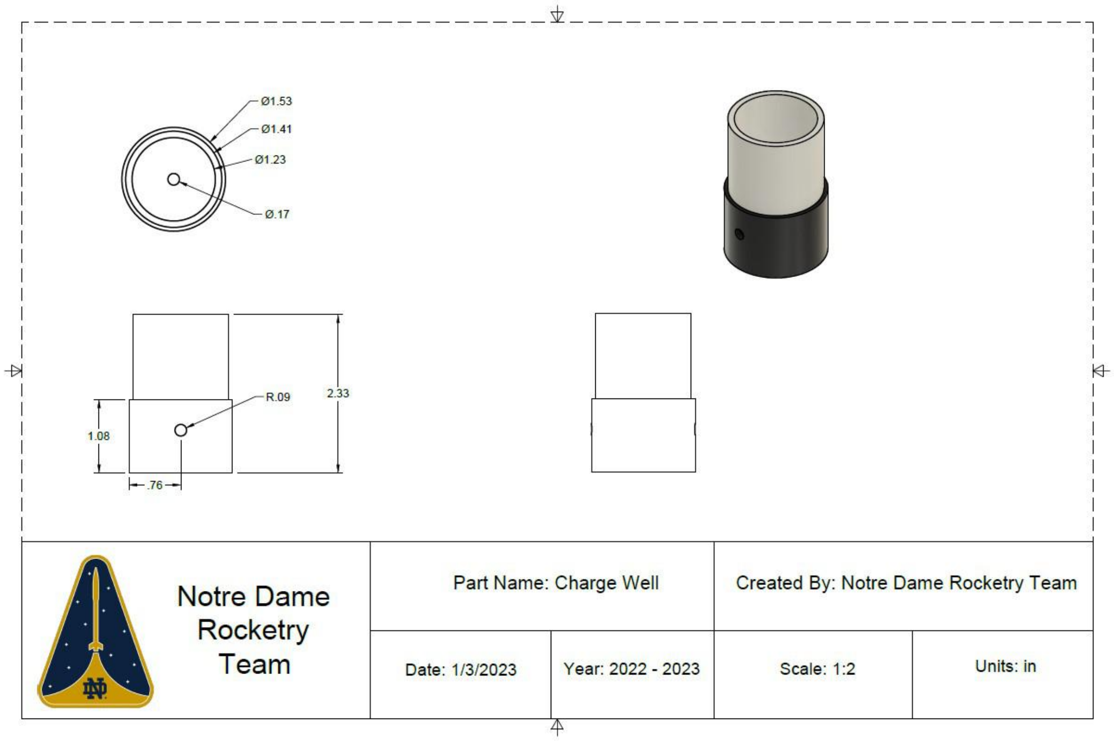


Figure 65: Ejection Charge Well Drawing

66. The GPS mount that is unique to the NED is structured similarly to the switchboard with a chamfered base. The GPS Mounting Board is shown in Figure 67. The NED Altimeter Mounting Board is shown in Figure 68. The PED/FED Altimeter Mounting Board is shown in Figure 69. The main difference between the two mounting boards is the placement of the holes that will be used to attach the altimeters.

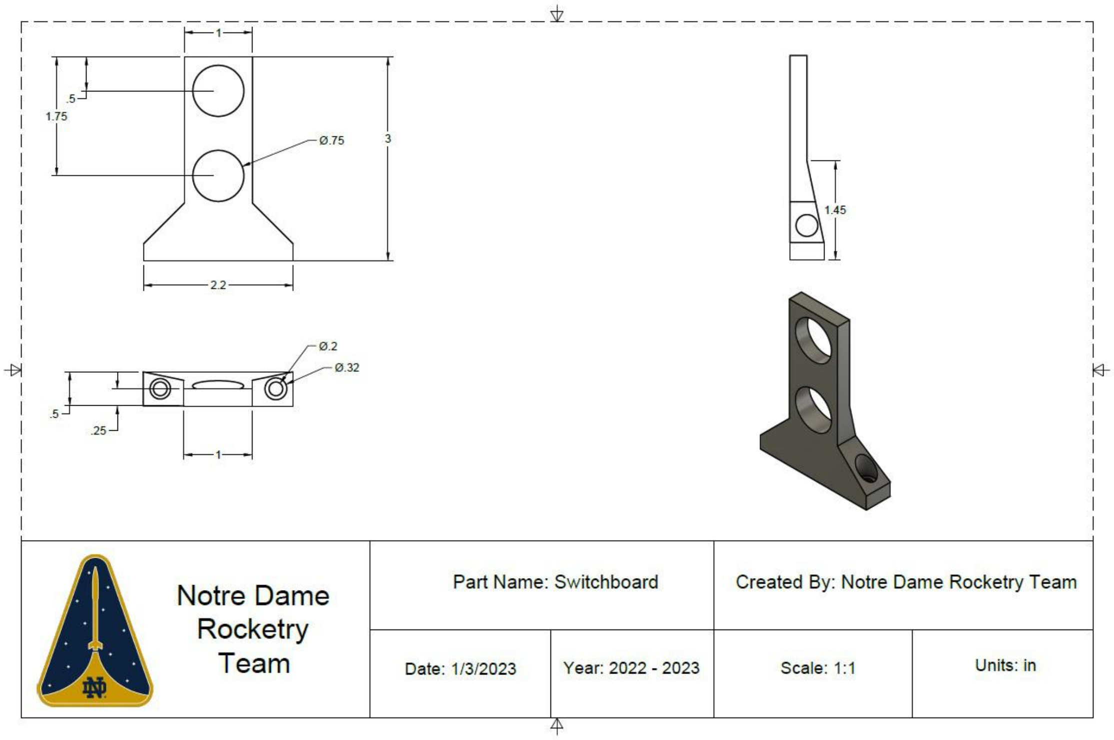


Figure 66: Switchboard Drawing

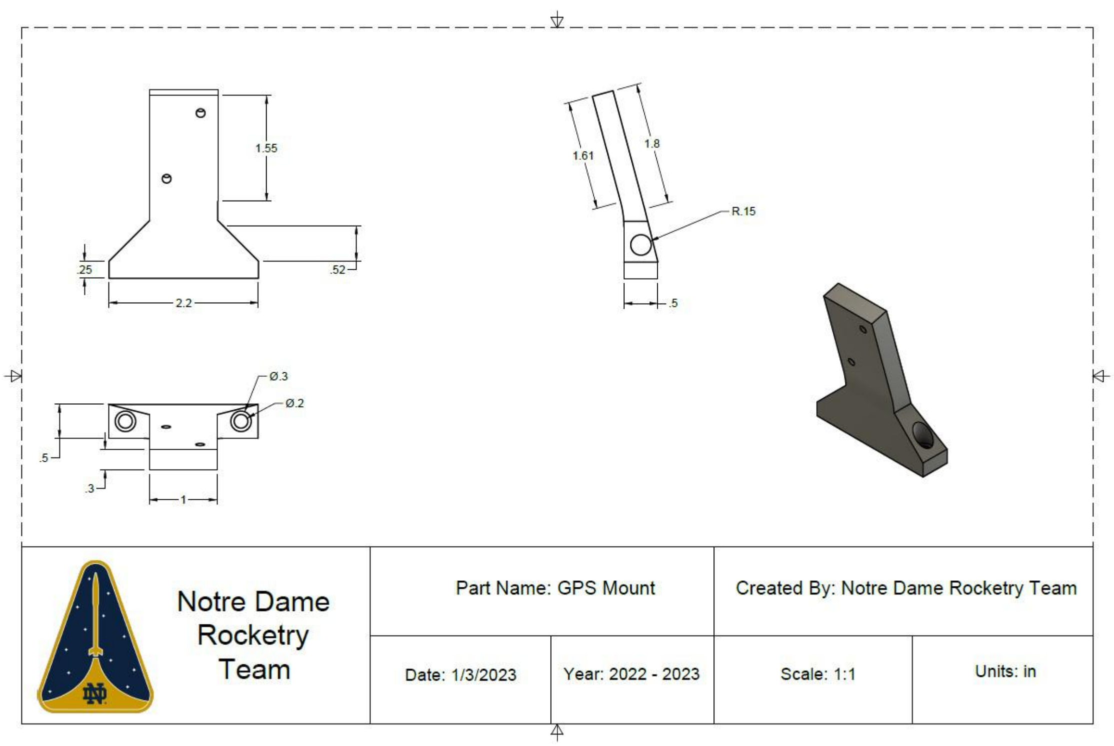


Figure 67: GPS Mounting Board

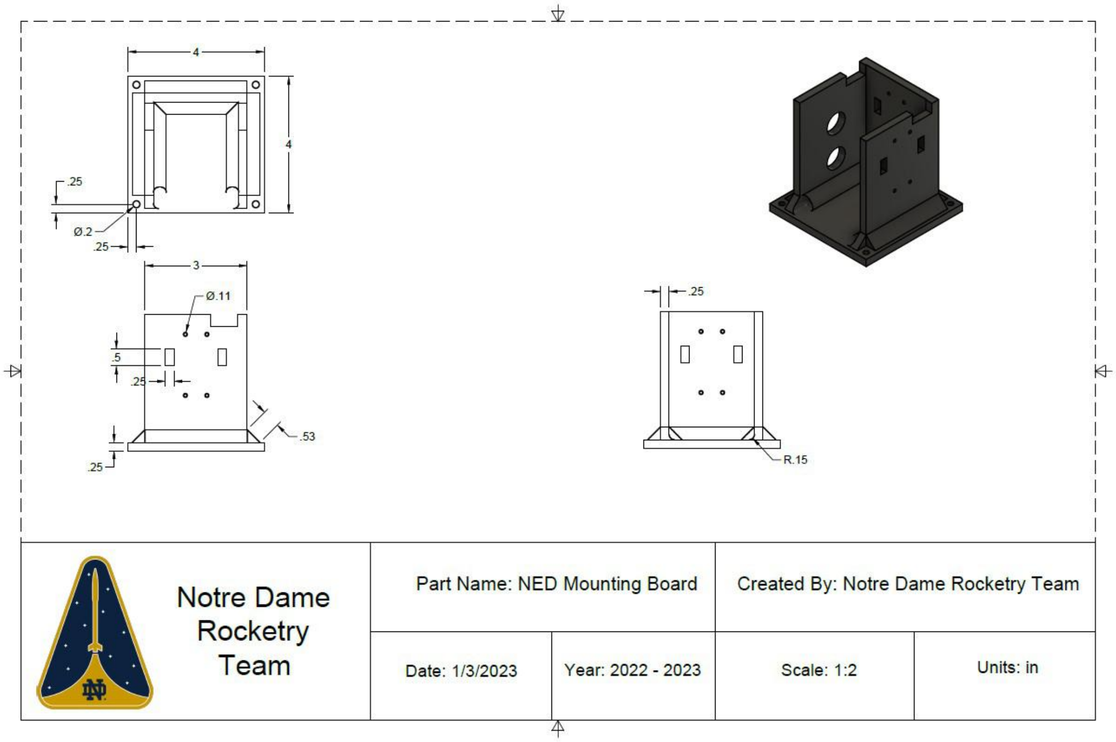


Figure 68: NED Altimeter Mounting Board Drawing

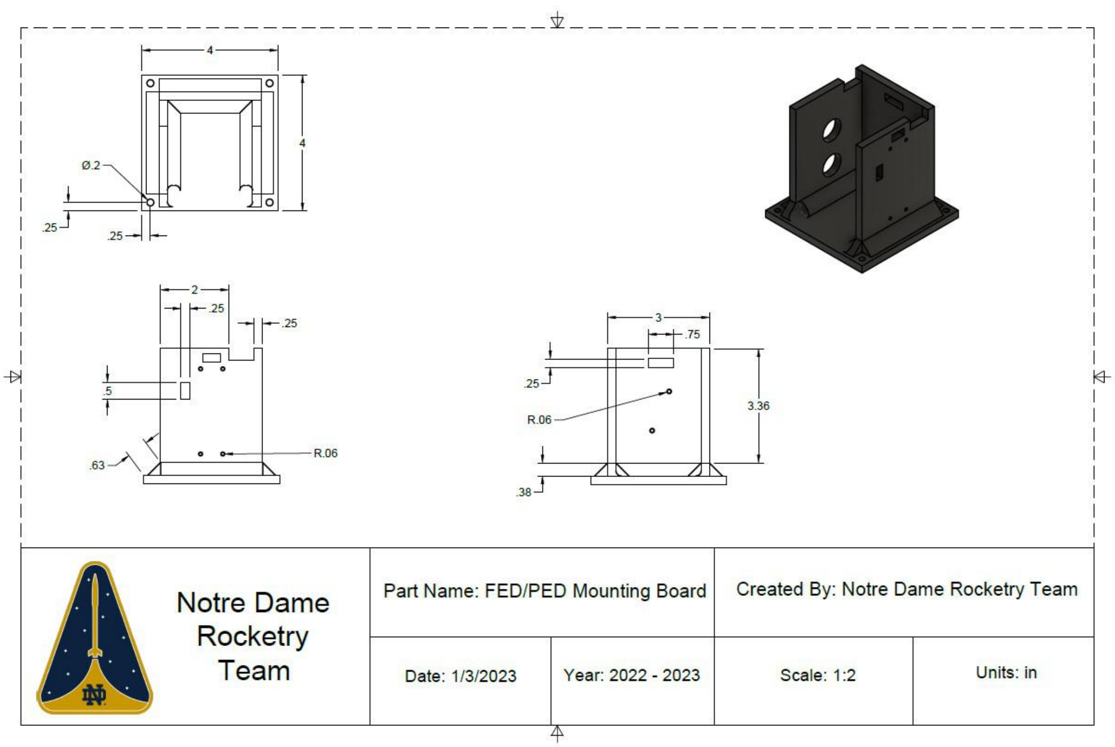


Figure 69: PED/FED Altimeter Mounting Board

4.5.3 Hardware and Fasteners

The hardware selected for the assembly of the recovery modules were chosen with strength, cost, and standardization in mind. The aluminum turnbuckle standoffs selected were made of carbon steel, which is capable of withstanding higher loads than aluminum and stainless steel, due to the fact that they are load-bearing in the NED. The shouldered eye bolt was chosen for its higher load capacity and ability to distribute the load over a reasonably large area of the bulkhead (due to the shoulder). This was deemed necessary for withstanding the forces of the main parachute deployment.

The nuts and bolts chosen for the altimeters were of a specific size and shape, as the mounting holes on the altimeters could not be changed. As for the rest of the mounting on the modules, the CAD model could be modified to create uniform hole sizes to decrease the number of unique nuts and bolts ordered. Lock nuts are to be used on bolts that would likely not need to be removed after assembly as they excel at resisting in-flight vibrations but are not very reusable. Normal nuts are used on components expected to be removed such as altimeters.

The various types of fasteners to be used on each module are listed in Table 42.

Table 42: Hardware and Fasteners per Recovery Module

Part	Frequency	
Module	NED	PED/FED
Carbon Steel Turnbuckle-Style Connecting Rod	3	3
Black-Oxide Alloy Steel Socket Head Screw	6	6
Stainless Steel Socket Head Screw	16	14
Stainless Steel Nylon-Insert Locknut	19	17
Steel Eyebolt with Shoulder (3in thread length)	1	1
3in Eyebolt Nut	1	1
3in Eyebolt Washer	1	1
Altimeter Mounting Bolt	10	6
Altimeter Mounting Nuts	10	6
Stainless Steel Body Tube Screw	4	4
Chargewell Mounting Screw	3	3
Chargewell Assembly Screw	3	3
Chargewell Assembly Nut	3	3

4.6 Avionics

The electronics to be used on the recovery modules either help trigger recovery events or locate the vehicle during decent. These systems will operate independently of both other payloads onboard the vehicle in accordance with NASA Req. 3.8. These electronics are also shielded from other onboard electronics by the carbon fiber bulkheads that resist RF transmissions. Detailed descriptions and layouts of the electronics selected for the recovery modules will be discussed in this section.

4.6.1 Altimeters

The recovery system will utilize six altimeters between the three recovery modules, with two altimeters in each module. The two altimeters allow for an independently redundant system, maximizing safety (NASA Req. 3.4). The altimeters were selected from the team's inventory due to their low cost and reliability as demonstrated in the PDR trade studies and prior team flights, including the subscale launch. The PED and FED will each have a Raven4 and Stratologger SL100 in order to ensure the safety and redundancy of the two parachute deployment events. The Raven4 is considered the most reliable altimeter and thus was assigned to execute the parachute events that are critical to the safety of the launch. Each of the three charge wells in the FED and PED will have two e-matches. Two of these chargewells will have an e-match from two independent altimeters while the third, final backup charge well will have two e-matches that both are triggered by the Raven 4 altimeter. Upgraded over last year's design which only included one e-match triggering each charge, the added redundancy of multiple e-matches per well ensures faulty e-matches are less likely to result in a failed deployment. The NED will contain two Stratologger SLCF altimeters. One charge well will have an e-match from both altimeters while the two backup charge wells will each be triggered by one e-match. While additional e-matches would be favorable for these two backup charge wells, it was deemed safer to have two backup charge wells each fed by one e-match than a single backup charge well with two e-matches. No more than four e-matches total could be added to this module due to the limitations of the Stratologger SLCF altimeters. New altimeters were not purchased to minimize overall costs and due to lack of availability due to supply chain shortages. Each altimeter will be wired to an independent switch, battery, and at least two e-matches (NASA Req. 3.5 and 3.6). The electrical schematics for each recovery module, including the wiring for each altimeter, are shown below in Figures 70 and 71.

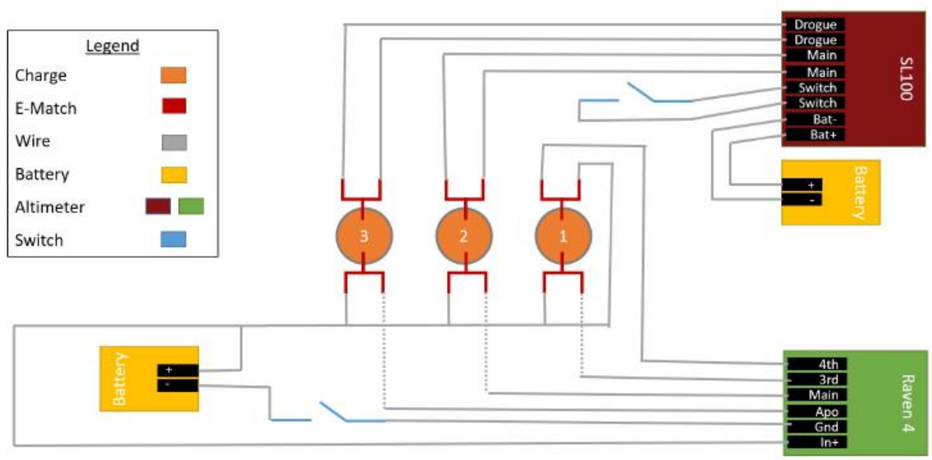


Figure 70: PED/FED Wiring Schematics

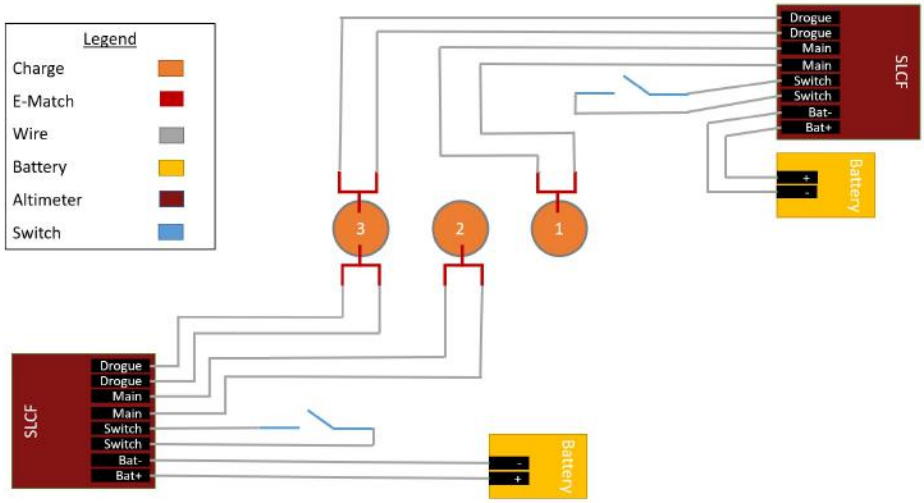


Figure 71: NED Wiring Schematics

The properties of each altimeter are listed in Table 43. The altimeters will be mounted on 3D-printed mounting boards (see Section 4.5.2). The altimeters are protected from interference from other electronic devices on the launch vehicle by the carbon fiber bulkheads and airframe which provide physical separation and block RF radiation (NASA Req. 3.13). The altimeters will not be in the same section as any RF transmitting devices (the GPS will be on the opposite side of the NED bulkhead as the altimeters).

Table 43: Specifications of Altimeters

Property	SL100	SLCF	Raven 4
Perceived Accuracy Rank	3	2	1
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)	N/A	N/A	170
Measured Mass (oz)	0.45	0.40	0.30
Current Draw (mA)	1.5	1.5	<5

The Stratologger SLCF and Stratologger SL100 will be powered by the Tattu 1S Lithium Polymer batteries. The E-Flite 1S Lithium Polymer battery will be used to power the Featherweight Raven4. This battery was selected because it was one of the largest batteries available that was under the 300 mAh limit imposed on the altimeter in the owner's manual. Specifications of both batteries and their expected lives are shown in Table 44 (NASA Req. 3.5). The batteries will be brightly colored using red tape and marked as dangerous using a permanent marker (NASA Req. 2.22). Tests on the actual capacity of each battery for their respective altimeter will be carried out prior to the first full-scale launch to ensure the vehicle can sit on the pad in a launch-ready configuration for a sufficient amount of time before launch.

Table 44: Altimeter Battery Specifications

Battery Parameter	Tattu 1S	E-Flite 1S
Capacity (mAh)	380	150
Voltage (V)	3.7	3.7
Constant Discharge Rate (C)	25	45
Expected Life (Hr)	233.3	30

4.6.2 GPS

The Featherweight GPS Tracker will mount on the NED to fulfill NASA Req. 3.12. One GPS is needed since all launch vehicle components will remain tethered together (NASA Req.3.12.1). The GPS connects to a ground station which can then be connected via Bluetooth to an iPhone. This allows the GPS to provide real-time altitude and location data directly to the team.

The GPS manual recommends a battery with at least a 150 mAh capacity and a voltage range of 3.4 V to 4.5 V. The battery must also accommodate the 50 mA consumed when the GPS tracker is not transmitting, the 90 mA consumed when the GPS tracker is transmitting, and an average of 75 mA consumed overall. A 400 mA battery will provide five hours of continuous use in the launch-ready configuration (NASA Req. 2.6). A 1S Lithium Polymer battery with the specifications outlined in Table 45 meet the Featherweight GPS Tracker requirements and NASA requirements and will thus be used. A full test of the actual battery life of the specific battery to be used will be conducted to ensure it actually lasts as long as intended.

Table 45: GPS Battery Specifications

Battery Parameter	Value
Capacity (mAh)	400
Voltage (V)	3.7
Constant Discharge Rate (C)	25

4.6.3 Auxiliary Electrical Components

The altimeters in PED, FED, and NED will all be armed using McMaster-Carr keyed rotary switches, which were chosen mainly due to their ease of use, ease of assembly, and reliability. These will be located on the recovery modules and be accessible from the exterior of the launch vehicle so they can be accessed easily on launch day. The keyed rotary switch type was selected due to the design's resistance to changing position due to in-flight forces. This will be confirmed with vibration tests before flight. Additionally, WAGO wire connectors will be used in order to ensure ease of connection from the altimeters to black powder charges which must be loaded at the launch field by the team mentor.

4.7 Mass Statement

The recovery components and their masses were crucial for mission performance calculations. Where possible, lighter components were selected to reduce the overall mass of the vehicle. Summaries of the predicted masses can be viewed in Table 46 below for the laundry assemblies in addition to the FED, PED, and NED modules. The FED and the PED, having identical mass makeups, are listed together.

Table 46: Recovery Predicted Mass Summaries

Component Type	PED/FED	NED	Drog. Laundry	Main Laundry	NC Laundry
Primary Structure (oz)	14.78	18.73	19.21	121.46	10.20
Secondary Structure (oz)	8.55	15.72	0	0	0
Batteries (oz)	0.71	1.00	0	0	0
Instruments (oz)	0.72	1.30	0	0	0
Wiring (oz)	8.14	1.04	0	0	0
Other Electronics (oz)	2.81	3.42	0	0	0
Total (oz)	35.71	40.85	19.21	121.46	10.20

5 Mission Performance Predictions

5.1 Flight Ascent Analysis

The ascent of the full-scale vehicle was modeled using commercially-available full flight rocketry simulation software. OpenRocket and RockSim 10 were selected due to the team's familiarly with the software and the proven reliability of the software with the subscale flight results, found in Section 3.5.

Per NASA CDR requirements, the flight ascent was modeled under various flight conditions. The launch vehicle was launched for three different launch rail angles: 5, 7, and 10 degrees. The launch rail angles were chosen based on NASA Req. 1.12. The launch vehicle was flown with wind speeds of 0, 5, 10, 15, and 20 mph. All five wind conditions were performed for all three launch rail angles. In total, 15 different flight conditions were flown.

The team made assumptions set up the OpenRocket and RockSim models. First, the temperature and pressure were kept at the international standard atmospheric values of 59.0^o F and 29.92 inHg. Second, the latitude, longitude, and altitude of the launch vehicle were set to 41.8° N, 86.6106° W, and 692 ft. These are the coordinates and altitude of Three Oaks, Michigan- the location of the team launch site. Third, for the RockSim model, the humidity was set to 83% to reflect the average humidity in Three Oaks, Michigan, in the month of February. Fourth, Section 5.2 details how the "true" deployment of the main parachute is approximately three seconds after black powder ignition; hence, steps were taken to better reflect the parachute deployment in the simulators. To clarify, the black powder ignition occurs above 500 feet (abiding by NASA Req. 3.1.1), but the main parachute does not fully open for another three seconds (the use of a three second time delay removes the simulators' assumption that the parachute is fully open at the exact time of deployment). For OpenRocket, the main parachute was set to deploy 3 seconds after the vehicle passed 584 ft. For RockSim, the simulator does not allow one to input a time delay after an altitude is reached. To determine the parachute deployment time, the simulator ran without the main parachute, and Equation 10 determined the altitude after 3 seconds have passed since passing 584 ft, which is where the first PED charge goes off. Using Equation 10, Table 47 lists the altitudes that were imputed into RockSim for all the respective flight conditions.

$$y_{true} = 584 + v_{y,584}\Delta t + \frac{1}{2}a_{y,584}\Delta t^2 \quad (10)$$

Where y_{true} is the "true" altitude of the main parachute deployment, $v_{y,584}$ is the vertical velocity at 584 ft, $a_{y,584}$ is the vertical acceleration at 584 ft, and Δt is the change in time, which for this scenario is 3 seconds.

Table 47: "True" Main Parachute Deployment Altitude, Used for RockSim Simulation Setup

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	291.4150 ft	291.6540 ft	295.9350 ft	292.4520 ft	292.6160 ft
10° Angle	293.1200 ft	293.5460 ft	294.9770 ft	294.4710 ft	293.7210 ft
15° Angle	291.8530 ft	294.0360 ft	291.8800 ft	295.2980 ft	295.1650 ft

The drogue parachute was set to deploy exactly at apogee. Unlike the main parachute, there is not assumed delay in deployment. The rest of the variables for flight initialization were kept constant.

Finally, the most important assumption is that the flight data assumes that ACS never operates at all; it is assumed in the simulators that the launch vehicle does not slow down with the use of drag flaps during flight. This ensures that the launch vehicle abides to all NASA requirements no matter the effectiveness of ACS on launch day. For a detailed look at how the ACS flaps will affect the flight trajectory, see Section 7.3.

5.1.1 Altitude

Table 50 lists the OpenRocket and RockSim Predicted Altitude for the fullscale launch vehicle at various flight conditions. Tables 48 and 49 lists the predicted apogees for OpenRocket and RockSim, respectively, given various flight conditions.

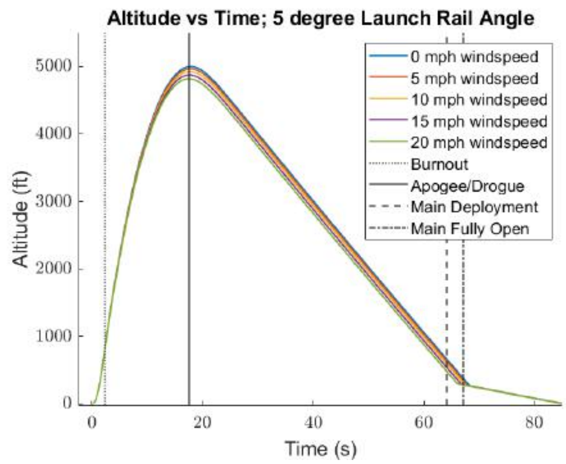
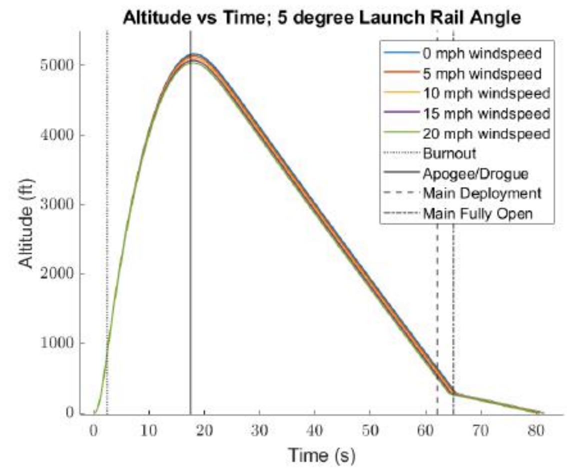
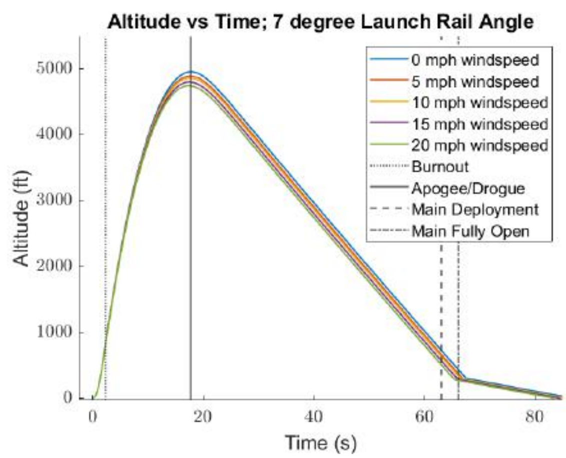
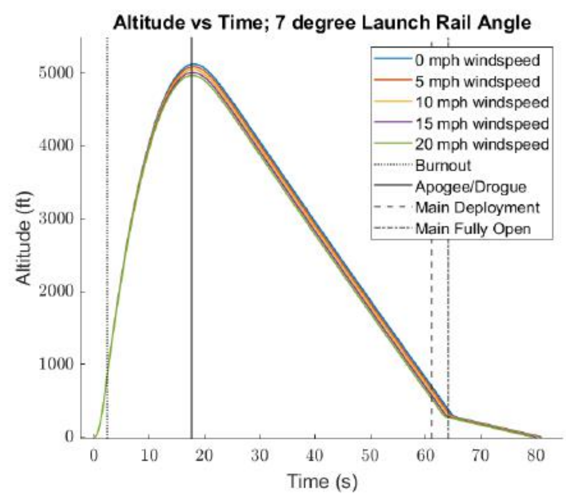
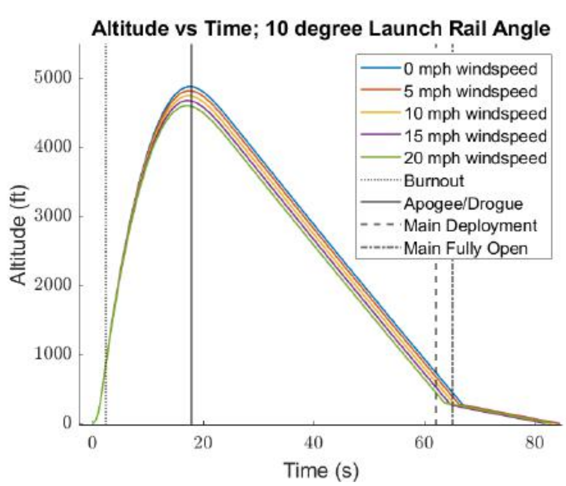
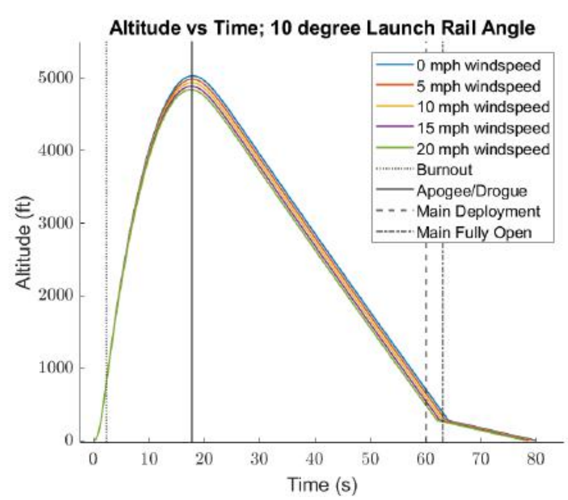
Table 48: OpenRocket Predicted Apogee for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	4998.4 ft	4965.1 ft	4922.0 ft	4871.5 ft	4815.2 ft
7° Angle	4956.9 ft	4892.8 ft	4860.4 ft	4801.6 ft	4745.1 ft
10° Angle	4875.9 ft	4817.3 ft	4744.9 ft	4674.9 ft	4601.5 ft

Table 49: RockSim Predicted Apogee for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle ft	5166.9 ft	5140.3 ft	5109.2 ft	5075.3 ft	5040.2 ft
7° Angle	5123.4 ft	5088.5 ft	5050.1 ft	5010.1 ft	4969.8 ft
10° Angle	5032.2 ft	4985.7 ft	4937.4 ft	4889.1 ft	4841.9 ft

Table 50: OpenRocket (Left) and RockSim (Right) Predicted Altitude for Various Flight Conditions

OpenRocket	RockSim
	
	
	

All flight conditions and all simulators predict that the launch vehicle will exceed the target apogee if ACS is not used; this will give ACS an opportunity to operate under all potential flight conditions to direct the launch vehicle towards the target apogee. More importantly, the flight data confirms that the launch vehicle stays within 4,000 to 6,000 feet, abiding by NASA Req. 2.1, with or without the use of the ACS. From the subscale flight, it was found that the OpenRocket model predicted the apogee better than the RockSim model, so the full-scale launch vehicle will perform closer to the OpenRocket values. This will be evaluated in greater detail in the FRR report once the vehicle demonstration flight is completed.

The average apogee value from the OpenRocket model is 4836.23 ft. The average apogee value from the RockSim model is 4965.40 ft. The average of the OpenRocket and RockSim apogees is 4900.82 ft.

5.1.2 Velocity

Tables 51 and 52 lists the predicted maximum velocity for OpenRocket and RockSim, respectively, given various flight conditions. Table 53 lists the OpenRocket and RockSim predicted total velocity for the full-scale launch vehicle at various flight conditions. Tables 54 and 55 lists the predicted off-rail velocity values for OpenRocket and RockSim, respectively, given various flight conditions.

Table 51: OpenRocket Predicted Max. Total Velocity for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	597.13 ft/s	596.98 ft/s	596.51 ft/s	595.89 ft/s	594.96 ft/s
7° Angle	597.4 ft/s	597.11 ft/s	596.8 ft/s	596.22 ft/s	595.4 ft/s
10° Angle	598.1 ft/s	597.97 ft/s	597.41 ft/s	596.87 ft/s	595.91 ft/s

Table 52: RockSim Predicted Max. Total Velocity for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	600.199 ft/s	600.203 ft/s	600.041 ft/s	599.734 ft/s	599.302 ft/s
7° Angle	600.456 ft/s	600.494 ft/s	600.365 ft/s	600.188 ft/s	599.785 ft/s
10° Angle	600.999 ft/s	601.183 ft/s	601.098 ft/s	600.867 ft/s	600.511 ft/s

Table 53: OpenRocket (Left) and RockSim (Right) Predicted Total Velocity for Various Flight Conditions

<table>
<tr><th>OpenRocket</th><th>RockSim</th></tr>
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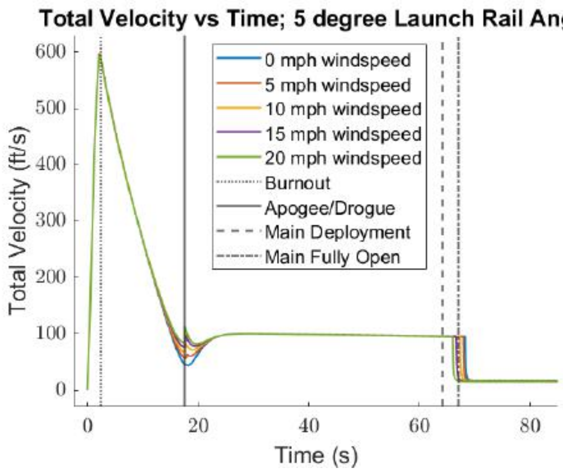

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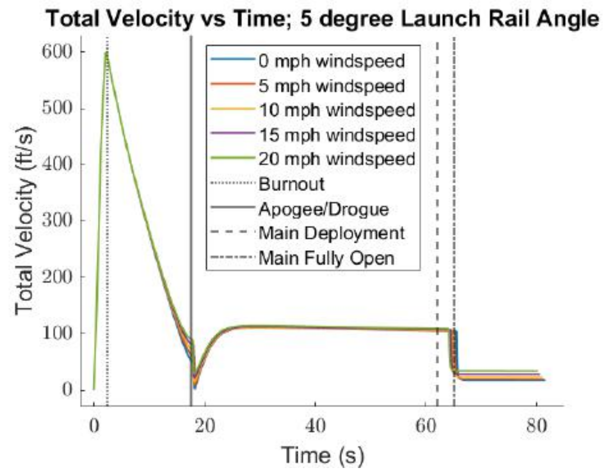

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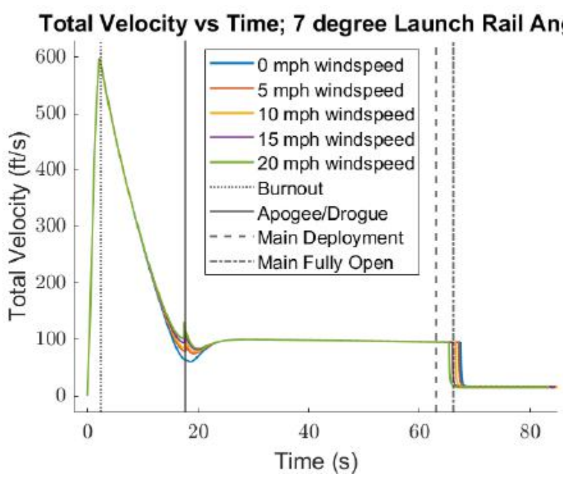

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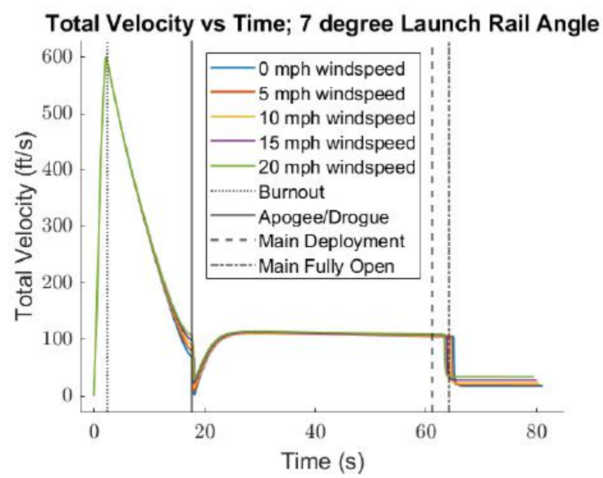

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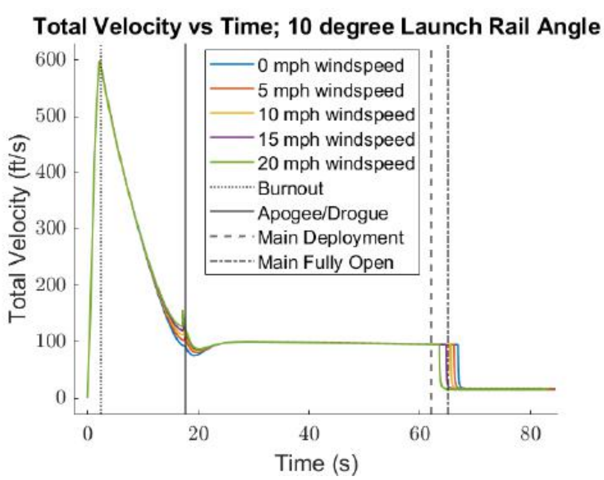

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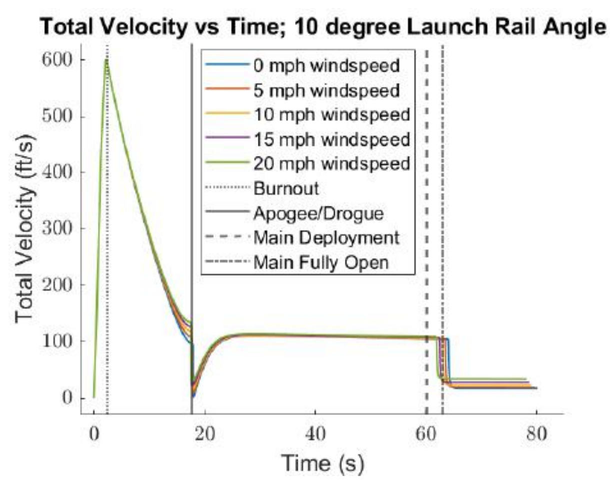

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Table 54: OpenRocket Predicted Off-Rail Total Velocity Values for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5^o Angle	87.0 ft/s	87.0 ft/s	87.0 ft/s	87.0 ft/s	87.0 ft/s
7^o Angle	87.1 ft/s	87.0 ft/s	87.0 ft/s	87.0 ft/s	87.0 ft/s
10^o Angle	87.1 ft/s	87.1 ft/s	87.1 ft/s	87.1 ft/s	87.1 ft/s

Table 55: RockSim Predicted Off-Rail Total Velocity Values for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5^o Angle	84.23 ft/s	84.23 ft/s	84.23 ft/s	84.23 ft/s	84.23 ft/s
7^o Angle	84.60 ft/s	84.60 ft/s	84.60 ft/s	84.60 ft/s	84.60 ft/s
10^o Angle	84.97 ft/s	84.97 ft/s	84.97 ft/s	84.97 ft/s	84.97 ft/s

The flight data shows the parachutes are successful in reducing the launch vehicle's velocity. The average maximum velocity value from the OpenRocket model is 596.7107 ft/s. The average maximum velocity value from the RockSim model is 600.3617 ft/s. The average of the OpenRocket and RockSim maximum velocity is 598.536 ft/s. The average maximum velocity value is important for running the CFD on the camera shroud, which the results can be found in Section 5.4. It is also important to note the precision between simulations in predicting the vehicle's velocity. More importantly, Tables 54 and 55 have velocity values much greater than 52 ft/s for all conditions, so the vehicle design abides by NASA Req. 2.17. Specifcially, the average off-rail velocity value from the OpenRocket model is 87.04 ft/s. The average off-rail velocity value from the RockSim model is 84.60 ft/s. The average of the OpenRocket and RockSim off-rail velocities is 85.82 ft/s. Again, the average values are all above 54 ft/s.

5.1.3 Acceleration

Table 56 lists the OpenRocket and RockSim predicted total acceleration for the fullscale launch vehicle at various flight conditions. Tables 57 and 58 lists the predicted maximum acceleration for OpenRocket and RockSim, respectively, given various flight conditions.

Table 56: OpenRocket (Left) and RockSim (Right) Predicted Total Acceleration for Various Flight Conditions

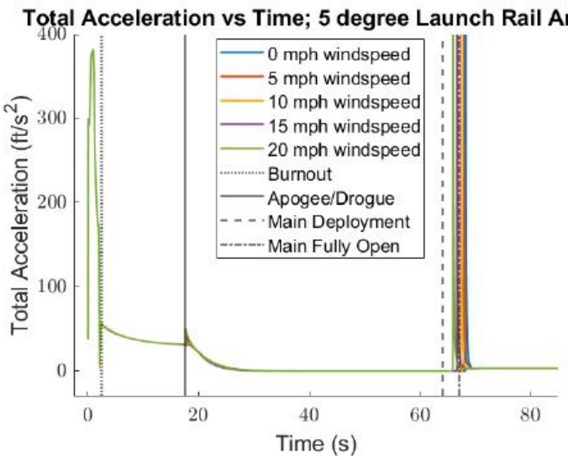
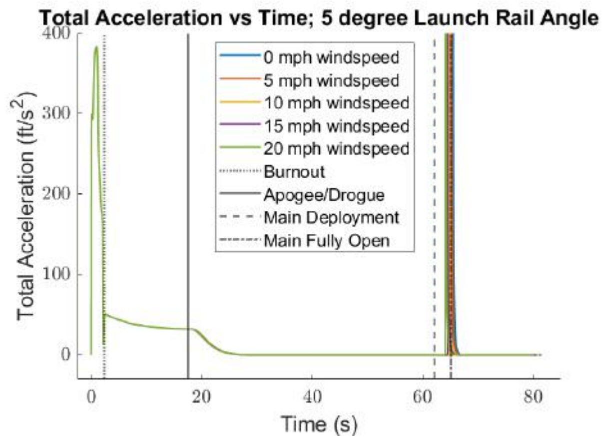
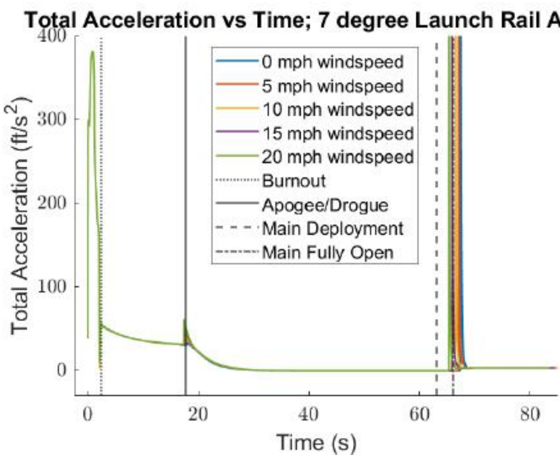
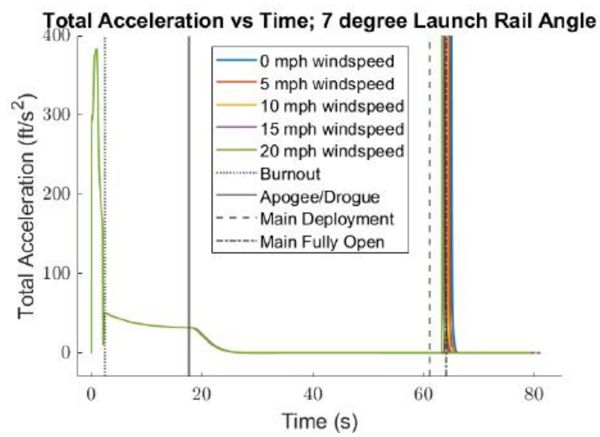
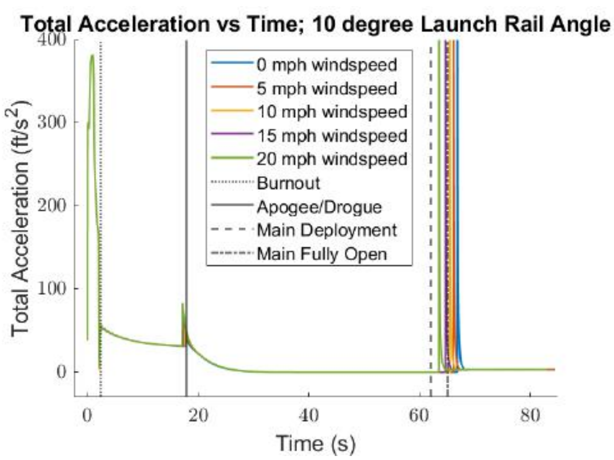
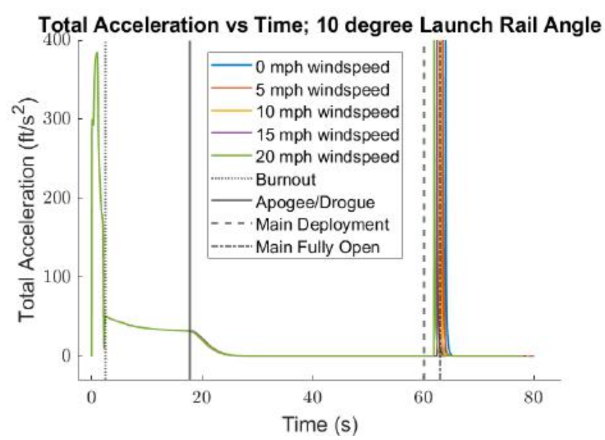
OpenRocket	RockSim
	
	
	

Table 57: OpenRocket Predicted Max. Total Acceleration for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	381.33 ft/s^2	381.45 ft/s^2	381.59 ft/s^2	381.76 ft/s^2	381.94 ft/s^2
7° Angle	381.46 ft/s^2	381.68 ft/s^2	381.79 ft/s^2	381.99 ft/s^2	382.25 ft/s^2
10° Angle	381.78 ft/s^2	381.99 ft/s^2	382.18 ft/s^2	382.42 ft/s^2	382.68 ft/s^2

Table 58: RockSim Predicted Max. Total Acceleration for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	383.616 ft/s^2	383.744 ft/s^2	383.884 ft/s^2	384.029 ft/s^2	384.164 ft/s^2
7° Angle	383.755 ft/s^2	383.918 ft/s^2	384.092 ft/s^2	384.429 ft/s^2	384.592 ft/s^2
10° Angle	384.044 ft/s^2	384.415 ft/s^2	384.645 ft/s^2	384.863 ft/s^2	385.057 ft/s^2

As you can tell from the flight data, the parachutes result in significant acceleration spikes, followed by much lower accelerations overall. The average maximum acceleration value from the OpenRocket model is 381.8860 ft/s^2. The average maximum acceleration value from the RockSim model is 384.2165 ft/s^2. It is important to note the precision between simulations in predicting the vehicle's acceleration overall. The average of the OpenRocket and RockSim maximum accelerations is 383.051 ft/s^2.

5.1.4 Stability

5.1.4.1 Static Stability Recall that Equation 1 is used to determine the static stability margin of the launch vehicle. Table 59 lists the Center of Gravity (CG), Center of Pressure (CP), and static stability margin of the fullscale launch vehicle, based on the OpenRocket and RockSim models:

Table 59: Static Stability Margin for Launch Vehicle

Method	CG Location (in.)	CP Location (in.)	Static Stability Margin (cal)
OpenRocket	76.465	98.510	3.57
RockSim (Barrowman Stability)	76.462	98.206	3.52
RockSim (RockSim Stability)	76.462	103.325	4.35

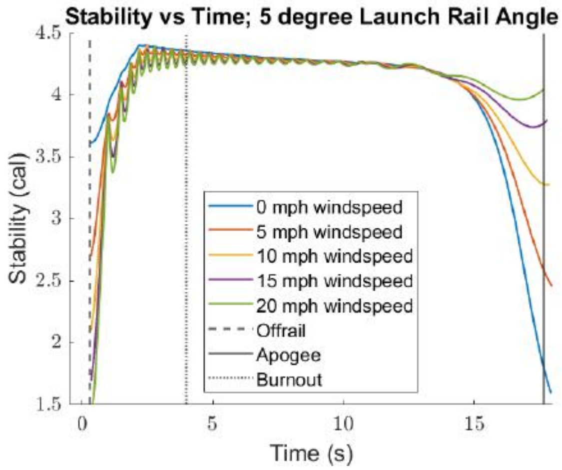
The difference between the Barrowman and RockSim methods is explained in greater detail in Section 5.1.4.2. All three simulations methods have a static stability margin greater than 2.00 cal, abiding by NASA Req. 2.14.

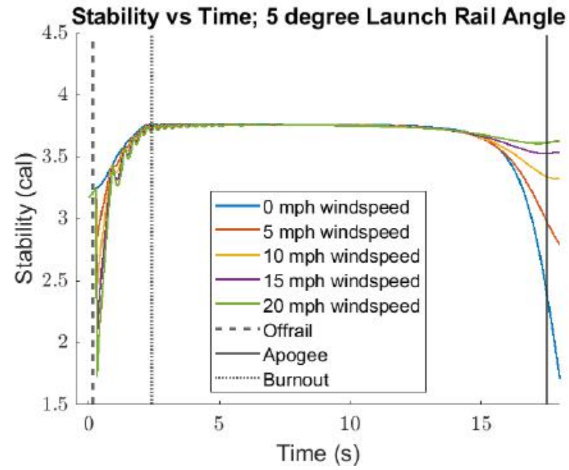
5.1.4.2 Dynamic Stability Recall that "dynamic" refers to the fact that there is an acceleration on the launch vehicle during flight; it can no longer be referred to as "static stability." While NASA Req. 2.14 requires a **static** stability greater than 2.00 cal at the launch rail exit, the team designed the launch vehicle with the goal of having a stability margin, both static and dynamic, greater than 2.00 cal at the launch rail exit. Section 5.1.4.1 already demonstrates that the static stability is greater than 2.00 cal.

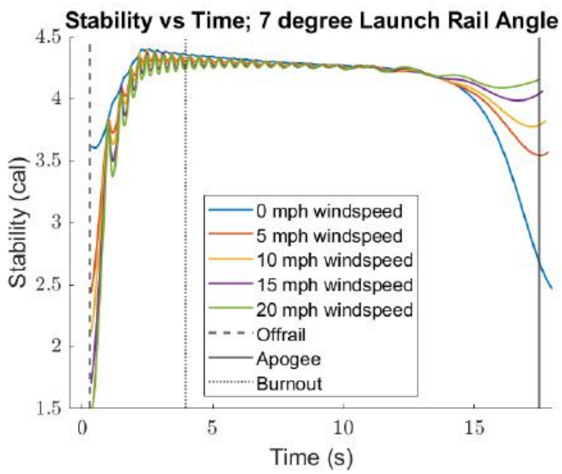
Table 60 lists the OpenRocket and RockSim predicted dynamic stability for the fullscale launch vehicle at various flight conditions. Tables 61 and 62 lists the predicted off-rail stability values for OpenRocket and RockSim, respectively, given various flight conditions.

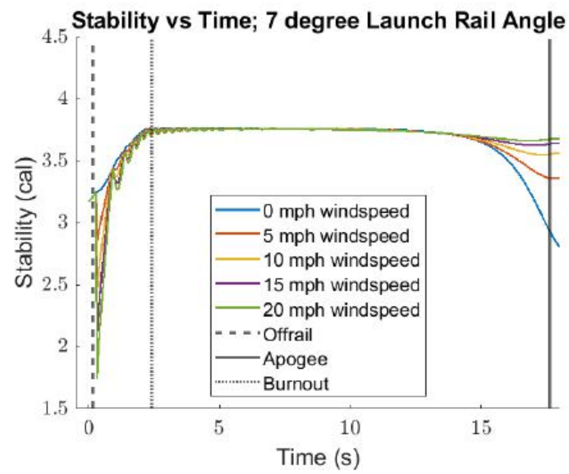
Table 60: OpenRocket (Left) and RockSim (Right) Predicted Dynamic Stability for Various Flight Conditions

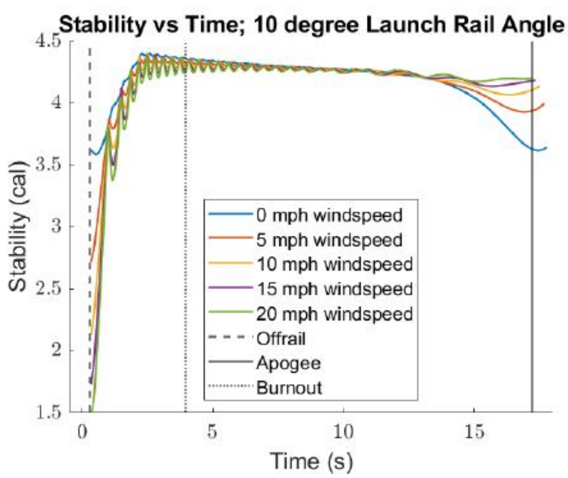
OpenRocket	RockSim











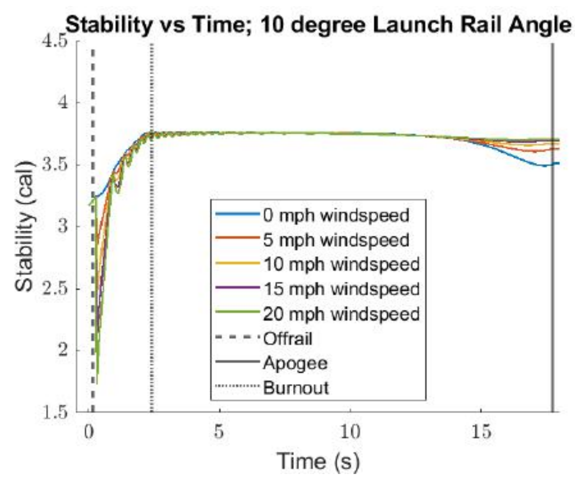


Table 61: OpenRocket Predicted Off-Rail Dynamic Stability Values for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	3.620 cal	2.704 cal	2.105 cal	1.694 cal	1.401 cal
7° Angle	3.620 cal	2.443 cal	2.115 cal	1.707 cal	1.417 cal
10° Angle	3.620 cal	2.719 cal	2.132 cal	1.729 cal	1.443 cal

Table 62: RockSim Predicted Off-Rail Dynamic Stability Values for Various Flight Conditions

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	3.247 cal	3.247 cal	3.247 cal	3.245 cal	3.245 cal
7° Angle	3.247 cal	3.247 cal	3.245 cal	3.245 cal	3.245 cal
10° Angle	3.245 cal	3.245 cal	3.245 cal	3.245 cal	3.242 cal

The flight data shows the parachutes are successful in reducing the launch vehicle's velocity. The average off-rail stability value from the OpenRocket model is 2.298 cal. The average off-rail dynamic stability value from the RockSim model is 3.245 cal. The average of the OpenRocket and RockSim off-rail dynamic stability values is 2.772 cal.

It is also important to note the imprecision between simulations in predicting the vehicle's velocity. This is due to the different ways that the CP is calculated. In an article published by Apogee Components, the creators of RockSim it is explained that RockSim calculates the CP based on the Barrowman equations, except the generic form of the Barrowman equations is used, removing many of the assumptions that are typically used when calculating: this is referred to as the "rocksim stability equations" in the software's settings. OpenRocket utilizes the "Extended Barrowman" equations, but they most likely have many of the assumptions still in place, given the drastic change in values. As well, the OpenRocket data does not give values of the stability before it fully detaches from the launch rail, but RockSim does. The stability greatly decreases the instant it separates from the launch rail, so it is advantageous to take the stability value when the launch vehicle leaves the launch rail, but on the time step before it leaves, not after; the OpenRocket data allows us only to take the value after departure from the rail, resulting in lower values overall. With such a high static stability value, there is little to no concern. This is noted to account for the large differences in values between the two simulators.

More importantly, Tables 54 and 55 have dynamic stability values greater than 2.00 cal for all launch angles with wind speeds at 10 mph or less. While the OpenRocket dynamic stability is less than 2.00 cal for 15 and 20 mph wind conditions, dynamic stability is **not** a NASA required characteristic and the team would not launch the full-scale launch vehicle in these conditions. If the average dynamic stability between individual OpenRocket and RockSim conditions is taken, the 15 and 20 mph wind conditions are now greater than 2.00 cal.

5.1.4.3 Flight Angle and Weathercocking This section serves to demonstrate that, while the launch vehicle has a large stability margin, the level of over-stability will not be detrimental to the flight ascent.

Table 63 lists the OpenRocket and RockSim predicted flight zenith angle for the fullscale launch vehicle at various flight conditions. Tables 64 and 66 list the altitude of the launch vehicle when the launch vehicle is at 40 ^{o} weathercocking. As well, Tables 65 and 67 list the percent of altitude left before reaching apogee when the launch vehicle is at 40° weather-cocking.

Table 63: OpenRocket (Left) and RockSim (Right) Predicted Flight Zenith Angle for Various Flight Conditions

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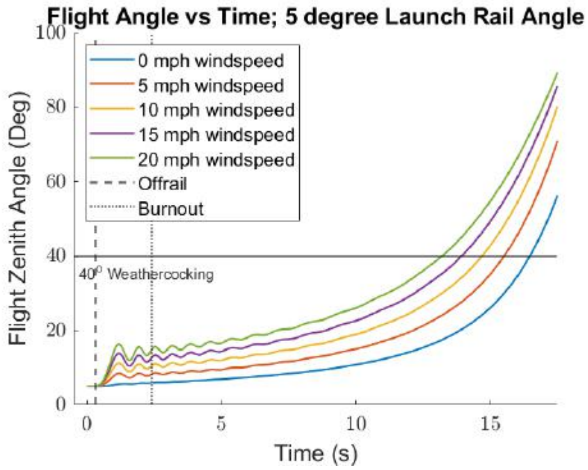

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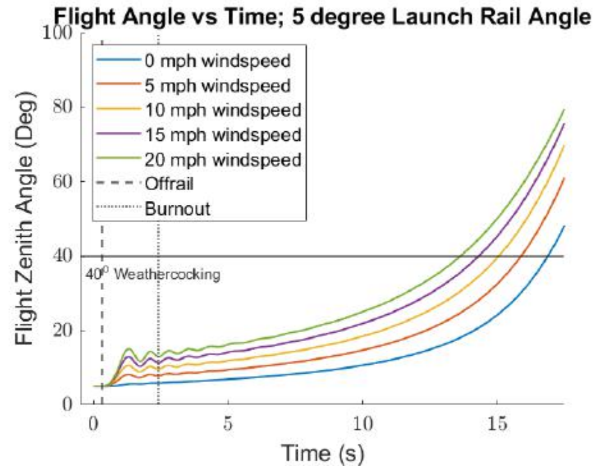

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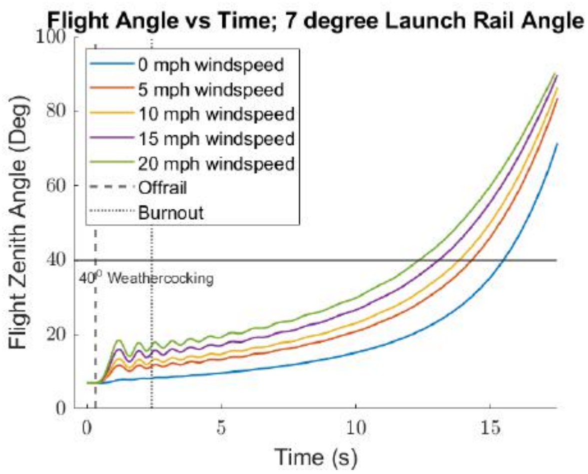

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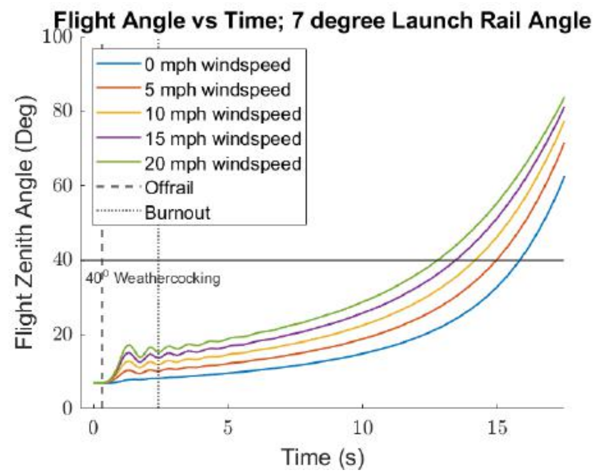

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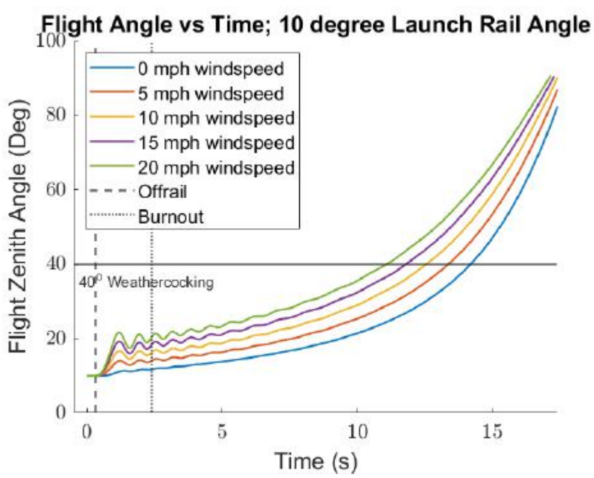

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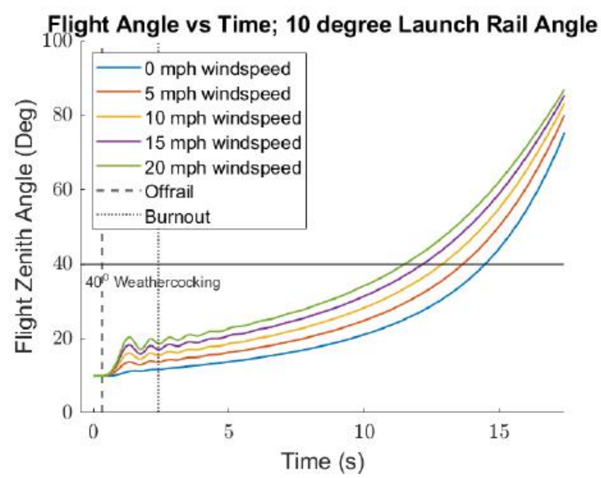

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Table 64: OpenRocket Predicted Altitude at the Point Where the Flight Angle is at 40°

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	4976.6 ft	4884.2 ft	4781.4 ft	4657.5 ft	4522.6 ft
7° Angle	4876.9 ft	4717.2 ft	4641.2 ft	4493.7 ft	4341.8 ft
10° Angle	4686.1 ft	4543.8 ft	4376.7 ft	4204.4 ft	4019.2 ft

Table 65: OpenRocket Predicted Percent Altitude Left to Reach Apogee at the Point Where the Flight Angle is at 40°

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	0.436 %	1.629 %	2.857 %	4.393 %	6.077 %
7° Angle	1.614 %	3.589 %	4.510 %	6.412 %	8.499 %
10° Angle	3.893 %	5.677 %	7.760 %	10.064 %	12.655 %

Table 66: RockSim Predicted Altitude at the Point Where the Flight Angle is at 40°

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	5093.102 ft	4996.879 ft	4880.052 ft	4744.895 ft	4595.426 ft
7° Angle	4994.159 ft	4869.212 ft	4726.368 ft	4573.145 ft	4409.262 ft
10° Angle	4790.684 ft	4629.39 ft	4449.807 ft	4264.369 ft	4064.379 ft

Table 67: RockSim Predicted Percent Altitude Left to Reach Apogee at the Point Where the Flight Angle is at 40°

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	0.655%	1.836 %	3.360 %	5.186 %	7.286
7° Angle	1.688 %	3.318 %	5.223 %	7.314%	9.644 %
10° Angle	3.957 %	6.103 %	8.606 %	11.267 %	14.314 %

It is clear that, while the launch vehicle does pass the 40° flight angle during launch, it is so close to apogee that the effects are almost negligible. All launch conditions that have double digit percentages left of altitude to reach apogee are conditions the team will not launch the launch vehicle in. Despite this, they are still at a level with less than 15.00% of the flight altitude left. 15.00% is safe given that all flight altitude simulations predict the launch vehicle to fly higher than realistically expected given that none of the altitude graphs utilize the ACS's ability to reduce the altitude with drag. If the ACS operates, the altitude where the 40° cone would be passed would be even **closer** to apogee, and thus weather-cocking would be less of a concern.

5.2 Flight Descent Analysis

The descent of the full-scale vehicle was modeled using both commercially-available full flight rocketry simulation software and custom MATLAB scripts. OpenRocket and RockSim 10 were selected due to the team's familiarity with the software and the proven reliability, especially in flight ascent, which both have shown in the past and as is further explored in Section 5.1. The new, in-house MATLAB script `full_vehicle_decsent_calc.m` (see Appendix) was also developed based on the team's understanding of the descent physics to determine numerous descent parameters that were instrumental in crucial design decisions. The `full_vehicle_decsent_calc.m` script has numerous inputs about both the vehicle itself and the environment which are provided by the `Input_Mass.m` and `Input_Parachutes.m` functions as well as numerous lines in the `full_vehicle_decsent_calc.m` script itself.

These input parameters include the following:

- Mass of each section of the vehicle (without laundry)
- Mass of the laundry in each section of the vehicle
- Dimensions of the full vehicle profile (length and diameter)
- Parachute dimensions, manufacturer drag coefficients, and expected performance adjustments
- Predicted apogee (using either the ACS target apogee and or an OpenRocket/RockSim apogee)
- Weather conditions including wind velocity (using the worst-case scenario of 20mph) and atmospheric air density
- Minimum charge detonation altitude (using the competition requirement of 500 ft
- Yes/No to the use of a deployment bag for the main parachute deployment.

The hand calculations carried out by this script still simplify the entire descent system considerably. The assumptions and simplifications of the script include the following:

- Drogue parachute opens instantly at apogee
- Main parachute opens 1 second after the first deployment charge in the absence of a deployment bag and 3 seconds after the first deployment charge when a deployment bag is used
- No drag from the main parachute is produced before this delay time has elapsed and the full drag produced by the main parachute is effective immediately after this delay time has elapsed
- No variation in wind speed/updrafts throughout the descent
- Apogee occurs directly above the launch pad for drift calculations
- The tumbling of the body tubes contributes to the full vehicle's drag throughout the descent
- The pilot parachute contributes to the drag produced during the main descent
- Shock cords are rigid for force calculations
- Only the mass inside of the body tube during impact with the ground is included for kinetic energy calculations (ex. parachutes are not included).

Several changes to the script the team used last year have been made to improve the accuracy of the hand calculations. One difference is the addition of a delay time for the main parachute to fully take effect after the first ejection charge detonates. Upon the review of last year's flights with a deployment bag, it could be observed that the main parachute does not actually start slowing the vehicle until as much as 4.5 seconds after the first recovery event occurred. This can be observed in the descent profile from the team's Huntsville competition flight from 4/23/2022 shown in Figure 72 below.

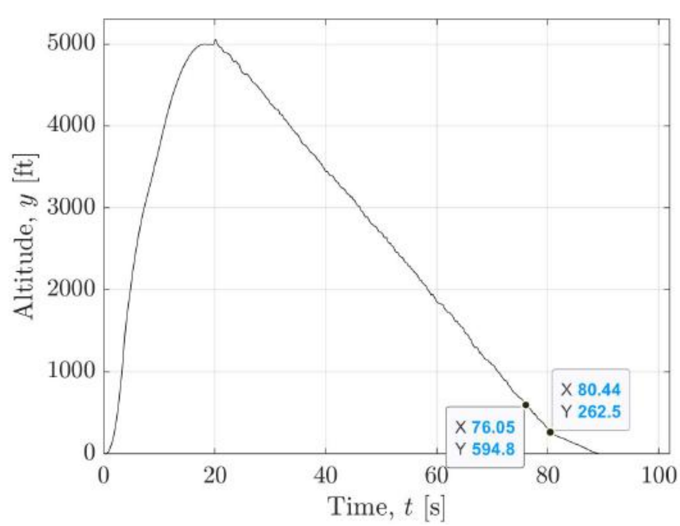


Figure 72: Huntsville Competition Flight Profile

The first ejection charge was set for 591 ft last year for the main parachute which occurred approximately at the same time the vehicle passed through 594.8 as shown on the descent profile. However, it can be seen that the vehicle does not actually slow to its main parachute descent rate until roughly 4.5 seconds later. In an earlier vehicle design flight on 4/3/2022, the main parachute took 3.5 seconds to fully take effect after the first main parachute recovery charge was detonated. Since longer delay times reduce descent time and thus drift, a conservative 3.0-second delay for deployment bags is incorporated into the hand calculations as mentioned in the inputs section above for the script.

Furthermore, as discussed in Section 4.4.1, it has been discovered this year that most commercially-available parachutes under-perform their specifications (especially Rocketman parachutes as noted during PDR presentation feedback). As such, it is not safe to assume that the team's parachutes will perform 100% up to their expected $C_d A$ values. This is why the "expected performance adjustment" input was added to the `Input_Parachutes.m` function this year. This allows the team to reduce a parachute's impact on a descent phase when deemed necessary. For example, the drogue and pilot parachutes used on this year's launch vehicle were also used on last year's vehicle. This allowed the team to retroactively look back at previous flights and determine the amount these parachutes underperform by looking at the descent rates the vehicle actually descended at. For both of the 2 ft parachutes to be used for the drogue and pilot this year, it was determined that they only provide about 87% of the drag advertised by the manufacturers. Last year's main parachute (a Standard Rocketman 12ft Parachute) typically provided about 50% of the drag advertised.

Lastly, a new component of vehicle drag due to tumbling was added. While relatively insignificant during the main parachute descent phase, it has been noted by prior team member observations that full-scale vehicles typically descend slower than expected during the drogue descent phase. However, it has also been observed that drogue parachutes typically under-perform during subscale launches where the drag due to the body tubes is negligible due to their small size. Therefore, it has been determined that an additional source of drag due to the large size of the full-scale vehicle likely slows it more than previously predicted. While team members conducted research into the drag produced by randomly tumbling cylinders in a subsonic environment, no perfectly matching journal articles could be found. Therefore, a report from U.S. Department of Energy about predicting C_ds for the tumbling drag of cylinders was adapted and implemented in the `Input_Parachutes.m` script. This adapted prediction of tumbling drag closely matched that observed in past flights and was thus kept for this year's predictions.

With the main parachute deployment delay, "expected performance adjustment" changes, and the addition of tumbling drag, predictions for last year's vehicle's descent profile were calculated. This was done to test the accuracy of the new hand calculation model against actual flight results. The difference between the predicted descent profile and actual descent profile for the Huntsville Competition Flight can be seen in Table 68.

Table 68: `full_vehicle_decsent_calc.m` Prediction vs. Actual Huntsville Flight Data

Descent Parameter	Prediction	Huntsville
Descent Time (s)	70.62	69.34
v_{main} (ft/s)	27.92	28.66
v_{drogue} (ft/s)	79.64	78.12

This suggests the new hand calculations facilitated by the `full_vehicle_decsent_calc.m` script has the potential to provide very accurate flight descent results, especially when the existing performance of a parachute is already known. While the performance of the main parachute is not yet known this year, the team is confident the SkyAngle XXL will perform closer to its advertised value due to the rigorous independent performance testing it is subject to according to SkyAngle's website (see 4.4.1). As such, it has been conservatively assumed for simulations the main parachute will provide 90% of its advertised drag. However, calculations show that even if the parachute under-performs by as much as 35%, the kinetic energy of the vehicle would still abide by NASA Req. 3.3. If the parachute performs 100% up to its advertised value, it will likewise still abide by drift time and drift radius requirements.

As a simple overview, the hand calculations run by the script calculate the descent velocity using a force-balance equation between drag and weight (terminal velocity) that shows

$$\frac{1}{2}\rho v_{\text{max}}^2 C_d A = m_{\text{tot}} g \tag{11}$$

where ρ is the standard air density, v_{descent} is the descent rate desired, $C_d A$ is the effective $C_d A$ of the whole vehicle (including parachutes, their adjustments, and tumbling) and the right side of the equation is the weight of the entire vehicle after burnout. Solving for v_{descent} the equation

$$v_{\text{descent}} = \sqrt{\frac{2 m_{\text{tot}} g}{\rho C_d A}} \tag{12}$$

is used to calculate the descent rate for both the main and drogue phases of descent. Table 69, below displays the calculated descent rates using hand calculations, OpenRocket, and RockSim.

Table 69: Predicted Descent Rates

Descent Phase	MATLAB v_{descent} (ft/s)	OR v_{descent} (ft/s)	RS v_{descent} (ft/s)
Drogue	83.51	96.60	106.04
Main	16.13	15.55	16.97

The following section will discuss the important descent parameters found using these rates as calculated via the `full_vehicle_decsent_calc.m` hand calculations and the full flight simulation software. The full `full_vehicle_decsent_calc.m`, `Input_Parachutes.m`, and `Input_Maas.m` can be found in Appendix A to further clarify the exact methodology used for hand calculations this year.

5.2.1 Kinetic Energy

The kinetic energy of each section of the launch vehicle must be calculated to ensure the vehicle adheres to NASA Req. 3.3. The equation used to calculate the kinetic energy of a given section was

$$KE = \frac{1}{2} m_{\text{section}} v_{\text{main}}^2 \tag{13}$$

where KE is the kinetic energy of a section, m_{section} is the mass of the entire contents of a section in its separated state (i.e. without parachutes, etc), and v_{main} is the descent velocity of the entire vehicle under the main parachute and thus at impact. The calculated kinetic energies for each section using the descent rates shown in Table 69 and the masses shown in Table 33 are shown in Table 70, below.

Table 70: Predicted Kinetic Energies at Landing

Section	MATLAB KE (ft-lb)	OR KE (ft-lb)	RS KE (ft-lb)
Nose Cone	18.30	17.02	20.27
Payload Bay	51.33	47.74	56.87
ACS Bay	44.91	41.77	49.76
Fin Can	51.70	48.09	57.28

OpenRocket predicts the smallest kinetic energies as it predicts the main parachute descent rate to be the smallest. Conversely, RockSim predicts the kinetic energy of each section to be marginally larger than both MATLAB and OpenRocket due to its larger predicted descent rate. All of the kinetic energy values across all methods are within 10 ft-lb for each section. Furthermore, even the largest kinetic energy values are below the 65 ft-lb goal which makes the team confident the vehicle will safely fall within NASA Req. 3.3.

5.2.2 Descent Time

The total descent time of the launch vehicle must be calculated to ensure the vehicle adheres to NASA Req. 3.11. The equation used to calculate the descent time during a given phase was

$$t_{\text{descent}} = \frac{\Delta h}{v_{\text{descent}}} \tag{14}$$

where t_{descent} is the descent time, Δh is the total height change during a given descent phase, and $v_{descent}$ is the descent rate during a given descent phase. For the drogue descent time, Δh is the difference between apogee and the main parachute's effective deployment altitude. For the main descent time, Δh is the difference between the main parachute's effective deployment altitude and the ground (0ft). These times are then summed to find the total descent time.

The descent times in OpenRocket and RockSim were calculated by determining the time it took the vehicle to descend from apogee to the ground. The descent time was calculated for three separate potential apogees: the projected apogee assuming ACS activates (4600ft), a worst-case (failed-ACS) apogee calculated using OpenRocket (0 mph wind and 5-degree launch angle under STP), and a worst-case (failed-ACS) apogee calculated using RockSim (same conditions as OpenRocket). The descent times for these different apogees can be viewed in Table 71.

Table 71: Predicted Descent Times

Apogee (ft)	MATLAB t_{descent} (s)	OR t_{descent} (s)	RS t_{descent} (s)
4600	71.75	X	X
4998	76.51	67.53	X
5167	78.54	X	62.25

In general, the MATLAB hand calculations predict the longest descent times while the RockSim predicts the shortest descent times. RockSim has been observed to predict smaller amounts of drag in both ascent and descent as reflected by the larger predicted apogees and shorter descent times. However, it is difficult to actually break down how RockSim arrives at these values as it is a closed-source software. The MATLAB code largely predicts longer descent times due to the addition of tumbling drag to the overall vehicle's drag profile. This especially impacts the vehicle during drogue descent and results in longer drogue descent times and slower descent velocities. While OpenRocket is said to take the tumble drag into account, it is likely less effective than the model selected by the team for hand calculations. It is worth considering that OpenRocket and RockSim have historically overpredicted the descent velocity during drogue descent by a notable margin. Therefore, the difference in predicted descent velocities is not concerning as all values are well below the 80-second limit imposed by NASA Req 3.11.

5.2.3 Drift Radius

The total drift of the launch vehicle must be calculated using the worst-case wind scenario of 20 mph to ensure the vehicle adheres to NASA Req. 3.10. The equation used to calculate the drift by hand during a given phase was

$$D = v_{\text{wind}} t_{\text{descent}} \tag{15}$$

where t_{descent} is the descent time, v_{wind} is the wind speed (20 mph), and D is the drift for a given descent phase. These drift distances are then summed to find the total drift.

The drift in OpenRocket and RockSim was calculated by determining the distance between the vehicle's position above the ground at apogee and the location it impacts the ground. The drift was calculated for three separate potential apogees: the projected apogee assuming ACS activates (4600ft), a worst-case (failed-ACS) apogee calculated using OpenRocket (20 mph wind and 5-degree launch angle under STP), and a worst-case (failed-ACS) apogee calculated using RockSim (same conditions as OpenRocket). The drift for these different apogees can be viewed in Table 72, below.

Table 72: Predicted Drift Distances

Apogee (ft)	MATLAB Drift (ft)	OR Drift (ft)	RS Drift (ft)
4600	2104.56	X	X
4815	2180.09	1596.28	X
5040	2259.12	X	1825.89

The drift predicted by the MATLAB hand calculations is notably the largest likely due to the longer predicted descent times considered in Section 5.2.2. However, all of the potential drift values still fall within NASA Req. 3.10. RockSim has a larger predicted drift than OpenRocket which is interesting considering its descent time is smaller. However, it is difficult to further explore why RockSim's drift is larger than OpenRocket's due to the closed-source nature of RockSi's proprietary methodology. Regardless, the various methods yield no indication that excessive drift will be a threat for the full-scale vehicle.

5.3 Structural Analysis

5.3.1 Peak Thrust

The L2200G-P motor applies intense forces on the launch vehicle. In order to ensure that the design can withstand the motors' forces, FEA was performed on all the major components of the vehicle. As listed in Section 3.4.3, the max thrust force of the L2200G-P motor is 697 lbf. This force was applied to the centering rings, motor mount tube, ACS body tube, and payload body tube. Figures 73, 74, 75, and 76 display the results of the FEA on the centering ring, motor mount tube, ACS body tube, and payload body tube, respectively. As well, Table 73 lists the component, the force applied, the peak stress, the breaking stress, and the factor of safety.

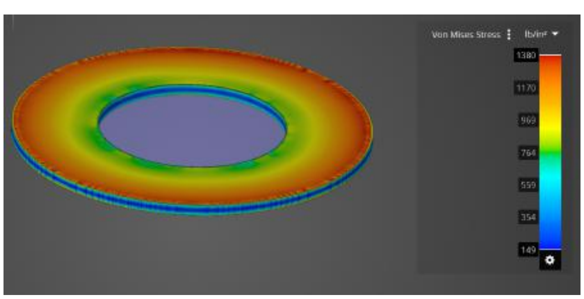


Figure 73: Centering Ring FEA

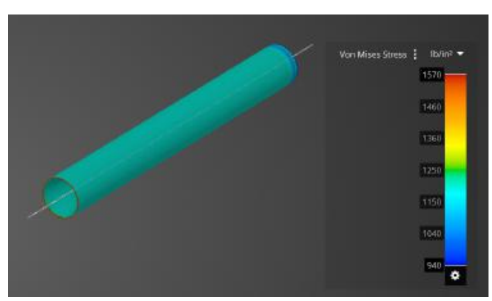


Figure 74: Motor Mount Tube FEA

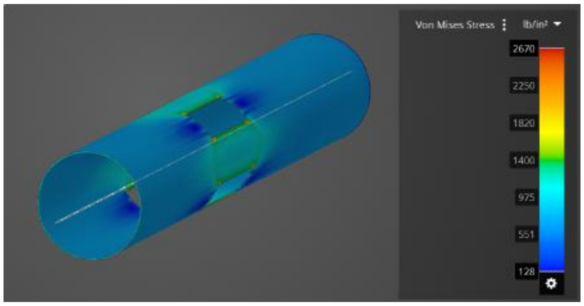


Figure 75: ACS Body Tube FEA

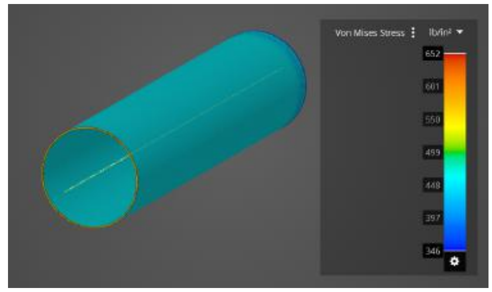


Figure 76: Payload Body Tube FEA

Table 73: Factors of Safety for Airframe Structural Components based on Ansys FEA Analysis

Component	F Applied (lb)	Peak Stress (psi)	Breaking Stress (psi)	FoS
Centering Rings	697	1380	63800	46.3
Motor Mount Tube	697	1570	507600	185.0
ACS Body Tube	697	2670	507600	323.3
Payload Body Tube	697	652	63800	97.8

Given the extremely large factor of safety of all components, it is safe to say that the vehicle airframe can withstand the thrust forces of the L2200G-P motor.

5.3.2 Main Deployment

The deployment of the main parachute produces some of the largest accelerations and forces expected during the course of the flight. Figure 77, below, shows a simplified free-body diagram of the launch vehicle and its components during this event.

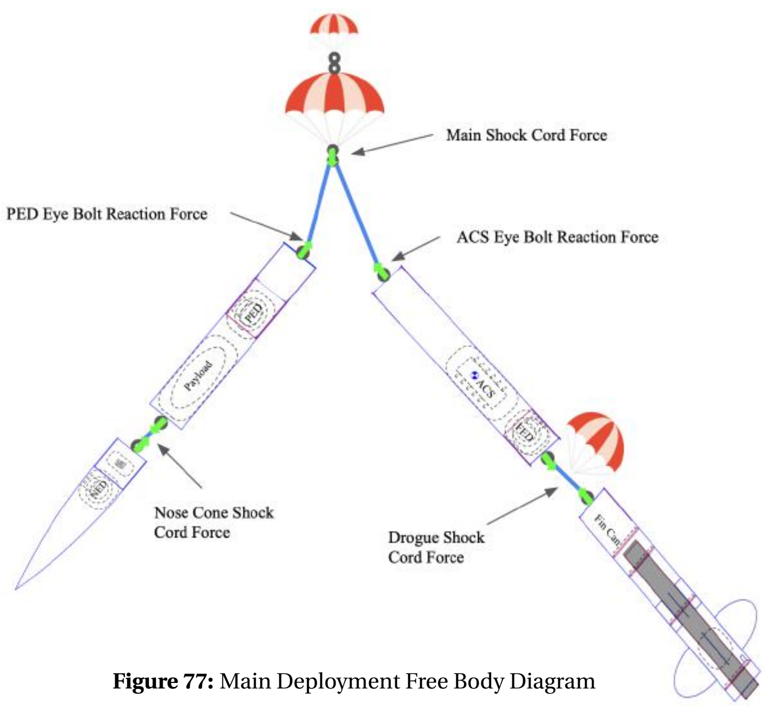


Figure 77: Main Deployment Free Body Diagram

The global acceleration of the entire launch vehicle must be found the calculate the force on each component. This force can be calculated using the equation

$$\sum F = D - W = ma \tag{16}$$

where D is the drag produced by the entire vehicle during the main descent (including the main and pilot parachutes), W is the weight of the entire vehicle after burnout, m is the mass of the entire vehicle after burnout, and a is the global acceleration. Solving for a it can be found

$$a = \frac{D}{m} - g \tag{17}$$

where g is the acceleration due to gravity. D is calculated using the equation

$$D = \frac{1}{2}\rho v_{\text{drogue}}^2 C_d A_{\text{main}} \tag{18}$$

where v_{drogue} is the descent rate under the drogue parachute and $C_d A_{\text{main}}$ is the effective $C_d A$ of the entire vehicle under the main and pilot parachutes. After substitution, the final equation for the global acceleration is

$$a = \frac{\frac{1}{2}\rho v_{\text{drogue}}^2 C_d A_{\text{main}}}{m} - g = 797.19\text{ft/s}^2 = 24.78\text{g} \tag{19}$$

The force experienced on a given shock cord can be calculated using the equation

$$\sum F = T - W_{\text{supported}} = m_{\text{supported}} a \tag{20}$$

where T is the tension in the shock cord, $W_{\text{supported}}$ is the weight of the supported components, and a is the global acceleration. Similarly, the force supported by a given eye bolt/bulkhead can be calculated by multiplying the sum of the global acceleration and the gravitational constant by the mass of the sections supported. This is especially relevant for the PED and ACS bulkhead force calculations which should sum to the total force on the main shock cord (assuming the main shock cord only supports the weight of the sections below it). The force on the eye bolts and bulkheads connected to both sides of the nose cone and drogue shock cords should be identical to the force on the shock cord itself. Therefore, the masses used in Table 74 were used to calculate the forces on each component listed in Table 75. The listed weights are the sum of the weights of all the supported items including both body tube sections and relevant laundry components.

Table 74: Weight Supported by Components

Component	Weight Supported (oz)
Main Shock Cord	687.58
PED Eye Bolt	285.86
ACS Eye Bolt	401.73
Nose Cone Shock Cord	82.65
Drogue Shock Cord	223.91

Table 75: Main Deployment Forces on Components

Component	Force Supported (lb)
Main Shock Cord	1107.76
PED Eye Bolt	460.54
ACS Eye Bolt	647.21
Nose Cone Shock Cord	133.15
NED Eye Bolt	133.15
Aluminum Ring Eye Bolt	133.15
Drogue Shock Cord	360.74
FED Eye Bolt	360.74
Fin Can Eye Bolt	360.74

The main shock cord and the eye bolts connecting it to the parachute experience the largest force as they support the weight of the entire vehicle except that of the main parachute, pilot parachute, and their associated components. The factor of safety for any given component can then be calculated using the equation

$$FoS = \frac{S}{F} \tag{21}$$

where FoS is the factor of safety, S is the designed maximum force for a component, and F is the expected load on that component. For example, the factor of safety for each screw used to transmit event loads from the recovery modules through the airframe interfacing blocks to the body tube was calculated using the equation

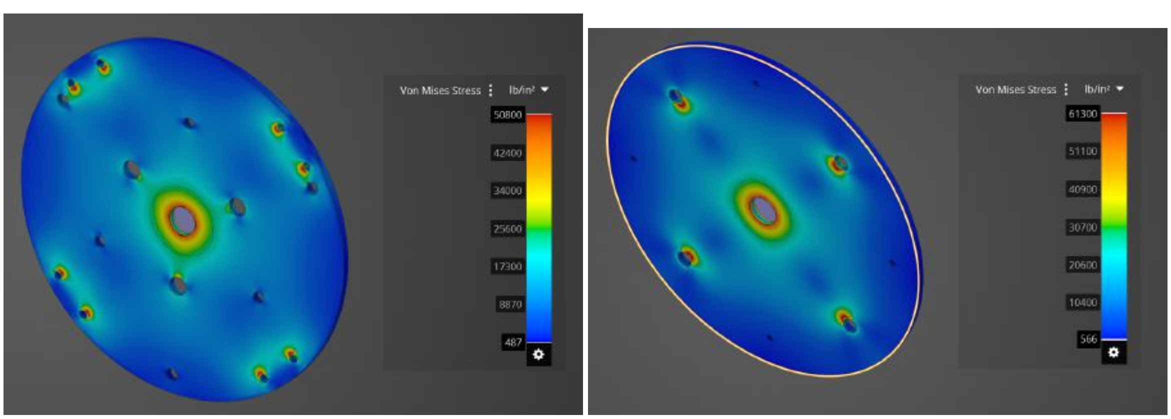
$$FoS = \frac{n\tau_{\text{shearmax}}\frac{\pi}{4}D^2}{F} \tag{22}$$

where τ_{shearmax} is the max shear strength of the 18-8 Stainless Steel Button Head Hex Drive Screw to be used (42000 psi), D is the diameter of the screw (0.164 in), n is the number of screws distributing the force (4), and F is the force to be transmitted to the body tube. The airframe interfacing block screws that will have to transfer the most load to the body tubes will be those on the ACS bulkhead as that bulkhead will experience a force of 647.21 lbs. For this screw, one can calculate the FoS to be 5.48 thus showing that these screws will be sufficient for all of the airframe interfacing blocks. The factor of safety for the full list of components in the primary load-bearing path can be viewed in Table 76, below.

Table 76: Factors of Safety for Load-Bearing Components

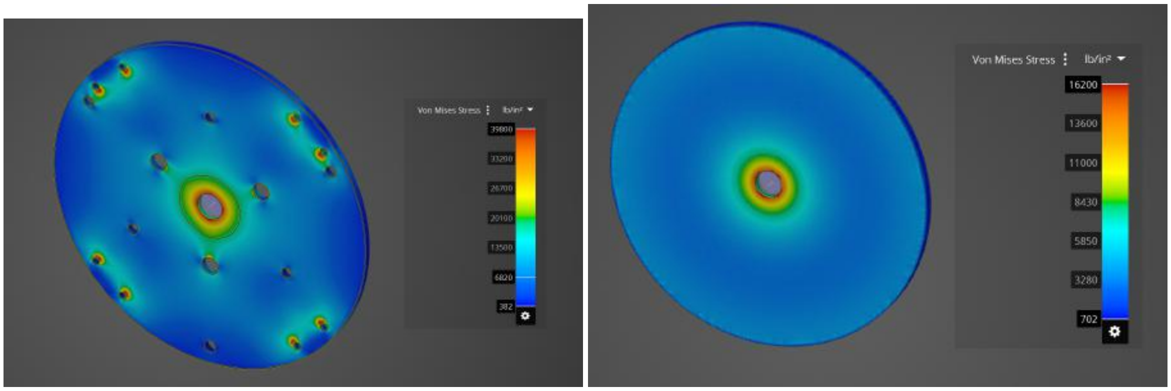
Component	Location	F Experienced (lb)	Breaking F (lb)	FoS
Main Shock Cord	Payload & ACS Bay	1107.76	4400	3.97
3/8" Steel QL	Main Parachute	1107.76	3600	3.24
3/8" Zinc QL	Payload Bay	460.54	2200	4.77
3/8" Zinc QL	ACS Bay	647.21	2200	3.40
3000lb Swivel	Main Parachute	1107.76	3000	2.71
7/16" Steel Eye Bolt	PED	460.54	2000	4.34
7/16" Steel Eye Bolt	ACS	647.21	2000	3.09
Drogue Shock Cord	ACS Bay & Fin Can	360.74	3200	8.87
3/8" Zinc QL	Drogue Parachute	360.74	2200	6.10
3/16" Steel QL	Payload Bay	360.74	990	2.74
3/16" Steel QL	Fin Can	360.74	990	2.74
7/16" Steel Eye Bolt	FED	360.74	2000	5.54
7/16" Steel Eye Bolt	Fin Can	360.74	2000	5.54
NC Shock Cord	NC & Payload Bay	133.15	5300	39.80
3/16" Steel QL	Nose Cone	133.15	990	7.44
3/16" Steel QL	Payload Bay	133.15	990	7.44
7/16" Steel Eye Bolt	NED	133.15	2000	15.02
1/4" Steel Eye Bolt	Al Ring	133.15	500	3.76

The bulkheads were analyzed using the Ansys Finite Element Software. The bulkheads with airframe interface blocks were fixed at the holes where those blocks will be mounted as this is where the force on the eye bolt will be transferred out of the bulkhead. For the fin can bulkhead, the entire perimeter of the circle is fixed as this will be epoxied into the fin can. Lastly, the aft NED bulkhead is fixed at the turnbuckle standoff holes as this is where the force from the eye bolt will exit the bulkhead as it is transferred to the fore NED bulkhead. The force of the eye bolt is applied over the area of the associated washer for each bulkhead as the eye bolt tries to pull said washer "through" the bulkhead. The results of each FEA analysis can be seen in Figures 78, 79, 80, and 81 below.



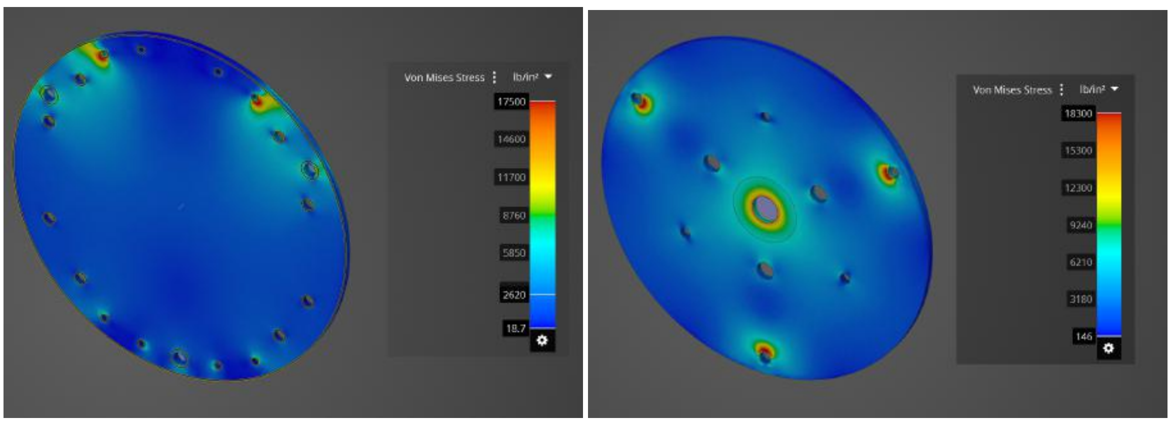
(a) PED Bulkhead Results (b) ACS Bulkhead Results

Figure 78: PED and ACS Bulkhead FEA



(a) FED Bulkhead Results (b) Fin Can Bulkhead Results

Figure 79: FED and Fin Can Bulkhead FEA



(a) NED Fore Bulkhead Results (b) NED Aft Bulkhead Results

Figure 80: NED Bulkheads FEA

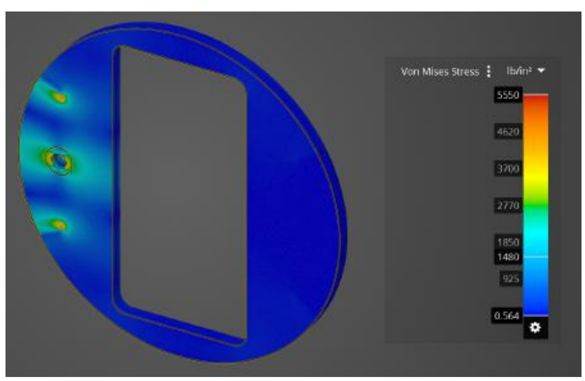


Figure 81: Aluminum Ring FEA

The results can also be viewed in tabular form in Table 77, below, along with the appropriate factor of safety calculated for each bulkhead.

Table 77: Factors of Safety for Bulkheads based on FEA Analysis

Bulkhead	F Applied (lb)	Peak Resultant Stress (ksi)	Strength (ksi)	FoS
PED Bulkhead	460.54	50.80	290	5.71
ACS Bulkhead	647.21	61.30	290	4.73
FED Bulkhead	360.74	39.80	290	7.29
Fin Can Bulkhead	360.74	15.80	290	18.35
NED Fore Bulkhead	133.15	17.50	290	16.57
NED Aft Bulkhead	133.15	18.30	290	15.85
Al Ring	133.15	5.55	30	5.41

5.3.3 Fin Flutter

In order to ensure that the fin design is safe during flight, an in-depth analysis of the fin flutter must be completed. Equation 23 can be used to determine the speed threshold, V_f, before fin flutter is a potential issue (per Apogee Components):

$$V_f = a\sqrt{\frac{\frac{G}{1.337AR^3P(\lambda+1)}}{2(AR+2)(\frac{t}{c})^3}} \tag{23}$$

where a is the speed of sound, G is the material's modulus (for the type of loads on the fins), AR is the aspect ratio, P is the pressure, λ is the taper ratio, t is the thickness, and c is the root chord. In order to find the speed of sound, the Equation 24 was used:

$$a = \sqrt{1.4 \times 1716.59 \times (T+460)} \tag{24}$$

In order to find the aspect ratio, Equation 25 was used:

$$AR = \frac{b^2}{S} \tag{25}$$

where b is the fin span, or height, and S is the fin area. In order to find the area of an elliptical fin, Equation 26 was used:

$$S = \frac{1}{4}\pi bc \tag{26}$$

Using Equation 26, the fin area is:

$$S = \frac{1}{4}\pi(6.00in)(6.00in) = 9\pi in^2 \approx 28.274in^2 \tag{27}$$

and thus, , given the fin height of 6.00 inches, the aspect ratio is:

$$AR = \frac{(6.00in)^2}{28.274in^2} = 1.273 \tag{28}$$

In order to determine the taper ratio, λ, Figure 82 was used. Given the aspect ratio of 1.273 and the fact that the wings are elliptical, the taper ratio of the fins is 0.44.

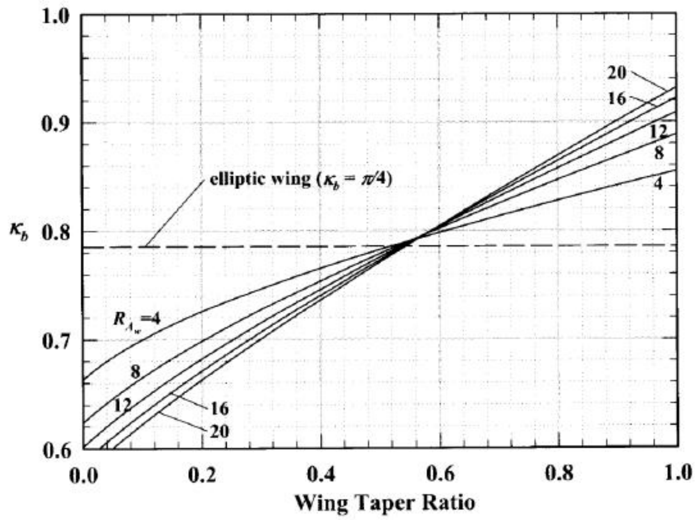


Figure 82: Taper Ratio Figure, taken from "Mechancs of Flight" from Warren F Phillips

In order to determine the temperature and pressure, the Earth atmosphere model was used. Equation 29 is used to find the temperature, T, given the input of height, h.

$$T = 59.0 - 0.00356h \tag{29}$$

Given that the international standard atmosphere temperature on the ground is 59 °F, and the international standard atmosphere model was used on both OpenRocket and RockSim for the temperature and pressure values, the results of this assumed temperature and pressure should be precise. In order to determine the pressure, P, Equation 30 was used:

$$P = \frac{2116}{144} \times \left(\frac{T + 459.7}{518.6}\right)^{5.256} \tag{30}$$

When inputting the starting temperature of 59^o, Equation 31 is the result:

$$P = \frac{2116}{144} \times \left(\frac{59 + 459.7}{518.6}\right)^{5.256} = 14.7psi \tag{31}$$

14.7 psi is equivalent to the international standard atmosphere pressure on the ground. Thus, at least for the starting conditions the Earth atmosphere model is a good assumption to use when calculating flutter. The approximate speed of sound at ground level is 1100 $\frac{ft}{s}$. Using Equation 24, Equation 32 is the speed of sound at ground level, using the international standard atmospheric temperature, in order to confirm a level of accuracy of the assumed calculation for the speed of sound:

$$a = \sqrt{1.4 \times 1716.59 \times (59 + 460)} \tag{32}$$

Given a value of 1116.8 $\frac{ft}{s}$, it can be deduced that the speed of sound equation has a level of precision, at least near the ground. Finally, the only unknown variable left to be determined before running the flight data is the modulus. Table 78 lists the mechanical properties of a G10 Fiberglass Laminate Sheet, as measured by MatWeb, a material property database. In order to ensure that the design is as safe as possible, the crosswise Flexural Modulus value, 2,400 ksi, will be chosen.

Table 78: MatWeb G10 Fiberglass Laminate Sheet Information

Type of Stress	Value	MatWeb Comments
Flexural Modulus	2,400 ksi	Crosswise; ASTM D790
Flexural Modulus	2,700 ksi	Lengthwise; ASTM D790

With the starting temperature, pressure, and modulus conditions known, the launch vehicle simulations can be ran for various wind speeds launch angles in order to determine the flight's characters over a span of potential launch conditions. Notably, the launch velocity, temperature, and pressure are to be collected from the simulations as a function of time. Using Equation 23 and OpenRocket and RockSim Data, Table 79 displays the launch vehicle flutter conditions for OpenRocket and RockSim, respectively, with the flight velocity data plotted alongside the flutter velocities. The flight conditions chosen for the two simulators is based on the conditions that yielded the highest velocity at burnout. As seen in Table 79, the launch vehicle velocity never reaches anywhere near the threshold of the flutter velocity. As well, the flutter was also calculated based on the simulators' calculations of pressure and speed of sound; temperature is only used to calculate pressure and speed of sound and is not used in Equation 23 directly. The flutter values overlap very closely. Thus it is confined that the use of Equations 24, 29, and 30 are valid. The validation of these equations allows the some of the assumptions made in Section 3.5.4.6 to be sound, validating the results. For the MATLAB code used to compute the OpenRocket fin flutter graph and the factor of safety, see Appendix Section C.1; the same principle was applied for the RockSim figure and factor of safety.

Table 79: OpenRocket (Left) and RockSim (Right) Predicted Fin Flutter Threshold

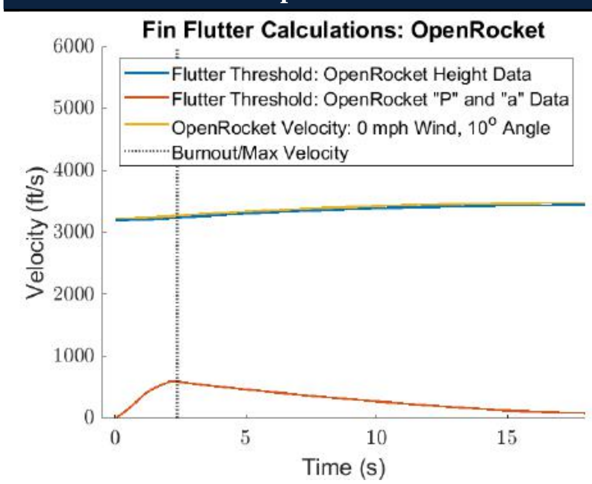
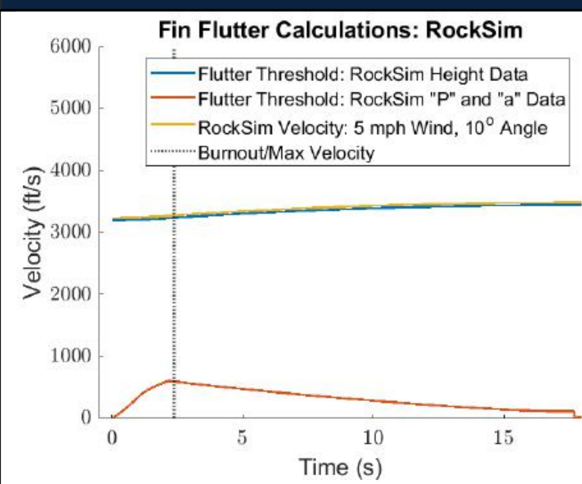
OpenRocket	RockSim
	

Table 80 also lists the maximum velocity of the launch vehicle during flight, the minimum fin flutter threshold velocity, and the factor of safety of this situation. There is an extremely high factor of safety on the system; the design is safe from flutter.

Table 80: Factors of Safety for the Fin Flutter

Method	Max. Simulator's Velocity (ft/s)	Min. Fin Flutter Threshold Velocity (ft/s)	FoS
OpenRocket	598.10	3198.40	5.35
RockSim	600.68	3198.58	5.32

5.4 CFD

NASA Req. 2.16 requires that a camera shroud can be used on the launch vehicle, as long as it is demonstrated that it will cause minimal affect of the launch vehicle's stability. Figures 83 and 84 display the velocity and pressure, respectively, of the launch vehicle surface. Since the focus is on the flow reattachment after the camera shroud, the fins have basically no effect and were removed from the model; this also had the unintended affect of simplifying the model, for it is abundantly known how computationally expensive — time, storage — CFD model can become. The figures also demonstrate that the flow does, in fact, reattach far before ever nearing the fins' location. Thus, the stability is not affected by the camera shroud, and NASA Req. 2.16 is followed. Therefore, the camera shroud can and will be used on the launch vehicle.

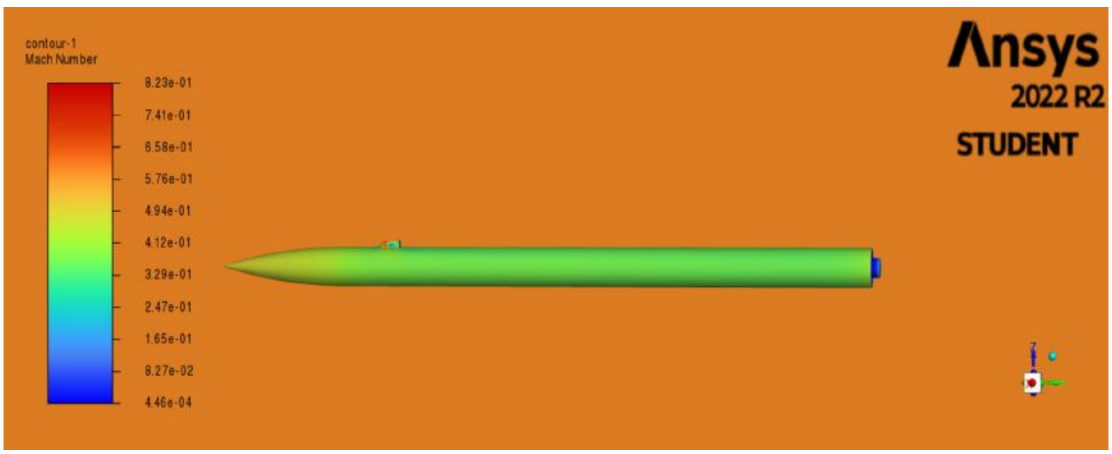


Figure 83: 2D CFD Model of the Velocity Over the Surface

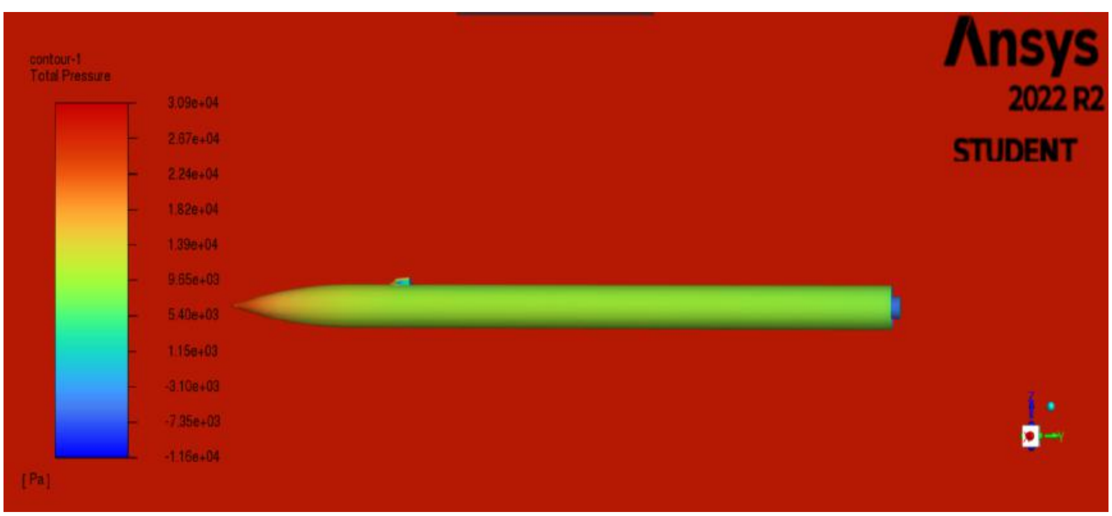


Figure 84: 2D CFD Model of the Pressure Over the Surface

6 Technical Design: 360° Rotating Optical Imager

6.1 Mission Statement

The Notre Dame Rocketry Team's scoring payload for the 2022-2023 NASA Student Launch Initiative is the **3**60° **R**otating **O**ptical **I**mager (**TROI**). The team is designing, building, and testing a payload that once landed receives RF communications, translates them into software commands, and deploys a camera subassembly outside the payload tube. The camera subassembly orients itself parallel to the z-axis, and it takes and stores images as instructed by the RF command sequence.

6.1.1 Success Criteria

The success of the payload mission will be determined with the following criteria:

- The TROI shall be rigidly fixed inside the launch vehicle's payload tube during flight, so that only the camera subassembly deploys quickly and accurately after landing (NASA Reqs. 4.2.3.3., 4.2.4.).
- The TROI shall operate in variable weather conditions and temperatures such that the mechanics and electronics are fully functional.
- The TROI shall protect the electronics from potential water damage or residue from the recovery systems.
- The TROI shall deploy the camera subassembly so that it is correctly oriented and freely rotates about the z-axis perpendicular to the ground plane (NASA Reqs. 4.2.1., 4.2.1.1.).
- The TROI shall take a series of clear, obstruction-less pictures when commands are received via RF communications. The TROI shall modify those images if requested per the RF commands (NASA Req. 4.2.2.).
- The TROI shall successfully receive and execute set commands sent by NASA's ARPS protocol (NASA Reqs. 4.2.2., 4.2.3.).
- The TROI shall save the sequence of time-stamped photos for future retrieval from the onboard microcontroller (NASA Req. 4.2.5.).
- The TROI shall be serviceable for changes during tests and the competition.

6.2 PDR Design Alternatives

Three design alternatives were considered in PDR. These included an internal system that remains in the launch vehicle, an external system that leaves the launch vehicle upon landing, and a semi-external system containing components that remain inside as well as components that exit the launch vehicle. A trade study was conducted using the criteria of reliability of deployment and the overall mission, design complexity, machinability, cost, and weight. The team selected the internal payload system for its deployment reliability and ease of development.

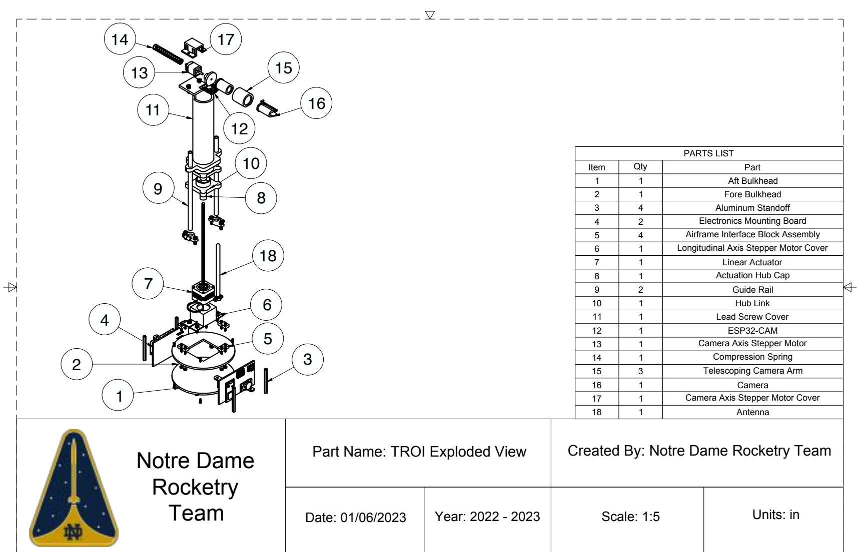
6.3 Design Overview

The TROI remains fixed throughout the flight and will receive instructions via RF to create commands upon landing. The camera subassembly will deploy outside the payload tube by actuating a lead screw along the longitudinal axis of the payload tube with a stepper motor. An accelerometer will determine the proper orientation for the camera subassembly, and a telescoping arm will deploy and position the camera above the payload tube (NASA Reqs. 4.2.1.1., 4.2.1.2., 4.2.4., 4.3.1.). The camera subassembly will use a stepper motor for full z-axis rotation capabilities. Images will be taken, processed, and stored in accordance with received RF commands on an onboard ESP32 microcontroller (NASA Req. 4.2.2.). The camera subassembly will rotate up to 360º about the z-axis based on received RF commands (NASA Reqs. 4.2.1., 4.2.1.1.). The RF commands are not received and processed until after the launch vehicle lands (NASA Req. 4.2.3.3.). The TROI will not electronically interface with either the recovery systems or the ACS (NASA Req. 3.8.). CAD renderings of the TROI in its retained and deployed configurations are shown in Figure 85.

(a) Retained Configuration (b) Deployed Configuration

Figure 85: TROI Rendering

An exploded view drawing of the TROI is provided in Figure 86.



PARTS LIST		
Item	Qty	Part
1	1	Aft Bulkhead
2	1	Fore Bulkhead
3	4	Aluminum Standoff
4	2	Electronics Mounting Board
5	4	Airframe Interface Block Assembly
6	1	Longitudinal Axis Stepper Motor Cover
7	1	Linear Actuator
8	1	Actuation Hub Cap
9	2	Guide Rail
10	1	Hub Link
11	1	Lead Screw Cover
12	1	ESP32-CAM
13	1	Camera Axis Stepper Motor
14	1	Compression Spring
15	3	Telescoping Camera Arm
16	1	Camera
17	1	Camera Axis Stepper Motor Cover
18	1	Antenna

Figure 86: TROI Exploded View

6.3.1 System Layout

The TROI features a tiered bulkhead structure as selected in PDR. The electronics will mount on two wooden mounting boards placed between the tiered bulkheads and connected via brackets. The electronics stored on the mounting boards include the ESP-WROOM-32 microcontroller, accelerometer, PCB, stepper motor drivers, the real time clock, and the transceiver module. The ESP32-CAM will mount on the telescoping camera arm. The Li-PO battery will be stored on the aft bulkhead. The guide rails for the deployment subsystem will mount on the fore bulkhead.

6.4 Retention

Four aluminum standoffs will connect the fore and aft bulkheads and ensure that the electronics experience minimal impact from vibrations during flight. The longitudinal axis lead screw stepper motor will bolt into the aft bulkhead. The stepper motor and lead screw assembly extends through a rectangular hole in the fore bulkhead. This ensures the lead screw assembly will experience minimal unwanted motion during flight, landing, and deployment. The secondary stepper motor which actuates the camera subassembly will be retained in place with a 3D printed case bolted to the 3D printed cylindrical sleeve surrounding the lead screw.

6.4.1 Vehicle Integration

Four airframe interface blocks bolted to the fore fiberglass bulkhead of the TROI will rigidly retain the payload relative to the launch vehicle throughout all aspects of flight, landing, and deployment. The TROI will be located in the payload body tube aft of the NED recovery module and fore of the PED recovery module.

6.5 Camera Deployment

The camera subassembly will deploy out the fore end of the payload tube. The deployment will be achieved through a set series of events, and the camera subassembly has four degrees of freedom as described in Section 6.5.1. The camera subsystem will deploy with a 1.5 in. clearance along the longitudinal axis of the payload tube. The camera will extend 1.5 in. above the payload tube using a custom telescoping camera arm (further described in Section 6.5.2). The team completed FEA and beam deflection calculations to validate the design choices for the CDR milestone and are included in Section 6.5.3.

6.5.1 Deployment Sequence

The following deployment sequence will be completed to deploy the camera subassembly:

- The TROI starts deployment in the retained configuration. The longitudinal axis stepper motor is then activated to rotate the lead screw and translate the camera subassembly forwards. The camera subassembly is constrained by the guide rails and does not rotate. The longitudinal translation is the first degree of freedom.
- At the end of the longitudinal translation, the camera subassembly exits the guide rails while locking onto the lead screw for stability and is free to rotate about the longitudinal axis. As the lead screw rotates, the camera subassembly will rotate about the longitudinal axis without translating, providing the 2nd degree of freedom. The longitudinal axis stepper motor will rotate to the correct orientation so that the camera is parallel to the z-axis, and then the stepper motor will deactivate.

- The camera axis stepper motor activates and rotates. After this predescribed rotation, the telescoping camera arm is no longer constrained, and it deploys. The camera is now raised above the payload body tube to take a higher quality picture. The telescoping camera arm is the third degree of freedom.
- The camera axis stepper motor can rotate the camera about the z-axis and provide for 360º rotation (NASA Reqs. 4.2.1., 4.2.1.1.). This is the fourth degree of freedom.

6.5.2 Telescoping Camera Arm

A cam latch-style locking mechanism will retain the telescoping camera arm, with a compressed spring contained within the concentric tubes. When the camera axis stepper motor activates and rotates, the locking mechanism is released and the spring decompresses, extending each successive telescoping tube. The maximum deployment distance of each tube is limited by the overlapping of rings at the bottom and top of the inner and outer tubes respectively. A drawing of the telescoping camera arm in the deployed state is shown in Figure 87. A drawing of the telescoping camera arm in the retained state is shown in Figure 88.

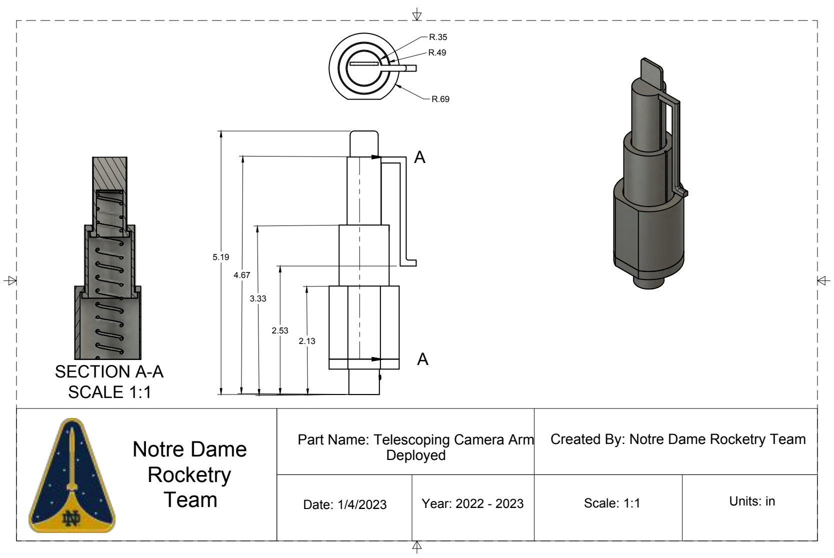


Figure 87: Deployed Telescoping Camera Arm

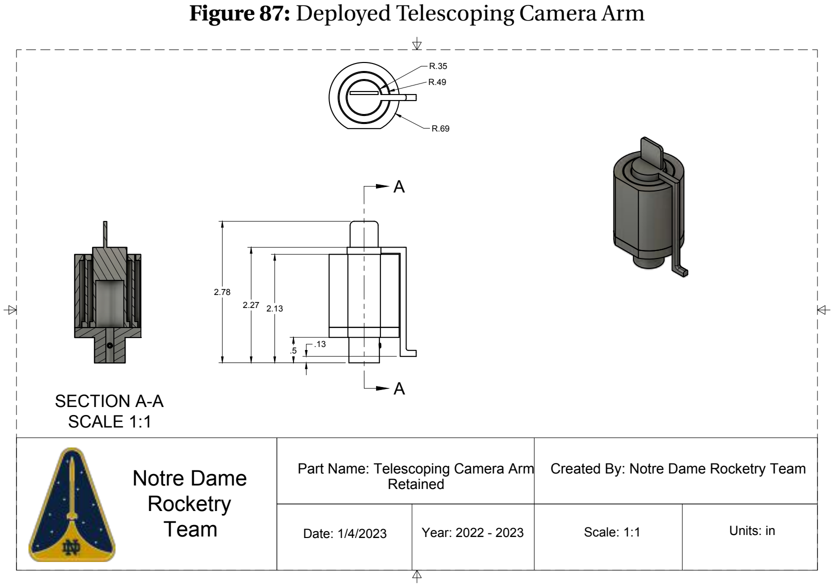


Figure 88: Retained Telescoping Camera Arm

6.5.3 FEA and Beam Deflection Calculations

The team performed beam deflection calculations on the TROI lead screw to determine the deflection present of the TROI in the deployed state. In the deployed state, the lead screw can be approximated as a cylindrical cantilever beam with a point load at its end. This point load is the weight of the camera subassembly plus the lead screw cover with a value of approximately 1.18 lbs (including 1.5 FOS). The following beam deflection equation was utilized,

$$\delta = \frac{PL^3}{3EI}, \tag{33}$$

where δ is the deflection of the beam, P is the point load, L is the length of the beam, E is the modulus of elasticity, and I is the moment of inertia of the cross section. The required 9.75 in. lead screw length will experience a maximum of approximately 0.0675 in. of deflection. A drawing of the lead screw cover is provided in Figure 89.

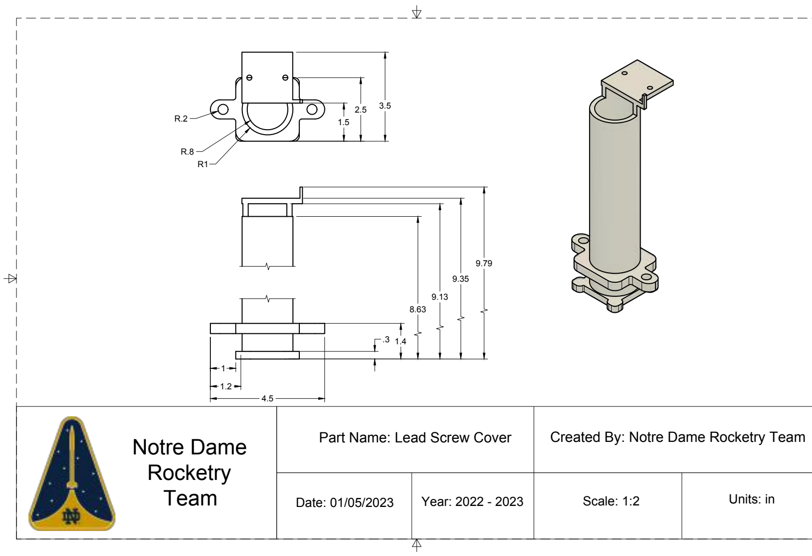


Figure 89: Lead Screw Cover Drawing

The team performed FEA on the lead screw cover to determine its max deflection and strain. A point load was placed at the top of the lead screw cover, and the base of the lead screw cover was fixed. The point load had the same value as the beam deflection calculation. The results of the FEA demonstrated there is negligible deflection and deformation in the lead screw cover with a factor of safety of greater than 1.5 (NDRT TROI.2). The combined max deflection of the lead screw cover and the lead screw is less than the tolerance between the camera subsystem and the removable wall, thus providing for a safe design from these factors (NDRT TROI.1).

6.5.4 Deployment Testing Overview

Several tests are planned to evaluate and improve the TROI deployment subsystem. Each stage of the deployment sequence will be tested independently to verify that the movement matches the expected result. The team will test the whole deployment subsystem to verify the transition between the deployment sequence stages at various angles and orientations to test its robustness. The TROI test plans are provided in Section 9.1.3.

6.6 Electronics

6.6.1 Overall System Electronics

The TROI electronics include an accelerometer, a camera module with microSD card for storage, an RF transceiver, a TNC, a real time clock, two drivers and two stepper motors, two microcontrollers, and a central battery. The electronics are partitioned into two subsystems, with one subsystem containing the ESP-WROOM-32 microcontroller, accelerometer, RF transceiver, TNC, and real time clock integrated on a custom printed circuit board, with external connections to the two stepper motors.

Referred to as the ESP32 Main subsystem, this subsystem represents the majority of electronic components in the overall system, and will be stored on the twin mounting boards located between the tiered bulkheads. This subsystem detects landing, controls the stepper motors, and receives RF commands.

The other subsystem, referred to as the ESP32-CAM subsystem, will contain the ESP32-S microcontroller and OV2640 camera, integrated as part of the commercial ESP32-CAM OV2640 module. This subsystem will attach to the moving camera arm and is free to rotate with the camera. The ESP32-CAM subsystem captures, processes, and stores images.

The two subsystems connect via a wireless communication protocol. The following sections discuss the details and integration of the batteries, sensors, microcontrollers, camera, transceiver, and motors.

6.6.1.1 Battery The TROI battery must have ample capacity to power the ESP32 Main and ESP32-CAM subsystems for the entire post-landing sequence and for possible launch delays of up to three hours, meeting NASA Req. 2.6. The battery must remain sufficiently compact and light to fit within the TROI bulkhead. The Tenergy Power Li-Po battery meets these criteria, with a capacity of 3Ah at a supply voltage of 11.1V. The output voltage can be regulated down to the 5V level required by both ESP32 microcontrollers, the TNC, and the OV2640 camera, as well as the 3.3V level required by the accelerometer, RF transceiver, and real time clock. The 11.1V output is sufficient to power each stepper motor driver since each driver has an 8-12V input requirement to operate.

6.6.1.2 Power Distribution The Tenergy Power Li-PO battery will be housed on the aft TROI bulkhead which connects to the two stepper motor drivers and the two printed circuit boards housing the ESP32 Main and ESP32-CAM subsystems, respectively. Connection to the ESP32 Main subsystem, nearby on the aft TROI bulkhead, is straightforward. Connection to the ESP32-CAM subsystem will be done strategically with sufficient wire length to ensure wires will not tangle or catch on any surfaces as the camera arm deploys and rotates post-landing.

The custom PCB for the ESP32 Main subsystem will contain a regulator to step-down the 11.1V input to 5V for the ESP-WROOM-32 microcontroller and TNC. Another regulator will be used to step-down from 5V to 3.3V for the accelerometer, transceiver, and real time clock. The PCB-based arrangement provides stronger connections and superior mechanical stability compared to alternative wiring methods, accommodates different voltage levels, and is the simplest option because the PCB will also be responsible for data connections between the three components.

The pre-assembled PCB for the ESP32-CAM contains the regulator to step-down from 11.1V to 5V for the ESP32-S microcontroller and OV2640 camera. The power distribution block diagram is shown in Figure 90.

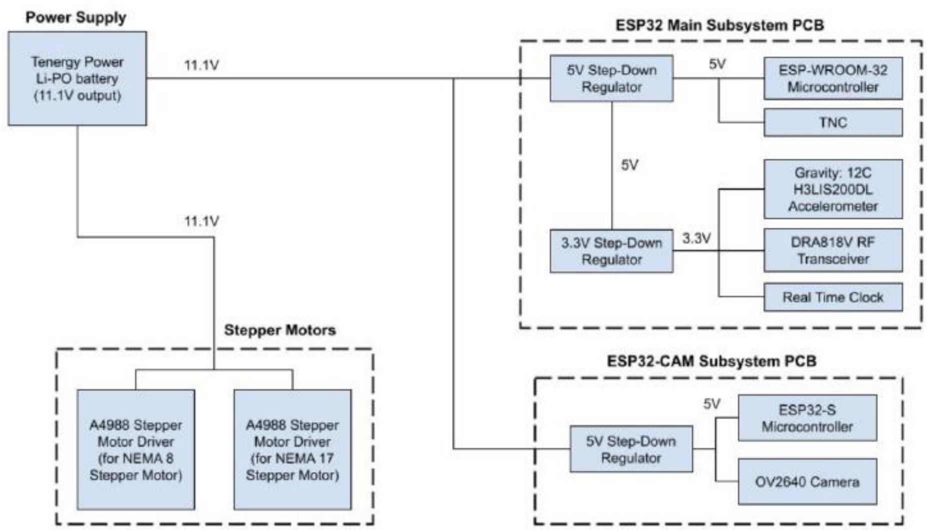


Figure 90: ESP32 Main and ESP32-CAM Power Distribution

6.6.1.3 Microcontroller The two microcontrollers used by the TROI are both ESP32 series microcontrollers by Espressif Systems. The main microcontroller (part of the ESP32 Main) will mount on a custom PCB which will interface with all major control sensors of the payload. These include the RF receiver, the stepper motors, the accelerometer, and the real-time clock. The ESP32-CAM subsystem will contain the second microcontroller, which is a prebuilt board interfaced with an Arducam OV2640 camera and a microSD card reader. These two ESP32 subsystems will communicate over the ESP-NOW protocol, which is a low-power 2.4GHz wireless protocol similar to Bluetooth. Both microcontrollers are powered with a regulated 5V source.

The team chose the ESP32 for its combination of utility and low cost. With the maximum ratings that the payload anticipates, the ESP32 provides an appropriate level of hardware capability to accomplish all functions without being too expensive or under powered. Another benefit is the pre-existing compatibility with an appropriate camera for the payload design requirements.

6.6.1.4 Sensors TROI includes two major sensors to determine command actions within the payload. These are the accelerometer and the real-time clock and help ensure proper payload deployment and image capture according to NASA requirements.

Firstly, the accelerometer's primary purpose is to detect when the launch vehicle lands to initiate deployment in accordance with NASA Req. 4.2.3.3.. Its secondary purpose is to orient the camera subsystem's axis of rotation along the z-axis (perpendicular to the ground plane) in accordance with NASA Req. 4.2.1.1.. The accelerometer selected for the design is the DFRobot Gravity 12C H3LIS200DL because of its high accuracy and low cost.

The real-time clock will be used to produce accurate timestamps for images captured by the payload in accordance with NASA Req. 4.2.1.3. The real-time clock selected for the design is Ximimark DS1307 because of its small package dimensions, low cost, and simple implementation.

6.6.2 Camera Subsystem

The Arducam OV2640 camera in conjunction with the ESP32-CAM board will take and save images. The OV2640 is a 2MP camera with high image quality and a robust software library for achieving desired functionalities like image-processing, and the ESP32-CAM board has quality-of-life features such as a built-in microSD card slot. The stock lens that comes with the OV2640 has a field of view of 68°, so a replacement lens will be used to accommodate a wider field of view. Lenses are available in 140° and 160° varieties, and a 140° wide-angle lens will be used in accordance with NASA Req. 4.2.1.2..

The ESP32-CAM board will receive power from the Tenergy Li-Po battery through a 5V voltage regulator. Powering the board with a regulated 5V source will allow access to complete camera operation, and having only the power cables connected to the ESP32 module of the rotating arm will simplify the mechanical actuation (specifically the rotation with wires) of the camera.

6.6.3 RF Subsystem

The RF subsystem consists of the ESP32 Main microcontroller, antenna, DRA818V transceiver, and a TNC based on the MicroModem. A licensed HAM radio Operator, KI5REN, has created a successful test with the ESP32 and DRA818V portion of the subsystem. The DRA818V verified receiving capabilities between 144.90 MHz and 145.10 MHz and disabled transmitting capabilities by hardwiring PTT to 3.3V to comply with NASA Req. 4.2.3.1. Code for configuring the transceiver and setting the frequency is provided in Appendix Figure **??**. First, the ESP32 initialized the settings of the DRA818V including the receiving frequency via the RXD/IO17 and TXD/IO16 U2UXD serial pin connection. After the initialization, the DRA818V remembers the settings and only needs to update to change to the desired new frequency. Next, the AF_OUT pin is stabilized and connected to an analog pin of the ESP32. This allows the ESP32 to sample the audio frequency and verify the transceiver is receiving correctly. The test verifying the system was performed with the following circuit shown in Figure 91.

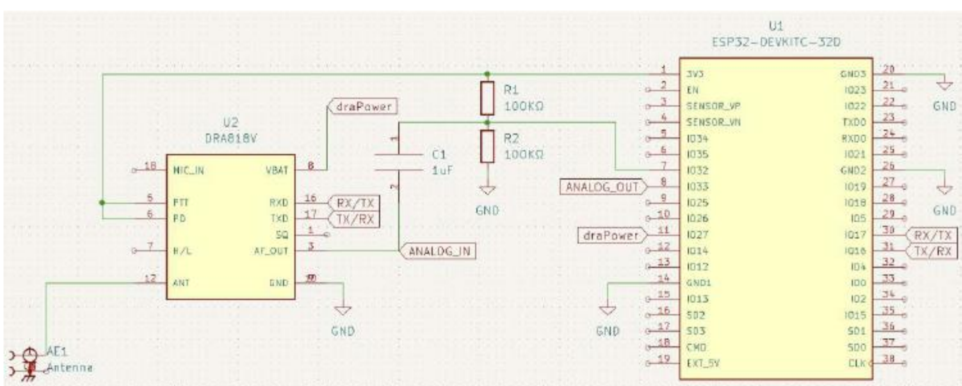


Figure 91: RF Circuit

The next stage of testing will be integrating the MicroModem based TNC into the system for APRS AX.25 AFSK 1200 baud packet demodulation. The MicroModem TNC was a compact, lightweight modem designed for Amateur Radio AX.25 packet communication. Before discontinuation, it was developed and sold by UnsignedIO, a company specializing in producing open-source hardware and software for Amateur Radio. The TNC will demodulate the received frequencies to be converted into usable data, then sent back to the ESP32 for parsing. Next, the ESP32 will parse the packets for the commands and then send the information to the second ESP32 for the commands to be performed (Note: The parsed data will only relay to the second ESP32 once the payload has landed in order to comply with the NASA Req. 4.2.3.3.). The licensed HAM radio Operator, KI5REN, shall test the TNC's ability to demodulate AX.25 AFSK 1200 packets by transmitting via a ground station consisting of a laptop, Easy-Digi Interface, and Baofeng radio. This will ensure TNC's ability to parse data, complying with NASA Requirement 4.2.2.. Figure 92 is the schematic of the current RF system including the ESP32, DRA818V, and MicroModem based TNC.

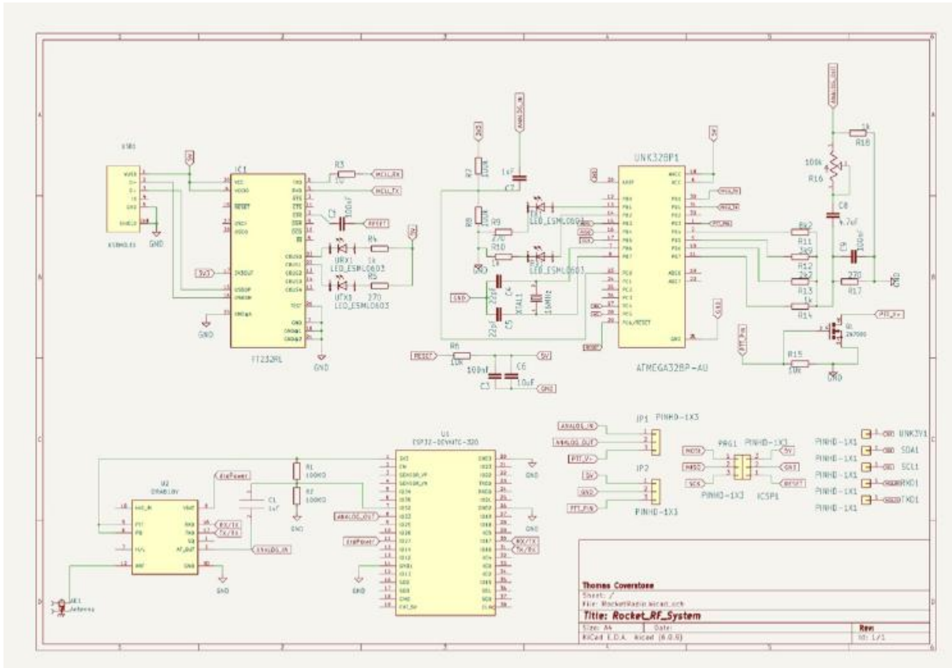


Figure 92: RF Schematic

6.6.4 Stepper Motor Interface

TROI utilizes one NEMA 17 stepper motor and one NEMA 8 stepper motor. A separate driver will control each stepper motor, and the A4988 Stepper Motor Driver Module has been selected due to compatibility with the ESP32 microcontroller and availability of several in team inventory. Each driver requires 8-12 V to power the stepper motors, and the drivers are powered from the central TROI battery. Each driver requires four pins to connect to the ESP32 Main.

6.7 Software

6.7.1 Overall Control Flow

The overall control flow design of the system is described by Figure 93.

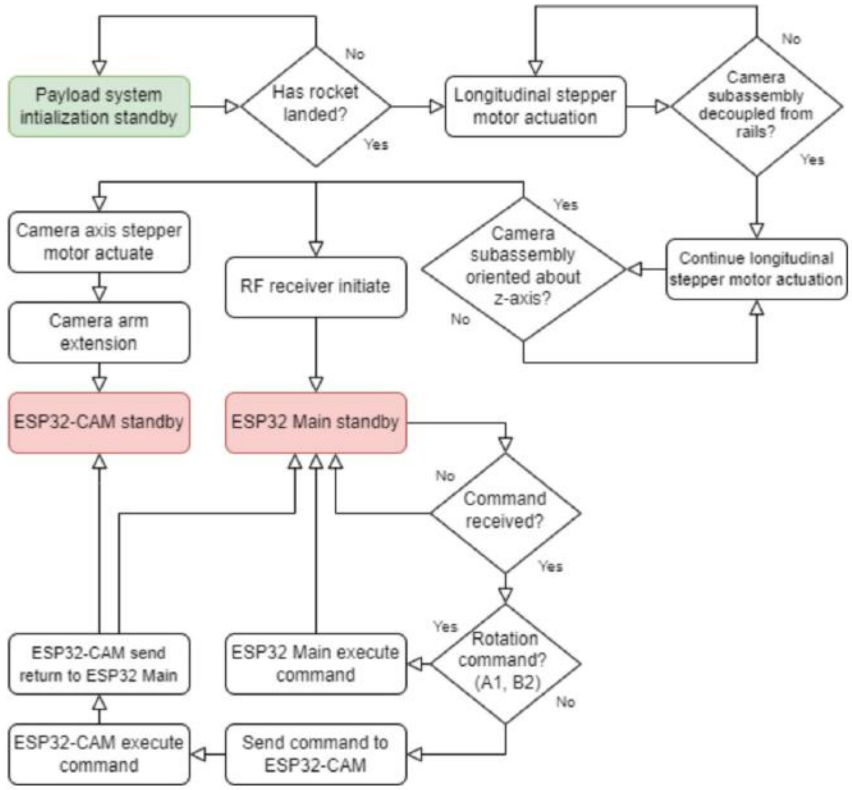


Figure 93: Overall Control Flow

The TROI deployment is first initiated once the launch vehicle re-encounters the planetary surface, which will be determined with the filtered accelerometer data. Once landing has been detected, ESP32 Main will actuate the stepper motor along the longitudinal axis to deploy the camera subassembly. Once the camera subassembly has decoupled from the rails along the body of the launch vehicle, the filtered accelerometer data will be used to orient the telescoping camera arm's axis of rotation along the z-axis perpendicular to the ground plane. The other stepper motor will also rotate slightly to extend the arm which the camera is mounted on. From that point, the RF receiver will activate and begin to passively detect the RAFCO.

Once a string of commands has been received, they will be demodulated by ESP32 Main and handled one at a time. At this point, one of two things can happen. One, if the command involves camera rotation about the z-axis (i.e. A1 or B2 according to NASA Req. 4.2.2.), then ESP32 Main will independently actuate the stepper motor to achieve this effect. Two, if the command involves either image capture or image processing (i.e. C3, D4, E5, F6, G7 or H8 according to NASA Req. 4.2.2.), then ESP32 Main will send a packet to ESP32-CAM via ESP-NOW and ESP32 Main will enter a standby state once it has been sent.

Once ESP32-CAM, which is defaulted to a standby state, has successfully received and executed the command, it will send a packet back to ESP32 Main to commence command interpretation. This will enable the TROI to execute all commands linearly and in a timely fashion with a maximum of 30 seconds elapsed between photos taken (NASA Req. 4.2.1.4.).

6.7.2 ESP32 Control Flow

The TROI requires communication to enable command flow between the two systems of independent microcontroller boards. The TROI utilizes the ESP-NOW protocol, which is an Espressif Systems low-power 2.4 GHz communication protocol similar to Bluetooth. ESP-NOW enables two-way communication between ESP32 microcontroller systems using messages with a payload of up to 250 bytes. As it operates on the 2.4 GHz band, there is no considerable latency. The transmission rate of ESP-NOW is 1 Mbps, which means that, with a packet-size of 250 bytes, the baud rate is 500 Hz. For the TROI, sending strings of 12 or fewer bytes per packet, the maximum required specifications fall within the constraints afforded by ESP-NOW.

6.7.3 Data Filters

As the TROI is required to deploy post-landing according to NASA Req. 4.2.3.3., the accelerometer data monitored in-flight by the payload must be filtered to ensure that a premature deployment does not occur. The accelerometer data will be filtered digitally according to legacy accelerometer data. In general, an impulse accompanied by a steady positive climb in acceleration will trigger the sequence required for deployment, and after, once a constant acceleration of 1g (within a margin of error) is detected for an extended period of time, the camera subassembly deployment process will commence.

6.7.4 RF Processing

The RF system consists of an ESP32 microcontroller, antenna, DRA818V transceiver, and a TNC based on the MicroModem. A successful test of the transceiver portion of the RF system was completed using the following code provided in Appendix Figure **??**. This method uses a modified version of the Arduino-DRA818V library. The program begins by initializing the DRA818V by the ESP32 via the RXD/IO17 and TXD/IO16 U2UXD serial pin connection at 9,600 bps baud rate. Once the serial connection is confirmed via the modified DRA818 library, the DRA818V settings are configured. For this test, the configuration was 144.500 MHz, squelch 4, volume 8, no ctcss, 12.5 kHz bandwidth, all filters activated. Once the DRA818V is configured, the settings are retained even if the DRA818V loses power. The received signal is outputted by the AF_OUT pin and stabilized. This data is now ready to be sent to the TNC. The next stage of testing includes coding and testing the TNC. The received AX.25 AFSK 1200 transmissions are parsed into usable signals by demodulation on the TNC. The TNC removes the carrier frequency to reveal the modulating wave. The TNC then outputs these signals to the ESP32. The ESP32 then uses the LibAPRS library to parse these signals into usable commands.

6.7.5 Camera Assembly Control

The camera subassembly control sequence will initiate autonomously by a flag from the accelerometer which indicates that the launch vehicle re-encountered the planetary surface. This flag signals to ESP32 Main that the longitudinal axis stepper motor should activate to deploy the camera subassembly. After the camera subassembly deploys, the RF receiver will begin passively detecting the RAFCO. As mentioned in the overall design flow Section 6.7.1, there are two separate categories of commands based on those given in NASA Req. 4.2.2.. One set of commands is handled by ESP32 Main and the other by the ESP32-CAM. These microcontroller command assignments are outlined in Table 81.

Table 81: Subsystem Command Partition

Command	Action	Subsystem
A1	Turn camera 60° to the right	ESP32 Main
B2	Turn camera 60° to the left	ESP32 Main
C3	Take picture	ESP32-CAM
D4	Change camera mode from color to grayscale	ESP32-CAM
E5	Change camera mode back from grayscale to color	ESP32-CAM
F6	Rotate image 180° (upside down)	ESP32-CAM
G7	Special effects filter	ESP32-CAM
H8	Remove all filters	ESP32-CAM

These commands are handled independently either by a combination of software implementation and mechanical actuation in the case of the ESP32 Main functions or pure software implementation in the case of the ESP32-CAM functions. Included within the "C3—Take Picture" command is an implicit function that will save the image to the microSD card in the built-in slot ESP32-CAM. The ESP32-CAM microcontroller and board can make use of a robust library which has access to all functionality that is outlined in C3 through H8 of NASA Req. 4.2.2..

6.7.6 Software Testing

Several tests are planned to evaluate the capabilities of the TROI software and to eliminate unforeseen issues. The TROI software will be tested independently for each subsystem as well as in an integrated, full-system form. The camera subassembly will be tested to demonstrate the TROI successfully taking, time-stamping, and saving images. The RF subsystem will be tested to demonstrate the TROI successfully receiving RF signals and processing them into system commands. The deployment subsystem will be tested to evaluate the orientation of the telescoping camera arm for various accelerometer readings. General tests have and will be conducted concerning system integration and battery duration. A detailed list and explanation of all the TROI tests is provided in Section 9.1.3.

6.8 Recovery Interface

The TROI interfaces with the recovery system via a removable wall and centering ring. To ensure that the TROI is not impacted by the gas and debris from the black powder charges when the nose cone is separated, a removable wall will be placed between the TROI and the NED recovery module. The removable wall will be retained in place relative to the rigid centering ring with masking tape. The removable carbon fiber wall will be machined smaller than the inner diameter of the body tube to ensure ease of removal. When NED energizes, the debris from the ejection charges will be inhibited from impacting the payload with the removable wall and centering ring combination. When the nose cone separates from the launch vehicle, the removable wall will pull free and remain attached to NED via a 0.19 in. Kevlar shock cord. NED and the nose cone remain attached to the launch vehicle via a shock cord and a ¼ in. eye bolt attached to the centering ring. This allows for the TROI to deploy through the centering ring and beyond the payload tube. A diagram of the TROI and recovery system interface can be seen in Figure 94 and is further discussed in Section 4.4.3.

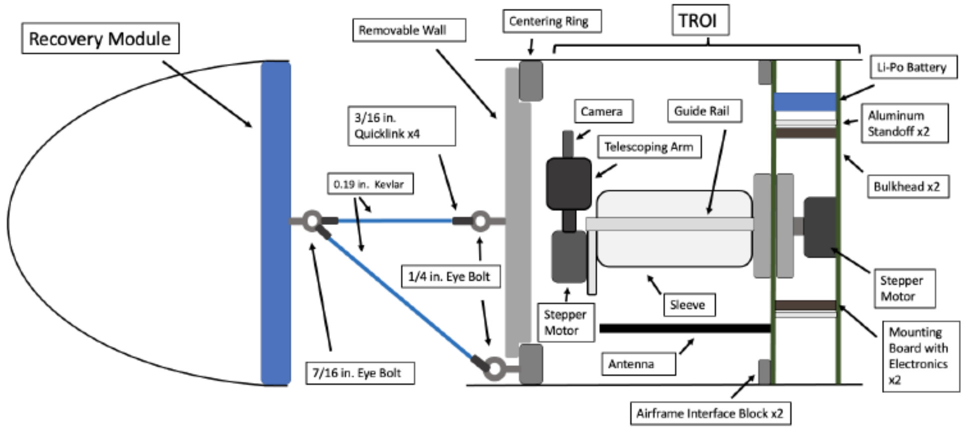


Figure 94: Recovery and Payload Interface

6.9 Mass Budget Summary

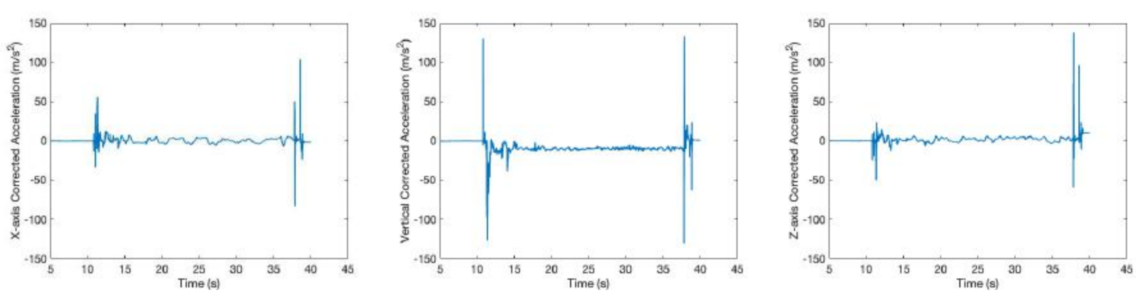
The total system predicted mass is 72.26 oz, and a summary table of the TROI mass budget is provided in Table 82.

Table 82: TROI Mass Summary

Component Group	Basic Mass (oz)	Predicted Mass (oz)	Percentage of Total Predicted Mass
Electrical	10.127	10.591	14.658%
Deployment	23.961	25.086	34.718%
Retention	34.775	36.579	50.624%
Total	**68.863**	**72.256**	**100%**

6.10 Subscale and Prototyping

Acceleration data was collected from the subscale launch from a designed subscale payload with an accelerometer. The collected data is shown in Figure 95.



(a) X-axis (b) Vertical (c) Z-axis

Figure 95: Payload Subscale Accelerometer Data

Figure 95 demonstrates spikes in the acceleration values at the moment of launch as well as at landing. This data will be used to configure the TROI software to deploy only after the launch vehicle lands. The TROI software must ignore the acceleration spikes throughout the various launch events. The TROI will only deploy when the acceleration values do not change over time across the x, y , and z components after experiencing launch events, thus demonstrating that the payload body tube has landed on the ground and is stationary. Rapid prototyping is an essential component of the TROI development. The payload will use several 3D printed parts, and these parts will be printed and assembled to evaluate and improve their performance. This is especially important for the development of the telescoping camera arm. The subscale payload was the first prototype of the TROI, as it collected data on the behavior of the accelerometers.

7 Technical Design: Apogee Control System

7.1 Mission Statement

The Apogee Control System (ACS) is a secondary payload that will be used to dynamically extend and retract four hinged drag-inducing flaps from the body of the launch vehicle after burnout. This will enable precise control over the cross-sectional area of the launch vehicle, and thus over the drag force acting on it. Its primary objective is to get the launch vehicle to within 25 feet of its 4600 feet target apogee. In addition to its mechanical design, the ACS also includes a robust suite of redundant sensors such as an accelerometer, altimeters, and an Inertial Measurement Unit (IMU) all mounted on a single two-layer printed circuit board. These will be used in a closed control loop with a microprocessor to determine the current state of the launch vehicle (acceleration, velocity, altitude, and orientation) and predict its apogee so that the servo motor actuating its drag flaps rotates to the correct angle as commanded by a Proportional Control Algorithm. Once the launch vehicle reaches its apogee, the flaps will be fully retracted and will remain retracted for the remainder of the flight and all flight data will be logged for post-launch analysis.

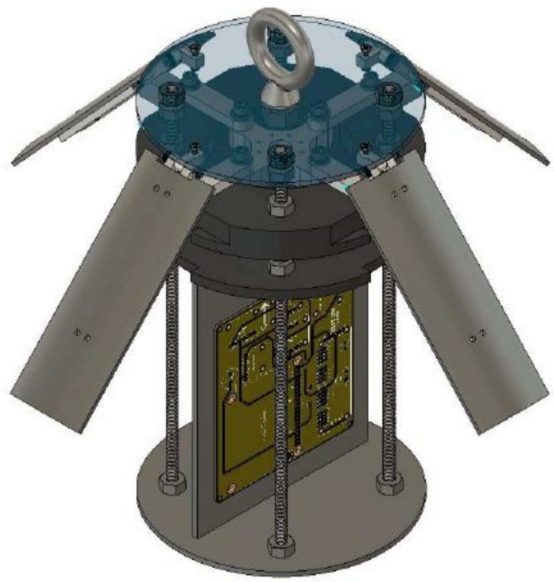
7.1.1 Success Criteria

The Apogee Control System requirements and mission success criteria are as follows:

- The system shall be located aft of the launch vehicle burnout CG (NASA Req. 2.16)
- The system shall only extend its flaps between the burnout and apogee stages of flight
- The system shall not negatively impact the stability margin of the launch vehicle
- The system shall be mechanically prevented from actuating its flaps asymmetrically
- The system shall ensure that apogee is kept within 25 feet of the 4600 feet target apogee
- The system shall be capable of fully actuating within 5 seconds from burnout
- The system shall accurately collect, filter, and record sensor data for in-flight use and post-flight analysis
- The system must perform a successful power-on self-test before it is armed
- The system shall be able to be fully integrated into the launch vehicle in under 30 minutes and should be capable of remaining armed on the launch pad for up to two hours prior to launch

7.2 Mechanical Design

The Apogee Control System's mechanism consists of a standard servo motor attached to a central hub, which links to four drag flaps that are flush with the body tube of the launch vehicle. The DS5180 High Torque Digital Servo Motor is housed in the motor mount bulkhead and fastened to the central hub. The central hub, when rotated by the servo motor, actuates the drag flaps via internal linkages and flap pusher arms. For structural support, the flap pusher arms interface with aluminum flap lever arms, which are fastened to the inner sides of the drag flaps. This allows the lever arms to bear the majority of the loads associated with actuating the mechanism instead of the drag flaps themselves. The pusher arms and lever arms are connected with a sliding drive pin that is able to move within a slot in the lever arms. Figure 96 shows the mechanism in its fully extended and fully retracted configurations as designed in Autodesk Fusion 360.



(a) Mechanism with flaps retracted (b) Mechanism with flaps extended

Figure 96: ACS Mechanism Rendering

7.2.1 Changes Made Since PDR

Several design changes were made since PDR to improve the performance and structural integrity of the ACS. One of these was the replacement of the flap brackets with flap lever arms that extend along almost the entire length of each drag flap. The flap lever arms will be capable of handling more stress than the flap brackets used in the previous design. Moreover, the ACS is still within its mass budget of 80oz as shown in Table 84. The central shaft was also replaced with a central hub that halves the required number of linkages, thus reducing mass and mechanism complexity. Finally, a motor bulkhead will be added below the slotted deck to mount the servo motor more securely and avoid unwanted motor movement. Electrical design changes are explained in sections 7.4.4.1 and 7.4.2.

7.2.2 Slotted Deck

The slotted deck, shown in Figure Figure 97, is a bulkhead that contains most of the moving system components and guides the motion of the mechanism. It has a counter-bore hole for the central hub, a smaller through hole that allows the central hub to fasten to the motor, and four slots which constrain the flap pusher arms' range of motion to a single axis perpendicular to the lever arms and drag flaps. Due to the slotted deck's size and thickness, it will be machined out of Nylon 6/6 using a multistage CNC milling process. This satisfies the design driver of weight while meeting the necessary strength and manufacturability requirements.

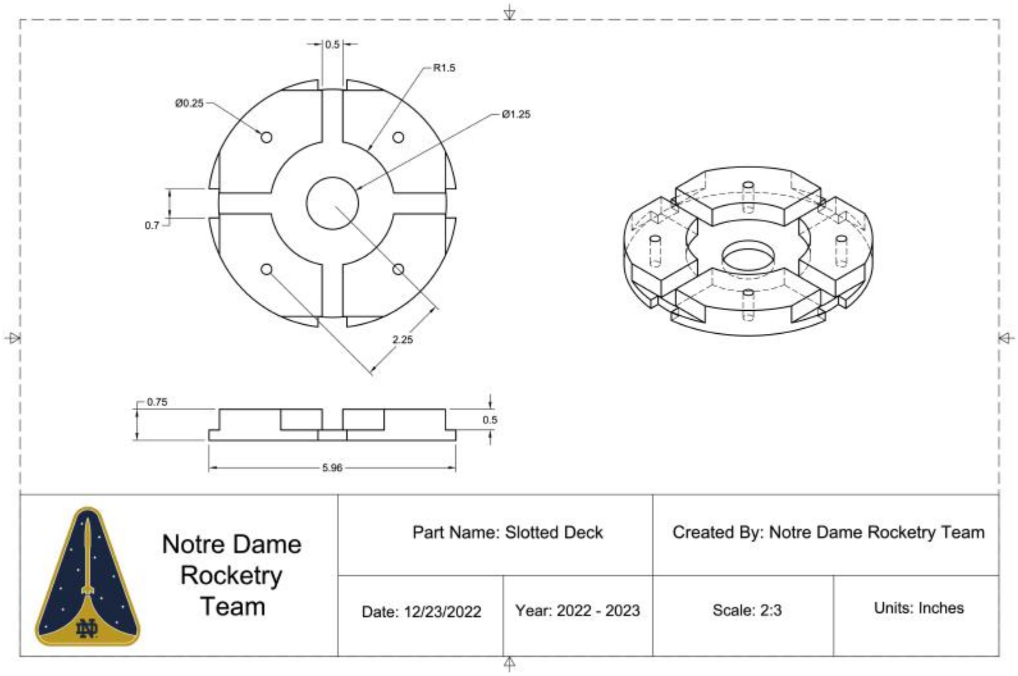


Figure 97: As Designed Slotted Deck

7.2.3 Central Hub

The central hub will fasten to the motor via a pattern of small bolts and be located in the center of the mechanism on the slotted deck. Four outer linkages will hinge to the central hub using linkage bolts, allowing the motor to actuate all four drag flaps simultaneously, thus eliminating the possibility of asymmetric actuation. It will be machined out of 0.5 in. thick 6061 aluminum sheet stock in a three step CNC milling process to ensure adequate precision during the ACS actuation. The design for this component emphasizes reliability, ease of manufacturing, and strength, since the central hub must transmit the entire load induced by the mechanism deployment. A drawing of the designed central hub is given in Figure 98.

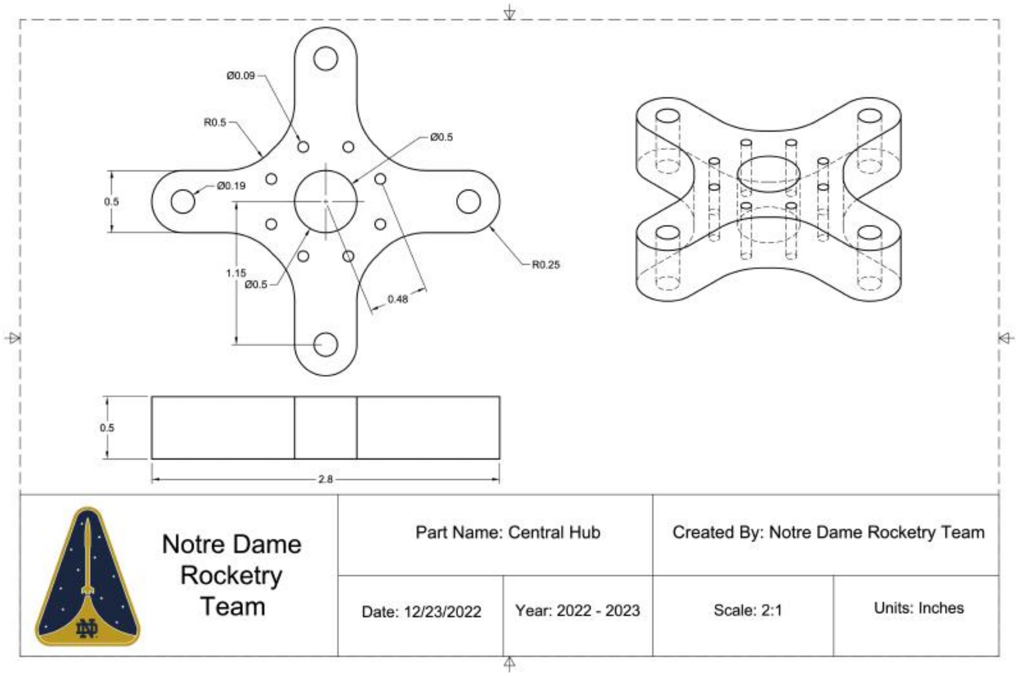


Figure 98: As Designed Central Hub

7.2.4 Linkages

The linkage is a component which connects the flap pusher arms to the central hub. It will extend due to the rotation of the central hub by the servo motor in order to perform flap actuation. Each linkage is connected to both the flap pusher arms and to the central hub by linkage bolts which are loose enough to allow them to rotate. The linkage bolts will also be threaded into holes in the central hub to secure them so that only the linkages can rotate around them. There are not many design constraints for this part as it only needs to fit between two existing manufactured components to act as a secondary load bearing structure. However, it must be able to sustain torsion forces from the servo motor, and so aluminum was chosen as its material. It will be made from a 0.25 in. thick 6061 aluminum sheet stock in a one step CNC milling process. A drawing of the designed linkage is shown in Figure 99.

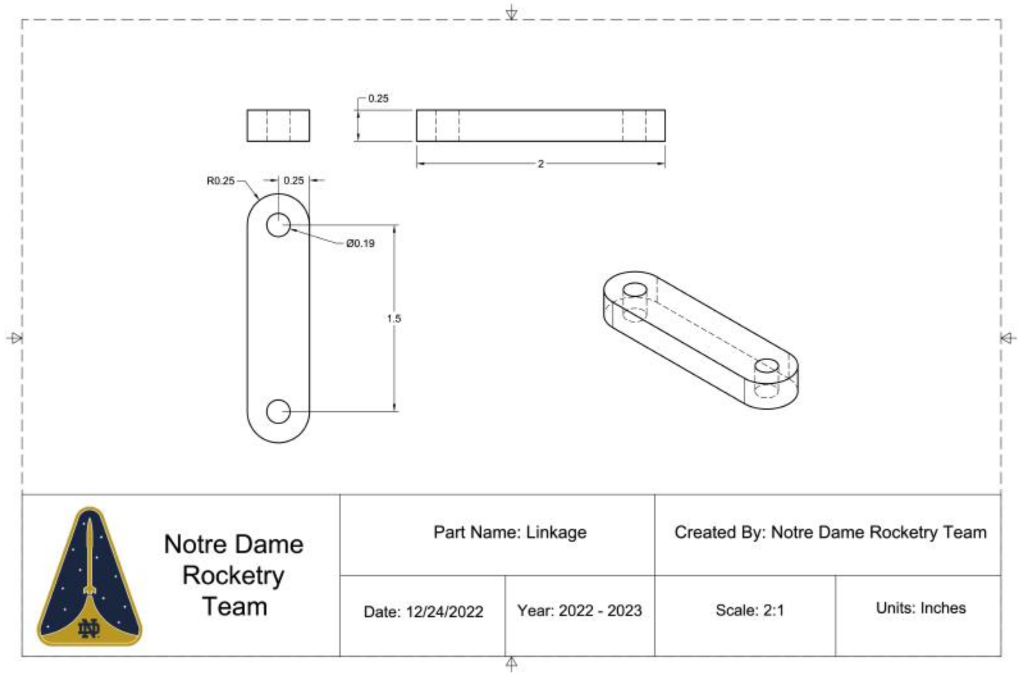


Figure 99: As Designed Linkage

7.2.5 Flap Pusher Arms

The flap pusher arm is the component that interfaces with the central hub's linkages and the flap lever arm. It is only capable of motion along a single axis due to the design of the slotted deck and it enables the hinged drag flaps to actuate at a specific angle relative to the body tube by pushing outwards on flap lever arms that are rigidly attached to the drag flaps. A linkage bolt secures each pusher arm to the central hub's linkage and a sliding drive pin secures it to the flap lever arm. The design constraints for the pusher arms are that they must be strong enough to withstand aerodynamic loads transmitted from the flap lever arms (primary load-bearing structures) and forces from the servo motor and linkages. They must also be lightweight to stay within the ACS mass budget and to avoid over-stressing the slotted deck. Therefore, they will be machined out of 0.5 in. thick 6061 aluminum sheet stock in a two step CNC milling process, which ensures that they will be manufactured precisely. Figure 100 shows a drawing of the designed flap pusher arm.

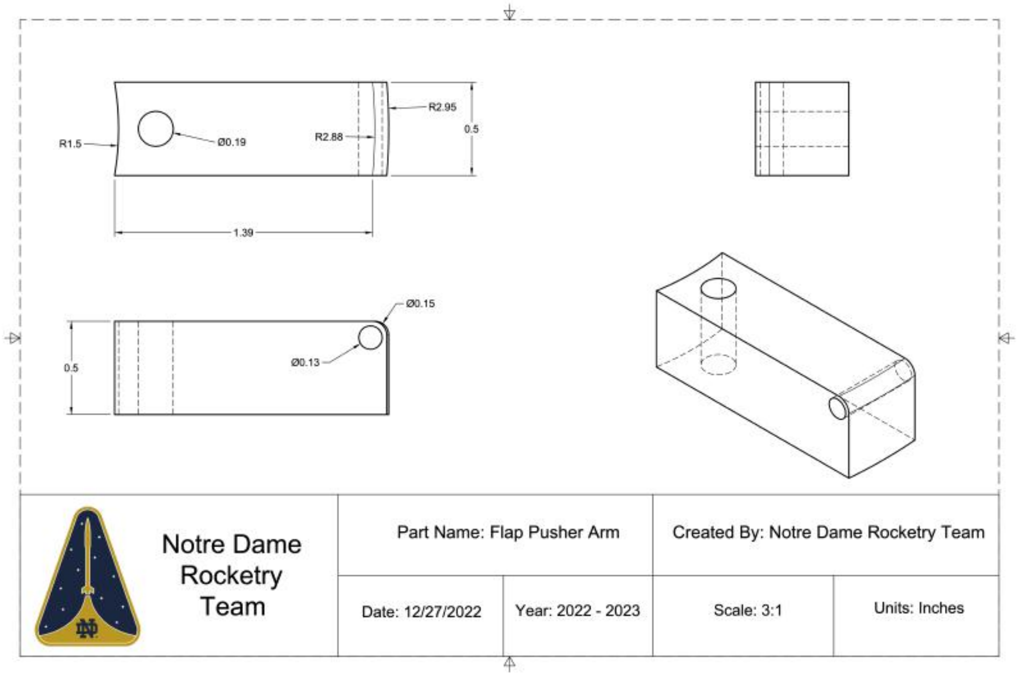


Figure 100: As Designed Flap Pusher Arm

7.2.6 Flap Lever Arms

The flap lever arm is a primary load bearing structure attached directly to the drag flaps via four screws. It contains a gap at its fore end allowing it to interface with the fore bulkhead hinge through a pin and nut. It also contains a slot that secures the flap pusher arm to the drag flap while also enabling the drive pin to slide along its length as the flaps extend and retract. The most important design constraint is that the flap lever arm must allow the drive pin from the flap pusher arm to slide sufficiently. This would require an adequate slot size so that it would not cause too much friction preventing movement, but would also need to be thick enough to not fail under aerodynamic loads. This requires precise and intricate machining of a sufficiently rigid material. Another design consideration is that the part would need to support the weight of the entire drag flap and the drag force, which could be very large during actuation, especially at burnout, so its material must be strong. Hence the four flap lever arms will be machined from a 0.5 in. thick 6061 aluminum sheet stock in a two step CNC milling process. A drawing of the designed flap lever arm is given in Figure 101.

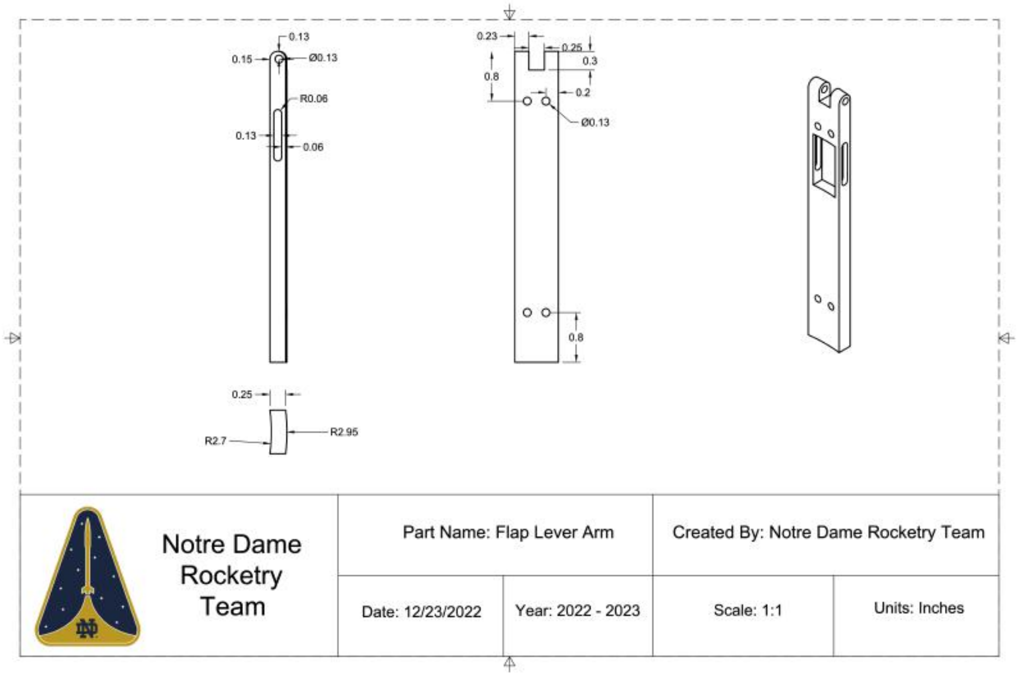


Figure 101: As Designed Flap Lever Arm

7.2.7 Drag Flaps

The drag flaps will be a set of four variable drag surfaces that can extend and retract from the launch vehicle body tube. They are connected on their inner side to flap lever arms using four small screws for secure attachment. The lever arms will be pushed outwards by the internal rotational system and will actuate at varying angles from the side of the launch vehicle. The aerodynamic loads act on the entire surface area of the drag flap as it is actuating and are then transmitted along the flap lever arms that are in contact. As the flap lever arm is much thicker than the drag flaps despite a smaller surface area, it will be able to support the load of the carbon fiber flaps. The major design constraint of the drag flaps is that they must be flush with the launch vehicle's body tube to avoid flow separation and parasitic drag before burnout. As such, the design must be made of the same material and thickness as the rest of the launch vehicle. The material must also be lightweight and rigid to minimize flutter. Therefore, the team has chosen to use cutouts from the ACS body tube as drag flaps. A small amount of additional material will also be removed around the cutouts to keep a sufficient gap for drag flap and hinge movement during actuation. A drawing of the drag flap to be cut out is shown in Figure 102.

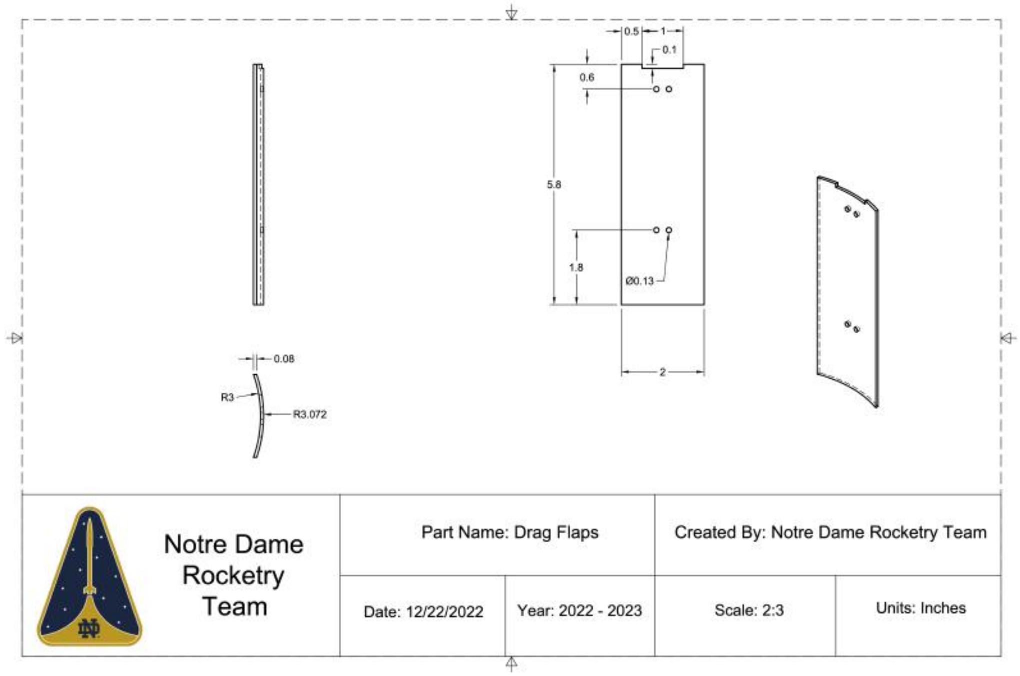


Figure 102: Drag Flap Cutout

7.2.8 Structural Bulkheads

The ACS primary structure consists of 3 bulkhead components: the fore bulkhead, the motor bulkhead, and the aft bulkhead. The bulkheads are thin circular disks (6" diameter) which provide primary structural support and enable system integration into the launch vehicle via airframe interface blocks. The bulkhead supports are threaded rods, secured with nuts, that run vertically through the entire length of the system. This enables the vertical positioning of bulkheads to be adjusted after assembly (to vary the maximum possible flap angle) while also keeping all bulkheads secure in flight. The bulkhead supports and nuts are externally sourced and are made of stainless steel. The fore and aft bulkheads will be cut out from a 0.125 in. thick carbon fiber sheet using a waterjet and the motor bulkhead will be cut from a 0.25 in. thick MDS-Filled Nylon sheet.

7.2.9 Bulkhead Hinges

The bulkhead hinges are components that attach to the fore bulkhead with a single screw and nut on one side and attach to the flap lever arms on the other side. These small components are used to secure the flap lever arms to the fore bulkhead while also leaving room for flap actuation. The hinges will be machined from 0.5 in. thick 6061 aluminum sheet stock in a one step CNC milling process to keep them strong and lightweight and will be curved at one end to fit into the flap lever arm. A drawing of the designed bulkhead hinge is shown in Figure 103.

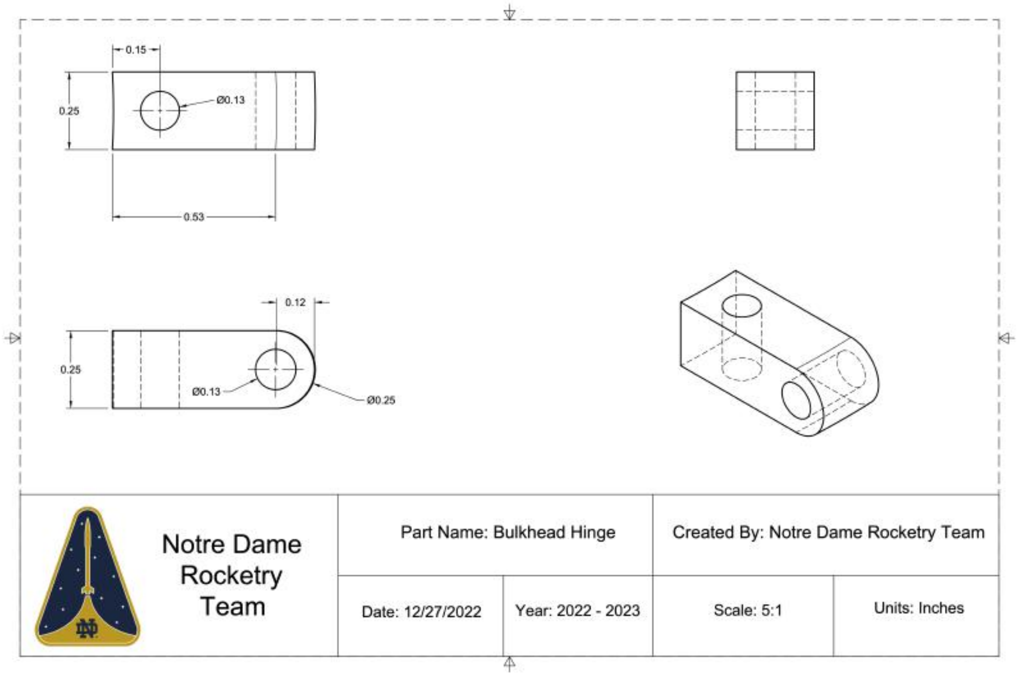


Figure 103: As Designed Bulkhead Hinge

7.2.10 Servo Motor

The three requirements considered during servo motor selection were: high stall torque, low stall current, and lightweight motor package. The DSSERVO DS5180 180° standard servo motor met all three requirements and was hence selected as the ACS mechanism's servo motor. Table 83 lists the motor's specifications at its nominal voltage of 7.4 V.

Table 83: Specifications of Selected Servo Motor: DS5180

Specification	Value
Stall Torque	1111 oz-in.
Stall Current	5 A
No Load Speed	0.17 s/60°
Weight	5.71 oz

7.3 Aerodynamic Analysis

Aerodynamic Analysis of the Apogee Control System involved the use of a model that estimates the drag force acting on the launch vehicle at every instant between burnout and apogee. The team has used the drag equation and Newton's second law to obtain a simplified model of launch vehicle trajectory. Solving for acceleration yields differential Equation 34.

$$x'' = -\frac{1}{2m}\rho x'^2 (C_{dl} A_l + C_{df} A_f) - g \tag{34}$$

where x'' is the acceleration of the launch vehicle, m is the launch vehicle burnout mass, ρ is the density of air, x' is the launch vehicle velocity, C_{dl} is the launch vehicle drag coefficient, A_l is the launch vehicle cross-sectional area,

C_{df} is the flap drag coefficient, and A_f is the drag flap area. C_{df} is estimated for varying flap angles using Equation 35.

$$C_{df} = 1.28sin(\alpha) \tag{35}$$

where α is the drag flap actuation angle. Equation 34 will be solved forward in time by the ACS microprocessor from burnout to apogee using a fourth order Runge-Kutta algorithm to continuously predict the launch vehicle apogee at a given flap angle. Figure 104 shows the results of RockSim simulations for various static flap angle configurations. These results are used to estimate the maximum possible apogee reduction that the ACS can achieve. The simulations assumed a constant air density, constant launch vehicle drag coefficient, infinitely thin rectangular flaps (6 in. x 2 in.), no wind, and zero launch rail angle.

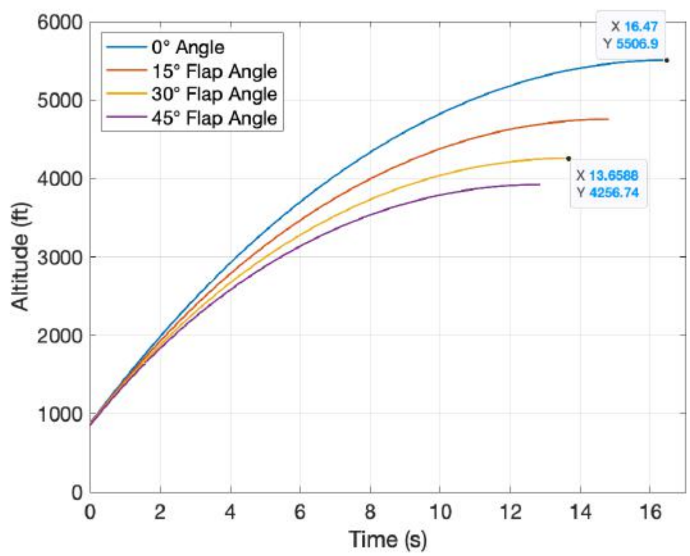


Figure 104: RockSim Altitude Simulations for Different Static Flap Angle Configurations

Although the maximum flap angle possible is 45°, the team used the 30° configuration from Figure 104 to estimate the maximum possible apogee reduction as flap actuation does not occur instantly at burnout, so using the 45° results would be an overestimate. The results show a maximum apogee reduction of 1250 ft (from 5507ft to 4257ft), which is more than enough to bring the launch vehicle down to its target apogee, regardless of launch rail angle, wind, or other external conditions on launch day.

7.4 Electrical Design

The ACS Electrical design consists of a sensor suite, control system, and a power system. The sensor suite consists of a 3-axis accelerometer, an IMU, and two altimeters. Its control system consists of a Raspberry Pi 4 microprocessor and PWM servo controller. Finally, the ACS power system consists of two independently powered circuits (5 V Logic Circuit and 7.4 V Servo Motor Circuit) and a DC/DC Boost Converter. Both circuits will be independently switched on and off using two pull-pin SPDT switches. Together, these subsystems enable the ACS to continuously vary its drag flap actuation based on the launch vehicle's altitude, velocity, acceleration, and orientation. All electronics will be mounted on a two-layer printed circuit board designed by the team. The system includes a PWM-controlled piezoelectric buzzer on the logic circuit for auditory feedback during the ACS initialization and arming stages.

7.4.1 Accelerometer

The accelerometer allows the system to determine the current state of the launch vehicle by evaluating when it has launched, when burnout has occured, and when apogee is reached. Acceleration data can also be used in the Kalman data filter to estimate launch vehicle velocity during flight. The team chose the Adafruit ADXL343 3-axis accelerometer, shown in Figure 105, because it has a range up to 16g, which is high enough to accurately detect launch, and because it has a sample rate over 100 Hz. It can also communicate with the microprocessor via I^2C protocol and has widely available software libraries.

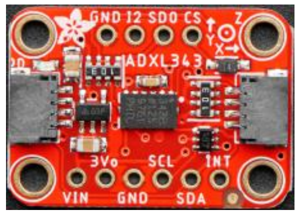
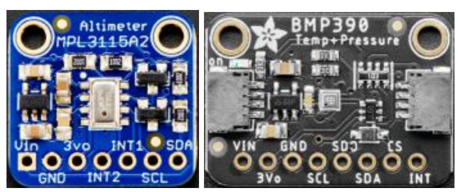


Figure 105: Adafruit ADXL343 Accelerometer

7.4.2 Altimeters

An altimeter allows the ACS to determine its current altitude based on barometric pressure. This information is useful as it can be used to verify when the system has launched and determine when it has overshot its target apogee. Combining this data with acceleration data allows the Kalman filter to more accurately determine launch vehicle velocity. The team chose two altimeters for redundancy. The selected altimeters are shown in Figure 106.



(a) Adafruit MPL3115A2 (b) Adafruit BMP390

Figure 106: ACS Altimeters

7.4.3 Inertial Measurement Unit (IMU)

The IMU is a sensor that provides multiple different data points which allow the system to accurately determine its trajectory. The IMU selected is a 9-DoF sensor that includes a 3-axis accelerometer, gyroscope, and magnetometer. It also runs its own fusion data algorithm to output orientation data in euler angles. This information can be used to improve the accuracy of the apogee prediction algorithm and more accurately determine the velocity of the launch vehicle. The selected IMU, the Adafruit BNO055, is shown in Figure 107.

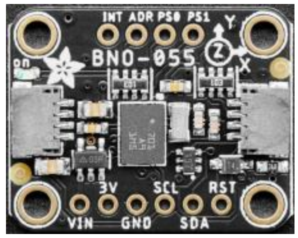


Figure 107: Adafruit BNO055 IMU

7.4.4 Power System

The ACS power system consists of a 3.7 V LiPo battery that powers a 5 V logic circuit and a 7.4 V LiPo battery that powers a 7.4 V servo motor circuit. A DC/DC boost converter is used to step up 3.7 V to 5 V in the logic circuit.

7.4.4.1 Battery Selection A 3.7 V LiPo battery is used to power the 5 V logic circuit. Since the logic circuit can draw as much as 2 A over an extended period of time, the 3.7 V battery must have a high capacity and discharge rate. The team chose the YDL 115659 3.7 V LiPo battery to power the logic circuit. This battery has a capacity of 5000 mAh and a 5 A maximum discharge current rating, both of which exceed the required specifications to keep the system electrically powered on the launchpad for two hours.

The 7.4 V LiPo battery powering the servo motor need not have a high capacity since the motor will only be active for about 10 seconds during flap actuation. However, the discharge current rating is more critical as the motor's stall current can be as high as 7.5 A. The team changed the previously selected battery (Ovonic 5000 mAh 2S) to the AlienModel 3000mAh 2S 7.4 V LiPo as the former was too large and heavy to be of practical use. The selected battery has a discharge rating of 5C which corresponds to a maximum discharge current of 15 A and is sufficient to run the servo motor at stall current for over 20 minutes.

7.4.4.2 DC/DC Boost Converter Selection The team selected the Adafruit PowerBoost 1000 Basic as the DC/DC Boost Converter as it has a 4A current limit which exceeds the expected 2 A logic circuit current draw and can easily be connected to a 3.7 V LiPo battery. The PowerBoost steps up the 3.7 V from the LiPo battery to 5 V which is necessary to power the Raspberry Pi 4 microprocessor. It also stabilizes the 5 V output so the microprocessor voltage does not fluctuate as the battery drains. The PowerBoost 1000 Basic is shown in Figure 108.

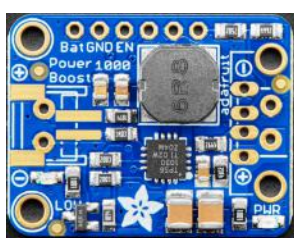


Figure 108: Adafruit PowerBoost 1000 Basic

7.4.4.3 5V Logic Circuit The 5V logic circuit consists of the sensor suite (accelerometer, altimeters, and IMU) and elements of the control system (microprocessor and PWM servo controller). The microprocessor and servo controller run on 5 V from the PowerBoost while all sensors run on the microprocessor's 3.3 V output to meet their voltage requirements.

7.4.4.4 7.4V Servo Motor Circuit The 7.4 V Servo Motor Circuit will be directly powered by the 7.4 V LiPo battery as the Servo Motor has a nominal voltage of 7.4V and an operating voltage ranging from 6 V to 8.4 V, so it does not require a constant voltage within that range. This circuit is independent from the logic circuit to avoid overloading the logic circuit, but both circuits share a common ground plane on the Printed Circuit Board. The logic circuit interfaces with the servo motor circuit via a PWM Servo Controller that sends PWM signals from the microprocessor to the servo motor, which adjusts the drag flap angle.

7.4.5 Printed Circuit Board (PCB) Design

The Apogee Control System will feature a two-layer printed circuit board that holds most of its electronics, including the logic circuit. Components will be soldered onto the PCB via THT (through hole technology) mounting with header pins so that the amount of wiring used is minimized. Using a PCB improves the reliability of electrical connections and it provides an electrical ground plane that minimizes the effects of external electromagnetic interference. Figure 109 shows the electrical schematic and Figure 110 shows the layout diagram of the PCB without the top copper pour and solder resist stop layers for visibility.

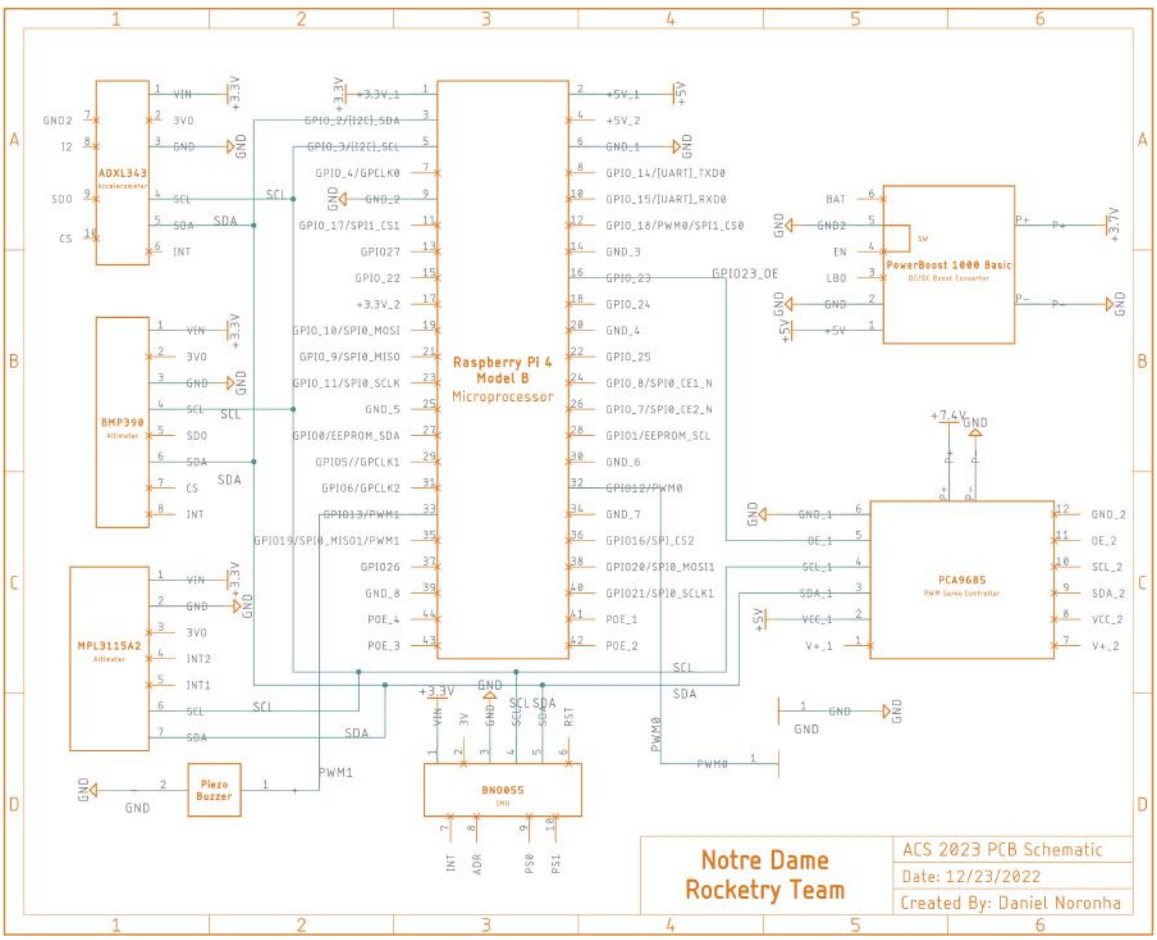


Figure 109: PCB Electrical Schematic Diagram

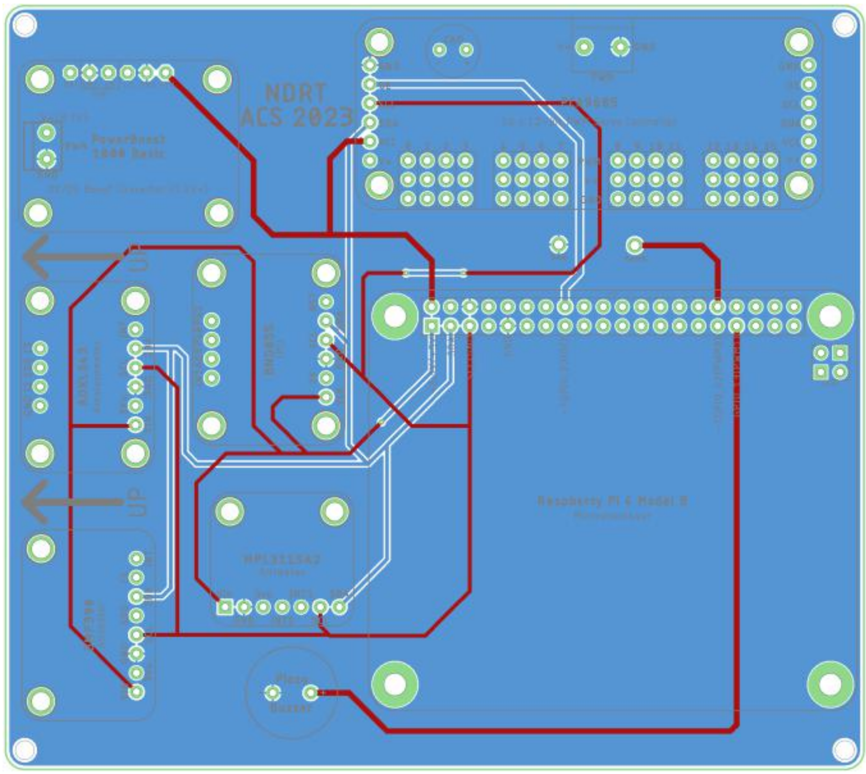


Figure 110: PCB Layout Diagram

The four major nets (signals) on the PCB are +3.3 V, GND, SCL, and SDA. All sensors are connected to the 3.3V power net via their Vin/Vcc pins and operate on 3.3 V logic. The SCL (Serial Clock) and SDA (Serial Data) are lines used by sensors and the microprocessor for communication via the I^2C protocol. Additionally, the microprocessor and servo controller are connected to the PowerBoost's 5 V power net as they run on 5 V logic. The buzzer is connected directly to the microcontroller GPIO 13 pin for audio feedback and an additional PWM pin (GPIO 12) and ground pin is kept connected on the PCB if required later for troubleshooting or adding another component. All components share a common ground plane on both the top and bottom copper layers.

The PCB was designed in the Autodesk Fusion 360 Electronics workspace and its design was validated using an Electrical Rules Check (ERC) and a Design Rules Check (DRC) with manufacturer specifications. Both tests were passed without any errors. The overall PCB dimensions are 4.5 in. x 4.0 in. x 1.6 mm and its fabrication will be outsourced to OSH Park.

7.5 Control System and Software Design

The ACS control system consists of a microprocessor, PWM servo controller and control software. All ACS code and libraries are written in Python 3 and maintained with versioning on the ACS 2023 GitHub Repository. The ACS sensor suite inputs data to the control system, which is processed by the microprocessor, and finally, the servo angle is relayed to the servo motor via the PWM servo controller in a closed-loop that cycles over 20 times per second as described in Figure 111.

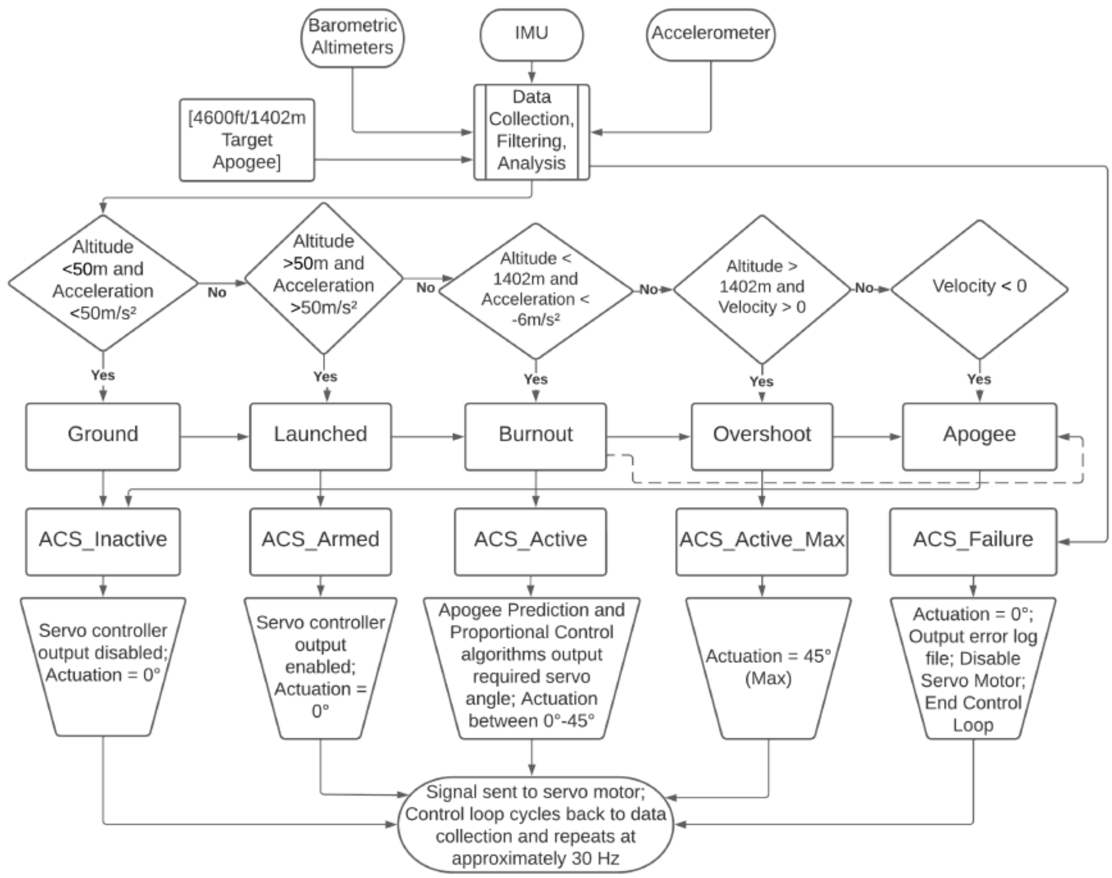


Figure 111: ACS Control Code Flowchart

The ACS microprocessor reads and Kalman filters sensor data to categorize the launch vehicle's state into one of 5 categories based on its altitude, velocity, and acceleration. Depending on the launch vehicle state, the ACS will itself be put into one of 5 states: Inactive, Armed, Active, Active_Max, and Failure. The Failure state is only triggered in the event of a runtime error and it disables most of the ACS functions to avoid uncontrolled actuation. The appropriate signal is then sent from the microprocessor to the servo motor via the servo motor controller, which controls flap actuation accordingly between burnout and apogee. Finally, the software cycles back to the start of its control loop and runs again.

7.5.1 Microprocessor

The ACS microprocessor is a Raspberry Pi 4 Model B. This single board computer was chosen because it offers relatively high computing power in a small, lightweight package. It runs a Linux Distribution (Raspbian OS) and has a removable SD card, making post-launch data analysis easy. Furthermore, the Raspberry Pi 4 supports SSH (Secure Shell) communication over WiFi, allowing flight data to be viewed and code to be edited without removing its SD card even at the launch field (through a mobile hotspot connection). Its 1.5 GHz Quad-Core processor and 4 GB of RAM allows it to perform compute-intensive tasks such as data filtering and apogee prediction with low latency. The Raspberry Pi is also capable of communicating with sensors via I^2C protocol and with the servo controller that adjusts the servo angle. Figure 112 shows the selected microprocessor.

Figure 112: Raspberry Pi 4 Model B Microprocessor

7.5.2 Servo Controller

The servo controller being used is an Adafruit PCA9685 16-Channel 12-bit PWM/Servo Driver compatible with the I2C interface of the microcontroller. It has a terminal block for 7.4 V power input and is 5 V compliant with a built-in clock, which makes it free running. Using a servo controller allows cleaner PWM signals to be passed from the microcontroller to the servo as opposed to connecting the servo directly to the microprocessor's PWM pins. This lets the microprocessor control the servo more precisely and minimizes servo motor jitter when actuating the ACS drag flaps. Figure 113 shows the chosen PWM servo controller.

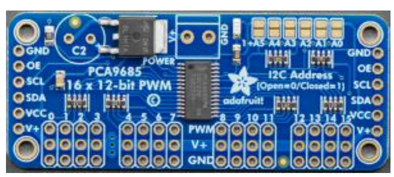


Figure 113: Adafruit PCA9685 I^{2}C interface PWM Servo Controller

7.5.3 Kalman Data Filter

The launch ACS sensors are reliable but not perfect. For example, while the barometric altimeter may output consistently accurate altitudes during ascent, it might output a small number of unusable inaccurate values, such as an altitude of 0. Inaccurate readings are not particularly rare because values such as altitude are constantly changing due to pressure fluctuations.

To lessen the impact of inaccurate sensor output data, a Kalman filtration algorithm is applied to filter the altitude and acceleration data. The Kalman filter is a method of linear quadratic estimation which uses prior knowledge to provide a statistical estimate of future values. It uses a series of values measured over time and estimates a joint probability distribution for each time step to estimate unknown (future) values, tending to be more accurate than single measurements. The Kalman filter can also predict related values, such as velocity from position and acceleration. In this case, the sensors will input previous values of altitude and acceleration to the microprocessor, which outputs reasonable estimates of the future altitude, velocity, and acceleration (at the next time step). An advantage of using the Kalman filter is that it is very memory efficient as only the current and future state matrices are stored at any time.

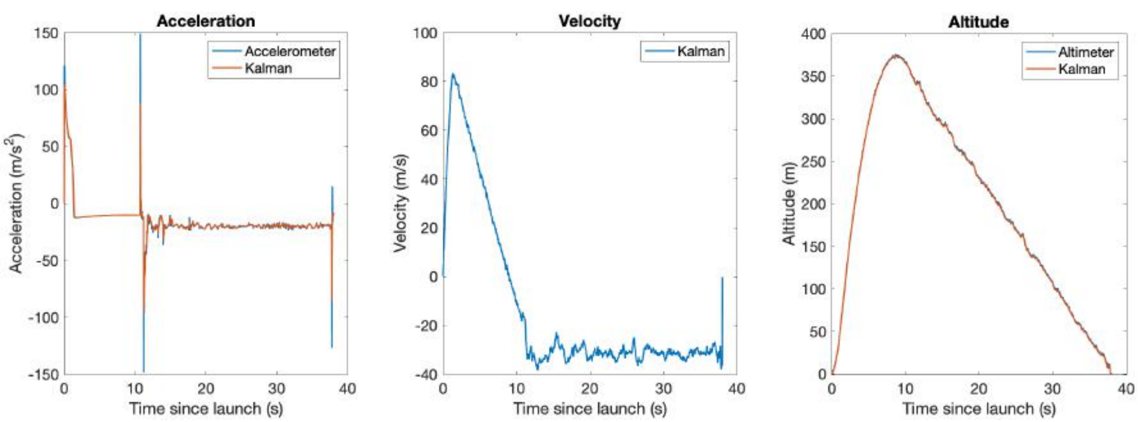
To implement the Kalman filter, the open-source Python library *filterpy* is used which contains the *filterpy.kalman.KalmanFilter* class. The filter is initialized with an x-dimension value of 3 to obtain three outputs (altitude, velocity, acceleration) and a z-dimension of 2 since there are two inputs (altitude, acceleration). The filter's measurement function matrix H, covariance matrix P, process noise matrix Q, and measurement noise matrix R are set to the values shown in Equation 36.

$$H = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{36}$$

Each filtration cycle, the state transition matrix Φ is set to the 3x3 matrix containing Δ values corresponding to the time elapsed between the current and previous time steps. This matrix is derived from basic kinematics equations and is shown in Equation 37.

$$\Phi = \begin{bmatrix} 1 & \Delta & \Delta^2/2 \\ 0 & 1 & \Delta \\ 0 & 0 & 1 \end{bmatrix} \tag{37}$$

The *KalmanFilter.predict* method is used to predict the values and actual altitude and acceleration values are then passed to *KalmanFilter.update* which stores the filter's updated predictions. The noise matrices P and Q in Equation 36 may be tuned by hand for more accurate estimates after analysing sensor readings. In a prior subscale flight (without drag surfaces attached), the Kalman filter successfully reduced noise from sensor readings and gave out a reasonable velocity approximation as shown in Figure 114.



(a) (b) (c)

Figure 114: Kalman-Filtered Subscale Data Plots

7.5.4 Proportional Control Algorithm

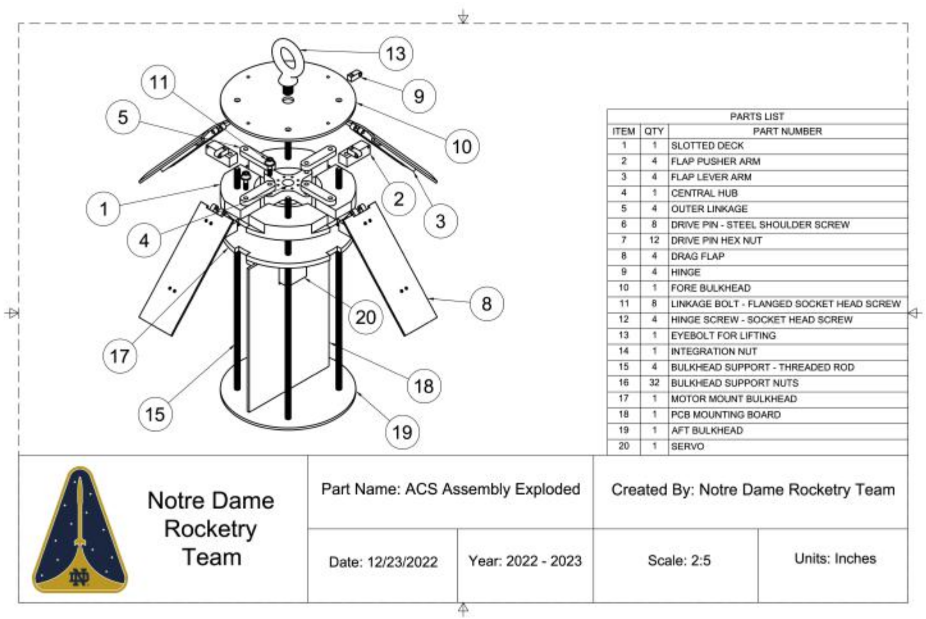
The ACS proportional control algorithm consists of two functions: an apogee prediction function and a proportional control function. It is only active between burnout and apogee as shown in Figure 111. The apogee prediction algorithm continuously solves Equation 34 forward in time from burnout until apogee using a fourth order Runge-Kutta numerical approximation as described in section 7.3. The predicted apogee returned is then provided as input to the proportional control function which calculates the apogee error as the difference between the predicted apogee and the 4600 ft target apogee at each time step. The function then determines the servo angle as a function of time according to the proportional control law given in Equation 38.

$$\theta(t) = K_P E(t) \tag{38}$$

where θ is the servo angle sent to the servo motor via the servo controller as a function of time, K_P is the proportionality constant determined by running software tests with legacy launch data for tuning, and $E(t)$ is the apogee error as a function of time. Regardless of the calculated angle, the servo angle will be software limited to prevent flap actuation past 45° and in the event of an apogee overshoot, the proportional control algorithm will be overridden with a direct command that actuates the servo to an angle corresponding to maximum flap actuation (i.e. a 45° flap angle). After apogee, the flaps will be commanded to fully retract and the ACS will be deactivated for the remainder of the flight as outlined in section 7.5.

7.6 System Integration

The Apogee Control System will be housed in the ACS bay of the launch vehicle close to its CP for maximum effectiveness, but aft of its burnout CG in compliance with NASA Req. 2.16. The ACS will be contained entirely between two carbon fiber bulkheads and will be secured to the ACS body tube via 4 aluminum airframe interface blocks mounted onto its aft bulkhead and retained using 8-32 screws. The body tube cutouts are 0.2 in. longer than the flaps themselves to allow the flaps and bulkhead hinges a greater range of movement. A sufficient margin will be kept around the flap cutouts to prevent flap contact with the ACS body tube. Since the drag flaps are flush with the ACS body tube, they may only be attached after the system has been fully integrated into the launch vehicle. Lastly, an eye bolt with a vertical loading capacity of 2000 lbs will be included on the fore bulkhead to facilitate the integration and removal of the ACS from the launch vehicle in accordance with the launch vehicle integration procedures outlined in paragraph 8.5.2.1. An exploded view of the fully assembled and integrated system in shown in Figure 115.



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	SLOTTED DECK
2	4	FLAP PUSHER ARM
3	4	FLAP LEVER ARM
4	1	CENTRAL HUB
5	4	OUTER LINKAGE
6	8	DRIVE PIN - STEEL SHOULDER SCREW
7	12	DRIVE PIN HEX NUT
8	4	DRAG FLAP
9	4	HINGE
10	1	FORE BULKHEAD
11	8	LINKAGE BOLT - FLANGED SOCKET HEAD SCREW
12	4	HINGE SCREW - SOCKET HEAD SCREW
13	1	EYEBOLT FOR LIFTING
14	1	INTEGRATION NUT
15	4	BULKHEAD SUPPORT - THREADED ROD
16	32	BULKHEAD SUPPORT NUTS
17	1	MOTOR MOUNT BULKHEAD
18	1	PCB MOUNTING BOARD
19	1	AFT BULKHEAD
20	1	SERVO

Figure 115: ACS Integrated System Exploded View

Although the bulkhead positions relative to each other are adjustable, the overall ACS dimensions will not exceed 12 inches in length and all bulkheads will have a 6 in. diameter. The total predicted mass for the ACS (excluding drag flap cutouts whose mass is included in the launch vehicle mass statement) is 79.733 oz which is within the maximum allowable ACS mass of 80 oz. Table 84 summarizes the ACS mass breakdown by component categories. The comprehensive ACS critical design mass statement may be found in Appendix C.4.

Table 84: ACS Mass Breakdown Summary

Category	Basic Mass (oz.)	Predicted Mass (oz.)
Retention	17.138	17.857
Structural	13.879	14.727
Electrical	12.027	12.110
Mechanical	33.690	35.037
Total	**76.733**	**79.733**

8 Safety

The NDRT Safety Officer for the 2022-2023 season is Christopher Fountain. The Safety Officer is primarily responsible for defining, evaluating, and mitigating the various failure modes that can occur throughout the design process of the team. The general responsibilities and duties carried out to analyze these failure modes are, but not limited to, the following:

- Update the Safety Handbook to reflect the most current information for the 2022-2023 season.
- Enforcing general practices throughout the design process.
- Teaching and assessing safe fabrication methods.
- Updating and creating Standard Workshop Operating Procedures so that team members have a proper understanding of fabrication methods during launch vehicle construction.
- Assessing various failure modes and possible mitigations with FMEA tables.
- Developing a detailed Standard Launch Operating Procedures prior to the first full-scale launch to ensure safe launches.
- Being a point of reference for any team member to refer to with safety-related questions.
- Attending all launches to ensure procedures are followed correctly.
- Contributing to the Safety portion of all NASA deliverables.
- Promoting a culture that promotes safety and proper design over deadlines and other time constraints.
- Developing and following a plan for disposing of hazardous waste materials.
- Developing and following a plan for handling broken launch vehicle items.
- Ensuring all team members follow all NAR, NASA, and University safety regulations.
- Ensuring all team members follow all state, county, and local safety regulations.

8.1 Launch Concerns and Operating Procedures

8.1.1 Introduction

Launches are a culmination of the team's hard work throughout the year, and is a significant time, cost, and safety investment. Thus, it is imperative that the actual launch day is well-planned out to maximize efficiency, chances of success, and, most importantly, safety. Standard Launch Operating Procedures have been written to facilitate the safe preparation, integration, and launch of the launch vehicle and should be followed by all team members and the Team Mentor, Dave Brunsting (NAR/TRA Level 3 Certified).

Note: All Launch Operating Procedures adhere to NAR/TRA regulations. Relevant regulations are given to team members when appropriate, but any more information can be found through going to the NAR official website, the TRA official website, or by asking the Safety Officer. At launches, the Range Safety Officer (RSO) and Launch Control Officer (LCO) have the final say in any and all launch operations.

Required Personnel:

NAR/TRA Level 3 Certified Team Mentor: Dave Brunsting

Safety Officer: Christopher Fountain

Project Manager: Lauren Falk

Systems Lead: Lyvia Li

Vehicles Lead: Michael Bonaminio

ACS Lead: Daniel Noronha

Recovery Lead: Paul du Vair

Payload Lead: Spencer Bullinger

Note: In the event that any one of these personnel cannot attend the launch, another required person may take up the responsibilities of another team member. Dave Brunsting, the Team Mentor, due to his NAR/TRA Level 3 Certification, must be at each launch in order to perform necessary tasks, such as motor installation and ignition wiring.

8.1.2 Launch Rehearsal

Before any launch, the team will host a launch rehearsal to initialize preparations for launch. These rehearsals consist of gathering the equipment listed on the launch checklist, going over launch procedures, and detailing any other important and relevant information. The Safety Officer will inform the team on the forecasted weather, team-wide launch procedures, and other important information. Standard Launch Operating Procedures, in addition to being available online, will be available in print at launch rehearsals. All team members (or designated necessary personnel) are expected to attend these rehearsals in order to participate in the actual launch. In addition, all team members must have completed the Safety Agreement and EIH Workshop Certification to attend any launch. It is noteworthy to mention that NDRT Mentor Dave Brunsting will not be present during these rehearsals, but he will still be responsible for all energetics handling at the launch site due to his NAR/TRA Level 3 certification.

8.1.3 Launch Checklist

Note: Failure to follow the following procedures may result in the following failure modes: LO.6, LO.8, LO.9, LO.10, LE.1, PE.9, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

The below list outlines exactly what must be brought to the launch site by the team. During the launch rehearsal, team members will pack necessary equipment into toolboxes and prepare it for departure the next morning. All required personnel must sign off on this list affirming that all necessary items have been packed.

Note: The team primarily uses lithium-polymer batteries as their main source of voltage. These batteries can become dangerous and a fire hazard if found to be defective. All batteries should be inspected prior to packaging to ensure they are safe to use. This checklist includes checking for any defects and determining the voltage.

Troubleshooting: What if batteries are found to be defective?

1. Team members that find a defective lithium-polymer battery that is defective should notify the Safety Officer immediately.
2. The team member tasked with disposing of the defective battery must wear safety glasses and heat resistant gloves, as defective batteries can become a fire hazard.
3. Place the defective battery in a fire resistant battery bag.
4. Dispose of the defective battery according to the pre-defined waste procedures (found in section 10.3 of the Safety Handbook).

Test: Testing the voltage of a lithium-polymer battery

1. Obtain a lithium-polymer battery and set it down on the table. Ensure it is not connected to any electrical component or device.
2. Obtain a multimeter, turn it on, and set the measured value on it to voltage (V).
3. Take one probe of the multimeter and set it on the wire on one side of the battery, and the other probe on the wire on the other side. Measure the voltage read out on the multimeter.
4. Compare this value to the nominal voltage given by the battery to determine if the values match and if the battery is fully charged. If the battery is not fully charged, continue to charge it until the nominal voltage and voltage reading on the multimeter match.

Personal Protective Equipment

- ☐ Dust masks (1 box)
- ☐ Nitrile gloves (1 box)
- ☐ Safety glasses (minimum 5)
- ☐ Closed toed shoes (everyone)
- ☐ Biohazard bags (minimum 3)
- ☐ Long sleeves (everyone)
- ☐ First aid kit
- ☐ Burn kit
- ☐ Fire extinguisher
- ☐ Safety gloves (minimum 1)
- ☐ Sunscreen (if needed)
- ☐ Hand warmers (if needed)
- ☐ Winter gloves (if needed)
- ☐ Fire resistant battery bags (minimum 5)
- ☐ Hair ties (for long hair)

Tools

- ☐ Electric drill
- ☐ Electric drill bits
- ☐ Screwdriver set
- ☐ Pliers
- ☐ Manual screwdriver
- ☐ Screws, nuts, and bolts (8-32)
- ☐ Hammer
- ☐ Files
- ☐ Adjustable wrench
- ☐ Exacto knife
- ☐ Tape measure
- ☐ Epoxy
- ☐ Epoxy applicators (minimum 5)
- ☐ Extra batteries (3.7 and 7.4 V)
- ☐ Duct tape
- ☐ Electrical tape
- ☐ Masking tape
- ☐ Sandpaper
- ☐ Allen wrenches (8-32)
- ☐ Scissors
- ☐ Drill bit case
- ☐ Digital calipers
- ☐ Wire cutters
- ☐ Wire strippers
- ☐ Clamps (minimum 3)

Electrical Equipment

- ☐ Multimeter
- ☐ AC/DC converter
- ☐ Soldering iron
- ☐ Scale
- ☐ Laptop with simulation software installed
- ☐ Wire spool
- ☐ Car power converter

General Equipment

- ☐ Water
- ☐ Sharpie/pens (minimum 5)
- ☐ Foldable tables (minimum 2)
- ☐ Plastic rails
- ☐ Wooden rail
- ☐ Battery chargers
- ☐ Calculator
- ☐ Garbage bags
- ☐ Digital camera
- ☐ Ladder

Vehicle Equipment

- ☐ Body tubes
- ☐ Access RockSim and OpenRocket
- ☐ Nose cone
- ☐ Shear pins
- ☐ Bulkheads
- ☐ Ballast mass
- ☐ Vehicle mount
- ☐ Airframe mounting screws
- ☐ Fin can
- ☐ Motor retainer cap

ACS Equipment

- ☐ Completed ACS
- ☐ Batteries
- ☐ Extension flaps
- ☐ Screws for fastening extension flaps
- ☐ Laptop with ACS code installed
- ☐ Extra SD cards
- ☐ Extra altimeters
- ☐ Extra batteries (3.7 and 7.4 V)
- ☐ Battery chargers

Recovery Equipment

- ☐ Extra batteries (3.7 V)
- ☐ Quick links
- ☐ Nomex blanket
- ☐ Dog barf
- ☐ Cellular phone for GPS test
- ☐ Dry lubricant
- ☐ Keys for turning switches
- ☐ Altimeter batteries (9)
- ☐ FED
- ☐ NED
- ☐ PED
- ☐ Drogue parachute
- ☐ Main parachute
- ☐ Pilot parachute
- ☐ Molding clay
- ☐ Batteries

Payload Equipment

- ☐ Extra batteries (11.1 V)
- ☐ Access to payload code
- ☐ Microcontroller
- ☐ Extra coating strips
- ☐ Extra servo motors
- ☐ Pull pin
- ☐ Completed payload module
- ☐ Payload batteries (11.1 V)
- ☐ SD cards
- ☐ FM radio
- ☐ Electronics shielding blanket
- ☐ Fire retardant blanket
- ☐ Terminal node controller (TNC)
- ☐ Baofang Handheld Radio
- ☐ Easy Digi UV-5R Interface
- ☐ Headphones splitter
- ☐ ESP32 (2)

Team Mentor-Specific Equipment

☐ Motor ☐ Ejection charges

Confirmation: I hereby attest that the packing list above has been completed and confirmed by all necessary team individuals, and the next stage of the launch procedures can commence. If batteries require disposal, I assure that team members will wear the proper PPE.

Safety Officer Signature: ______________________________________

Team Mentor Signature: ______________________________________

Recovery Lead Signature: ______________________________________

ACS Lead Signature: ______________________________________

Payload Lead Signature: ______________________________________

Vehicles Lead Signature: ______________________________________

8.1.4 Transportation

Note: Failure to follow the following procedures may result in the following failure modes: EV.1, EV.2, EV.3, EV.4, EV.5, EV.6, EV.8, EV.9, EV.10, EV.11, EV.12, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, LE.1, PR.9, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ During the week preceding the launch, the Safety Officer will examine the forecast to assess for any of the following weather conditions: Winds above 20 miles per hour, temperatures below 15 or above 90 degrees Fahrenheit, precipitation of any kind, hail, low visibility, considerable fog, considerable precipitation at the launch site in the last week, considerable snow melt at the launch site in the last week, or lightning. If any of these weather conditions appear to have a non-negligible probability of occurring while at the launch, the launch will either be postponed to a time with more favorable weather conditions or canceled altogether.
- ☐ All members, prior to the day of the launch, will receive a call time when they must be present in the workshop prepared to depart for the launch site. Any member who is not present at this time risks being left behind.
- ☐ All necessary equipment will be packed at the launch rehearsal and left out for the team to pack into the vehicles prior to departure.
- ☐ The Project Manager will conduct a head count to determine the number of people present at the beginning of the launch day and to compare it to a head count prior to departing the launch site.
- ☐ Only those that have a valid driver's license and access to a registered vehicle are eligible to provide transport to and from the launch site.
- ☐ Prior to the day of the launch, the team will organize a set list of personnel that will be attending the launch and recording which of those are able to provide transport to and from the launch site. The Project Manager will ensure that only as many team members are able to attend the launch as many as can be safely transported to and from the launch site without exceeding any of the vehicle's seating capacity.
- ☐ The Project Manager will be responsible for communicating with designated drivers to and from the launch site on when they individually should arrive at the workshop and where they should park their vehicles.
- ☐ Upon arrival at the workshop, the Safety Officer will assess all team member's preparedness for the forecasted weather at the launch site. If any team member appears unprepared, the Safety Officer will either provide necessary assistance and/or equipment or send that team member home.

- ☐ All launch components and tools outlined in the Launch Checklist section (provide hyperlink) will be carefully placed into the vehicles. Only drivers with a NAR/TRA Level 2 Certification or higher are allowed to drive with energetics in their vehicle.
- ☐ All designated drivers will practice responsible driving while en route to the launch site, obeying all traffic laws and noting any local or statewide driving law changes. The team member that is sitting up front with the driver will be responsible for providing directions to the launch site. At no point will the designated driver be able to access their cellular device; they must keep their eyes on the road at all times.
- ☐ All vehicles will be responsible for communicating with one another about their whereabouts and proximity to the launch site, and if necessary, notify the Project Manager of unexpected or considerable delays or early arrivals.

Confirmation: I hereby attest that the transportation measures listed above have been followed and understood by all necessary team individuals before travel to the launch field commences.

Safety Officer Signature:____________________________________

Project Manager Signature:____________________________________

8.1.5 Upon Arrival at Launch Field

Required Personnel: Safety Officer, Project Manager, Range Safety Officer (RSO)

Required PPE: None

Note: Failure to follow the following procedures may result in the following failure modes: EV.1, EV.2, EV.3, EV.4, EV.5, EV.6, EV.7, EV.8, EV.9, EV.10, EV.11, EV.12, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, VS.10, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Upon arrival at the launch site, the Safety Officer and Project Manager must meet with the RSO to confirm that the launch is still able to take place.
- ☐ The Safety Officer must take note of the conditions at the launch site. Specifically, the Safety Officer must confirm that there are: Minimal trees present, no major roads present in a 2,500 foot radius, minimal power lines present, and a stable ground for the launch rail and launch pad. If any of these conditions occur, the team must request to the RSO that they move within the launch site to a location that satisfies the above requirements. If the RSO declines, the team must move to a different launch site that satisfies the above conditions.
- ☐ During the week preceding the launch, the Safety Officer will examine the forecast to assess for any of the following weather conditions: Winds above 20 miles per hour, temperatures below 15 or above 90 degrees Fahrenheit, precipitation of any kind, hail, low visibility, considerable fog, considerable precipitation at the launch site in the last week, considerable snow melt at the launch site in the last week, or lightning. If any of these weather conditions appear to have a non-negligible probability of occurring while at the launch, the launch will either be postponed to a time with more favorable weather conditions or canceled altogether.
- ☐ Upon verifying with the RSO that the launch can still take place and that the weather and launch site conditions are satisfactory, the team may begin to set up the launch vehicle for the launch. Team members will assist in unloading all equipment from the transport vehicles and organizing them on the foldable tables.
- ☐ The Safety Officer will hand out copies of Launch Operating Procedures to each squad to allow for a more efficient but safe launch setup. A liaison on each squad will be designated to oversee Launch Operating

Procedures to ensure all procedures are followed and signed by the appropriate personnel. Questions can still be directed to the Safety Officer, who is still responsible for overseeing the successful completion of all Launch Operating Procedures.

Confirmation: I hereby attest that the launch site arrival procedures have been followed and that the launch site passes all necessary quality standards.

Safety Officer Signature:______________________________________

Project Manager Signature:______________________________________

RSO Signature:______________________________________

8.2 Recovery Preparation

Required Personnel: Safety Officer, Project Manager, Recovery Squad Lead, NDRT Team Mentor Dave Brunsting, Several team members

Required PPE: Safety Glasses, Nitrile Gloves

8.2.1 Inspection Checklist

Note: Failure to follow the following procedures may result in the following failure modes: R.1, R.2, R.3, R.4, R.6, R.7, R.11, R.15, VS.4, VS.5, VS.10, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Check to make sure the eye bolts are securely fastened. Tug on the eye bolts to verify that they do not move and refasten if necessary.
- ☐ Verify that the charging wells are properly secured to ensure proper separation of the vehicle.
- ☐ Inspect the mounting board for damage and ensure that it is properly fixed in place.
- ☐ Ensure that electrical switches are secure and are able to be turned on and off. Failure to do so will result in charges that cannot be armed, leading to failure mode R.3 and/or R.4.
- ☐ Ensure Team Mentor Dave Brunsting has the correct ejection charge masses. These accurate measurements will ensure proper separation of the launch vehicle while preventing damage to it. The necessary ejection charge masses are listed below:

  - NED Ejection Charge: 1.75 g
  - NED Ejection Charge: 2.25 g
  - NED Ejection Charge: 2.25 g
  - PED Parachute Charge: 4.4 g
  - PED Parachute Charge: 4.9 g
  - PED Parachute Charge: 4.9 g
  - FED Parachute Charge: 2.7 g
  - FED Parachute Charge: 3.2 g
  - FED Parachute Charge: 3.2 g

- ☐ Confirm that the parachutes are not ripped or frayed. Failure to do so may result in vehicle sections landing with more than 65 lb ft of kinetic energy, violating NASA Req 3.3.

- ☐ Ensure that the shroud lines of the parachute are not tangled, taped, or damaged. Inspect all shroud lines for these characteristics before continuing.
- ☐ Ensure all shock cords are not tangled, frayed, damaged, or taped. Inspect all shock cords before continuing. Failure to do so may result in the shock cords breaking, or failure mode R.15.
- ☐ Use a multimeter to check the voltage of all batteries. All 3.7 V batteries must have a voltage between the range of 3.2 and 4.235 V and all 7.4 V batteries are between the range of 6.4 and 8.47 V. If the batteries fall out of these ranges either use a new battery or charge the battery until it falls within the appropriate range.
- ☐ Ensure all quick links are securely fastened to their appropriate locations on all recovery modules.
- ☐ Confirm that the Nomex blanket and fiberglass wall are properly connected to the main parachute, to ensure that the payload is able to leave the payload bay. Failure to do so may result in faulty parachute deployments.

Confirmation: Confirmation: I hereby certify that all above inspection procedures have been performed and passed before moving on to any further recovery procedures.

Team Mentor Signature:______________________________________

Safety Officer Signature:______________________________________

Recovery Lead Signature:______________________________________

8.2.2 Pre-Flight Checklist

8.2.2.1 Main Parachute Folding Note: Failure to follow the following procedures may result in the following failure modes: R.1, R.7, R.8, R.9, R.10, R.13, R.14, VE.15, VS.5, VS.10, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

Figure 116: Picture of Subscale Main Parachute

- ☐ Ensure all of the cords are untangled and relatively straight.
- ☐ Layout parachute on the floor and fold it in half such that the white sections are together at the bottom and the blue sections are at the sides.
- ☐ Fold the parachute in half again so that the blue sections are now together.
- ☐ Fold the parachute in half again so all four sides are together. The blue section of the parachute should now be on top of the white section.
- ☐ Fold the parachute in thirds by folding the sides in along the length of the parachute.
- ☐ Along the same axis (the length of the parachute), fold the parachute in half again.
- ☐ Divide the top half of the parachute into thirds (the yellow section), only this time across horizontal axes. Create a “Z” with the thirds of the parachute and fold them on top of each other.
- ☐ Fold the bottom half of the parachute over this newly folded section.

- ☐ Set a weight on top of the folded parachute to release any excess air. This step will aid in the parachute fitting into the parachute bag.
- ☐ Test the functionality of the parachute folding by tossing the parachute away from the user. If the parachute easily unfolds by the time it touches the ground, the parachute will easily deploy during descent. Repeat the previous procedures in the exact same manner they were performed the first time.
- ☐ Attach the parachute to the inside of the parachute bag with a quick link.
- ☐ Roll the parachute along the vertical axis as tight as possible. Once completely rolled, slide the parachute into the parachute bag. If the parachute does not fit, restart the previous four procedures until it does. It is likely that the user did not release enough air from the folded parachute or roll the parachute tight enough.
- ☐ Wrap the cords of the parachute in the elastic of the parachute bag. Ensure that the user travels up and down the same column before crossing the stitching.
- ☐ Attach the pilot parachute to the top of the deployment bag with a quick link.
- ☐ Roll the pilot parachute, folding its cords into its center.

Troubleshooting: What if the parachute does not unfold when tossed?

1. If the parachute does not unfold when tossed, repeat the previous procedures more slowly and with extra caution.
2. Have a team member toss the parachute away from themselves again.
3. If the parachute still does not unfold, consult with the Recovery Lead on necessary adjustments to the folding procedures. Any adjustments must be tested by tossing the parachute away from oneself and assessing if the parachute unfolds by the time it hits the ground.
4. If the parachute continues to not unfold when tossed, the launch cannot proceed.

Confirmation: I hereby attest that the main parachute has been folded according to the procedures listed above and that it easily unfolds when it is tossed towards the ground.

Safety Officer Signature:______________________________________

Recovery Lead Signature:______________________________________

8.2.2.2 Drogue Parachute Folding

Note: Failure to follow the following procedures may result in the following failure modes: R.2, R.3, R.6, R.8, R.9, R.10, R.13, VE.15, VS.5, VS.10, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Lay the parachute on a table or otherwise flat surface.
- ☐ Arrange the parachute so that the actual parachute is in a semicircle resembling a two-dimensional picture of a fully deployed parachute. The shroud lines should extend below the parachute with quick links attached. The quick links should be centered and below the parachute.
- ☐ Keep shroud lines organized and untangled during the following procedures to prevent the parachute from being tangled while deploying during flight.
- ☐ Fold the parachute in half, folding one side of the parachute across the vertical axis of symmetry that extends through the quick links.

- ☐ Fold the parachute again, once more across a vertical axis. However, instead of folding one side over the other, fold the two ends of the parachute toward each other to meet in the center. To achieve this fold, align the "gores", or the black fabric in the parachute, with each other.
- ☐ Divide the parachute into thirds, only this time across horizontal axes. Create a "Z" with the thirds of the parachute and fold them on top of each other.
- ☐ Verify that the shroud lines remain untangled. Failure to do so may result in failure mode R.6.
- ☐ Wrap the shroud lines around the folded parachute so that the quick links almost are in physical contact with the parachute.
- ☐ Test the functionality of the parachute folding by tossing the parachute away from the user. If the parachute easily unfolds by the time it touches the ground, the parachute will easily deploy during descent. Repeat the previous procedures in the exact same manner they were performed the first time.
- ☐ Ensure quick links attachments are closed and firmly attached to the shroud lines by applying a force. Failure to do so may result in a recovery failure mode.
- ☐ Carefully, but loosely, place the parachute in a Nomex bag.

Confirmation: I hereby attest that the drogue parachute has been folded according to the procedures listed above and that it easily unfolds when it is tossed towards the ground.

Safety Officer Signature:____

Recovery Lead Signature:____

8.2.2.3 Fin Can Energetic Device (FED) Pre-Flight Assembly

Note: Failure to follow the following procedures may result in the following failure modes: VS.13, VFM.1, R.2, R.3, R.4, R.6, R.8, R.9, R.10, R.13, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Slide the FED module into the ACS body tube. Use dry lubricant to assist integration as needed.
- ☐ Fasten the FED module to the air frame interfacing blocks using #8-32 screws. Failure to do so may result in the module coming apart during launch, or failure mode VS.13.
- ☐ Attach a quick link to the FED eye bolt. Verify that the quick link is attached to recovery laundry, the relevant parachute, Nomex blanket, and shock cords.
- ☐ Ensure the Nomex blanket is connected to the shock cord which is connected to the appropriate parachute.
- ☐ Fold the recovery laundry into the aft side of the ACS body tube.

Confirmation: I hereby certify that the FED module has been correctly integrated into the launch vehicle body tube and is secure in its installation.

Safety Officer Signature:____

Recovery Lead Signature:____

8.2.2.4 Payload Energetic Device (PED) Pre-Flight Assembly

Note: Failure to follow the following procedures may result in the following failure modes: VS.13, VFM.1, R.1, R.3, R.4, R.5, R.7, R.9, R.13, R.14, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

☐ Slide the PED module into the payload bay. Use dry lubricant to assist integration as needed.

☐ Fasten the PED module to the air frame interfacing blocks using 8-32 screws. Failure to do so may result in the module coming apart during launch, or failure mode VS.13.

☐ Attach a quick link to the PED eye bolt. Verify that the quick link is attached to recovery laundry, the relevant parachute, Nomex blanket, and shock cords.

☐ Ensure the Nomex blanket is connected to the shock cord which is connected to the appropriate parachute.

☐ Fold the recovery laundry into the aft side of the payload bay.

Confirmation: I hereby certify that the PED module has been correctly integrated into the launch vehicle body tube and is secure in its installation.

Safety Officer Signature:_______________________________________

Recovery Lead Signature:_______________________________________

8.2.2.5 Nose Cone Energetic Device (NED) Pre-Flight Assembly

Note: Failure to follow the following procedures may result in the following failure modes: VS.13, VFM.1, R.3, R.4, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

☐ Slide the NED module into the fore side of the payload bay.

☐ Fasten the NED module to the air frame interfacing blocks using #8-32 screws. Failure to do so may result in the module coming apart during launch, or failure mode VS.13.

Confirmation: I hereby certify that the NED module has been correctly integrated into the launch vehicle body tube and is secure in its installation.

Safety Officer Signature:_______________________________________

Recovery Lead Signature:_______________________________________

8.2.2.6 Black Powder Separation Charges

Note: Only Team Mentor Dave Brunsting can install the ejection charges due to his NAR/TRA Level 3 certification. The Team Mentor must wear nitrile gloves and safety glasses when performing the following procedures.

Note: Failure to follow the following procedures may result in the following failure modes: LO.3, R.1, R.2, R.3, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

☐ Shunt all ejection charges together by wiring them in series to prevent accidental ignition.

☐ Obtain all ejection charges and fill the charges according to the masses described below:

- NED Ejection Charge: 1.75 g
- NED Ejection Charge: 2.25 g
- NED Ejection Charge: 2.25 g
- PED Parachute Charge: 4.4 g
- PED Parachute Charge: 4.9 g

- PED Parachute Charge: 4.9 g
- FED Parachute Charge: 2.7 g
- FED Parachute Charge: 3.2 g
- FED Parachute Charge: 3.2 g

☐ Ensure all altimeters are turned off before proceeding.

☐ Connect all ejection charges to their appropriate altimeters.

☐ Insert all ejection charges into their respective charge wells.

☐ Cover all charge wells with masking tape to aid in air flow as well as a safety precaution when recovering the launch vehicle. Inspection of the presence of masking tape on the charge wells will confirm that the ejection charge had gone off.

Note: Do not completely cover the charge well with masking tape; leave a small section open to direct the force of the charge as it exits the charge well.

Confirmation: I hereby certify that the above procedures were done correctly and by only Team Mentor Dave Brunsting. The Team Mentor attests that they were using proper PPE when carrying out the procedures.

Team Mentor Signature:____

Safety Officer Signature:____

Recovery Lead Signature:____

Overall Recovery Confirmation: I hereby certify that all Recovery procedures have been completed according to the procedures described above and that all components have passed quality standards before proceeding to any further operating procedures.

Team Mentor Signature:____

Project Manager Signature:____

Safety Officer Signature:____

Recovery Lead Signature:____

8.3 TROI Preparation

Required Personnel: Safety Officer, Project Manager, Payload Squad Lead, NDRT Team Mentor Dave Brunsting

Required PPE: None

8.3.1 Inspection Checklist

Note: Failure to follow the following procedures may result in the following failure modes: TROI.4 or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

☐ Verify that the TROI system battery read a voltage within the acceptable range of 9.6 to 12.6 V using a digital multimeter. If any battery does not have an acceptable voltage, charge the battery using a portable DC power supply or replace the battery.

Confirmation: I hereby certify that the TROI batteries are within an acceptable voltage range.

Safety Officer Signature:____

Payload Lead Signature:____

8.3.2 Pre-Flight Checklist

Note: Failure to follow the following procedures may result in the following failure modes: TROI.8, TROI.9, TROII.3, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ In order to ensure the TROI system is operational, verify that the correct code is loaded onto the microcontroller.
- ☐ With the battery status verified, connect the microcontroller to the battery.
- ☐ Once the battery connection is made, the microcontroller will be searching for radio signals. Once the circuit is in its "listening" stage, an LED light will light up on the circuit indicating that it is on and functional.
- ☐ **Note:** If this LED light does not flash, obtain the Payload Squad Lead's laptop to ensure that the correct code is uploaded to the microcontroller. If the LED light still does not flash, turn the system off and restart this procedure.
- ☐ Ensure that the indicator light on all accelerometers is on. If this light does not flash, resolder or rewire connections as necessary.
- ☐ Ensure that the indicator light on the RF transceiver module is on. If this flight does not flash, resolder or rewire connections as necessary.
- ☐ Ensure that the indicator light on the camera is on. If this light does not flash, resolder or rewire connections as necessary.
- ☐ Ensure that the indicator light on the ground station is on. If this light does not flash, resolder or rewire connections as necessary.

Confirmation: I hereby that the TROI passes all quality standards and the above procedures have been closely followed.

Safety Officer Signature:____

Payload Lead Signature:____

8.3.2.1 Radio Interference Test

Note: Failure to follow the following procedures may result in the following failure modes: TROI.1, TROI.5, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Ensure that there is no interference from the ground station to the payload bay. To test this requirement, ensure all electronics are active and set the ground station and payload bay to a defined frequency that is different from the NASA-defined frequency.
- ☐ Transmit a set of image capture instructions from the ground station to the payload bay and inspect whether or not the e-match switches fire.
- ☐ If the e-match switches do not fire, turn off all electronic equipment and reactivate it before repeating these procedures. Failure to confirm a lack of interference may result in failure mode TROI.1, which would cause a complete mission failure.

Confirmation: I hereby certify that the above test was performed according to the procedures and there is no interference between the ground station and the e-matches.

Safety Officer Signature:____

Payload Lead Signature:____

8.3.2.2 Calibration Test

Note: Failure to follow the following procedures may result in the following failure modes: TROI.1, TROI.2, TROII.3, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Ensure calibration before integration is satisfactory. Obtain the laptop with the appropriate code and set up the ground station to send instructions to the TROI.
- ☐ Set up the TROI to receive radio frequencies.
- ☐ From the ground station at a certain radio frequency separate from the NASA-defined frequency, send a set of movements to be performed by the TROI.
- ☐ Observe the TROI's movement and inspect if the payload moves as expected from the set transmission. If the payload does not move as expected, turn off the system and apply extra coating strips to allow the motor arms to work properly. Reactivate the electronics and repeat these procedures.
- ☐ Verify that the accelerometer is not drifting. Analyze the data sent to the ground station and verify that it is reasonable data. If the data is nonsensical, reconnect the accelerometer with wires or soldering as necessary. Repeat these procedures to ensure that the updated connections ensure the accelerometer does not drift.
- ☐ **Note:** If reconnecting the accelerometer does not fix the drifting, verify that the transmission as received and that all subsystems are active.

Troubleshooting: What if the payload's movement is failing during the calibration test?

1. Initialize the ground station and prepare for transmission.
2. Initialize the payload radio and prepare for transmission.
3. Transmit a series of commands from the ground station to the payload radio.
4. Assess whether any commands were received and if they were comprehended correctly by the payload radio.
5. If the payload radio does not properly receive the ground station commands, ensure the radio frequency is correct and that there is no static on that frequency. Following those checks, repeat procedures one through four.

Confirmation: I hereby certify that the calibration test has been performed according to the above procedures and that the TROI can operate in all defined ranges of motion when given movement commands.

Safety Officer Signature:____

Payload Lead Signature:____

Overall Payload Confirmation: I hereby certify that all payload inspection and pre-flight assembly procedures have been followed properly according to the procedures above. Proper PPE was used as according to the above procedures.

Team Mentor Signature:____

Project Manager Signature:____

Safety Officer Signature:____

Payload Lead Signature:____

8.4 Apogee Control System (ACS) Preparation

Required Personnel: Safety Officer, Project Manager, ACS Squad Lead, NDRT Team Mentor Dave Brunsting

Required PPE: Safety Glasses

8.4.1 Inspection Checklist

Note: Failure to follow the following procedures may result in the following failure modes: ACS.1, ACS.3, ACS.5, ACS.9, ACS.11, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Inspect the ACS to ensure there is no visible physical or electrical damage.
- ☐ Inspect all wires of the ACS to ensure that no wires are frayed. If any wires are frayed, tape around them with electrical tape or replace them with new wires. Failure to follow this procedure may lead to electrical fires and failure mode ACS.5.
- ☐ Rotate all flap lever arms and verify that they are able to freely rotate about their axes of rotation. If the arms do not fully rotate, detach the arms and sand them down with sandpaper until they are able to freely rotate on their axes of rotation. Failure to do so may result in failure mode ACS.3.
- ☐ Using a multimeter, check the voltage of all ACS batteries to ensure they are fully charged. For all 7.4 V batteries, the voltage must lie between 6.4 and 8.47 V. For all 3.7 V batteries, the voltage must lie between 3.2 and 4.235 V. If any of the battery voltages fall outside this range, charge them or use extra batteries that meet this requirement. If any low voltage light is illuminated, recharge the battery until fully charged or use a backup battery of the same nominal voltage.

Confirmation: I hereby certify that all above inspection procedures have been performed and passed before moving on to any further ACS procedures.

Safety Officer Signature:____

ACS Lead Signature:____

8.4.2 Pre-Flight Checklist

Note: Failure to follow the following procedures may result in the following failure modes: ACS.3, ACS.6, ACS.7, ACS.9, ACS.10, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Turn on the logic circuit battery. Once activated, the Raspberry Pi should sound a noise and display a light confirming its activity. Such confirmation will indicate all other systems in the ACS are on and functional. If this activity does not occur, turn off the Raspberry Pi and reactivate it and verify that it is functioning. If the Raspberry Pi continues to not sound a noise or display a light, replace the SD card in the unit and reactivate the system. Failure to follow this procedure may result in unpredictable behavior from the servo motor, or failure mode ACS.6.

- ☐ Turn on the servo motor battery and wait for the lever arms to self actuate. This actuation will confirm the servo motor is operational. Failure to adhere to this procedure may result in an inability for the ACS to actuate during flight.
- ☐ Check that all battery connections are secure. If any battery connection looks to be unstable, use electrical tape or resolder the connection to ensure security. Failure to follow this procedure may result in failure mode ACS.7, leading to the ACS failing to function in any capacity.
- ☐ Verify that there is a confirmation light on the IMU. If the light does not appear, turn off and reactivate the IMU and confirm that a light is present. If a light is still not present, check the soldering work done on the part and resolder if it appears to be faulty.
- ☐ Verify that there is a confirmation light on the accelerometer. If the light does not appear, turn off and reactivate the accelerometer and confirm that a light is present. If a light is still not present, check the soldering work done on the part and resolder if it appears to be faulty.
- ☐ Verify that there is a confirmation light on all altimeters. If the light does not appear, turn off and reactivate the accelerometer and confirm that a light is present. If a light is still not present, replace the faulty altimeter with a spare altimeter and reinspect for the confirmation light.

Confirmation: I hereby certify that all above inspection procedures have been performed and passed before moving on to any further ACS procedures.

Safety Officer Signature:______________________________________

ACS Lead Signature:______________________________________

Overall ACS Confirmation: I hereby certify that all above ACS pre-flight and inspection procedures have been followed according to what is outlined above. I also attest that all participants in these procedures were wearing proper PPE.

Team Mentor Signature:______________________________________

Project Manager Signature:______________________________________

Safety Officer Signature:______________________________________

ACS Lead Signature:______________________________________

8.5 Launch Vehicle Preparation

Required Personnel: Safety Officer, Systems Lead, Project Manager, ACS Squad Lead, Recovery Squad Lead, Payload Squad Lead, Vehicles Squad Lead, NDRT Team Mentor Dave Brunsting

Required PPE: Safety Glasses, Nitrile Gloves

8.5.1 Launch Vehicle Inspection

Note: Failure to follow the following procedures may result in the following failure modes: VS.2, VS.3, VS.4, VS.5, VS.7, VS.13 or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Inspect the launch vehicle body tube and ensure no cracks or other major physical damage is present. Verifying the structural integrity of the body tubes is critical for successful integration and flight.

- ☐ Inspect the couplers, fins, and camera shroud to ensure there are no cracks or other major physical damage. Cracks or lapses in structural integrity of any component can potentially lead to failure mode VS.5 due to the dynamic load at landing.
- ☐ Ensure bulkheads are tethered correctly. Improper tethering of bulkheads can pose a safety risk for observers of launch alongside loss of launch vehicle components, resulting in an inability for reuse.
- ☐ Obtain the ACS, payload bay, and all three recovery modules. Ensure all eye bolts are tethered correctly. Improper tethering can pose a safety risk as eye bolts may come loose during launch and damage internal components, leading to falure mode VS.15.
- ☐ Obtain all launch vehicle components that will be integrated into the launch vehicle and in flight during launch. Inspect to ensure all internal and external components are not structurally deficient. Failure to complete this procedure may result in structural failures during launch and unpredictable behavior.

Confirmation: I hereby certify that all above inspection procedures have been completed with the proper PPE.

Safety Officer Signature:______________________________________

Vehicles Lead Signature:______________________________________

8.5.2 Launch Vehicle Integration

Note: Make sure to fasten all internal components when integrating each launch vehicle component. Failure to properly secure internal components may result in the center of gravity shifting during flight, resulting in inconsistencies with simulations and therefore unpredictable behavior.

8.5.2.1 ACS Integration

Note: Failure to follow the following procedures may result in the following failure modes: VS.13, ACS.4, ACS.9, ACS.11, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Ensure all previous procedures for ACS have been completed before moving onto its integration into the launch vehicle.
- ☐ Obtain at least two team members as well as the ACS Squad Lead. Have at least two team members hold the launch vehicle in place while one inserts the ACS into the launch vehicle. The symmetry of the device means that there is no specific orientation required for the ACS, but the lever arms must be the horizontal center of the sections removed from the body tube. Failure to adhere to this procedure may result in the actuation flaps failing to successfully actuate.
- ☐ After ensuring that the ACS is in the proper configuration inside the body tube, line up the fastener holes on the launch vehicle with the ones on the ACS airframe interface blocks and fasten the system into its appropriate bay and position inside the launch vehicle. Failure to follow this procedure may result in ACS.4 or VS.13 as the system will not be properly fastened.
- ☐ Once fastened, look inside the body tube cuts to ensure that all confirmation lights on the electronics are still active and on, confirming that the functionality of the ACS was not harmed by its installation into the launch vehicle. If any lights were turned off while being integrated, remove the ACS from the launch vehicle and reactivate the system that had been deactivated. Failure to follow this procedure may result in failure modes ACS.9 as critical components may or may not be activated.

- ☐ Obtain the Safety Officer to observe the following procedure: Attach the actuation flaps to the lever arms of the ACS within the launch vehicle. Use appropriate fastening tools to ensure that the actuation flaps on the launch vehicle are secure.

Confirmation: I hereby certify that all above inspection procedures have been performed and passed before moving on to any further ACS procedures.

Project Manager Signature:_______________________________________

Safety Officer Signature:_______________________________________

Systems Lead Signature:_______________________________________

Vehicles Lead Signature:_______________________________________

ACS Lead Signature:_______________________________________

8.5.2.2 TROI Integration

Note: Failure to follow the following procedures may result in the following failure modes: VS.13, TROI.2, TROII.4, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Slide the TROI system into the payload bay. Use dry lubricant if needed.
- ☐ Attach the TROI system to the air frame interfacing blocks using #8-32 screws. Failure to properly attach these screws may result in VS.13 as the system will not be fully secured.
- ☐ Verify the TROI system is properly retained within the payload bay by applying cyclical horizontal and vertical forces to the system. If the TROI system experiences displacement or any screws loosen, refasten the system to the air frame interfacing blocks and repeat the process.
- ☐ Obtain the Payload Lead and have them integrate the electronics shielding blanket.
- ☐ Integrate the PED Recovery Module. Ensure the integration is according to the procedures outlined in PED Module Integration.

Confirmation: I hereby certify that the above integration procedures have been performed and that the system is securely fastened inside the launch vehicle.

Project Manager Signature:_______________________________________

Safety Officer Signature:_______________________________________

Systems Lead Signature:_______________________________________

Vehicles Lead Signature:_______________________________________

Payload Lead Signature:_______________________________________

8.5.2.3 Recovery Integration

Note: Failure to follow the following procedures may result in the following failure modes: VFM.1, VS.13, R.1, R.2, R.3, R.4, R.5, R.6, R.7, R.8, R.9, R.10, R.13, R.14, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Ensure all procedures for integrating the NED, PED, and FED into the launch vehicle have been completed.

Confirmation: I hereby certify that all procedures for integrating the NED, PED, and FED into the launch vehicle have been completed with the appropriate PPE.

Project Manager Signature:______________________________________

Safety Officer Signature:______________________________________

Systems Lead Signature:______________________________________

Vehicles Lead Signature:______________________________________

Recovery Lead Signature:______________________________________

8.5.2.4 Flight Camera Integration

Note: Failure to follow the following procedures may result in the following failure modes: VS.13, VFM.1, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Insert the appropriate SD card into the back of the camera.
- ☐ Turn the camera on, which is done by pressing and holding on the power button until a light appears. This light indicates that the camera is on.
- ☐ Press the record button, indicated by a camera button. The power light will flash, which indicates that the camera is recording. The recording feature should not be activated until the estimated time from initial activation plus approximately two hours is within the camera's predetermined recording battery life. Failure to do so may result in the camera failing to catch the launch on recording.
- ☐ Once the camera is confirmed to have started recording, insert it into the camera mount onto the vehicle. The camera lens should be pointing down towards the ground so that it records the launch vehicle's flight trajectory.
- ☐ Insert the cover plate at the bottom of the camera mount to hold the camera in place.
- ☐ Ensure that the camera mount is securely attached to the launch vehicle.

Confirmation: I hereby certify that the flight camera passes all quality standards and has been properly integrated into the launch vehicle according to the above procedures.

Safety Officer Signature:______________________________________

Vehicles Lead Signature:______________________________________

8.5.2.5 Shake Test

Note: Failure to follow the following procedures may result in the following failure modes: VS.13 or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Ensure the launch vehicle is fully integrated before conducting this test.
- ☐ With two hands, firmly pick up the launch vehicle and hold it some distance above the ground.
- ☐ Apply a rapidly oscillating horizontal force to the launch vehicle to listen for any audible sounds.
- ☐ The only noise that should be heard is the sound of the metal quick links coming into contact with the bulkhead or other nearby components.
- ☐ **Note:** If any other audible sounds are present, halt the horizontal force and set the launch vehicle down on a foldable table. Open the launch vehicle and determine which component(s) was/were loose. Tighten components as necessary and repeat the test. Failure to correct for loose components may result in failure

mode VS.13 and thus unpredictable behavior during launch.

Confirmation: I hereby certify that all launch vehicle components are securely fastened and no audible noises were observed when conducting a shake test.

Safety Officer Signature:______________________________________

Vehicles Lead Signature:______________________________________

8.5.2.6 Motor Preparation and Inspection

Note: Team Mentor Dave Brunsting is the only individual allowed to perform the following procedures due to their NAR/TRA Level 3 Certification. The Team Mentor must wear nitrile gloves and safety glasses when performing these procedures.

Note: Failure to follow the following procedures may result in the following failure modes: LO.2, VS.1, VS.8, VFM.5, VFM.6, VE.1, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ **Note:** Team Mentor Dave Brunsting is the only individual allowed to perform the following procedures due to their NAR/TRA Level 3 Certification. The Team Mentor must wear nitrile gloves and safety glasses when performing these procedures.
- ☐ Remove the motor from its packaging.
- ☐ Inspect the motor to ensure all components are intact and void of any physical damage. If there are any deficiencies present, set aside the motor and use a motor that passes the above quality standards. Failure to inspect the motor may result in failure modes VS.1 or VS.8 due to a potentially faulty motor.
- ☐ Ensure with the team mentor that the motor is safe to use.

Confirmation: I hereby certify that NDRT Team Mentor Dave Brunsting performed all above steps and the motor being used is void of any physical deficiencies.

Team Mentor Signature:______________________________________

Project Manager Signature:______________________________________

Safety Officer Signature:______________________________________

Vehicles Lead Signature:______________________________________

8.5.2.7 Motor Integration

Note: Failure to follow the following procedures may result in the following failure modes: LO.2, VS.1, VS.8, VS.9, VFM.3, VFM.5, VFM.6, VFM.7, VE.1, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Only Team Mentor Dave Brunsting is authorized to complete the following procedures due to his NAR/TRA Level 3 certification. The Team Mentor must be using nitrile gloves and safety glasses when performing these procedures.
- ☐ Ensure there are two spacers preceding where the inserted motor will be.
- ☐ Ensure centering rings are present inside the fin can. This procedure is critical in ensuring that the motor is aligned vertically. Failure to follow this procedure may result in failure mode VS.9, which could pose major risks to bystanders due to the launch vehicle's unpredictable flight pattern.

- ☐ Insert the motor into the motor casting.
- ☐ Screw on the rear casting closing, ensuring it is tightly fastened.
- ☐ Insert the motor and motor casting component into the motor mount tube inside the fin can. The end of the motor where the propellant will shoot from should be the end of the motor that faces away from the rocket and thus the last part of the component to be slid into the launch vehicle.
- ☐ Attach the retainer ring to the end of the motor.
- ☐ Ensure that the retainer ring is securely fastened.
- ☐ Ensure the entire motor component is securely fastened to the fin can and launch vehicle. Failure to do so may result in the motor coming loose during ignition, leading to failure modes VFM.3 or VFM.7 and potentially major safety risks to bystanders from an unpredictable flight path.

Confirmation: I hereby certify that the motor has been integrated into the launch vehicle according to the above procedures. I also attest that NDRT Team Mentor Dave Brunsting was the only person performing the above procedures and was wearing the proper PPE while doing so.

Team Mentor Signature:______________________________________

Project Manager Signature:______________________________________

Safety Officer Signature:______________________________________

Vehicles Lead Signature:______________________________________

8.5.2.8 Stability Test

Note: Failure to follow the following procedures may result in the following failure modes: VFM.1, VFM.2, VFM.3, VFM.4, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Ensure all components are securely fastened and integrated before proceeding.
- ☐ Obtain the wooden rail. Carefully set the launch vehicle on the rail, with the vehicle's center resting on the rail. Gently move one's hands slightly below the launch vehicle so that the vehicle is free to move but can be caught if it begins to move in one direction.
- ☐ Inspect if the launch vehicle balances itself and obtains equilibrium at the location it is placed on the wooden rail. If the vehicle is not stable and begins to tip, readjust the launch vehicle's placement along the wooden rail until balance is achieved.
- ☐ When the launch vehicle is able to balance itself on the wooden rail, use a marking tool to mark, on the launch vehicle, where that location is. This value will serve as the calculated center of gravity.
- ☐ Obtain the laptop that has a RockSim and/or OpenRocket subscription installed and has the launch vehicle's simulation data. Compare the calculated center of gravity to that obtained by the simulation data from both softwares. Measure the values onto the launch vehicle and ensure they are within a reasonable distance from each other. Failure to perform this procedure may result in unpredictable and incorrect ACS actuation, inconsistent touchdown locations, and oscillations in flight that lead to rapid unscheduled disassembly. The launch vehicle, without performing this procedure, may be overstable or understable, resulting in the above consequences as a result of failure modes VFM.1 or VFM.4.
- ☐ Report the calculated center of gravity along with its relation to the software-derived calculations to NDRT

Team Mentor Dave Brunsting for approval before proceeding onto the next set of procedures.

Troubleshooting: What if the center of gravity determined at the launch site does not match the software value?

1. If the calculated center of gravity does not agree with the software-derived values or NDRT Team Mentor Dave Brunsting does not approve of the measurements, obtain all design and operational leads.
2. Weigh each squad's system and compare masses to that provided in the most current mass estimates.
3. If the masses are inaccurate, insert ballast to necessary launch vehicle components to obtain accurate measurements and recalculate the center of gravity using the procedures listed in the Stability Test.
4. If the masses are accurate, insert ballast to the launch vehicle in necessary locations to move the center of gravity to a more acceptable location. Recalculate the center of gravity using the procedures listed in the Stability Test.
5. **Confirmation:** Only add ballast as to not violate NASA Req. 2.23.7. If the team cannot add any additional ballast or allotted ballast does not adjust the calculated center of gravity to more acceptable measurements, cancel further launch procedures until an acceptable solution can be arrived at by the team.
6. After recalculating the center of gravity, compare measurements to software-derived values and present findings to NDRT Team Mentor Dave Brunsting for approval before proceeding.

Confirmation: I hereby certify that the calculated center of gravity is within a reasonable distance of the software-derived center of gravity locations on the launch vehicle. The team reported these values to NDRT Team Mentor Dave Brunsting for approval and was granted such approval to proceed in launch vehicle preparation.

Team Mentor Signature:___________________________________

Project Manager Signature:___________________________________

Safety Officer Signature:___________________________________

Vehicles Lead Signature:___________________________________

8.5.2.9 Shear Pin Integration

Note: Failure to follow the following procedures may result in the following failure modes: VS.6 or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

☐ Locate all shear pin holes on the launch vehicle.

☐ Place shear pins into the appropriate holes.

☐ Ensure all shear pin holes have been filled. Failure to do so may result in failure mode VS.6.

Confirmation: I hereby certify that all shear pins have been properly inserted into their correct holes on the launch vehicle.

Team Mentor Signature:___________________________________

Project Manager Signature:___________________________________

Safety Officer Signature:___________________________________

Vehicles Lead Signature:___________________________________

Overall Confirmation: I hereby certify that all launch vehicle procedures have been completed according to the proper procedures and all launch vehicle components have passed the appropriate quality standards.

Team Mentor Signature:___________________________________

Project Manager Signature:____

Safety Officer Signature:____

Vehicles Lead Signature:____

Payload Lead Signature:____

Recovery Lead Signature:____

ACS Lead Signature:____

Systems Lead Signature:____

8.6 Setup on Launch Pad

Note: Failure to follow the following procedures may result in the following failure modes: VFM.7, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ The Safety Officer and at least one other team member must inspect the ground that the launch pad is placed on. Verify that the ground is firm and even. If the launch pad location fails either one of these criteria, ask the RSO and LCO for permission to move the launch pad to a new location that has suitable ground. Failure to do so may result in the launch vehicle launching at an unpredictable angle, or failure mode VFM.7.
- ☐ Ensure that the launch pad and rail is void of any debris or defects. If it is, replace and clean as necessary before proceeding.
- ☐ Verify with the RSO and LCO that the ground is firm and is safe to launch the launch vehicle at the pad's final location.
- ☐ Verify with the RSO and LCO that the team can use their launch controller for the launch.

Confirmation: I hereby certify that the launch pad has been thoroughly inspected and has passed all quality standards. The RSO and LCO certify have given permission for the team to use their launch equipment and that the ground on which the launch pad is located is firm and safe for a launch.

Team Mentor Signature:____

Project Manager Signature:____

Safety Officer Signature:____

Vehicles Lead Signature:____

LSO Signature:____

RCO Signature:____

8.6.1 Launch Site Evaluation

Required Personnel: Safety Officer, NDRT Team Mentor Dave Brunsting, Project Manager, Range Safety Officer (RSO), Launch Control Officer (LCO), Vehicles Squad Lead, ACS Squad Lead, Payload Squad Lead, Several team members

Required PPE: Safety Glasses, Nitrile Gloves

Note: Failure to follow the following procedures may result in the following failure modes: EV.1, EV.2, EV.3, EV.4,

EV.5, EV.6, EV.7, EV.8, EV.9, EV.10, EV.11, EV.12, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ At the launch pad, verify the following weather conditions, as mentioned in section 8.1.5 are still valid: Winds above 20 miles per hour, temperatures below 15 or above 90 degrees Fahrenheit, precipitation of any kind, hail, low visibility, considerable fog, considerable precipitation at the launch site in the last week, considerable snow melt at the launch site in the last week, or lightning. If any of these weather conditions appear to have a non-negligible probability of occurring while at the launch, the launch will either be postponed to a time with more favorable weather conditions or canceled altogether.
- ☐ At the launch pad, verify the following environment conditions, as mentioned in section 8.1.5 are still valid: Minimal trees present, no major roads present in a 2,500 foot radius, minimal power lines present, and a stable ground for the launch rail and launch pad. If any of these conditions occur, the team must request to the RSO that they move within the launch site to a location that satisfies the above requirements. If the RSO declines, the team must move to a different launch site that satisfies the above conditions.
- ☐ If any of these weather conditions are occurring or appear to have a non-negligible probability of occurring during the launch, the launch will either be delayed to a later time that day with more favorable weather conditions or cancelled altogether.
- ☐ Confirm with the RSO and LCO that all functions and systems of the launch vehicle are functional. The RSO and LCO will give final approval for the launch to proceed. The team cannot move forward in the launch operating procedures without this approval.

Confirmation: I hereby certify that the environmental and weather conditions are still valid. The RCO and LSO have verified these conditions and have been satisfied and that it is safe to proceed with launch setup.

Team Mentor Signature:________________________________

Project Manager Signature:________________________________

Safety Officer Signature:________________________________

LCO Signature:________________________________

RSO Signature:________________________________

8.6.2 Launch Equipment Setup

Note: Failure to follow the following procedures may result in the following failure modes: VFM.5, VFM.6, VFM.7, LE.1, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Obtain a wooden launch block that will go in between the motor and the launch pad.
- ☐ No additional equipment should be present besides that provided by the launch site officials, per NASA Req. 1.12.
- ☐ Register the team, launch vehicle, and launch rail with the RSO and LCO.
- ☐ Verify with the RSO and the LCO the launch angle the team desires to launch at is an approved angle, per local, NAR/TRA, and NASA regulations.
- ☐ Obtain Team Mentor Dave Brunsting and three to five team members, one of which must be the Safety Officer. Have at least three team members carry the launch vehicle to the launch location, having both hands on the

launch vehicle at all times. Failure to do so may result in the launch vehicle being dropped.

- ☐ Place the launch pad on the flat and even ground found in section 8.1.5. Setup the launch pad according exactly to the Team Mentor's instructions. Failure to do so may result in faulty launch equipment setup and a launch failure.
- ☐ Obtain a team member and, using a protractor, verify that the launch pad is even with the ground. The launch pad must be within zero to one degrees above or below the horizontal. Failure to do so may result in an unacceptable launch angle, or failure mode VFM.7.

Confirmation: I hereby certify that all above procedures were followed properly while setting up the launch equipment and preparing the launch vehicle to be loaded onto the launch rail. The LSO and RCO still certify that a launch is permissible.

Team Mentor Signature:_______________________________________

Project Manager Signature:_______________________________________

Safety Officer Signature:_______________________________________

LSO Signature:_______________________________________

RCO Signature:_______________________________________

8.6.3 Launch Rail Checklist

8.6.3.1 Place Launch Vehicle on Launch Pad **Note: Failure to follow the following procedures may result in the following failure modes:** VS.12, VFM.5, VFM.6, VFM.7, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Ensure no launch wires in the launch vehicle are live before proceeding. This procedure is critical as an accidental ignition would seriously harm or kill the personnel setting the launch vehicle on the launch rail.
- ☐ Ensure that the launch vehicle will have a clean and smooth rail to launch off from. Verify that the launch rail is void of any debris or defects. If any defects are used, halt launch procedures and find a replacement launch rail that is void of defects.
- ☐ Attach the launch rail to the launch pad, securely fastening the two together.
- ☐ Lower the launch rail to be approximately even with the horizontal.
- ☐ Have the team members that were carrying the launch vehicle to the launch rail carefully and slowly align the launch rail knobs on the launch vehicle to the launch rail.
- ☐ Have the same team members slowly slide the launch vehicle onto the launch rail, with the fin can going in first. Team members must keep both hands on the launch vehicle during this process to prevent the launch vehicle from falling off of the launch rail. Failure to do so may result in dropping the launch vehicle, or failure mode VS.12.
- ☐ Before fully sliding the launch vehicle onto the launch rail, place the launch block between the launch pad and the bottom of the fin can.
- ☐ Continue to slide the launch vehicle onto the launch rail until all knobs on the launch vehicle are inside the launch rail. Halt sliding at this point and before the fin can make contact with the launch block.
- ☐ The Team Mentor should fasten the knobs on the launch rail so that the launch vehicle is held completely by the launch rail.

- ☐ Allow the team members to slowly let go of the launch vehicle to ensure that the launch rail holds the launch vehicle to it.
- ☐ Apply a gentle shake to the launch vehicle and ensure it does not move when on the launch rail. If the launch vehicle does move, have the team members place both of their hands back onto the launch vehicle while the Team Mentor fastens the knobs further. Repeat this procedure until the launch vehicle does not move when shaken. Failure to do so may result in an unpredictable flight pattern.
- ☐ With the launch block between the bottom of the fin can and touching the launch pad, move the launch rail so that it is aligned with the vertical.
- ☐ Obtain a ladder to reach the necessary heights in the following electronic verification procedures.

Confirmation: I hereby certify that all above procedures were properly followed by both the Team Member and team members. Team members took extra precaution while handling the launch vehicle.

Team Mentor Signature:______________________________________

Safety Officer Signature:______________________________________

8.6.3.2 Activate Recovery Electronics

Note: Failure to follow the following procedures may result in the following failure modes: VS.3, VS.4, VS.5, VS.7, VS.10, R.1, R.2, R.3, R.4, R.13, R.14, R.16, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8, VE.15, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Obtain the Recovery Squad Lead.
- ☐ Locate the e-match switches in the FED module and use a key to turn each switch ON. Verify the switches are turned ON by listening for an audible beep signaling that each altimeter is ready to receive data. Verify with the Recovery Squad Lead that this procedure was correctly completed. The Safety Officer, Recovery Squad Lead, and at least three other personnel must confirm that this procedure was completed. Failure to do so may result in the altimeters not igniting the ejection charges during launch, or failure more R.4.
- ☐ Locate the e-match switches in the PED module and use a key to turn each switch ON. Verify the switches are turned ON by listening for an audible beep signaling that each altimeter is ready to receive data. Verify with the Recovery Squad Lead that this procedure was correctly completed. The Safety Officer, Recovery Squad Lead, and at least three other personnel must confirm that this procedure was completed. Failure to do so may result in the altimeters not igniting the ejection charges during launch, or failure more R.4.
- ☐ Locate the e-match switches in the NED module and use a key to turn each switch ON. Verify the switches are turned ON by listening for an audible beep signaling that each altimeter is ready to receive data. Verify with the Recovery Squad Lead that this procedure was correctly completed. The Safety Officer, Recovery Squad Lead, and at least three other personnel must confirm that this procedure was completed. Failure to do so may result in the altimeters not igniting the ejection charges during launch, or failure more R.4.
- ☐ If any of the e-match switches do not emit an audible noise, remove the launch vehicle from the launch rail and separate the Recovery module in question from the rest of the launch vehicle.
- ☐ Turn off all other components that have already been modified during this procedure. Inspect individual electronic components to determine the faulty component. Replace and repair components and necessary before repeating individual system integration, launch vehicle integration, and launch pad setup procedures.

Confirmation: I hereby certify that all e-switches are activated before proceeding to any further recovery launch procedures.

Team Mentor Signature:______________________________________

Safety Officer Signature:______________________________________

Recovery Lead Signature:______________________________________

8.6.3.3 Verify ACS Power

Note: Failure to follow the following procedures may result in the following failure modes: ACS.1, ACS.3, ACS.9, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Obtain the ACS Squad Lead.
- ☐ Using a ladder, climb to the appropriate height to view inside the ACS bay. Verify the state of the ACS.
- ☐ If the system is in the launched state, an LED light should be visible from looking inside the bay from outside the launch vehicle. The ACS Squad Lead should verify that they do not see this light.
- ☐ If the LED light is visible, remove the launch vehicle from the launch rail and separate the ACS from the rest of the launch vehicle. Turn off all other components that have already been modified during this procedure. Inspect individual components and reset the system so that it is not in the launched state. Replace and repair components are necessary. Repeat system integration, full-scale integration, and launch pad setup procedures before moving on from this step.
- ☐ Verify that the ACS has power.

Confirmation: I hereby certify that the ACS power is functional while the launch vehicle is on the launch pad. All above procedures were followed thoroughly when verifiying the ACS functionality.

Team Mentor Signature:______________________________________

Safety Officer Signature:______________________________________

ACS Lead Signature:______________________________________

8.6.3.4 Verify TROI Power

Note: Failure to follow the following procedures may result in the following failure modes: TROI.4 or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Once the launch vehicle is on the launch rail, pull the pullpin to engage the system. There should be an audible noise once the pin is pulled.
- ☐ If this noise is not heard, take the launch vehicle off of the launch rail and reintegrate the payload, ensuring all electronics are on and active. Turn off all other components that have already been modified during this procedures.

Confirmation: I hereby certify that the payload is active and there was an audible noise when the pull pin was removed from the launch vehicle.

Team Mentor Signature:______________________________________

Safety Officer Signature:______________________________________

Payload Lead Signature:______________________________________

8.6.3.5 Finalize the Launch Rail Position

Note: Failure to follow the following procedures may result in the following failure modes: VFM.6, VFM.7, LE.2, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Obtain Team Mentor Dave Brunsting. Instruct Dave on the launch angle the team desires to launch at.
- ☐ Loosen the launch vehicle from the launch rail after ensuring it is being held by team members.
- ☐ Allow the Team Mentor to adjust the launch vehicle to the appropriate angle. The angle should be between five and ten degrees with the vertical.
- ☐ Have a team member present at the launch pad use a protractor to verify the angle of the launch vehicle with the horizontal. When the desired angle is reached, fasten the launch vehicle to the launch rail. Confirm once more that the launch vehicle is at the proper angle with the vertical. If not, repeat these procedures. Failure to do so may result in the launch vehicle launching at an unacceptable launch angle and leaving the launch rail with an unpredictable flight pattern, or failure mode VFM.7.
- ☐ Have the same team member confirm that the launch pad is still level with the horizontal using a protractor. The launch pad must be within zero to one degrees above or below the horizontal.
- ☐ Verify with a protractor or an online angle measuring application that the launch rail is at the desired angle.

Confirmation: I hereby certify that the launch rail is at the proper angle by following the above procedures thoroughly.

Team Mentor Signature:_______________________________________

Safety Officer Signature:_______________________________________

8.6.3.6 Igniter Installation

Note: NDRT Team Mentor Dave Brunsting is the only individual allowed to handle the igniter due to their NAR/TRA Level 3 Certification. The Team Mentor must wear nitrile gloves and safety glasses while carrying out these procedures.

Note: Failure to follow the following procedures may result in the following failure modes: LO.2, VS.1, VS.8, LE.3, LE.4, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8 or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ After installing the igniter, the Safety Officer and RSO must verify that all bystanders are, at a minimum, at least 300 feet away from the launch vehicle on the launch pad, per NAR regulations.
- ☐ All team personnel must return to the observation area. Only Team Mentor Dave Brunsting is allowed to proceed with igniter installation due to his NAR/TRA Level 3 Certification. The Team Mentor must be completing the following procedures with safety glasses and heat resistant gloves.
- ☐ The team mentor should obtain the igniter. They should inspect it for any defects or damages, replacing it if necessary. Additionally, they should verify that the wires of the igniter are at least three inches in length. If these checklist items are verified, the Team Mentor may proceed. Failure to do so may result in an a faulty igniter and failure modes VS.1 or VS.8, both of which would result in a complete mission failure.
- ☐ The Team Mentor should remove the clips that connect the igniter to the ground station. Wait several seconds to allow the current to dissipate through the igniter.

- ☐ Ensure the low resistance ends of the igniter are not live. The team mentor can verify this procedure by touching the ends of the wire away from the launch vehicle and observing if sparks are present. In the case of audible or visible sparks, the Team Mentor should return to the ground station and notify the LCO and RSO that the launch wires are live. If no sparks can be observed, the Team Mentor may proceed. Failure to do so may result in a premature ignition when the Team Mentor inserts the igniter into the motor, causing him serious harm or death.
- ☐ The Team Mentor should carefully insert the thin bridge of the igniter into the motor.
- ☐ The Team Mentor must reconnect the clips that connect the ground station to the igniter, ensuring sufficient connections.
- ☐ After all above procedures have been completed the Team Mentor may return to the ground station and alert the RSO and LCO that the igniter is connected and live, and that the launch vehicle is prepared for launch.

Confirmation: I hereby certify that Team Mentor Dave Brunsting was the only individual handling the igniter and the above procedures. The Team Mentor certifies they were wearing the proper PPE. The RCO and LSO cerify that the igniter is live.

Team Mentor Signature:____

Safety Officer Signature:____

RCO Signature:____

LSO Signature:____

8.7 Launch Flight Procedures

Required Personnel: Safety Officer, NDRT Team Mentor Dave Brunsting, Project Manager, Range Safety Officer (RSO), Launch Control Officer (LCO), One team member

Required PPE: Safety Glasses, Nitrile Gloves

Note: Failure to follow the following procedures may result in the following failure modes: LO.2, LO.4, LO.5, LO.7, VS.1, VS.8, VFM.5, VFM.6, LE.3, LE.4, VE.2, VE.3, VE.4, VE.5, VE.6, VE.8 or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ The Safety Officer or the Team Mentor must confirm with the RSO and LCO that all previous launch operating procedures have been sufficiently completed.
- ☐ The Team Mentor must remind the RSO and the LCO that the ignition wires are live and that the launch vehicle is ready for launch.
- ☐ Obtain one team mentor to press the ignition button to simulate launch. It is not important which team mentor completes this step.
- ☐ Ensure all team members are at least 300 feet away from the launch pad, per NAR regulations.
- ☐ The LCO will give an introduction to the team and the purpose of their launch. The LCO will confirm that the team is ready to launch, which the team will confirm.
- ☐ The LCO will give a countdown for the launch.
- ☐ When the countdown reaches one, the team member designated to push the ignition button will do so.
- ☐ All team members, the Team Mentor, and the LCO will observe to verify that the launch vehicle does ignite and

leave the launch rail.

- ☐ After the launch vehicle leaves the launch rail, all team members will inspect the launch vehicle's trajectory in the sky, pointing to it as it travels.
- ☐ Team members will observe the launch vehicle's recovery process and track its trajectory as it descends. Failure to do so may result in failure mode LO.7.
- ☐ If the launch vehicle is descending towards spectators or team members themselves, appropriate warnings with instructions to move out of the launch vehicle's path must be issued.
- ☐ If the launch vehicle is descending towards spectators or team members themselves, appropriate warnings with instructions to move out of the launch vehicle's path must be issued.
- ☐ If the launch vehicle's recovery system partially or does not deploy, team members that become aware of this event should make it known to others. If the launch vehicle is falling with a faulty recovery deployment towards spectators or team members, heightened warnings should be delivered to immediately move out of the launch vehicle's path. Failure to do so can result in serious injury or death. Team members or bystanders must NOT make an attempt to catch the launch vehicle during its descent. Attempts may result in serious injury or death.
- ☐ Once the launch vehicle lands, select team members (including all leads) and the Team Mentor must wait until the RSO gives permission to retrieve the vehicle. The Team Mentor must wear heat resistant gloves for when they remove the motor from the launch vehicle, and team members should be sure to bring a digital camera for documentation and adequate clothing and footwear to walk through the launch field.

Troubleshooting: What if the igniter does not start the launch sequence?

- If the launch vehicle does not ignite when the ignition button is pressed, the LCO will give permission for the Team Mentor to travel to the launch pad to perform an inspection. The Team Mentor must be wearing safety glasses and heat resistant gloves.
- The Team Mentor must ensure first, above all else, to disconnect the ignition wires from the clips that connect it to the ground station.
- Wait several seconds to allow the current to dissipate. The Team Mentor should verify that the charge wires are not live by touching the ends of the wires away from the rocket. If the Team Mentor can observe sparks, that means that the wires are still live and they should return to the ground station to alert the LCO of this fact. If no sparks are observed, the Team Mentor may proceed.
- The Team Mentor should carefully and slowly remove the igniter from the launch vehicle's motor.
- The Team Mentor should install a new igniter, carefully following the motor preparation procedures.
- Repeat procedures to attempt another launch. If this launch also fails, the Team Mentor should repeat these procedures from step 1 to step 4.
- Once the Team Mentor removes the igniter from the motor, they should obtain several team members.
- All team members should place both hands on the rocket as the Team Mentor carefully loosens the launch rail and lowers it to be even with the horizontal.
- The Team Mentor should unfasten the launch vehicle.
- Team members and the Team Mentor should carefully slide the launch vehicle off of the launch rail.
- The Team Mentor should remove the motor and inspect it for any defects. If any defects are found, immediately replace the motor with a new one void of any defects. Repeat procedures for motor installation, appropriate launch pad setup, and launch flight.
- If no defects are found, the Team Mentor should verify with the LCO and RSO that all ground station components are functional. If this step is verified, reinstall the motor and reset the launch vehicle for launch, following appropriate procedures.

- Proceed with launch flight procedures.
- If the launch vehicle still does not launch, consult the RSO and LCO for further guidance on how to proceed.

Confirmation: I hereby certify that the above procedures were thoroughly followed when launching the launch vehicle. Spectators maintained a safe distance from the launch pad and paid close attention to the launch vehicle's trajectory during launch.

Team Mentor Signature:______________________________________

Safety Officer Signature:______________________________________

Project Manager Signature:______________________________________

RCO Signature:______________________________________

LSO Signature: ______________________________________

8.8 Post Launch Procedures

Required Personnel: Safety Officer, NDRT Team Mentor Dave Brunsting, Project Manager, Range Safety Officer (RSO), Launch Control Officer (LCO)

Required PPE: Safety Glasses, Nitrile Gloves, Heat Resistant Gloves

8.8.1 Retrieving the Launch Vehicle

Note: Failure to follow the following procedures may result in the following failure modes: LO.1, LO.4, LO.7, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

- ☐ Select team members and the Team Mentor should, with the permission of the RSO and LCO, make their way out to the launch vehicle.
- ☐ Once the launch vehicle is reached, designate a team member to take pictures using the digital camera for post-flight documentation.
- ☐ All team members besides the Team Mentor should remain a safe distance away from the launch vehicle. The status of the recovery charges are unknown at this time, and they could very well still be live and hurt someone. Failure to do so may result in failure mode LO.1.
- ☐ The Team Mentor, wearing heat resistant gloves and safety glasses, should carefully approach the launch vehicle and verify that all nine ejection charges have gone off, most easily verified by observing the status of the tape on the charge wells. Removed tape signifies that the ejection charges have gone off. If any charges remain, the Team Mentor must carefully and manually remove these. Failure to remove any live charges may result in accidental discharge when bystanders and team members are around and cause serious harm or death.
- ☐ Team members can now safely approach the launch vehicle, but must stay clear of the fin can unless they are wearing heat resistant gloves.
- ☐ Locate the camera mount on the body tube. Remove the camera from the mount and confirm that it is still recording. If the camera is still recording, turn off the recording feature by pressing the camera button down. The light on the camera should return to a static light, confirming that the camera is idle. If the camera battery died before the team reached it, it would have recorded up to the end of its battery life and thus still possibly filmed some or all of the flight.

- ☐ Locate and remove quick links from the parachutes.
- ☐ Locate and remove the Nomex blankets and parachute bags.
- ☐ Obtain several team members to carry the various launch vehicle components back to the team's ground station. Whichever team member is carrying the fin must wear heat resistant gloves because the motor may still be hot. Failure to do so may result in burns and failure mode LO.1.
- ☐ Verify, before leaving the landing site, that all components are being taken back to the team's ground station.

Troubleshooting: What if the igniter does not start the launch sequence?

- Determine which ejection charges are still active.
- Only the Team Mentor is allowed to complete these next procedures, and they must be wearing nitrile gloves and safety glasses.
- Turn off all appropriate altimeters to ensure accidental ignition does not occur.
- Ensure all appropriate altimeters are turned off.
- If the NED still has active charges, separate the nose cone from the payload bay.
- If the PED still has active charges, separate the payload bay from the ACS bay.
- If the FED still has active charges, separate the ACS bay from the fin can.
- Unscrew the NED, PED, and/or FED depending on which ejection charges are still active.
- Remove the NED, PED, and/or FED depending on which ejection charges are still active.
- Unhook black power charges from their wired connections.
- Remove all black powder charges from the charge wells.
- Properly dispose of the black charges per the University of Notre Dame's regulatory compliance with hazardous waste (see section 10.3 of the Safety Handbook).

Confirmation: I hereby certify that the Team Mentor ensured all ejection charges were not live upon retrieving the launch vehicle. The team certifies that they followed the above procedures and took extra caution when first approaching the launch vehicle. The launch vehicle was retrieved and brought back to the team's base of operations.

Team Mentor Signature:______________________________

Safety Officer Signature:______________________________

Project Manager Signature:______________________________

8.9 Post Launch Analysis

Required Personnel: Safety Officer, NDRT Team Mentor Dave Brunsting, Project Manager, Range Safety Officer (RSO), Launch Control Officer (LCO), Systems Lead, Vehicles Squad Lead, Recovery Squad Lead, Payload Squad Lead, ACS Squad Lead

Required PPE: Safety Glasses, Nitrile Gloves

Note: Failure to follow the following procedures may result in the following failure modes: VE.9, VE.10, VE.11, VE.14, or another unidentified failure mode. Occurrence of these failure modes may lead to a partial or complete mission failure.

If the team plans to launch an additional time:

- ☐ Upon return to the team's ground station, the Team Mentor must remove the motor casting from the launch vehicle's fin can using heat resistant gloves and safety glasses. Only the Team Mentor can complete this procedure.

- ☐ The ACS Lead must remove the microcontroller from the ACS and download the data onto their computer. Using this data, the ACS Lead should be able to confirm whether or not the ACS flaps actuated during flight.
- ☐ The Recovery Lead must remove all three altimeters from the NED, PED, and FED. They must then download the data from those nine altimeters and determine the launch vehicle's apogee for all.
- ☐ Average the apogee measurements and compare that value with the team's officially predicted apogee of 4,600 feet.
- ☐ A team member must remove the SD card from the camera mount of the launch vehicle. Putting this SD card into a laptop and analyzing the footage should confirm whether or not the ACS flaps actuated.
- ☐ Confirm with the RSO and LCO that the team may launch again.
- ☐ Proceed with reintegration for a second launch, repeating all launch operating procedures starting from section 8.2. Make necessary changes to the launch vehicle during this process, but such changes cannot violate or interfere with safety precautions, team-derived or NASA requirements, or launch operating procedures.
- ☐ When bringing the launch vehicle to the RSO and LCO prior to setup on the launch pad, make any changes made during re-integration known.

Confirmation: I hereby certify that the appropriate post-launch procedures were carried out and that the RSO and LCO approve of an additional launch.

Team Mentor Signature:______________________________________

Safety Officer Signature:______________________________________

Project Manager Signature:______________________________________

LSO Signature:______________________________________

RCO Signature:______________________________________

If the team does not plan to launch an additional time:

- ☐ Upon return to the team's ground station, the Team Mentor must remove the motor casting from the launch vehicle's fin can using heat resistant gloves and safety glasses. Only the Team Mentor can complete this procedure.
- ☐ The ACS Lead must remove the microcontroller from the ACS and download the data onto their computer. Using this data, the ACS Lead should be able to confirm whether or not the ACS flaps actuated during flight.
- ☐ The Recovery Lead must remove all three altimeters from the NED, PED, and FED. They must then download the data from those nine altimeters and determine the launch vehicle's apogee for all.
- ☐ Average the apogee measurements and compare that value with the team's officially predicted apogee of 4,600 feet.
- ☐ A team member must remove the SD card from the camera mount of the launch vehicle. Putting this SD card into a laptop and analyzing the footage should confirm whether or not the ACS flaps actuated.
- ☐ Procedure steps two through five for not launching again may be alternatively done at the workshop on campus instead of at the launch site.
- ☐ Put away all launch vehicle components into the team member's vehicles. The Team Mentor must take any motors and ejection charges with them due to their NAR/TRA Level 3 Certification.
- ☐ Disconnect all batteries and return them to their fireproof bags.

- ☐ Pack away all materials brought to the launch field into the team member's vehicles.
- ☐ All team members should perform an inspection of their surroundings and the surrounding area of the team's work station. Any and all trash should be cleaned. There should be almost no trace that the team was ever at the launch site. Failure to do so may result in environmental harm and failure modes VE.9, VE.10, VE.11, and VE.14.
- ☐ Upon returning to the campus workshop, launch vehicle materials should be returned to their proper location.
- ☐ Upon returning to the campus workshop, all launch materials should be returned to their proper location.
- ☐ Upon returning to the campus workshop, all waste should be properly disposed of or recycled.

Confirmation: I hereby certify that the appropriate post-launch procedures were carried out by each design squad and that the launch site was left void of any waste. All launch equipment was returned to its appropriate location at the campus workshop, disposed of, or recycled.

Team Mentor Signature:____

Project Manager Signature:____

Safety Officer Signature:____

Systems Lead Signature:____

Vehicles Lead Signature:____

Recovery Lead Signature:____

Payload Lead Signature:____

ACS Lead Signature:____

8.10 Project Concerns

8.10.1 Personnel Risks

Table 85: Construction Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
C.1	Team member is punctured by a tool	1. Inattentiveness to task at hand 2. Improper workshop training 3. Lack of knowledge about tool 4. Insufficient PPE	1. Minor or serious physical injury to team member 2. Infection if injury results in open wound 3. Damage to workshop tools	4	4	16	1. Team members will be knowledgeable about the construction and fabrication methods 2. Team members will be trained in proper PPE usage 3. First-Aid and emergency resources will be readily available	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and the Notre Dame police number is posted inside the workshop 3. The Safety Handbook and Standard Workshop Operating Procedures will be available for all team members	2	4	8
C.2	Team member ingests toxin	1. Inattentiveness to task at hand 2. Improper workshop training 3. Insufficient PPE	1. Serious potential injury to team member 2. Possibility of death depending on the inhaled toxins severity	2	4	8	1. Team members will be knowledgeable about the construction and fabrication methods 2. Team members will be trained in proper PPE usage 3. First-Aid and emergency resources will be readily available	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are posted clearly inside the workshop 3. The Safety Handbook and Standard Workshop Operating Procedures are available for all team members	1	4	4
C.3	Team member is burned	1. Inattentiveness to task at hand 2. Improper workshop training 3. Lack of knowledge about tool, 4. Insufficient PPE	1. Serious injury or death to team member 2. Spreading of fire to other members or workshop itself 3. Damage to workshop equipment	2	4	8	1. Team members will be knowledgeable about the construction and fabrication methods 2. Team members will be trained in proper PPE usage 3. First-Aid and emergency resources will be readily available	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook and Standard Workshop Operating Procedures are available for all team members	1	4	4
C.4	Fire in workshop	1. Inattentive team members 2. Improper workshop training 3. Lack of knowledge of method or tool	1. Serious injury or death for team members and any other occupants of the building 2. Loss of property and equipment	2	4	8	1. Knowledge of fire exits 2. Understanding of safe construction methods	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook and Standard Workshop Operating Procedures are available for all team members	1	4	4

C.5	Launch vehicle breaks during assembly	1. Inattentiveness during integration 2. Faulty construction	1. Partial or complete loss of launch vehicle 2. Project timeline setback	3	4	12	1. Base knowledge of construction methods 2. Close attention and care while construction and integration	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook and Standard Workshop Operating Procedures are available for all team members	2	3	6
C.6	Team member comes into physical contact with toxic substance	1. Improper following of workshop procedures 2. Lack of appropriate PPE	1. Minor serious damage to skin, internal organs, or other body parts 2. Team member is potentially poisoned	2	4	8	1. Knowledge of proper workshop procedures 2. Appropriate PPE during fabrication or construction 3. Appropriate leadership supervision 4. Readily available resources to help in the event a team member is in contact with toxic substances	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook and Standard Workshop Operating Procedures are available for all team members 4. Safety glasses will be worn for all construction in addition to any other necessary PPE	1	3	3
C.7	Horseplay in the workshop	1. Inattentive team members 2. Improper following of workshop procedures	1. Potential for serious injury 2. Damage to launch vehicle 3. Potential to damage or break a workshop machine	3	3	9	1. Prohibition and enforcement of horseplay in the workshop 2. Knowledge of general safe workshop practices among team members 3. Squad leads will be present in workshop	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook and Workshop Operating Procedures are available for all team members 4. Any official NDRT function in any construction space will include at least one member of the leadership team	1	3	3
C.8	Explosion in the workshop	1. Improper following of workshop procedures 2. Failure of a workshop tool	1. Major injury or death to team members or others in the building 2. Fire 3. Loss to property and launch vehicle	2	4	8	1. Knowledge of fire exits 2. Understanding of safe construction methods	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook and Workshop Operating Procedures are available for all team members	1	4	4
C.9	Injury to eyes during constructing	1. Improper following of workshop procedures 2. Lack of eye protection during construction	1. Damage to eyes, temporary or permanent blindness	3	4	12	1. Knowledge of proper workshop procedures 2. Appropriate eyewear during construction 3. Appropriate supervision	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook and Workshop Operating Procedures are available for all team members 4. All team members will wear safety glasses for any construction procedures along with any other necessary PPE	1	3	3

C.10	Exposure to epoxy	1. Improper following of workshop procedures 2. Lack of appropriate PPE	Irritation for contact area	3	2	6	1. Knowledge of proper workshop procedures 2. Appropriate PPE 3. Presence of team leadership of other supervision during epoxy application	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook is available for all team members 4. The Workshop Standard Operating Procedures, which are available for all team members, include detailed procedures on how to safely use epoxy	1	2	2
C.11	High noise levels	1. Inherent noise levels of construction methods 2. Lack of appropriate PPE	Temporary or permanent ear damage	2	3	6	1. Knowledge of proper workshop procedures 2. Earphones for necessary machines and environments 3. Presence of team leadership or other supervision	1. All team members are required to sign a safety contract and complete a basic EIH certification in order to participate in any construction or attend launches 2. The First-Aid/burn kit in the workshop is fully stocked and emergency contacts are clearly posted in the workshop 3. The Safety Handbook and Workshop Operating Procedures will be available for all team members 4. Appropriate ear protection will be provided when in necessary noise environments	1	3	3
C.12	Improper disposal of chemically hazardous materials	Improper knowledge of disposing of chemical waste	1. Physical or chemical harm to individuals disposing of chemical waste 2. Potential harm to environment that waste is transported to	3	3	9	All team members will be knowledgeable of and how to dispose of the materials that need to be disposed of differently than general waste due to their chemical nature before construction	Procedures for disposing of chemically dangerous materials will be published by the Safety Officer and readily available for all team members	1	3	3

Table 86: Launch Operations Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
LO.1	Recovery of launch vehicle	1. Team members touch the launch vehicle without proper authorization 2. Motor is still hot 3. Sharp pieces are extruding from launch vehicle	Burns or penetration during recovery	3	3	9	1. Team members will exercise extreme caution when approaching the launch vehicle after launch 2. Team members will be knowledgeable about the risks associated with touching a launch vehicle post-launch	NDRT Team Mentor Dave Brunsting will be responsible for inspecting the launch vehicle and ensuring that all charges are dead before permitting anyone to touch the launch vehicle. Team members will be reminded of this procedure the night prior to the launch during the Launch Rehearsal	1	3	3

LO.2	Incorrect motor installation	Improper motor handling from lack of knowledge or certification	1. Uncontrollable flight path 2. Motor failure or explosion upon launch 3. Serious injury to team members 4. Serious damage to launch vehicle	4	4	16	The team will ensure that the personnel installing the motor is properly NAR certified to handle that specific motor	1. NAR/TRA Level 3 certified NDRT Team Mentor Dave Brunsting will be responsible for any and all black powder charge operations, made clear on all launch procedures 2. Team members will be reminded of the above procedure at the launch rehearsal the night before the launch	1	4	4
LO.3	Improper black powder charge handling before launch	Team members are not cautious with the energetics during integration	1. Separation charges are not correctly installed and thus do not properly function during launch 2. Launch vehicle fails to separate and recovery system fails to operate	3	4	12	The team will ensure that the personnel installing black powder charges is properly NAR certified to handle such energetics	1. NAR/TRA Level 3 certified NDRT Team Mentor Dave Brunsting will be responsible for any and all black powder charge operations, made clear on all launch procedures 2. Team members will be reminded of the above procedure at the launch rehearsal the night before the launch	1	4	4
LO.4	Distracted team members	Reckless behavior or general inattention	Team members miss important instructions and jeopardize safety of other team members and/or bystanders	3	3	9	Team members will be reminded of the danger that high-powered rocketry poses to the individual and will be reminded to take extra caution for themselves and their teammates	1. All team members are required to sign a team contract affirming that they will be attentive and obey all launch orders from the Safety Officer and RSO 2. A reminder about being alert and attentive will be emphasized at the launch rehearsal the night before the launch	1	2	2
LO.5	Team members come too close to the launch vehicle before launch	Disregard of the safety precautions set in place by the local launch site	1. Possible burns from motor ignition 2. Serious potential injury or death in the event of motor explosion	2	4	8	1. All team members will be located a distance no less than 300 feet from the launch vehicle per NAR guidelines 2. The Safety Officer will aid in ensuring that all team members abide by this minimum safety distance	The RSO will have the final verdict over whether or not a launch is safe to initiate given team member's proximity to the launch vehicle	1	4	4
LO.6	Sun exposure	Lack of sunscreen	Sunburn and an increased risk of skin diseases	4	2	8	1. Team members will be reminded of the dangers UV exposure poses to the body 2. Team members will be reminded to consider the weather and bring sunscreen to the launch site 3. Team members will be required to wear sunscreen if heavy UV exposure is present on launch day	1. The Safety Officer will bring a spare bottle of sunscreen to ensure members are adequately protected should the sun pose harmful UV radiation the day of the launch 2. Announcements and reminders concerning the weather will be sent out to the team before launch day	2	2	4

LO.7	Launch vehicle is lost	1. High drift radius from parachute 2. Uncontrollable flight pattern 3. Poor visibility	1. Complete loss of launch vehicle 2. Large project budget setback	2	4	8	The launch vehicle will not be launched under high winds (speeds above 20 miles per hour) or considerably poor visibility (i.e., fog)	The Safety Officer and Project Manager will continually check the weather to assess wind speeds and cloud cover and determine if launch conditions are safe for launch	1	2	2
LO.8	Lack of hydration during launch	1. Inadequate amounts of water present at launch	Dizziness, lightheadedness, and more serious symptoms of dehydration	1	3	3	The Safety Officer will inform all team members that they must bring water to ensure that they are properly hydrated during the launch	1. Announcements and reminders will be sent out to the team encouraging members to bring water 2. Bottles of water will be provided as part of launch equipment	1	1	1
LO.9	Heat exhaustion or stroke during launch	1. Lack of hydration 2. Heavy physical exertion during launch day	Loss of consciousness, fatigue, and other serious potential harm to team members	1	4	4	1. The Safety Officer will inform all team members about the dangers of heat exhaustion and will require all members to be properly hydrated and be mindful of how much they exert themselves during the launch 2 If excessive heat is forecasted the launch will be postponed	1. Announcements and reminders will be sent out to the team regarding bringing water 2. Bottles of water will be provided as part of brought launch equipment 3. The Safety Officer and Project Manager will continually assess the weather and determine if projected launch day temperatures are safe to operate in	1	1	1
LO.10	Frigid conditions	Inadequate clothing for cold temperatures	Hypothermia, frostnip, frostbite, dizziness, loss of consciousness, loss of appendages	4	4	16	The Safety Officer will inform all team members about the dangers of cold temperatures and will require all members to be properly clothed for the weather	1. Team members that arrive to the launch not properly clothed for the cold temperatures will be sent home 2. Extra hand warmers will be brought to the launch site as part of launch equipment 3. The Project Manager and Safety Officer will continually assess the weather and determine if the temperatures are safe to launch in 4. The team will send announcements further reminding the entire team about the cold temperatures	2	4	8

8.10.2 Design Risks

Table 87: Vehicle Structures Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After

VS.1	Motor ignition failure	1. Incorrect installation of motor 2. Motor is misaligned 3. Faulty motor purchased	1. Launch vehicle fails to launch 2. Complete mission failure	4	4	16	1. Motor installation will be carefully monitored by a team member with proper certification and experience 2. Motor purchased is Aerotech L2200G-PS, a high quality and reliable motor	1. Team Mentor (NAR/TRA Level 3 Certified) Dave Brunsting will be responsible for handling and installing all energetics and will abide by NAR regulations while doing so 2. Motor purchased will be from a trusted and respected brand	1	4	4
VS.2	Bulkhead failure	1. Improper analysis of static loading for faulty material, material imperfections 2. Improper sizing of bulkhead	1. Bulkhead may fracture during flight 2. Internal components damaged by flying bulkhead debris 3. Internal components are not contained, jeopardizing stability	3	4	12	1. Bulkhead material will be tested and/or analyzed to verify it can withstand maximum static loading 2. Construction of bulkheads will be intentional and thorough	1. Standard Workshop Operating Procedures that outline how to use all fabrication tools are available for all team members 2. Bulkhead material and design will be tested to verify it can withstand maximum static loading during launch with a factor of safety of 1.5	1	4	4
VS.3	Nose cone failure	1. Material imperfections 2. Nose cone fails to withstand maximum static loading during flight 3. Blunt force to nose cone	1. Nose cone fractures and fails to distribute drag force to the launch vehicle 2. Stability is jeopardized due to non-uniform air flow	2	4	8	1. Bulkhead material will be tested and/or analyzed to verify it can withstand maximum static loading 2. Construction of nose cones will be intentional and thorough 3. Weather will be inspected to avoid the presence of blunt force during launch (i.e., hail)	1. Standard Workshop Operating Procedures that outline how to use all fabrication tools are available for all team members 2. Nose cones material and design will be tested to verify it can withstand maximum static loading during launch with a factor of safety of 1.5 3. The Safety Officer will continually inspect launch weather forecasts to ensure no blunt force in the air (i.e., hail) will be present during launch that may harm the nose cone	1	4	4
VS.4	Body tube failure during launch	1. Blunt force to body tube during launch (i.e., hail) 2. Blunt force to the body tube upon landing (i.e., high descent velocity) 3. Imperfections in material 4. Separation charges damage body tube	1. Minor to major damage to launch vehicle 2. Potential harm to internal components	1	3	3	1. Body tube material will be of high quality and tested to ensure that separation charges do not damage it 2. Successful recovery system 3. Material for the body tube will be of high quality 4. Weather will be consistently inspected to avoid the presence of blunt force during launch (i.e., hail)	1. The Safety Officer will continually inspect launch weather forecasts to ensure no blunt force in the air will be present during launch that may harm the nose cone 2. Material for the body tube will be from a trusted vendor and approved by the Project Manager and Vehicles Squad Lead prior to purchase 3. The body tube will be tested with the black powder charges to ensure, upon inspection, that the combustion reaction does not damage the body tubes 4. The procedures for inserting the separation charges are outlined in Launch Operating Procedures, which is made available to all team members. NDRT Team Mentor Dave Brunsting is the only individual allowed to handle the ejection charges due to his NAR/TRA Level 3 certification 5. The recovery system will be verified through a subscale launch before a full-scale launch	1	3	3

VS.5	Launch vehicle is damaged at landing	1. Blunt force to launch vehicle at landing 2. Unacceptable descent velocity at landing 3. Failure for parachutes to deploy	Minor to major damage to launch vehicle	3	3	9	1. Body tube material will be of high quality and strength material 2. The recovery system will be tested to be functional prior to launch	1. The material for the body tube will be of high quality and/or from a trusted and respected vendor 2. Recovery system has been verified through a subscale launch before a full-scale launch	2	3	6
VS.6	Shear pin failure	1. Separation charges are not sized or installed properly 2. Faulty shear pins	1. Launch vehicle fails to separate when necessary 2. Launch vehicle separates unpredictably 3. Recovery system fails to function 4. Flying debris during launch	3	4	12	1. Shear pins purchased will be of high quality 2. Separation charges will be installed properly 3. Selection of shear pins will be verified through testing and/or simulation of black powder charges to analyze the appropriate force of separation range	1. The shear pins will be purchased from a respected and trusted vendor and will be approved by the Project Manager and Vehicles Squad Lead prior to purchase 2. All energetics will be handled and installed by Team Mentor (NAR/TRA Level 3 Certified) Dave Brunsting 3. Shear pins will be selected based on simulations of black powder charges and the results of these simulations only	1	4	4
VS.7	Coupler failure	1. Material imperfections 2. Damage from separation charges to couplers	1. Launch vehicle may not separate upon separation charge ignition 2. Coupler does not properly hold in place separation points	2	3	6	1. Material for couplers will be of high quality and durability 2. Coupler material will be verified to be able to withstand the force and combustion experienced from the separation charges	1. Coupler material will be purchased from a respected and trusted vendor and selection will be approved by the Project Manager and Vehicles Squad Lead prior to purchase 2. Coupler material will be analyzed or tested to withstand the maximum combustion force with a factor of safety of 1.5	1	3	3
VS.8	Motor explosion	1. Improper motor installation 2. Motor is misaligned 3. Faulty motor purchased	1. Major damage to launch vehicle 2. Potential fire 3. Potential injury to bystanders	3	4	12	1. Motor installation will be carefully monitored by a team member with proper certification and experience 2. Motor purchased is Aerotech L2200G-PS, a high quality motor	1. Team Mentor (NAR/TRA Level 3 Certified) Dave Brunsting will be responsible for handling and installing all energetics and will abide by NAR regulations while doing so 2. Motor purchased will be from a trusted and respected vendor and approved by the Project Manager and the Vehicles Squad Lead prior the purchase	1	4	4
VS.9	Centering ring failure	1. Imperfections in material used 2. Misalignment or improper installation	1. Motor is misaligned 2. Launch vehicle flight pattern is not controlled 3. Unsuspecting objects are in new flight path that would have otherwise been safe	3	4	12	1. Centering rings will be installed carefully and will be verified by a third party 2. Material used for centering rings will be of high quality	1. Centering rings will be purchased from a trusted and respected vendor and approved by the Project Manager and Vehicles Squad Lead prior to purchase 2. The Vehicles Squad Lead and the Safety Officer will both sign off on the Standard Launch Operating Procedures that the centering rings were installed properly 3. Procedures for installing centering rings are available for all team members and are outlined in the Launch Operating Procedures	1	4	4

VS.10	Epoxy breaks from landing	1. High impact upon launch 2. Faulty recovery deployment leading to high descent velocity 3. Stiff ground 4. Disadvantageous landing position putting excess stress on the epoxy	1. Minor damage to launch vehicle 2. Additional time and resources spent rebuilding repairing broken components	2	3	6	Epoxy will be installed carefully and thoroughly to ensure a strong bond between launch vehicle components	1. Standard Workshop Operating Procedures for installing epoxy are readily available for all team members 2. A design lead will be present whenever epoxy is being applied to ensure proper installation	1	3	3
VS.11	Epoxy melts near the fin	Heat generated by motor ignition	Weakened bonds leading to fractures before landing or during launch	2	3	6	1. Epoxy will be installed carefully and thoroughly to ensure a strong bond between launch vehicle components 2. A high quality epoxy will be selected with a consideration for its heat resistance	1. Standard Workshop Operating Procedures for installing epoxy are readily available for all team members 2. A design lead will be present whenever epoxy is being applied to ensure proper installation 3. The epoxy selected will be from a respected and quality vendor and will be approved by the Project Manager and Vehicles Squad Lead before purchase	1	3	3
VS.12	Vehicle is dropped	1. Launch vehicle is not carefully carried 2. Reckless behavior	Minor to major damage of the launch vehicle	2	3	6	Team members will exercise extreme caution when handling the launch vehicle during integration and launch setup	Three members will be required to have both hands (one hand above the launch vehicle and one below) in contact with the launch vehicle whenever it is being moved	1	3	3
VS.13	Vehicle components vibrate inside vehicle during flight	Components are not secured properly during integration	Components may come lose and both cause and sustain substantial damage to vehicle during flight	3	4	12	All vehicle components will be securely fastened during integration and verified by the Safety Officer and Vehicles Squad Lead	A section on the Standard Launch Operation Procedures ensures that the Vehicles Design Lead oversees the fastening of all launch components during integration and verifies that they are properly fastened	1	4	4

Table 88: Vehicle Flight Mechanics Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After

VFM.1	Launch vehicle is overstable	1. Improper placement of internal components in launch vehicle 2. Incorrect mass estimates 3. Center of gravity or center of pressure is not correctly estimated	Launch vehicle trajectory gradually turns towards the wind	3	4	12	1. Mass estimates will be closely monitored during construction 2. The center of pressure and center of gravity will be verified before launch 3. The center of pressure and gravity will be calculated after integration but before launch and compared to the experimental values	1. Mass of materials will be recorded on a shared spreadsheet readily available to all team members and continually updated as construction proceeds 2. The Safety Officer and Vehicle Squad Lead will sign off on this procedure agreeing that the center of pressure and center of gravity estimates match with the experimental values before proceeding with the Standard Launch Operating Procedures	1	4	4
VFM.2	Launch vehicle is overweight	1. Incorrect mass estimates 2. Improper budgeting of material	1. Launch vehicle falls short of apogee 2. Shock cords experience more force when deployed, possibly leading to a fracture and sending the launch vehicle into free fall	2	3	6	1. Mass estimates will be closely monitored during construction 2. Material used will be recorded	1. Mass of materials will be recorded on a shared spreadsheet and readily available to all team members 2. Spreadsheet will be continually updated to keep up with design changes and the construction process	1	3	3
VFM.3	Launch vehicle is underweight	1. Incorrect mass estimates 2. Improper budgeting of material	Launch vehicle reaches above predicted apogee and possibly violates NASA Req. 2.1.	2	3	6	1. Mass estimates will be closely monitored during construction 2. Material used will be recorded	1. Mass of materials will be recorded on a shared spreadsheet and readily available to all team members 2. Spreadsheet will be continually updated to follow design changes and the construction process	1	3	3
VFM.4	Fins fails to keep launch vehicle stable	1. Improper sizing of fins 2. Fin material fails to withstand static loading of flight	Launch vehicle fails to maintain stability and gradually directs its trajectory into the wind, leading to weathercocking	2	4	8	1. Fin sizing will be carefully calculated to induce the necessary stability 2. Fins will be tested to ensure they can withstand maximum static loading	1. The Project Manager and Vehicles Squad Lead must agree to the shape and size of the fins before proceeding in their construction 2. Fin material will be purchased from a trusted and respected vendor and will be approved by the Project Manager and Vehicles Squad Lead prior to purchase 3. Fin material will be tested or analyzed to verify it can withstand the maximum static loading with a factor of safety of 1.5	1	4	4

VFM.5	Launch vehicle exits the launch rail with too low of an exit velocity	1. Faulty motor performance 2. Partial motor failure 3. Centering ring failure	Launch vehicle flight pattern is unpredictable	3	4	12	1. Motor will be properly and safety installed 2. Centering rings will be properly centered during integration 3. Motor selection will provide proper combustion to initiate successful launch	1. Team Mentor (NAR/TRA Level 3 Certified) Dave Brunsting will be the sole individual responsible for handling and installing all motor functions and will abide by NAR guidelines while doing so 2. Standard Launch Operating Procedures for installing the centering rings properly are clearly written and made available to all team members 3. The motor purchased is the Aerotech L2200G-PS, which will provide adequate thrust for the mission. 4. The motor bought is the Aerotech L2200G-PS, a reliable and respected product	1	4	4
VFM.6	Launch vehicle fails to leave launch rail	1. Motor failure 2. Centering ring failure	1. Active motor remains inside launch vehicle 2. Team members are unable to confidently determine if the launch vehicle is safe to remove from launch rail 3. Complete mission failure	2	4	8	1. Motor will be properly and safety installed 2. Centering rings will be properly centered during integration 3. Motor selection will provide proper combustion to initiate successful launch	1. Team Mentor (NAR/TRA Level 3 Certified) Dave Brunsting will be the sole individual responsible for handling and installing all motor functions and will abide by NAR guidelines while doing so 2. Standard Launch Operating Procedures for installing the centering rings properly are clearly listed and made available to all team members on the Standard Launch Operating Procedures 3. The motor purchased is the Aerotech L2200G-PS, which will provide adequate thrust for the mission. 4. The motor bought is the Aerotech L2200G-PS, a reliable and respected product	1	4	4
VFM.7	Incorrect launch angle	1. Incorrect calculation of vehicle flight path 2. Incorrect flight simulations	1. Unpredictable flight pattern 2. Potential for the vehicle to impact objects or persons that are not under proper precautions of the launch area if vehicle launches closer to the ground	1	4	4	1. Launch angle will be chosen based on careful calculation and analysis of the project flight patterns given the launch vehicle characteristics 2. Safe launch angle guidelines will be followed	Launch angle will be chosen on a quantitative basis based on the results from multiple rocket software simulations 3. All NAR and NASA guidelines will be observed when selecting a launch angle 4. Detailed launch procedures on setting the launch angle are outlined in the Standard Launch Operating Procedures	1	4	4
VFM.8	Fin flutter	Incorrect calculation of forcing frequency of launch	Fins experience resonance possibly leading to fracture and a loss of stability	3	4	12	The team will calculate the velocity necessary for fin flutter to occur and ensure, via launch simulations, that it is not reached during launch	The calculated velocity and launch simulations will be approved or done entirely by the Vehicles Squad Lead	1	4	4

Table 89: Recovery Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	a Severity	After

R.1	Main parachute does not deploy	1. Parachute was installed incorrectly 2. Black powder charges failed to ignite 3. Shear pins held launch vehicle together through the detonation of black powder charges 4. Altimeter failed to send data to the separation charges	1. Launch vehicle lands with unacceptable descent velocity 2. Launch vehicle may sustain considerable damage 3. Launch vehicle landing creates unsafe landing area	3	4	12	1. Parachute installation will be closely monitored by the Recovery Squad Lead and Safety Officer 2. Procedures for installing the main parachute are clearly defined in the Standard Launch Operating Procedures 3. The recovery system will feature altimeter redundancy with proper shielding	1. Both the Recovery Squad Lead and Safety Officer will monitor the main parachute installation and sign off on the Standard Launch Operating Procedures that it was installed correctly 2. The system will feature altimeter redundancy with appropriate electromagnetic shielding material (i.e., electric tape) shielding any altimeter present from electromagnetic interference 3. Procedures for installing the main parachute will are clearly written out in the Standard Launch Operating Procedures and will be reviewed during the launch rehearsal the day before the launch 4. Parachute installation procedures are readily available for all team members in the Standard Launch Operating Procedures	2	4	8
R.2	Drogue parachute does not deploy	1. Parachute was installed incorrectly 2. Black powder charges failed to ignite 3. Shear pins held launch vehicle together 4. Altimeter failed	1. Launch vehicle likely lands with unacceptable descent velocity 2. Main parachute may not be able to sustain high shock of deployment 3. Launch vehicle landing may create an unsafe landing area 4. Shock cords must sustain a higher impulse when main parachute deploys due to higher descent velocity	3	3	9	1. Parachute installation will be closely monitored by the Recovery Squad Lead and Safety Officer 2. Procedures for installing the drogue parachute will be clearly defined 3. Shock cords will be reinforced in the event that the drogue parachute does not deploy 4. The recovery system will feature altimeter redundancy with proper shielding	1. Both the Recovery Squad Lead and Safety Officer will monitor the main parachute installation and sign off on the Standard Launch Operating Procedures that it was installed correctly 2. The system will feature altimeter redundancy with appropriate electromagnetic shielding material (i.e., electric tape) encapsulating any altimeter present which will be verified with inspection of the launch vehicle 3. Installing the drogue parachute are clearly written out in the Standard Launch Operating Procedures and will be reviewed during the launch rehearsal the day before the launch 4. Shock cords will be capable of handling the maximum impulse of descent with a factor of safety of 1.5 5. Parachute installation procedures are readily available for all team members in the Standard Launch Operating Procedures	2	3	6
R.3	Launch vehicle fails to separate after apogee	1. Improper installation of black powder charges 2. Shear pins provide too much force for the charges to separate the launch vehicle	1. Main nor drogue parachute deploys, launch vehicle becomes ballistic 2. Launch vehicle sustains considerable damage upon landing	3	4	12	1. Black powder charges will be installed carefully and properly 2. Black powder charges will be tested before launch to ensure separation will occur	1. Team Mentor (NAR/TRA Level 3 Certified) Dave Brunsting will be responsible for handling and installing all energetics, and will abide by NAR regulations while doing so 2. The black powder charges will be tested and capable of separating launch vehicle components with the procedures available to all team members	2	4	8

R.4	Altimeter fails to ignite black powder charge	1. Altimeter fails to send data to separation charges for detonation 2. Faulty circuit wiring/soldering 3. Electrical interference 4. Loss of power 5. Dead battery	1. Launch vehicle does not separate 2. Parachute does not deploy and launch vehicle becomes ballistic	4	4	16	1. The recovery system will feature altimeter redundancy 2. Soldering activities will be closely reviewed to ensure quality electronic connections 3. Altimeters shall have proper electromagnetic shielding	1. Each recovery device will feature at least two altimeters which will be verified by inspection 2. Any altimeter present in the system will be properly shielded by an appropriate shielding material (i.e., electric tape) with will be verified by inspection of the launch vehicle 3. Soldering procedures are available to all team members on the Standard Workshop Opearting Procedures	2	4	8
R.5	Main parachute deploys prematurely	1. Improper altimeter performance 2. Shear pins do not provide enough strength to hold launch vehicle together	Launch vehicle drifts outside acceptable radius from launch site, violating NASA Req. 3.10.	3	3	9	1. The recovery system will feature altimeter redundancy with proper shielding 2. Shear pins will be analyzed via simulations to ensure they will separate with a predetermined amount of black powder charge	1. Each recovery device will feature at least two altimeters with appropriate shielding material encapsulating it (i.e., electric tape) which will be verified by inspection of the launch vehicle 2. Test procedures for verifying shear pin and black powder charge strength are available for all team members on the Standard Launch Operating Procedures	2	3	6
R.6	Drogue parachute shroud lines tangle	Improper packing of drogue parachute	1. Drogue parachute will not adequately slow the launch vehicle's descent 2. Main parachute sustains considerably more shock during its deployment 3. Launch vehicle's descent may exceed the maximum descent velocity	3	3	9	Drogue parachute installation will be closely monitored by the Recovery Squad Lead and Safety Officer	1. Both the Recovery Squad Lead and Safety Officer will monitor the drogue parachute installation and sign off on the Standard Launch Operating Procedures that it was installed correctly 2. Parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures	1	3	3
R.7	Main parachute shroud lines tangle	Improper installation of main parachute	1. Main parachute will not adequately slow the launch vehicle's descent 2. Launch vehicle's descent may fall outside the maximum descent velocity, violating NASA Req. 3.3. 3. Landing area becomes unsafe	4	4	16	Main parachute installation will be closely monitored by the Recovery Squad Lead and Safety Officer	1. Both the Recovery Squad Lead and Safety Officer will monitor the drogue parachute installation and sign off on the Standard Launch Operating Procedures that it was installed correctly 2. Parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures	1	4	4

R.8	Parachute deploys below the minimum deployment height	1. Improper parachute installation 2. Failure for altimeter to send calculations (or correct calculations) to separation charges	1. Launch vehicle descent velocity exceeds the maximum limit per NASA Req. 3.3. 2. Violation of NASA Req. 3.1.1. 3. Landing area becomes unsafe	3	4	12	1. Main and drogue parachute installations will be closely monitored by the Recovery Squad Lead and Safety Officer 2. The system will feature altimeter redundancy with appropriate electromagnetic shielding	1. Both the Recovery Squad Lead and Safety Officer will monitor the main and drogue parachute installation and sign off on the Standard Launch Operating Procedures that it was installed correctly 2. Parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures 3. The system will feature altimeter redundancy with appropriate electromagnetic shielding material (i.e., electric tape) which will be verified by inspection of the launch vehicle	2	4	8
R.9	Parachute deploys but fails to slow the launch vehicle below maximum descent velocity	1. Improper parachute installation 2. Improper parachute sizing 3. Altimeter fails to send correct data to separation charges	Launch vehicle descent velocity is above the maximum limit, violating NASA Req. 3.3.	3	3	9	1. Parachute sizing calculations will be closely reviewed 2. Main and drogue parachute installations will be closely monitored by the Recovery Squad Lead and Safety Officer	1. Both the Recovery Squad Lead and Safety Officer will monitor the main and drogue parachute installation and sign off on the Standard Launch Operating Procedures that it was installed correctly 2. The parachute will be bought from a trusted and respected vendor and approved by the Project Manager and Recovery Squad Lead prior to purchase 3. The system will feature altimeter redundancy with appropriate electromagnetic shielding material (i.e., electric tape) which will be verified by inspection of the launch vehicle	1	3	3
R.10	Drogue parachute does not leave the parachute bag	Improper drogue parachute installation	1. Drogue parachute fails to or only partially deploys 2. Main parachute shock cords must endure more force, possibly causing them to break 3. Descent velocity is uncontrolled and launch vehicle may become ballistic	3	4	12	Drogue parachute installation will be closely monitored by the Recovery Squad Lead and Safety Officer	1. A section on proper parachute installation procedures will be included on the Standard Launch Operating Procedures 2. Both the Recovery Squad Lead and Safety Officer will monitor the drogue parachute installation and sign off on the Standard Launch Operating Procedures that it was installed correctly 3. Parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures 4. Shock cords will be capable of handling the maximum impulse of descent with a factor of safety of 1.5	1	3	3
R.11	Frayed shock cords	Failure to examine shock cords before launch	1. Shock cords may not be able to handle parachute deployment force and may break upon separation, causing a ballistic descent	3	4	12	1. Shock cords will be calculated to withstand the expected loads during launch 2. Shock cords will be examined before launch	1. A section on checking the status of the shock cords are included on the Standard Launch Operating Procedures 2. The Safety Officer and Recovery Squad Lead will sign off on the Standard Launch Operating Procedures to ensure shock cords are not frayed during integrating on launch day 3. Shock cords will be tested or analyzed to be able to withstand the maximum expected force during launch with a factor of safety of 1.5	1	4	4

R.12	E-match position cannot be verified	Inability to see inside the launch vehicle once fully integrated	1. Lack of confidence in altimeter and charge detonation statuses 2. Significant time spent verifying switch position because launch vehicle must be taken apart in order to see the E-match	5	1	5	Multiple team members will verify the E-match position before recovery is in the correct position	1. The Safety Officer has included a section verifying the completion of this integration step on the Standard Launch Operating Procedures 2. The Safety Officer, Recovery Lead, and at least three other members must verify that the E-match switches are in the correct setting before integrating it into the launch vehicle	1	1	1
R.13	Launch vehicle exceeds drift radius	1. Main and/or drogue parachute is installed incorrectly 2. Incorrect altimeter data 3. Software error	1. Launch vehicle becomes hazard for those not in the drift radius defined by NASA Req. 3.10. 2. Partial mission failure due to violation of NASA Req. 3.10.	3	3	9	1. The system will feature altimeter redundancy with proper shielding, parachute installation will be closely monitored 2. Software will be tested with test data to ensure its functionality	1. The system will feature altimeter redundancy with appropriate electromagnetic shielding material (i.e., electric tape) encapsulating any altimeter present and will be verified by inspection of the launch vehicle 2. Procedures for testing software with simulated data are available for all team members on the Standard Launch Operating Procedures 3. Parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures 4. The Recovery Squad Lead and Safety Officer will oversee the installation of the parachute and sign off on the Standard Launch Operating Procedures that its correct installation occurred	2	3	6
R.14	Main parachute is not pulled from parachute bag during flight	1. Improper main parachute installation 2. Recovery electronics are improperly activated	Launch vehicle is not sufficiently slowed, leading to an unsafe descent velocity and/or one that is unacceptable per NASA Req. 3.3.	3	4	12	Main parachute installation will be closely monitored by the Recovery Squad Lead and Safety Officer	1. Parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures 2. Both the Recovery Squad Lead and Safety Officer will monitor the main parachute installation and sign off on the Standard Launch Operating Procedures that it was installed correctly	1	4	4
R.15	Shock cords break	1. Failure to examine shock cords before launch 2. Incorrect calculations when sizing shock cords	Launch vehicle begins ballistic descent	3	4	12	Shock cords will be calculated to withstand the expected loads during launch	Shock cords will be tested or analyzed to be able to withstand the maximum expected force during launch with a factor of safety of 1.5	1	4	4

R.16	Nose cone fails to separate from launch vehicle	1. Altimeter fails to ignite black powder charges 2. Shear pins hold nose cone in place	1. Drogue parachute does not deploy, causing the launch vehicle a high descent velocity that may violate NASA Req. 3.3. 2. Payload is not able to deploy 3. Complete mission failure	3	4	12	1. There will be at least two altimeters with appropriate electromagnetic shielding present in each recovery bay to ensure redundancy 2. Shear pin selection will be based on calculations of expected force from the black powder charges and reviewed and approved before selection	1. The Recovery Lead will verify the calculations of the shear pin selection 2. The system will feature altimeter redundancy with appropriate electromagnetic shielding material (i.e., electric tape) which will be verified by inspection of the launch vehicle	1	4	4
R.17	Removeable wall from payload bay is forceably removed	1. The removeable wall is stuck in a abnormal position during payload deployment 2. The tape used to mount the removeable wall to the aluminum ring of the TROI is too strong and is thus removed when the payload is deployed	The payload cannot deploy	2	4	8	The team will conduct ground testing of different types of tape during the ground black powder testing	Procedures for conducting these tests will be written and made available for all team members	1	4	4

Table 90: Apogee Control System Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
ACS.1	ACS battery dies while the launch vehicle is on the launch pad	1. Battery is not charged sufficiently 2. Calculation for necessary battery is incorrect	Complete system failure	3	3	9	The ACS battery shall be capable of being operational for the maximum time (two hours) on the launch pad at the NASA SLI National Competition	The ACS battery will be capable of being operational for three hours starting from a full charge	1	3	3

ACS.2	ACS placement within the launch vehicle decreases stability during flight	1. Improper calculation of launch vehicle stability 2. Inaccurate mass estimates	Launch vehicle is unstable during flight	3	4	12	1. The ACS will be as close to the center of pressure as possible 2. The ACS will to be aft of the center of gravity location after burnout, per NASA Requirement 2.16.	The placement of ACS into the launch vehicle will be verified by the Vehicles Lead before construction to ensure it is at the correct location in relation to the vehicle's center of pressure and center of gravity	1	4	4
ACS.3	ACS fails to perform accurate actuation compared to predicted estimates	1. Improper calculation for system performance during launch 2. Software errors 3. Insufficient servo motor	Improper actuation	4	2	8	1. The servo motor will be capable of performing accurate actuation under predicted maximum static loading 2. The software will be continually reviewed to ensure it is accurate to flight conditions	1. The ACS shall be tested to perform accurate actuation under the maximum static loading with a factor of safety of 1.5 2. The software will be tested by using simulated data to perform the various required functions of the system	2	1	2
ACS.4	Actuation tabs are not securely fastened before launch	1. Improper fastening during integration 2. Improper integration	1. Actuation tabs fracture during launch creating debris 2. System does not function properly	3	3	9	The ACS Squad Lead will ensure that, during integration, actuation tabs are securely fastening to the launch vehicle before completing ACS integration	The Safety Officer and ACS Squad Lead will inspect the fastening of the actuation tabs and sign off on the Standard Launch Operating Procedures that it was completed correctly	1	3	3
ACS.5	Frayed electrical wires	1. Poor wire organization 2. Failure to inspect wire condition 3. High usage of electrical wires	Short circuiting	2	4	8	1. The ACS will minimize the number of physical wires used and maximize the distance between those that remain 2. Wires will be neatly organized to avoid frayed electrical wires 3. Wires will be continually inspected to identify fraying	1. The ACS will use a printed circuit board (PCB) to avoid short circuits and promote wire management 2. Heat shrink will be used to cover any frayed wires 3. The only physical wires present will be those connecting to the servo motor and battery	1	3	3
ACS.6	Servo motor interference	Heavy current draw from the motor and continuous change in current, creating a magnetic field	Motor experiences partial or complete failure	1	3	3	1. Shielding will be put over the servo motor to prevent interference 2. Continuous changes in current draw will be minimized	1. The servo motor will only turn on and off once during flight, minimizing current change 2. Electrical tape will be put over the servo motor to prevent a magnetic field becoming present	1	2	2
ACS.7	Insufficient voltage provided to batteries	Current draw from servo motor takes away from that of batteries	Microcontroller may behave erratically	2	3	6	Stall current of servo motor and other components will be limited	Servo motor and other components requiring current draw shall not exceed a combined current of three amps	1	3	3

ACS.8	Servo motor current is too strong	Stall current of motor is too high	System may overheat or explode	3	4	12	Stall current of servo motor will be limited	Servo motor will be chosen and purchased that is reliable and does not exceed a stall current draw of three amps	1	4	4
ACS.9	Altimeter fails to send data to servo motor	1. Failure of batteries 2. Errors in software	Complete system failure	3	3	9	The ACS will implement redundancy to account for the failure of an altimeter	1. Two altimeters will be present with appropriate electromagnetic shielding in the ACS to ensure redundancy 2. The redundancy of ACS will be verified with inspection of the launch vehicle	2	3	6
ACS.10	Noisy signal data from servo motor	Software composition	Vibration of drag flaps when extended and suboptimal performance	3	2	6	The signal to the servo motor will be streamlined	A pulse-width modulation (PWM) controller will be present in the ACS to prevent noisy signal to the servo motor	1	2	2
ACS.11	PWM to servo motor is ripped	Mismanaged wires	1. Other wires may be ripped or disconnected 2. System or individual component failure 3. Fire may occur inside ACS bay from ripped wires	3	4	12	1. The ACS will minimize the number of physical wires used and maximize the distance between those that remain 2. Wires will be neatly organized to avoid frayed electrical wires 3. Wires will be continually inspected to identify fraying	1. The ACS will use a PCB to avoid short circuits and promote wire management 2. The only physical wires present will be those connecting to the servo motor and battery	1	4	4

Table 91: Payload Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
TROI.1	Interference from other sensors and other electronics	Improper shielding of sensors and electronics may interrupt transmission to or from the payload system	Launch vehicle status is not properly assessed, causing the system to fail to extend from body tube and complete mission	2	4	8	Proper shielding will be installed on all applicable payload components	The shielding for the electronics will be tested and verified prior to use by the electronics sub team and the Payload Lead	1	4	4
TROI.2	Mechanical interference with payload system	Improper organization and placement of various systems	Payload is damaged and may not be able to function as intended	3	3	9	The payload system will be placed to not interfere with the recovery system	The Payload Lead will verify with the other design leads that the placement of the system does not harm the functionality of other launch vehicle systems	1	3	3

TROI.3	Camera fails to capture images of objects other than vehicle body tube	1. Improper orientation of payload camera 2. Improper sizing of extension arm 3. Incorrect calculation in software 4. Motor failure	Partial mission failure as payload fails to take all necessary photos, violating NASA Req. 4.2.1.	3	3	9	The payload will raise the camera system above the vehicle tube to provide for clear images	The payload will be tested at different landing angles and configurations	2	3	6
TROI.4	Payload battery dies during launch	1. Improper selection of battery 2. Insufficient consideration of temperature's impact on battery health	Payload fails to function	3	4	12	The payload battery shall be capable of being operational for the maximum time (two hours) on the launch pad at the NASA SLI National Competition	1. The payload battery will be capable of being operational for three hours starting from a full charge which will be verified with a battery test 2. The procedures for testing the payload battery are available to all team members in the Standard Launch Operating Procedures	1	4	4
TROI.5	Payload system is set to the wrong radio frequency	Improper selection of radio frequency prior to launch	Payload fails to receive any commands from ground station and thus is a complete mission failure	2	4	8	The payload system shall be tested to confirm it receives sample radio commands on the correct frequency prior to launch in accordance with NASA Req. 4.2.3.1.	The Safety Officer has included a section on the Standard Launch Operating Procedures to ensure that the radio frequency is at the correct setting prior to integration	1	4	4
TROI.6	Camera breaks or is damaged during or upon landing	Camera system was not properly retained or securely fastened	Camera fails to take images demanded	3	4	12	1. Camera system is tested to verify it can handle maximum descent kinetic energy 2. The camera system will be securely fastened to the payload and approved by the Safety Officer and Payload Squad Lead prior to launch	Test procedures to conduct the camera durability test will be readily available for all team members once written	1	4	4
TROI.7	Low quality image	1. Quality of camera is insufficient Camera is in motion when picture is taken 3. Debris falls onto the camera	1. Images related to ground station are not acceptable 2. Partial mission failure	2	3	6	1. The payload system will utilize a high quality camera 2. The payload system will be tested at different configurations to verify that the camera is stationary before taking a picture	1. The camera selected will be from a trusted and respectable vendor which will be approved by the Payload Squad Lead and Project Manager 2. Test procedures for verifying the camera's motion are available for all team members on the Standard Launch Operating Procedures	1	3	3
TROI.8	Images are not stored after being taken	1. Improper software structure 2. SD card runs out of space	Complete mission failure	3	4	12	The payload digital storage space will be verified prior to every launch and/or payload test	The Safety Officer has included a section on the Standard Launch Operating Procedures that the digital storage space will be verified prior to launch and the completion of this test will be verified by the Payload Lead	1	4	4

TROI.9	Time stamps for resultant images are inaccurate	1. Incorrect software structure 2. Improper syncing of clock	1. Images sent to ground station are of the incorrect time 2. Partial mission failure 3. Failure of NASA Req. 4.2.1.3.	2	3	6	The payload system will pass a basic functionality test prior to being used, which includes verification of proper timestamps on images	Test procedures to conduct this test will be readily available for all team members once written	1	3	3

Table 92: Payload Integration and Deployment Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
TROII.1	Water damage	1. Launch vehicle lands in water which seeps into the payload bay 2. Precipitation during launch leads to water presence inside payload bay	1. System experiences partial or complete failure from water damage 2. Possibility of short circuiting and other electrical damage from water exposure to payload electronics	2	4	8	1. All electronics will be tested before integration into launch vehicle 2. A bulkhead will be installed within the payload bay just above the electronics to prevent water presence in the electronics bay	1. A section on the Standard Launch Operating Procedures include procedures on verifying the functionality of all payload electronics 2. The bulkhead's presence in the launch vehicle will be verified via inspection of the launch vehicle	1	3	3
TROII.2	Payload deployment is limited by an obstruction	1. Disadvantageous landing orientation 2. Large debris in ground where launch vehicle lands	1. Payload fails to fully deploy 2. Partial or complete mission failure	1	4	4	The payload system will feature an emergency stopping software component that automatically halts deployment (and takes pictures from that point) if the system senses an obstruction. Its functionality verified through testing	The procedures for conducting the functionality test for the emergency stopping system will be readily available for all team members	1	3	3
TROII.3	Sensors fail to accurately assess launch vehicle status	Software composition of system was done incorrectly	Payload fails to leave the launch vehicle and complete its mission	4	4	16	All sensors will have verified functionality prior to launch	The Safety Officer has included a section on the Standard Launch Operating Procedures to ensure that sensors are tested prior to launch to verify the system can assess the launch vehicle status	1	4	4

TROII.4	Payload retention system is damaged or completely fails	1. Retention system strength and durability were unable to withstand forces associated with launch and landing 2. Payload is integrated into the launch vehicle incorrectly	Camera system fails to extend outwards and capture required images	3	4	12	Retention system will be made of a material that is durable and capable of withstanding reasonable landing forces	Retention system will be tested with differing forces with simulation software to verify that no damage occurs upon landing	2	4	8
TROII.5	Motors lack enough torque to meet system demands	Trade studies and evaluation of components were done incorrectly	Payload fails to operate in any capacity	2	4	8	Trade studies and calculations associated with system demands will be done twice to ensure redundancy	Selected motors will be checked and approved by the Payload Lead	1	4	4

Table 93: Launch Equipment Failure Modes and Effects Analysis

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
LE.1	Insufficient launch material is brought to the launch site	Inadequate planning during launch rehearsal and morning of launch	1. Insufficient material to complete integration 2. Unnecessary time is spent retrieving additional material 3. Launch window may be missed	4	2	8	1. A packing list will be developed to ensure that all necessary items are brought to the launch site 2. Team members will work together before the launch to complete this packing list	1. The Safety Officer has created a comprehensive packing list on the Standard Launch Operating Procedures 2. The team will conduct a launch rehearsal the night before the launch to pack all necessary items on the packing list that will be checked the morning of the launch before departure by the Safety Officer for additional redundancy	2	2	4
LE.2	Launch rail is at an incorrect angle	1. Incorrect calculation of predicted flight path 2. Inattentiveness during launch setup	1. Uncontrollable flight path 2. Potential for launch vehicle to impact objects or persons that have taken proper precautions	2	4	8	1. Launch angle will be closely monitored during flight setup 2. The Range Safety Officer (RSO) will monitor the launch setup 3. The team will use NAR guidance and regulations to determine the appropriate launch angle	1. The Safety Officer and the Vehicles Squad Lead will be responsible for ensuring the launch vehicle is set to the proper angle 2. NDRT Mentor Dave Brunsting will be responsible for setting the launch vehicle to the proper angle 3. The RSO will verify that the launch vehicle is set to a proper angle that is between five and ten degrees of the vertical, per NAR regulations	1	4	4

LE.3	Launch wires do not function	1. Improper wiring 2. Wires are in need of replacement	Launch vehicle fails to initiate motor burn and flight does not occur	2	4	8	1. The team will only launch at official NAR/TRA launch sites 2. The team will verify that the wires are functional before launch	1. The team will primarily launch at the Michiana Rocketry Club's launch field on official launch days. Alternative sites will also be assured to be NAR/TRA certified before traveling to them 2. The RSO will verify that all components are functional before launch	1	4	4
LE.4	Launch wires are live during vehicle setup	Failure to check wire status before vehicle setup	Launch vehicle may initiate launch prematurely before team members have had time to leave the launch rail	2	4	8	The team will verify that the launch wires are not live before bringing the launch vehicle to the launch rail	1. The team will verify with the RSO that the launch wires are not live 2. The Safety Officer has included a step to verify launch wires are not live during ignition setup on the Standard Launch Operating Procedures	1	4	4

8.10.3 Environmental Risks

Table 94: Vehicle Risks to Environment

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
VE.1	Motor explosion expels gases into atmosphere	Low-quality motor purchase	1. Emitted gases from explosion may harm local wildlife 2. Emitted gases contribute to global warming by acting as greenhouse gases	5	2	10	1. The motor purchased is an Aerotech L2200G-PS, a reliable product 2. Minimal black powder charges will be used 3. Distance from those that an explosion would impact will be maximized	1. The launch vehicle will be launched in an open field, void of most wildlife 2. The motor will be an Aerotech L2200G-PS, which was approved by the Project Manager prior to purchase 3. The team will analyze, determine, and use the minimum amount of black charges needed to safely initiate a successful recovery sequence 4. All team members and bystanders will be required to stay a minimum of 300 feet away from the launch rail, per NAR guidelines	5	1	5
VE.2	Launch vehicle hits tree	1. Uncontrollable flight path 2. High winds 3. Improper motor installation	1. Minor to major damage to launch vehicle 2. Possible harm to tree and thus local environment	2	3	6	The launch vehicle will launch in area that is void of trees and other wildlife	1. The team will primarily launch at the Michiana Rocketry Club launch site which is in a farming area with minimal trees present 2. The Safety Officer and other design leads will inspect the site upon arrival (if not the Michiana Rocketry Club launch site) to ensure that minimal trees are present	1	3	3

VE.3	Launch vehicle hits a power line	1. Uncontrollable flight path 2. High winds 3. Improper motor installation	1. Electrical fire or explosion 2. Partial or complete loss of launch vehicle 3. Loss of power for local residents 4. Property damage from fire 5. Loss of funds from property repairs	2	4	8	The launch vehicle will launch in area that is void of power lines	1. The team will primarily launch at the Michiana Rocketry Club launch site which is in a farming area with minimal power lines present 2. The Safety Officer and other design leads will inspect the site upon arrival (if not the Michiana Rocketry Club launch site) to ensure that minimal power lines are present	1	4	4
VE.4	Launch vehicle hits spectators, the crowd, or a team member	1. Uncontrollable flight path upon launch 2. Poor visibility 3. Drogue or main parachutes fail to deploy 4. Inattentive spectators/team members 5. Unacceptable drift radius	Serious injury or death to personnel hit by launch vehicle	2	4	8	1. All team members and bystanders will be required to remain at least 300 feet, the NAR-derived Minimum Safe Distance, away from the launch vehicle before launch 2. All team members will be knowledgeable in safe operating procedures in watching the launch vehicle descend	1. The RSO and Safety Officer will ensure that all team members and bystanders abide by the Minimum Safe Distance measurement before launch 2. All team members will be reminded of the safe operating procedures should the launch vehicle be descending in their vicinity	1	4	4
VE.5	Launch vehicle hits a car	1. Uncontrollable flight path 2. Unacceptable drift radius 3. Parachutes fail to deploy	1. Minor or major damage to car 2. Sustained damage to launch vehicle 3. Possibility of fire or explosion if launch vehicle hits the car at a critical point 4. Potential legal action from the victim	3	3	9	1. Launch attendees will be reminded of the danger that they put their vehicles in by parking near the launch site 2. The team will use minimal transport to attend the launch	1. The Safety Officer will remind the team of the dangers that owner's cars face by attending the launch during the Launch Rehearsal the day before the launch 2. Carpooling will be utilized in order to minimize cars at the launch site	3	3	9

VE.6	Launch vehicle lands on a major road	1. Unacceptable drift radius 2. Uncontrollable flight path	1. Potential for complete loss of launch vehicle if hit by oncoming traffic 2. Presence of launch vehicle becomes major road hazard and causes traffic 3. An oncoming car that hits the launch vehicle will sustain major damage and possibly become involved in an accident 4. Motor may explode from being run over by traffic	2	4	8	The launch vehicle will launch in area that is void of major roads or highways	1. The team primarily launches at the Michiana Rocketry Club launch site, a site where no major roads are present within the maximum allowable drift radius, per NASA Req. 3.10. 2. The Safety Officer and other design leads will inspect the launch site (if different than the Michiana Rocketry Club launch site) upon arrival to ensure that no major roads are present within the maximum allowable drift radius from NASA Req. 3.10.	1	4	4
VE.7	Launch vehicle expels carbon dioxide into air	Natural byproduct of combustion reactions	1. Contribution to greenhouse gas emissions into atmosphere 2. Decrease in air quality for local residents	5	2	10	The purchased motor will be of high quality and expel minimal emissions into the atmosphere	The Aerotech L2200G-PS motor was reviewed by the Vehicles Squad Lead and the Project Manager to ensure that it is an environmentally sound purchase	5	1	5
VE.8	Launch vehicle hits a house	1. Uncontrollable flight path 2. Unacceptable drift radius 3. Parachutes fail to deploy	Minor or major damage to house 4. Potential to injury and inhabitants that were present when the launch vehicle impacted the building 5. Potential legal action from inhabitants of house that is hit	2	4	8	The launch vehicle will launch in area that is void of houses	1. The team will primarily launch at the Michiana Rocketry Club launch site which is in a farming area with minimal houses present 2. The Safety Officer and other design leads will inspect the site upon arrival (if not the Michiana Rocketry Club launch site) to ensure that minimal houses are present	1	4	4

VE.9	General waste	Team members do not clean up general waste (i.e., food wrappers, water bottles) before departing the launch site	1. Immediate launch site environment health is harmed 2. Nearby water sources may be harmed from any debris that spills over into it 3. Wildlife may attempt to eat general waste and become physically injured	4	2	8	1. Team members will be responsible for ensuring all waste is cleaned up before departing the launch site 2. The Safety Officer will ensure that waste cleanup occurs	1. There are procedures on the Standard Launch Operating Procedures for team members to clean up all general waste 2. All team members will be required to inspect the team's setup area to confirm no waste is left behind	2	2	4
VE.10	Launch vehicle equipment waste	General operating of launch vehicle may leave behind trace waste materials (i.e., chipped paint, string from parachutes)	1. Immediate launch site environment health is harmed 2. Nearby water sources may be harmed from any debris that spills over into it 3. Wildlife may attempt to eat general waste and become injured	5	2	10	1. Team members that assist in any stage of launch will be responsible for ensuring all launch vehicle waste is cleaned up in the area of their respective stage 2. The Safety Officer will ensure that waste cleanup occurs	1. The Safety Officer will include a step to inspect the area where the launch vehicle is integrated, launched from, and recovered to find any launch vehicle waste and dispose of it properly 2. All team members that assist in any stage of the launch will be required to analyze their immediate area for any launch vehicle waste before moving onto the next stage of the launch	2	2	4
VE.11	Improper disposal of chemically hazardous materials during launch	1. Improper knowledge of chemical waste	1. Potential contamination of soil and water sources 2. Harm to wildlife	2	3	6	All team members will be knowledgeable of and how to dispose of the materials that need to be disposed of differently than general waste due to their chemical nature before the launch	Procedures for disposing of chemically dangerous materials will be published by the Safety Officer and readily available for all team members	1	3	3
VE.12	Fire	Motor combustion may set fire to the landscape upon launch	1. Immediate damage to the launch site soil 2. Land is temporarily unable to be used for agriculture or any other purpose 3. Serious physical harm or death to any wildlife in that area	2	3	6	1. Fire extinguishers will be available in the event of a fire during launch 2. The launch rail will be located in an area void of flammable objects 3. The motor selected will be of high quality	1. The Safety Officer will confirm that the launch rail is in an area void of flammable objects before launch 2. The motor purchased is an Aerotech L2200G-PS, a trusted product. This purchase was approved by the Project Manager and Vehicles Lead	1	3	3

VE.13	High noise levels during launch	Launch generates loud sound source to the surrounding area	1. Possible hearing damage to nearby wildlife and/or bystanders 2. Startling of local wildlife can lead to unsafe conditions for bystanders nearby	4	2	8	1. The launch vehicle will be launched in an area void of most wildlife and bystanders 2. Appropriate ear protection will be provided as needed	The team will launch their launch vehicle in an open farm, far from most houses and wildlife	1	2	2
VE.14	Battery acid leakage	Failure for the battery components to remain closed	Acidity leaks out of the battery and contaminates the soil and/or water sources	3	3	9	1. All team members will be knowledgeable of the disposal of faulty batteries 2. The battery used will be of high quality	1. All batteries will be inspected prior to launch and is a step on the Standard Launch Operating Procedures, which is available to all team members 2. Team members will be able to access procedures for how to dispose of faulty batteries 3. Batteries purchased will be from a trusted vendor and approved by the Project Manager prior to launch	1	3	3
VE.15	High-velocity impact upon landing	Partial or complete failure of recovery system	Damage to the soil in contact with the launch vehicle that would be used for agriculture	2	2	4	The recovery system will be thoroughly and carefully integrated into the launch system to ensure a soft landing	1. The recovery integration will follow the Standard Launch Operating Procedures written by the Safety Officer	1	2	2

Table 95: Environment Risks to Vehicle

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
EV.1	Vehicle experiences high drift radius during recovery stages	High winds	1. Launch vehicle is potentially lost 2. Launch vehicle may land in a congested area of people, wildlife, or structures 3. Launch vehicle lands outside of acceptable drift radius, violating NASA Req. 3.10.	3	3	9	The team will not launch in wind speeds of higher than 20 mph	The Safety Officer will continually monitor the weather forecast in the week preceding the launch to ensure that winds stay within acceptable ranges. If forecasted or actual wind speeds exceed 20 mph during launch day, the launch will be postponed	1	3	3

EV.2	Failure of batteries or other electrical components	Cold temperatures decrease battery and electronics performance	1. Individual systems fail to perform basic functions 2. Complete or partial mission failure	3	4	12	1. The team will not launch in temperatures lower than 15 degrees Fahrenheit 2. Batteries will not be stored in cold temperatures 3. All electronics will be tested to ensure that they are capable of performing at temperatures ranging from 0 to 100 degrees Fahrenheit, per NDRT Requirement IN.1	1. In cold temperatures, batteries will be kept in a temperature-controlled environment (i.e., a car) until it is necessary to integrate them into the launch vehicle. 2. The Safety Officer will continually monitor the weather forecast in the week preceding the launch to ensure that temperatures remain in acceptable conditions. If expected (or observed if on the day of the launch) temperatures fall below 15 degrees Fahrenheit, the launch will be postponed 3. Batteries and other electronics will be stored at room temperature whenever possible while setting up for launch	1	4	4
EV.3	Water leaks into launch vehicle	1. Rain, snow, sleet, or high humidity brings high moisture presence around launch vehicle 2. Insufficient fastening and tightening of launch vehicle subcomponents	1. Electrical fires or explosions due to water coming into contact with electronics 2. Partial or complete mission failure	3	4	12	1. The team will not launch in an area with any form of precipitation 2. Batteries/electronics and the launch vehicle will be kept dry whenever possible	The Safety Officer will continually monitor the weather forecast in the week preceding the launch to ensure that precipitation chances remain minimal. If expected (or observed if on the day of the launch) precipitation is apparent launch will be postponed, batteries/electronics and the launch vehicle will be stored inside the workshop and in a dry area until it is necessary to launch	1	4	4
EV.4	Physical damage to launch vehicle or electronics	Hail	1. Hail may hit critical launch components, causing partial or complete mission failure 2. Fire or explosion if hail hits motor	1	4	4	The team will not launch in hail	The Safety Officer will continually monitor the weather forecast in the week preceding a launch. If it is apparent (or observed on launch day) that there is hail present, the launch will be postponed	1	4	4
EV.5	Electrical discharge during launch	Rain, snow, thunderstorms	1. Electrical fires or explosions 2. Electrical components fail to function during launch	2	4	8	The team will not launch with any form of precipitation	The Safety Officer will continually monitor the weather forecast in the week preceding a launch. If it is apparent (or observed on launch day) that there is precipitation, the launch will be postponed	1	4	4
EV.6	Inability to track launch vehicle movement	Fog	1. Loss of launch vehicle 2. Inability to notify spectators or team members if returning vehicle is inbound towards them	3	3	9	The team will not launch in an area with considerable fog or generally low visibility	The Safety Officer will continually monitor the weather forecast in the week preceding a launch. If it is apparent (or observed on launch day) that there is low visibility and/or fog, the launch will be postponed	1	3	3

EV.7	Unstable launching ground	The ground on which the launch pad is located is too wet to provide stable ground	Launch vehicle launches at an unacceptable or unpredictable launch angle	3	4	12	1. If considerable precipitation has occurred in the days and weeks leading up to the launch that would give reason to believe the launch pad would not be on stable ground, the launch will be postponed 2. The team and RSO will ensure that the ground the launch pad is located on is firm and suitable for using as a base for the launch pad and launch vehicle	1. The Safety Officer will inspect the ground where the launch pad is located and ensure it is stable to provide appropriate support for the launch 2. The RSO will provide further confirmation that the ground is firm enough to launch a launch vehicle from 3. The Safety Officer will continually monitor the weather forecast in the week preceding a launch. If it is apparent (or observed on launch day) that there is considerable precipitation that would cause the launch pad to not be on stable ground, the launch will be postponed until this condition is met	1	4	4
EV.8	Thermal expansion of launch vehicle components	High temperatures	1. Launch vehicle fails to integrate properly 2. Increased pressure on joints possibly leading to fractures	2	2	4	1. Launch vehicle components will be kept in room temperature for as long as possible 2. The team will not launch in considerably high temperature	1. The team will not launch in temperatures higher than 90 degrees Fahrenheit The Safety Officer will continually monitor the weather forecast in the week preceding the launch to ensure that temperatures remain in acceptable conditions. If expected (or observed if on the day of the launch) temperatures cross above 90 degrees Fahrenheit, the launch will be postponed 3. Launch vehicle components will be kept in the workshop or another temperature-controlled environment and only brought outside when needed for integration and launch 4. When the launch vehicle is at the launch site, it will be left in a car or another moderate temperature environment until needed	1	2	2
EV.9	Thermal contraction of launch vehicle components	Cold temperatures	1. Launch vehicle fails to integrate properly 2. Increased pressure on joints possibly leading to fractures	3	2	6	1. Launch vehicle components will be kept in room temperature for as long as possible 2. The team will not launch in considerably high temperature	1. The team will not launch in temperatures lower than 15 degrees Fahrenheit 2. The Safety Officer will continually monitor the weather forecast in the week preceding the launch to ensure that temperatures remain in acceptable conditions. If expected (or observed if on the day of the launch) temperatures fall below 15 degrees Fahrenheit, the launch will be postponed 3. Launch vehicle components will be kept in the workshop or another temperature-controlled environment and only brought outside when needed for integration and launch 4. When the launch vehicle is at the launch site, it will be left in a car or another temperature-controlled environment until needed	1	2	2
EV.10	High voltage	1. Increased temperatures increase resistance of wires	1. Overheating 2. Possible electrical fires or explosions 2. Failure of critical system components	2	4	8	1. High quality electrical components will be used 2. The team will not launch in temperatures above 90 degrees	1. Electrical components will be from a trusted vendor and approved by the Project Manager before purchase 2. The Safety Officer will continually monitor the weather forecast in the week preceding a launch. If it is apparent (or observed on launch day) that there are temperatures exceeding 90 degrees Fahrenheit or a lightning storm, the launch will be postponed	1	4	4

EV.11	Errant launch vehicle trajectory	1. High winds 2. Lightning	1. Launch vehicle flies in unpredictable trajectory 2. Possibility to land in areas of high population or wildlife density	2	4	8	The team will not launch in winds exceeding 20 mph or in a lightning event	The Safety Officer will continually monitor the weather forecast in the week preceding a launch. If it is apparent (or observed on launch day) that there is winds exceeding 20 mph or a lightning storm, the launch will be postponed	1	4	4
EV.12	Launch vehicle is struck by lightning	Presence of thunderstorm	1. Electrical fires or explosions 2. Complete or partial launch vehicle 3. Debris being released from the launch vehicle with possibility of hitting persons or team members	2	4	8	The team will not launch in a lightning storm	The Safety Officer will continually monitor the weather forecast in the week preceding a launch. If it is apparent (or observed on launch day) that there is a lightning storm, the launch will be postponed	1	4	4

8.10.4 Project Risks

Table 96: Project Risks

Label	Hazard	Cause	Outcome	Probability	Severity	Before	Mitigation	Verification	Probability	Severity	After
PR.1	Team depletes all available funds	1. Reckless spending 2. Lack of organized budget	1. Team no longer has funds to continue the competition 2. Complete mission failure	1	4	4	1. The team will limit purchases to only those necessary for project success	1. The Project Manager will meet with each squad to determine a reasonable budget for each squad 2. The Project Manager will be responsible for creating a budget spreadsheet that tracks all purchases 3. The Project Manager will set up a form to allow for necessary team purchase requests which can be approved or rejected at the Project Manager's discretion	1	4	4
PR.2	Team misses a major deliverable report to NASA Student Launch Initiative	Inadequate project management planning	1. Disqualification from competition 2. Complete mission failure	2	4	8	The team will set internal deadlines in addition to NASA derived deadlines to ensure the team meets deliverable requirements	The Project Manager will meet with each squad at the beginning of the academic year to set reasonable internal deadlines, which will be visualized through the use of Gantt Charts	1	4	4

PR.3	Team member becomes sick	1. Seasonal illnesses 2. General spreading of illness in high population density areas such as college campuses	1. Member is unable to fully participate in team mission 2. Potential for illness to progress to a more serious affliction	5	1	5	Team members will be encouraged to monitor their own health and refrain from engaging in team activities and meetings if they feel ill	All team members are required to sign a team contract to participate in any construction or attend any launches, which includes a clause on refraining from attending meetings and/or launches if one feels ill	5	1	5
PR.4	Team member is infected with COVID-19	Prevalence of COVID-19 in the United States	1. Member is unable to fully participate in team mission for duration of their sickness 2. Possibility of the virus progressing to a more serious affliction 3. COVID-19 may pass onto other team members resulting in depleted productiveness	3	3	9	1. Team members will be encouraged to monitor their own health and test if they suspect they have COVID-19 2. Team members will take appropriate precautions to prevent infection and spreading of COVID-19	1. All team members are required to sign a team contract to participate in any construction or attend any launches, which includes a clause on refraining from attending meetings and/or launches if they test positive for COVID-19 2. All team members will abide by the University requirements on COVID-19 testing, contact tracing, masking, and isolation/quarantine	2	3	6
PR.5	Compliance issues with regulations set forth by FAA, NAR, or TRA	Inattention or lack of knowledge of regulations	Potential legal action and unsafe launch conditions	3	4	12	Team members will be informed of relevant regulations as they pertain to the design process and launch	1. The Safety Officer and Project Manager will be responsible for informing team members about relevant FAA, NAR, and TRA regulations 2. FAA, NAR, and TRA regulations will be readily accessible for team members	1	4	4
PR.6	Loss of team members	1. Lack of interest or participation as the school year progresses 2. Schoolwork becomes increasingly demanding on team members' schedules	1. Lack of personnel to complete necessary tasks 2. Increased strain on remaining team members	5	2	10	1. Understanding of the natural decrease of members in a voluntary club 2. Respect for those that must leave the design team 3. Improved understanding of an individual's responsibility on the team	1. Design Leads and other involved members are aware of assuming added responsibilities from any team member that may choose to leave the club 2. The team will make team meetings engaging and enjoyable 3. Team members will work on tasks that are appropriate for their knowledge level 4. The team will promote a culture that is accepting of any team member that chooses to leave	4	1	4

PR.7	Shipping delays	1. Global supply chain issues 2. General logistics of shipping goods	1. Lack of material to perform tests or aid in construction 2. Elevated time constraint to complete major deliverables by deadlines	5	2	10	1. Parts will be ordered well in advance of their intended use timeline 2. An organized system for ordering parts with the team's budget will be implemented	1. A purchase request form is currently open for any lead that wishes to purchase a piece for construction 2. Leaders are consistently reminded to order parts as early as they can	4	2	8
PR.8	Insufficient testing material	1. Lack of available testing equipment on campus 2. Certain testing equipment is restricted for undergraduate students	1. Inability to verify the functionality of certain system 2. Confidence in launch vehicle safety is compromised due to lack of understanding of how systems function	3	3	9	1. Appropriate staff with access to requested testing equipment are reached out to well in advance of deliverable deadlines 2. Appropriate research is done on design functionality 3. Different systems that can be appropriately tested are explored	1. Appropriate staff are contacted at least two months ahead of the deliverable or testing deadline for the particular system 2. If a system cannot be tested, appropriate research and analysis will be done in place of the test and will be approved by the appropriate design lead, Safety Officer, and Project Manager before it is proceeded with 3. The team will explore at least one different concept that can be appropriately tested and verify that it is not more efficient or effective than the original design before proceeding with the concept that cannot be appropriately tested (which would be analyzed and researched in place of being tested)	1	3	3
PR.9	Missing PPE	Necessary PPE is used and not refilled in a timely manner	Team members are not able to safely participate in construction, halting the assembly process	4	3	12	1. The Safety Officer will be responsible for inspecting and purchasing additional PPE 2. Team members will be encouraged to report missing PPE to the Safety Officer	1. The Safety Officer shall conduct an inspection of the workshop to identify missing PPE every two weeks. Missing PPE will promptly be reported to the Project Manager to purchase additional equipment 2. Team members will be encouraged to reach out to the Safety Officer with reports of any missed PPE	1	3	3

9 Project Plan

9.1 Testing

Table 97: Testing Overview

Test ID	Title	Requirements Satisfied	Result
LVT.1	Launch Vehicle Demonstration Flight	2.1., 2.3., 2.5., 2.6., 2.19.1., 2.19.1.1., 2.19.1.4., 2.19.1.6., 2.19.1.9., 2.19.2.1., 2.23.6., IN.6	Incomplete
LVT.2	Subscale Demonstration Flight	2.18., 2.18.1., 2.18.2.	Pass
LVT.3	Battery Duration Test	2.6.	Incomplete
LVT.4	Vibration Test	LV.5	Incomplete
LVT.5	Bulkhead Static Loading Test	LV.6	Incomplete
LVT.6	Motor Mount Static Loading Test	LV,6	Incomplete
RT.1	Launch Vehicle Demonstration Flight	3.1., 3.3., 3.10., 3.11., 3.12.2.	Incomplete
RT.2	Simulated Flight Test	3.1.1., 3.1.2.,	Incomplete
RT.3	Ground Ejection Test	3.2.	Incomplete
RT.4	Integrated Electronics Shielding Test	3.13.4.	Incomplete
RT.5	Bulkhead Static Loading Test	R.2	Incomplete
RT.6	GPS Functionality Test	3.12., 3.12.2.	Incomplete
TROIT.1	Payload Demonstration Test	4.1., 4.2.1.3., 4.2.1.4., 4.2.2., 4.2.2.1., 4.2.3., 4.2.3.1., 4.2.3.2., 4.2.3.3., 4.2.4., TROI.6	Incomplete
TROIT.2	Camera System Rotation Test	4.2.1., 4.2.1.1.	Incomplete
TROIT.3	Camera System Deployment Test	TROI.1, TROI.4, TROI.6	Incomplete
TROIT.4	Camera Baseline Imaging Test	4.2.1.3., 4.2.1.4., TROI.3	Incomplete
TROIT.5	Camera RF Integration Test	4.2.2., 4.2.2.1., 4.2.3., 4.2.3.1., 4.2.3.2.	Incomplete
TROIT.6	Payload State Identification Test	4.2.3.3	Incomplete
ACST.1	Flap Mechanism Activation Test	ACS.1	Incomplete
ACST.2	Mechanism Torque Output Test	ACS.2	Incomplete
ACST.3	Data Acquisition Test	ACS.3, ACS.4	Pass
ACST.4	State Transition Manager Test	ACS.5	Incomplete
INT.1	Battery Duration Test	IN.1	Incomplete
INT.2	Integrated Electronics Shielding Test	IN.2	Incomplete
INT.3	Camera Shielding Test	IN.5	Incomplete

9.1.1 Launch Vehicle Testing

LVT.1, RT.1: Launch Vehicle Demonstration Flight

Objective: Verify nominal performance of all launch vehicle systems and reusability of vehicle

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.1	Launch vehicle performs nominally during flight sequence; vehicle is reusable	2.1., 2.3., 2.5., 2.6., 2.19.1., 2.19.1.1., 2.19.1.4., 2.19.1.6., 2.19.1.9., 2.19.2.1., 2.23.6., IN.6	Incomplete
RT.1	Recovery modules perform nominally	3.1., 3.3., 3.10., 3.11., 3.12.2.	Incomplete

Materials and Equipment Needed: For equipment, PPE, and tools required for launch, refer to Launch Operating Procedures.

Test Setup: Use the Launch Operating Procedures to follow the Launch Rehersal steps. The test setup will take no more than 2 hours (NASA req. 2.5.).

Test Procedure: Use the Launch Operating Procedures and follow all outlined steps.

Analysis Procedure:

1. After launch, inspect launch vehicle and subsystems for signs of visible damage
2. Using footage from the on-board camera and and ground viewers, verify correct timing of recovery events

Results: Incomplete. Scheduled for February

Next Steps: If all success criteria are met, the demonstration flight is passed. Repeat demonstration flight if one or more success criteria are not met after identifying and addressing cause(s) of failure.

LVT.2: Subscale Demonstration Flight

Objective: Verify aerodynamic properties of full-scale vehicle and collect flight data

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.2	Flight data is measured and displays favorable aerodynamic performance	2.18., 2.18.1., 2.18.2.	Pass

Materials and Equipment Needed: Fully asssembled subscale launch vehicle, fully assembled internal component(s) capable of collecting flight altitude during launch

Test Setup:

1. Launch the subscale launch vehicle in an NAR approved launch field. For NDRT, the nearest NAR approved launch site is in Three Oaks, MI.
2. Fully construct a subscale launch vehicle, making sure to keep the characteristics of the fullscale design as close as possible

Test Procedure:

1. While at the launch site, fully assemble the subscale launch vehicle, making sure to have a fully-charged altimeter on board
2. Place the launch vehicle on the launch rail, taking note of the launch angle, wind speed, temperature, and pressure at the time of launch
3. Launch and retrieve the launch vehicle
4. Demonstrate that the subscale launch has a successful recovery device deployment, using the altitude data as evidence

Analysis Procedure:

1. Check that the subscale launch vehicle collected flight altitude data, and the subscale launch vehicle had a successful flight ascent and recovery descent

Results: Completed. See Section 3.5.4

Next Steps: Vehicle demonstration flight

LVT.3, INT.1: Battery Duration Test

Objective: Verify all onboard batteries power system electronics for the desired amount of time

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.3	Batteries power system electronics for a minimum of three hours	2.6.	Incomplete
INT.1	Batteries power system electronics for a minimum of three hours	IN.1	Incomplete

Materials and Equipment Needed: Fully assembled NED, PED, FED, TROI, and ACS
Test Setup:

1. The outside temperature should be below 20°F for this test to be conducted
2. Fully assemble each system in its flight-ready conditions
3. Fully charge all batteries

Test Procedure:

1. Activate all systems and plug in batteries
2. Choose a location outside that can be easily observed from indoors, then place each system outside
3. Set a three hour timer
4. Bring systems inside after three hours without inplugging or deactivating them

Analysis Procedure:

1. Check that all systems have remained on and are functional

Results: Incomplete. Scheduled for February

Next Steps: Test passes if all systems remain on and functional after three hours have elapsed. Revisit battery selection if any system loses power, then repeat the demonstration.

LVT.4: Vibration Test

Objective: Verify components do not detach from their connections due to vibration

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.4	Components do not dislodge from their connections when the launch vehicle is vibrating	LV.5	Incomplete

Materials and Equipment Needed: Fully assembled NED, PED, FED, TROI, ACS, and launch vehicle with all internal components secured inside
Test Setup:

1. Assemble the fullscale launch vehicle, with all internal components secured inside.

Test Procedure:

1. Have 3-4 team members hold the launch vehicle up

2. Begin to shake the launch vehicle. If any part becomes dislodged, stop the procedure. Continue to shake for around a minute.

Analysis Procedure:

1. Check that all systems remain in their secured position once the launch vehicle is shook for a period of time

Results: Incomplete. Scheduled for February

Next Steps: Revisit this test before any fullscale launch

LVT.5, RT.5: Bulkhead Static Loading Test

Objective: Verify bulkheads in recovery modules and other sections of the launch vehicle can withstand at minimum 1.5 times the predicted in-flight forces

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.5	Bulkhead assemblies do not exhibit signs of failure from forces less than 1.5 times the predicted values	LV.6	Incomplete
RT.5	Recovery module bulkheads do not exhibit signs of failure from forces less than 1.5 times the predicted values	3.1., 3.3., 3.10., 3.11., 3.12.2.	Incomplete

Materials and Equipment Needed: Carbon-fiber body tube section, fiberglass coupler section, carbon-fiber bulkhead with same dimensions as PED and FED bulkheads, carbon-fiber bulkhead with same dimensions and holes as NED bulkheads, G10 Fiberglass with the same dimensions and holes as the fixed bulkhead, airframe interfacing blocks and screws, eyebolts, frame to secure shock cord, safety glasses

Test Setup:

1. Assemble the airframe interfacing blocks onto the recovery carbon fiber bulkheads
2. Epoxy fiberglass bulkhead onto a body tube, ensuring appropriate curing time
3. Attach eyebolts and airframe interface blocks to bulkheads, then attach bulkheads to the body tube with the use of screws

Test Procedure:

1. For each test section:

   (a) Hang weights from the bulkheads' eyebolt, based on calculations of the static force on the bulkhead that is equivalent to the force of the parachutes

Analysis Procedure:

1. Check the test section for any signs of damage

Results: Incomplete. Scheduled for February

Next Steps: Reconsider the material selection and thickness if the bulkhead becomes damaged, then repeat the demonstration.

LVT.6: Motor Mount Static Loading Test

Objective: Verify the motor mount can withstand at least 1045.5 lbf, which is 1.5 times the predicted maximum thrust

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.6	The motor mount does not exhibit signs of failure before reaching forces of 1.5 times the predicted value at minimum	LV.6	Incomplete

Materials and Equipment Needed: Carbon-fiber motor mount tube, load cell rig for applying compressive force, safety glasses

Test Setup:

1. Consult equipment expert for special safety procedures and help securing motor mount tube in load cell
2. Secure motor mount tube as instructed for compressive static loading test

Test Procedure:

1. Increase load until 1045.5 lbf or signs of damage

Analysis Procedure:

1. Check test section for signs of damage
2. Record final load value

Results: Incomplete. Scheduled for February

Next Steps: Reconsider material selection and thickness if the body tube becomes damaged, then repeat the demonstration.

9.1.2 Recovery Testing

RT.2: Simulated Flight Test

Objective: Verify nominal communication between altimeters and components required for in-flight separation

Test ID	Success Criteria	Requirements Satisfied	Result
RT.2	Lights representing ematches turn on at the desired altitude	3.1., 3.3., 3.10., 3.11., 3.12.2.	Incomplete

Materials and Equipment Needed: Altimeter, LED lights, Breadboard, Computer with Featherweight Interface Program and Raven4PRM software installed, 3.7 V battery and wire leads

Test Setup:

1. Connect the altimeter to the breadboard, light, and battery, then switch the altimeter to "ON" position
2. Connect the USB cable to the altimeter and computer
3. Open altimeter software and input desired altitude for separation event

Test Procedure:

1. For each altimeter:

   (a) Upload simulated altitude and flight data to altimeter
   (b) Repeat for additional altitudes as desired

Analysis Procedure:

1. Observe whether LED light turn on at desired altitudes

Results: Incomplete. Scheduled for January

Next Steps: If the LED light turns on at all desired altitudes as displayed on the computer, the test passes. If not, identify the source(s) of failure and rerun the test.

RT.3, INT.3: Ground Ejection Test

Objective: Verify correct sizing of black powder charges for in-flight separation events and that charge debris does not damage TROI components

Test ID	Success Criteria	Requirements Satisfied	Result
RT.3	Force of separation is deemed appropriate by mentor	3.1., 3.3., 3.10., 3.11., 3.12.2.	Incomplete
INT.3	Black powder charge debris is not visible near the TROI camera system	IN.5	Incomplete

Materials and Equipment Needed: Fully assembled launch vehicle, calculated and sized black powder charges, safety glasses, battery with ematch and wire leads, cling film

Test Setup:

1. Load black powder into a charge well with an ematch: done by team mentor only
2. Assemble the launch vehicle, ensuring that the wires are accessible from an RSO-determined safe distance
3. Cover the TROI camera system in cling wrap
4. Clear any obstructions and place launch vehicle on the ground

Test Procedure:

1. Repeat for each separation point:
   (a) Ignite black powder by closing circuit on the battery
   (b) Handle launch vehicle sections only after they have come to rest

Analysis Procedure:

1. Consult RSO and/or team member on charge sizing. Charges were too small if sections did not separate upon ignition, and too large if they separated with excessive force.
2. Inspect cling wrap for signs of black powder debris.

Results: Incomplete. Scheduled for February

Next Steps: The test is passed if the team mentor approves of charge sizing and black powder debris is not present on cling wrap surrounding TROI. If less than both success criteria are met, analyze and address failures. Conduct testing until both success criteria are met.

RT.4, INT.2: Integrated Electronics Shielding Test

Objective: Verify onboard electronics do not interfere with recovery electronics during flight

Test ID	Success Criteria	Requirements Satisfied	Result
RT.4	Ensure all Recovery Electronic Systems are operational through component indicator lights	3.1., 3.3., 3.10., 3.11., 3.12.2.	Incomplete

Materials and Equipment Needed: Fully assembled launch vehicle, fully charged electronics

Test Setup:

1. Connect a light to each altimeter
2. Connect a battery to each altimeter
3. Verify all arming switches are in the "OFF" position
4. Integrate PED into payload body tube

Test Procedure:

1. Flip arming switches to "ON" position
2. After activating the GPS transmitter, bring it near the payload body tube
3. After activating the TROI transmission module, bring it near the payload body tube
4. After activating the ACS motor, bring it near the payload body tube
5. De-activate external systems after five minutes
6. Remove PED from the payload body tube, keeping arming switches in the "ON" position

Analysis Procedure:

1. Ensure that none of the light bulb indicators are on

Results: Incomplete. Scheduled for February

Next Steps: Repeat demonstration if any light indicators turned on after determining the cause of the failure.

RT.5: Bulkhead Static Loading Test

Objective: Verify bulkheads in recovery modules can withstand at minimum 1.5 times the predicted in-flight forces

Test ID	Success Criteria	Requirements Satisfied	Result
RT.7	Bulkhead assemblies withstand dynamic loading up two times the force of the parachute	3.1., 3.3., 3.10., 3.11., 3.12.2.	Incomplete

Materials and Equipment Needed: Carbon fiber bulkhead with dimensions that match NED, PED, and FED, airframe interfacing blocks and screws, eyebolts, safety glasses, frame to secure module

Test Setup:

1. Assemble the airframe interfacing blocks onto the bulkheads
2. Epoxy bulkheads into the center of the body tube and coupler sections, ensuring appropriate curing time
3. Attach eyebolts to bulkheads, then attach another eyebolt to the frame
4. Use a shock cord to connect the frame eyebolt to a bulkhead eyebolt
5. Calculate the height the test setup needs to fall from to simulate the force of the parachute deployment

Test Procedure:

1. For each test section:
   (a) Find an area where the test section can fall the appropriate height without obstruction
   (b) Drop the test section from the appropriate calculated height

Analysis Procedure:

1. Check the test section for any signs of damage

Results: Incomplete. Scheduled for February

Next Steps: Reconsider the material selection and thickness if the bulkhead becomes damaged, then repeat the demonstration.

RT.6: GPS Functionality Test

Objective: Verify the recovery GPS device is functional

Test ID	Success Criteria	Requirements Satisfied	Result
RT.9	GPS transmits and is received at 5000 ft distance	3.12., 3.12.2.	Incomplete

Materials and Equipment Needed: GPS transmitter and battery, GPS receiver, smartphone with GPS app
Test Setup:

1. Select outdoor environment to prevent structures from blocking GPS signals
2. Connect GPS to ground station and ground station to smartphone, then load the user interface

Test Procedure:

1. Move the GPS and smartphone to be approximately 5000 feet apart
2. Record coordinates given by GPS

Analysis Procedure:

1. Verify that the transmitter and receiver remain connected and read a distance of 5000 ft
2. Verify that the coordinates given by the GPS are accurate using satellite imagery overlay

Results: Incomplete. Scheduled for February

Next Steps: If the GPS functions in the range of 5000 feet and displays accurate coordinates, the test passes. Identify the cause of the failure if the GPS transmitter and receiver cannot remain connected or display inaccurate coordinates, then repeat the test.

9.1.3 TROI Testing

TROIT.1: Payload Demonstration Flight

Objective: Verify performance capabilities of final TROI design

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.1	TROI successfully activates after launch vehicle landing, responds to RAFCO, and takes accurate and time-stamped images.	4.1., 4.2.1.3., 4.2.1.4., 4.2.2., 4.2.2.1., 4.2.3., 4.2.3.1., 4.2.3.2., 4.2.3.3., 4.2.4., TROI.6	Incomplete

Materials and Equipment Needed: See the Payload Equipment section in the Launch Operating Procedures.

Test Setup: See TROI preparation in the Launch Operating Procedures.

Test Procedure:

1. Activate TROI and integrate into the launch vehicle

2. Activate the ground station that simulates RAFCO
3. Follow Launch Flight Procedures to launch the vehicle.
4. Send RAFCO signal from ground station
5. Collect images stored within the camera system

Analysis Procedure:

1. Verify images have been collected and are as expected

Results: Incomplete. Scheduled for February

Next Steps: If success criteria is met, payload demonstration flight is passed. If one or more criteria is not met, the cause of failure must be identified and addressed. Payload demonstration flight must be repeated.

TROIT.2: Camera System Rotation Test

Objective: Verify camera system is able to rotate 360° about the z-axis and comply with potential RF commands

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.2	The imaging subsystem correctly completes all possible imaging commands	4.2.1., 4.2.1.1., 4.2.1.2., 4.2.1.3., 4.2.1.4., 4.2.2.	Incomplete

Materials and Equipment Needed: ESP32-CAM, ESP32 Main, battery, telescoping camera arm, camera axis stepper motor, camera

Test Setup: Charge battery and position telescoping camera arm to fully deployed state. Connect electronics. Prepare and document a set list of commands, including everything from NASA Req. 4.2.2., for the imaging subsystem to perform. Place the camera so that it faces a landscape, optimally with variations and many colors.

Test Procedure:

1. Activate camera axis stepper motor and electronics
2. Allow camera assembly to rotate 360° both clockwise and counterclockwise. Document its performance
3. Complete set list of commands, documenting each step

Analysis Procedure:

1. Plot angular position vs. time for the z direction
2. Evaluate if the camera completed a full revolution for both the clockwise and counterclockwise directions
3. View images stored on microSD card
4. Compare the live test documentation to the order of commands and evaluate what commands succeeded by inspection
5. Evaluate if each image met the command it was given. Compare with live test documentation

Results: Incomplete. Scheduled for February

Next Steps: If success criteria is met, the imaging subsystem is ready to be integrated with other subsystems for future tests. If success criteria is not met, identify which commands were not executed correctly. Isolate the incomplete commands and repeat the test.

TROIT.3: Camera System Deployment Test

Objective: Verify that the imaging subsystem is able to successfully deploy under various landing conditions without interference from the payload body tube or recovery assembly

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.3	The imaging subsystem is able to successfully deploy under various landing conditions without interference from the payload body tube or recovery assembly	TROI.1, TROI.4, 4.2.1., 4.2.1.1.	Incomplete

Materials and Equipment Needed: See the Payload Equipment section in the Launch Operating Procedures.

Test Setup: Remove nose cone and integrate the TROI into payload body tube. Charge battery. Move lead screw and telescoping camera arm to respective retained positions.

Test Procedure:

1. Place assembled payload body tube in a position parallel to horizontal axis
2. Activate stepper motor and the TROI electronics
3. Allow the TROI to fully deploy. Document its performance
4. Reset the TROI to initial position
5. Repeat procedure for angles of -15º, +15º, +30º, and +45º relative to the horizontal axis

Analysis Procedure:

1. Evaluate if the TROI was able to deploy linearly without interference from the payload body tube or recovery assembly at each angle relative to the horizontal axis
2. Evaluate if the TROI camera extended 1.5 inches above the payload body tube

Results: Incomplete. Scheduled for February

Next Steps: If success criteria is met, the deployment subsystem is ready to be integrated with other subsystems for future tests. If success criteria is not met, identify which stage of the deployment sequence failed for a given angle relative to the horizontal axis. Compare the recorded orientation of the accelerometer compared to the final orientation of the telescoping camera arm. Identify possible failure modes that have not already been established.

TROIT.4: Camera Baseline Imaging Test

Objective: Verify that the camera captures images with acceptable quality and with appropriate time stamps, as well as within the proper time amount outlined in the requirements.

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.4	Camera successfully captures images in totality in the correct coloring and orientation	TROI.3, TROI.4, 4.2.1.3., 4.2.1.4.	Incomplete

Materials and Equipment Needed: TROI's camera, control camera, camera stand, and a secondary device (computer)

Test Setup: Place TROI's camera so that it faces a landscape, optimally with variations and many colors. Set up a second camera (control camera), in close proximity to TROI's camera, that captures clear images and has time stamps.

Test Procedure:

1. Set up and power on TROI's camera and the control camera

2. Capture three images with the each camera in their original positions
3. Rotate TROI's camera to a different position
4. Move the control camera to a similar position in close proximity of TROI's camera
5. Repeat steps 2-4 twice more to obtain images from various positions
6. Power down the cameras
7. Download the images from both cameras to a secondary device
8. Analyze the images

Analysis Procedure:

1. Check that TROI's camera captured all nine images
2. Compare the images from TROI's camera to the images captured by the control camera
    (a) Compare images for differences in color and discoloration
    (b) Compare images for differences in quality (bluriness, completeness of image, exposure)
    (c) Compare time stamps
3. Record in a spreadsheet whether or not TROI's images are satisfactory or non-satisfactory in comparison to the control images
4. Compare the consecutive time stamps on TROI's images to ensure they reach the time requirement and mark whether their time differences are satisfactory or non-satisfactory

Results: Incomplete. Scheduled for February

Next Steps: For any non-satisfactory image comparisons, the settings of TROI's camera must be adjusted and fixed to more closely resemble the control camera's images. Retest the camera with the same procedure until each comparison is satisfactory.

TROIT.5: Camera RF Integration Test

Objective: Verify the performance of the camera and RF subsystems when integrated together

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.5	The imaging subsystem correctly responds to commands received from the RF subsystem	4.2.1.3., 4.2.1.4., 4.2.2., 4.2.1.1., 4.2.3., 4.2.3.1.	Incomplete

Materials and Equipment Needed: ESP32-CAM, ESP32 Main, RF ground station, battery

Test Setup: Charge battery and assemble TROI electronics. Connect the imaging code to the RF code such that the deployment subsystem is not used and the TROI remains rigid throughout the test. Prepare and document a list of commands for the TROI.

Test Procedure:

1. Identify transmitting frequency
2. Activate TROI electronics and the ground station
3. Ground station transmits commands to the TROI
4. Imaging subsystem takes images and saves to microSD card

Analysis Procedure:

1. View images stored on microSD card

2. Compare sequence, and timing of images compared to documented commands
3. Identify if the recorded images are correct by inspection
4. Identify what, if any, commands were not successful

Results: Incomplete. Scheduled for February

Next Steps: If success criteria is met, add in the deployment subsystem for a future test. If success criteria is not met, identify if the RF and/or imaging subsystems did not work correctly. Isolate and improve on the necessary subsystem.

TROIT.6: Payload State Identification Test

Objective: Demonstrate that the TROI successfully records and filters accelerometer data to identify the state of the launch vehicle

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.6	The accelerometer successfully identifies state as in motion or stationary for a prototype test. Accelerometer thresholds are determined for full-scale launch.	4.2.3.3.	Incomplete

Materials and Equipment Needed: Accelerometer, ESP32 Main, battery

Test Setup: Fix all materials to a singular, transportable object. Charge battery and ensure ESP32 microcontroller has the correct code to record accelerometer values.

Test Procedure:

1. Activate accelerometer and ESP32 Main electronics
2. Leave the object stationary, then move it to provide an impulse, before leaving it stationary again
3. Stop accelerometer data collection and retrieve relevant data

Analysis Procedure:

1. Plot acceleration vs. time for all directions. Determine the spikes of acceleration from the object movement by inspection
2. Evaluate if the relevant code correctly determined if the object was stationary or in motion
3. Adjust the acceleration thresholds as necessary and repeat test
4. Use recorded subscale accelerometer data to identify acceleration thresholds for full-scale launch

Results: Incomplete. Scheduled for February

Next Steps: If success criteria is met, relevant code can be scaled up for the full scale launches.

9.1.4 ACS Testing

ACST.1: Flap Mechanism Actuation Test

Objective: Verify drag flaps actuate across the full range of motion

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.1	Drag flaps respond to motor commands for actuation from 0° to 45°	ACS.1	Incomplete

Materials and Equipment Needed: Fully assembled ACS, motor command capabilities, protractor
Test Setup:

1. Connect ACS servo motor to servo controller board

Test Procedure:

1. Send PWM signals to the servo motor for incremental actuation across the full range of motion

Analysis Procedure:

1. Visually verify, then measure that the drag flaps actuate along the full range of motion

Results: Incomplete. Scheduled for January

Next Steps: The test passes if the drag flaps successfully actuate along the full range of motion. If not, identify and address failure modes and rerun the test.

ACST.2: Mechanism Torque Output Test

Objective: Verify drag flaps can actuate without damage under maximum predicted loading conditions

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.2	Drag flaps do not exhibit signs of damage or failure after loaded actuation	ACS.2	Incomplete

Materials and Equipment Needed: Fully assembled ACS, PCB, motor connected to servo controller board, weights, adhesive
Test Setup:

1. Activate ACS servo motor
2. Attach weights to each individual drag flap

Test Procedure:

1. Send PWM signals to the servo motor for incremental actuation across the full range of motion
2. After actuation cycle is complete, remove weights from drag flaps

Analysis Procedure:

1. Inspect drag flaps and flap lever arms for signs of damage or failure

Results: Incomplete. Scheduled for January

Next Steps: The test passes if the drag flaps and flap lever arms do not exhibit signs of fatigue or failure. If not, reconsider drag flap materials and flap lever arm sizing and rerun the test.

ACST.3: Data Acquisition Test

Objective: Verify ACS software can read and store data points at acceptable sample rates

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.3	ACS software can collect data at sample rates of at least 10 Hz	ACS.3, ACS.4	Pass

Materials and Equipment Needed: Raspberry Pi Microprocessor, Python data logging code, ACS accelerometer and altimeters, breadboard, cables
Test Setup:

1. Connect Raspberry Pi microprocessor to the desired sensor using a cable
2. Run the Python data logging code

Test Procedure:

1. While the code is running, physically move the sensor in use
2. After the code has stopped running, repeat test setup and Step 1 for remaining sensors

Analysis Procedure:

1. Review Python data logging code to determine sample rates of each sensor

Results: Pass. The accelerometer has a sample rate of 100 Hz and the altimeters have sample rates of 50 Hz.

Next Steps: N/A

ACST.4: State Transition Manager Test

Objective: Verify the state transition manager can accurately transform the launch vehicle state

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.4	The state transition manager accurately transforms launch vehicle state against known parameters	ACS.5	Incomplete

Materials and Equipment Needed: State transition manager, ACS sensor suite, legacy data, computer and cable
Test Setup:

1. Activate the ACS sensor suite

2. Use the cable and computer to upload legacy data to the sensor suite

Test Procedure:

1. Activate the state transition manager

Analysis Procedure:

1. Compare the real-time state transition to the expected state transition.
2. Determine whether any exceptions were raised as the legacy data was read

Results: Incomplete. Scheduled for January

Next Steps: Test passes if the correct state transitions were performed without raising exceptions. If not, revisit code within the state transition manager and rerun the test.

9.2 Requirements Compliance

9.2.1 NASA General Requirements

Table 98: NASA General Requirements

Req. ID	Description	Status	Verification Method	Verification Description	Location
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)...	Complete	I	The team mentor, Dave Brunsting, will conduct all motor assembly, handle all black powder, and prepare all electric matches. Students will be responsible for and complete all other components of the project. The team's student leadership will remind all students to not use previous year's work excessively.	8.2.2.6, 8.5.2.6
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.	Complete	I	The Project Manger, Lauren Falk, is responsible for providing and maintaining a project plan. The STEM Engagement Co-Leads, Kathryn Sherman and Sophia Yu, will be responsible for the STEM engagement component of the project plan. The safety officer, Christopher Fountain, will be responsible for the risks and mitigations components of the project plan.	9.3, 9.4, 9.5
1.3.	The team shall identify all team members who plan to attend Launch Week activities by the Critical Design Review (CDR). Team members will include:	Complete	I	The Project Manager has created a team roster and has included the final roster of team members who will attend Launch Week activities in the CDR. Inspection will ensure the attending team members meet the requirements listed in NASA Reqs. 1.3.1, 1.3.2, and 1.3.3.	See team roster submission.
1.3.1.	Students actively engaged in the project throughout the entire year.	Complete	I	All actively engaged student team members have been identified. The team plans on bringing 30 student members to Launch Week activities. Team leadership will select eligible members based on their contributions to the project and STEM engagement events, as well as adherence to all safety requirements.	8.1.1
1.3.2.	One mentor (see requirement 1.13)	Complete	I	The team has identified the team mentor as Dave Brunsting.	1.1
1.3.3.	No more than two adult educators	Complete	I	The team has identified two adult educators: graduate student and NDRT alum Joseph Gonzales, and NAR/TRA-certified mentor Dave Brunsting.	See Section 1.1 of Proposal.
1.4.	Teams shall engage a minimum of 250 participants in Educational Direct Engagement STEM activities in order to be eligible for STEM Engagement scoring and awards. These activities can be conducted inperson or virtually ...	In Progress	I	The team has engaged 188 participants in Educational Direct Engagement STEM activities across 7 events as of CDR submission and will host more events in future months. The current STEM Engagement Activity Report is included in the CDR.	9.3
1.5.	The team will establish and maintain a social media presence to inform the public about team activities.	Complete	I	The team has social media accounts on Facebook, Instagram, LinkedIn, and Twitter. Accounts are managed by the Social Media Lead, Sarah Wells.	See Section 1.1 of PDR.
1.6.	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 ...	Complete	I	The Project Manager will email all delieverables or provide downloadable links to the NASA team. Team leadership and Technical Editors enforce a report-writing schedules that will verify that all delieverables were emailed by their respective deadlines.	N/A

Table 98: NASA General Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Description	Location
1.7.	Teams who do not satisfactorily complete each milestone review (PDR, CDR, FRR) shall be provided action items needed to be completed following their review and shall be required to address action items in a delta review session . . .	Complete	I	The team is prepared to complete and address any necessary action items provided by NASA in a delta review session if necessary.	N/A
1.8.	All deliverables shall be in PDF format.	Complete	I	The team uses LaTeX to write reports, which enables conversion of documents to PDF format.	N/A
1.9.	In every report, teams will provide a table of contents including major sections and their respective sub-sections.	Complete	I	The team has created a report template that includes a table of contents with major sections and their respective sub-sections.	See table of contents.
1.10.	In every report, the team will include the page number at the bottom of the page.	Complete	I	The team has created a report template that includes page number tracking so that each page is numbered at the bottom.	N/A
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 . . .	Complete	I	The team has reserved university video teleconferencing equipment and is able to use the university WiFi network to connect to the teleconferencing meeting. Team members will provide personal cellular phones as a last resort.	N/A
1.12.	All teams attending Launch Week will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted at the NASA Launch . . .	Complete	I, A	The launch vehicle is designed to use a 12-foot 1515 rail and compatible rail buttons. Mission performance simulations were conducted for varying cants of the launch rails from 5 to 10 degrees.	5.1
1.13.	Each team shall 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, . . .	Complete	I	The team has identified Dave Brunsting, NAR (#85879) and TRA (#12369) Level 3 certified for the motor impulse of the launch vehicle, as the mentor. Dave has flown and recovered more than 2 flights in this or a higher impulse class prior to PDR. Dave will travel with the team to Launch Week.	1.1
1.14.	Teams will track and report the number of hours spent working on each milestone.	Complete	I	The team is utilizing an Excel sheet template to track the number of hours spent.	1.1

9.2.2 NASA Launch Vehicle Requirements

Table 99: NASA Launch Vehicle Requirements

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.1.	The vehicle will deliver the payload to an apogee altitude between 4,000 and 6,000 feet above ground level (AGL). Teams flying below 3,500 feet or above 6,500 feet on their competition launch will receive zero altitude points . . .	In Progress	A, D	Launch vehicle apogees will be calculated with OpenRocket and RockSim to verify they fall within the range. Demonstration flights will also confirm the apogee requirements are fulfilled.	Predicted apogees across multiple launch angles and wind speeds range from 4,601 ft to 5,167 ft. Full-scale demonstration flights will occur in Spring 2023.	5.1.1
2.2.	Teams shall declare their target altitude goal at the PDR milestone . . .	Complete	I	Inspection of PDR will verify the presence of a listed target apogee.	PDR reports that the target apogee is 4,600 feet.	See Section 5.2.1.3 in PDR

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.3.	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.	In Progress	I, D	Inspection of the launch vehicle after flight will verify the launch vehicle is recoverable and reusable. The demonstration flight will show that the launch vehicle has a functional recovery module that enables it to be recoverable and reusable.	Full-scale demonstration flights will occur in Spring 2023.	test
2.4.	The launch vehicle will have a maximum of four (4) independent sections . . .	Complete	I	Inspection of the launch vehicle will verify that the there is a maximum of four (4) independent sections.	The launch vehicle has four independent sections: the nosecone, payload bay, ACS body tube, and fin can.	3.2
2.4.1.	Coupler/airframe shoulders which are located at in-flight separation points will be at least 2 airframe diameters in length . . .	Complete	I	Inspection will verify that the coupler/airframe shoulders will be the appropriate length.	The team will use G12 fiberglass and carbon fiber couplers of length 12 in and outer diameter of 6 in.	3.3.3
2.4.2.	Nosecone shoulders which are located at in-flight separation points will be at least ½ body diameter in length.	Complete	I	Inspection will verify that the nosecone shoulders will be the appropriate length.	The nosecone shoulders will have length 3 in, which is ½ of the body diameter of 6 in.	3.3.1
2.5.	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.	Incomplete	D	The team will demonstrate at the launch site that they are capable of preparing the launch vehicle for flight within the desired time frame.	Full-scale demonstration flights are scheduled for Spring 2023.	test.
2.6.	The launch vehicle and payload will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours . . .	Incomplete	D, T	Testing will verify all electrical components will be capable of remaining operational for at least two hours. Demonstration at the launch site will confirm the validity of this test.	The battery duration test and full-scale demonstration flights are scheduled for Spring 2023.	test, test
2.7.	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider.	Complete	I	Inspection will verify that the launch vehicle is capable of being launched by the stated system	Launch procedures verify that the launch vehicle is capable of being launched by the standard system.	8.7
2.8.	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other . . .	Complete	I	Inspection will verify that the team is not using any external support to initiate the launch sequence.	Launch procedures verify that the team will not require additional circuitry or ground support equipment.	8.7
2.9.	Each team shall use commercially available ematches or igniters. Hand-dipped igniters shall not be permitted.	Complete	I	Inspection will verify that the team is using permissible ejection components.	The team will use commercially available ematches in its recovery modules.	4.6.1
2.10.	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate . . .	Complete	I	Inspection will verify that the team is using only permissible motors for the launch vehicle.	The team is using an AeroTech L2200G-18 motor, which falls under permissible motor categories.	3.4.3
2.10.1.	Final motor choices will be declared by the Critical Design Review (CDR) milestone.	Complete	I	Insepction will verify that the official and final motor selection is state in CDR.	The team is using an AeroTech L2200G-18 motor.	3.4.3
2.10.2.	Any motor change after CDR shall be approved by the NASA Range safety officer (RSO). Changes for the sole purpose of altitude adjustment will not be approved . . .	Incomplete	I	Inspection will verify that the RSO is the only personnel approving any and all motor changes.	The team will track any and all motor changes including the personnel that approved such changes. Any motor changes will be reported on official design review documents and will be verified upon inspection of those reports.	N/A

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.11.	The launch vehicle will be limited to a single motor propulsion system.	Complete	I	Inspection will verify that the launch vehicle only contains a singular motor.	Models of the launch vehicle made in simulations confirm the presence of a singular motor.	3.2
2.12.	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).	Complete	I	Inspection will verify that the impulse utilized by the team does not exceed the L-class specification.	The team is using an AeroTech L2200G-18 motor, which does not exceed the L-class motor category.	3.4.3
2.13.	Pressure vessels on the vehicle will be approved . . .	Complete	I	The team is not using a pressure vessel.	The team is not using a pressure vessel.	N/A
2.13.1.	The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) . . .	Complete	A	The team is not using a pressure vessel.	The team is not using a pressure vessel.	N/A
2.13.2.	Each pressure vessel will include a pressure relief valve that sees the full pressure . . .	Complete	I, A	The team is not using a pressure vessel.	The team is not using a pressure vessel.	N/A
2.13.3.	The full pedigree of the tank will be described . . .	Complete	I	The team is not using a pressure vessel.	The team is not using a pressure vessel.	N/A
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 . . .	Complete	A	OpenRocket and RockSim models will verify that the launch vehicle meets the minimum static stability margin.	Static stability margins based on models range from 3.57 to 4.35 cal, which is above the required value.	5.1.4
2.15.	The launch vehicle will have a minimum thrust to weight ratio of 5.0 : 1.0.	Complete	A	OpenRocket simulations will verify the launch vehicle meets the minimum thrust to weight ratio.	The OpenRocket thrust to weight ratio is 8.99:1, which exceeds the minimum value required.	3.4.2
2.16.	Any structural protuberance on the rocket will be located aft of the burnout center of gravity. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the rocket's stability.	Complete	I, A	Inspection of the launch vehicle will verify any non-camera housing protuberances are located aft of the burnout center of gravity. Analysis through computational fluid dynamic simulations will verify the team's camera housing has minimal impact on the launch vehicle's stability.	Drag flaps in ACS are located aft of the burnout center of gravity. CFD verifies the camera shroud causes negligible flow separation in the context of vehicle performance.	3.4.1, 5.4
2.17.	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	Complete	A	RockSim and OpenRocket flight simulations will confirm that launch vehicle exit velocity will reach the required value. Analysis of post-flight data will further verify these simulations.	All predicted off-rail velocity values at varying launch angles and wind speeds exeed 84 fps.	5.1.2
2.18.	All teams will successfully launch and recover a subscale model of their rocket prior to CDR. Success of the subscale is at the sole discretion of the NASA . . .	Complete	D	CDR will demonstrate proof of a successful subscale launch. The report will also demonstrate the use of a minimumum motor impulse class of E.	Subscale flight data is reported in CDR. The team used a I357 motor.	3.5.2, 3.5.4
2.18.1.	The subscale model should resemble and perform as similarly as possible to the full-scale model; however, the full-scale will not be used as the subscale model.	In Progress	D	FRR will demonstrate proof of a successful launch that utilized a different launch vehicle than the one used in subscale.	The subscale launch vehicle was scaled for similar aerodynamic performance to the full-scale launch vehicle. FRR and a successful full-scale demonstration flight will be completed by March 6th.	3.5.3, test
2.18.2.	The subscale model will carry an altimeter capable of recording the model's apogee altitude.	Complete	I, D	Inspection of the launch vehicle and subscale flight results will verify the presence of a functional altimeter capable of performing the required duties.	The subscale altimeter successfully measured altitude data from both subscale flights.	3.5.4.2, test

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.18.3.	The subscale rocket shall be a newly constructed rocket, designed and built specifically for this year's project.	Complete	I	Inspection of the launch vehicle will verify that it is of original design.	The subscale rocket was designed with dimensions scaled specially for this year's full-scale project.	3.5.3
2.18.4.	Proof of a successful flight shall be supplied in the CDR report.	Complete	I	Inspection of CDR will verify that the team provides proof of a successful flight.	Discussion of flight data and recovery of the subscale launch vehicle is included in CDR.	5.3
2.18.4.1.	Altimeter flight profile graph(s) OR a quality video showing successful launch, recovery events, and landing as deemed by . . .	Complete	I	Inspection of CDR will verify that altimeter profile graphs and/or a launch video is included as proof of a successful flight.	A complete altimeter flight profile graph is included in CDR.	3.5.4.2
2.18.4.2.	Quality pictures of the as landed configuration of all sections of the launch vehicle shall be included in the CDR . . .	Complete	I	Inspection of CDR will verify that quality pictures of the launch vehicle's landing configuration are included in the report.	Quality pictures of the landed configuration of all sections of the subscale launch vehicle are included in CDR.	3.5.2
2.18.5.	The subscale rocket shall not exceed 75% of the dimensions (length and diameter) of your designed full-scale rocket. For example, if your full-scale rocket is a 4" diameter 100" length rocket . . .	Complete	I	Inspection of the subscale launch vehicle will verify that the dimensions are, at most, 75% of the minimnum projected dimensions of the full-scale launch vehicle. Such dimensions will be listed on CDR.	A scaling factor of 50% was applied to most areas of the subscale launch vehicle, with no scaling factor exceeding 75%.	3.5.3
2.19.	All teams will complete demonstration flights as outlined below.	Incomplete	I	Inspection will verify that all demonstration flights and associated requirements are met.	The team will schedule required demonstration flights at the local launch site. Additional requirements will be verified using appropriate methods.	N/A
2.19.1.	Vehicle Demonstration Flight—All teams will successfully launch and recover their full-scale rocket prior to FRR in its . . .	Incomplete	D	The team will demonstrate and provide the relevant proof of a successful full-scale launch in FRR.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	N/A
2.19.1.1.	The vehicle and recovery system will have functioned as designed.	Incomplete	D	The team will verify during the full-scale launch that the vehicle and recovery system perform to their desired function. Proof of successful functionality will be provided in FRR.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	test
2.19.1.2.	The full-scale rocket shall be a newly constructed rocket, designed and built specifically for this year's project.	Complete	I	Inspection of the 2022-2023 launch vehicle will verify it is of original design. Proof of the newly constructed launch vehicle will be provided on the full-scale demonstration flight in FRR.	All design elements and materials are unique to this year's project, which is verified by diligent discussion and analysis throughout this submission.	N/A
2.19.1.3.	The payload does not have to be flown during the full-scale Vehicle . . .	Incomplete	I	Inspection will verify that all full-scale Vehicle Demonstration Flight requirements are met.	Full-scale Vehicle Demonstration Flight requirements will be verified using appropriate methods.	N/A
2.19.1.3.1.	If the payload is not flown, mass simulators will be used to simulate the payload mass.	Incomplete	I	Inspection of the full-scale demonstration flight analysis on FRR will verify that, if the payload is not flown, an appropriate mass approximation is used in place of the payload device.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	N/A
2.19.1.3.2.	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.	Incomplete	I	Inspection of FRR will verify the location of the mass simulators within the launch vehicle, if the payload was not flown in the full-scale demonstration flight.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	N/A
2.19.1.4.	If the payload changes the external surfaces of the rocket (such as camera housings or external probes) or manages the . . .	Incomplete	D	The non-scoring payload (ACS) has drag flaps that will change the external surfaces and will be active during all full-scale demonstration flights.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	test

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.19.1.5.	Teams shall fly the competition launch motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance ...	Incomplete	D	The team is using an AeroTech L2200G-18 motor. Inspection of FRR will verify that this motor is used in both the full-scale demonstration and competition flights.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	test
2.19.1.6.	The vehicle shall be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted ...	Incomplete	D	Inspection of FRR will verify the team used a specified ballasted weight during the full-scale demonstration flight.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	test
2.19.1.7.	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).	Incomplete	I	Inspection of the launch vehicle prior to the competition flight will verify that the team did not make any alterations to the launch vehicle after the full-scale demonstration flight.	FRR and a successful full-scale demonstration flight will be completed by March 6th. The team will be approved to launch the vehicle used for the full-scale demonstration flight before the competition flight in April 2023.	N/A
2.19.1.8.	Proof of a successful flight shall be supplied in the FRR report.	Incomplete	I	Inspection of FRR will verify that the team provided proof of a successful flight.	Upon submission of FRR, the team will verify that proof of a successful flight is included in the report. FRR will be completed by March 6th.	N/A
2.19.1.8.1.	Altimeter flight profile data output with accompanying altitude and ...	Incomplete	I	Inspection of FRR will verify the team supplied the required flight data from altimeters.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	N/A
2.19.1.8.2.	Quality pictures of the as landed configuration of all sections of the launch vehicle shall be included in the FRR ...	Incomplete	I	Inspection of FRR will verify the team included quality pictures in the report.	FRR and a successful full-scale demonstration flight will be completed by March 6th.	N/A
2.19.1.9.	Vehicle Demonstration flights shall be completed by the FRR submission deadline. No exceptions will be made ...	Incomplete	I, D	Inspection of FRR will verify that the team completed it before the deadline.	FRR will be completed by March 6th.	test
2.19.2.	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 rocket flown shall be the same rocket to be flown as their competition launch ...	Incomplete	I	Inspection of FRR will verify that the team launched a successful full-scale demonstration flight. Inspection of the launch vehicle at LRR will verify that it is the same vehicle flown in the full-scale demonstration flight.	FRR and a successful full-scale demonstration flight will be completed by March 6th. The team must present their launch vehicle to verify that it is the same launch vehicle as the one used in the full-scale demonstration flight at LRR in April 2023.	N/A
2.19.2.1.	The payload shall be fully retained until the intended point of deployment (if applicable), all retention mechanisms shall function as designed, and the retention mechanism shall not sustain damage requiring repair.	Incomplete	D	The full-scale demonstration flight will demonstrate the payload device is fully retained for the entirity of the launch. This requirement will be confirmed by inspection of the launch vehicle after the launch. This data will be made available in FRR.	FRR and a full-scale demonstration flight will be completed by March 6th.	test
2.19.2.2.	The payload flown shall be the final, active version.	Incomplete	I	Inspection of the payload will verify that the payload is not modified during flight.	Full-scale demonstration flight is scheduled for Spring 2023.	N/A
2.19.2.3.	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.	Incomplete	I	Inspection of FRR will verify if a complete full-scale demonstration flight is completed. Inspection of the team will verify that the team is aware of the action items required if the full-scale demonstration flight criterion are not all met.	FRR and a full-scale demonstration flight will be completed by March 6th. If necessary, the FRR Addendum will be completed by the required deadline.	N/A

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.19.2.4.	Payload Demonstration Flights shall be completed by the FRR Addendum deadline. NO EXTENSIONS WILL BE GRANTED.	Incomplete	I	Inspection will verify that the team is aware of the additional responsibilities and actions that come with submitting an FRR Addendum.	If necessary, the FRR Addendum will be completed by the required deadline.	N/A
2.20.	An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASA . . .	Incomplete	I	Inspection of FRR will verify if the team needs to complete an FRR Addendum.	If necessary, the FRR Addendum will be completed by the required deadline.	N/A
2.20.1.	Teams required to complete a Vehicle Demonstration Re-Flight and . . .	Incomplete	I	If necessary, inspection of the FRR Addendum will verify that it was completed by the deadline.	If necessary, the FRR Addendum will be completed by the required deadline.	N/A
2.20.2.	Teams who successfully complete a Vehicle Demonstration Flight but fail to qualify the payload by satisfactorily completing the Payload Demonstration Flight . . .	Incomplete	I	Inspection of FRR will verify if the team completed a successful full-scale demonstration flight.	A full-scale demonstration flight will be completed by March 6th.	N/A
2.20.3.	Teams who complete a Payload Demonstration Flight which is not fully successful may petition the NASA RSO for permission to fly the payload at launch week. Permission will . . .	Incomplete	I	If necessary, the team is aware of the added action items necessary to demonstrate a successful payload during launch week should the full-scale demonstration flight not be successful.	The team will complete a successful payload in the full-scale demonstration flight that will be completed by March 6th. If necessary, a successful payload demonstration will be completed during launch week.	N/A
2.21.	The team's name and Launch Day contact information shall be in or on the rocket airframe as well as in or on any . . .	Incomplete	I	Inspection of the launch vehicle will verify that the relevant contact information is included in or on the launch vehicle airframe.	The presence of contact information will be confirmed on Launch Day.	N/A
2.22.	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.	Incomplete	I	Inspection of the launch vehicle will verify that any and all lithium polymer batteries are sufficiently labeled and protected.	The team will schedule demonstration flights throughout winter and spring 2023 leading up to the competion flight, in which all polymer batteries will be sufficiently labeled protected.	N/A
2.23.	Vehicle Prohibitions	In Progress	I	Inspection will verify that all Vehicle Prohibitions requirements are met.	Vehicle Prohibitions will be addressed during design of the launch vehicle. All requirememnts will be verified using appropriate methods.	N/A
2.23.1.	The launch vehicle will not utilize forward firing motors.	Complete	I	Inspection will verify that the team only utilizes acceptable motors for flight.	The team is using an AeroTech L2200G-18 motor, which is an acceptable motor.	3.4.3
2.23.2.	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)	Complete	I	Inspection will verify that the team does not utilize motors expelling titanium sponges.	The team is using an AeroTech L2200G-18 motor, which does not expel titanium sponges.	3.4.3
2.23.3.	The launch vehicle will not utilize hybrid motors.	Complete	I	Inspection of the motor will verify it is not a hybrid motor.	The team is using an AeroTech L2200G-18 motor, which is not a hybrid motor.	3.4.3
2.23.4	The launch vehicle will not utilize a cluster of motors.	Complete	I	Inspection of the launch vehicle will verify it does not utilize a cluster of motors.	The team is using an AeroTech L2200G-18 motor, which is a singular motor.	3.4.3
2.23.5.	The launch vehicle will not utilize friction fitting for motors.	Complete	I	Inspection of the launch vehicle will confirm friction fitting is not utilized.	The motor retention system utilizes a motor mount tube, centering rings, and motor retaining ring, none of which utilize friction fitting.	3.3.7

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.23.6	The launch vehicle will not exceed Mach 1 at any point during flight.	In Progress	A, D	Analysis through RockSim or OpenRocket flight simulations will confirm Mach 1 is not achieved by the launch vehice. Vehicle demonstration flight will further confirm the launch vehicle does not reach Mach 1.	Modeling shows a maximum velocity of 600 fps, or Mach 0.533. Appropriate demonstration flight data will be provided with FRR that will be submitted by March 6th.	5.1.2, test
2.23.7	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad (i.e. a rocket with an unballasted weight of 40 lbs. on the pad may contain a maximum of 4 lbs. of ballast).	In Progress	I, A	Inspection and analysis of the launch vehicle's total weight and the weights of its components will confirm that the vehicle ballast does not exceed 10% of the unballasted weight.	The maximum vehicle ballast is 89.8 oz using the predicted ascent mass of the launch vehicle. Standard launch operating procedures include measures to avoid exceeding this value	3.4.2, 8.5
2.23.8.	Transmissions from onboard transmitters, which are active at any point prior to landing, will not exceed 250 mW of power (per transmitter).	Complete	I	Inspection of all onboard transmitters will confirm that they are under the maximum power allowance. Demonstration of these transmitters at demonstration flights will confirm successful operating at power levels under 250 mW.	The team utilizes onboard transmitters, but they are not active at any point prior to landing.	6.6.1, 6.6.1.4
2.23.9.	Transmitters will not create excessive interference. Teams will utilize unique frequencies, . . .	Complete	I	Inspection of all demonstration flights will confirm that transmitters on the launch vehicle do not have excessive interference.	The transceiver utilized in the TROI system will be configured and set to a unique frequency.	6.6.3
2.23.10.	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 . . .	Complete	I	Inspection of the launch vehicle and its construction process will confirm minimal general metal and no dense metal usage.	The majority of components will be constructed with composites. Aluminum will be used for components that experience high loading such as eye bolts.	3.4.1, 4.5.3

9.2.3 NDRT Launch Vehicle Requirements

Table 100: NDRT Launch Vehicle Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
LV.1	The distance between ACS and CP location of the launch vehicle shall be minimized during design and subsequent construction.	The ACS must be located near the CP in order to reduce the impact it will have on launch vehicle stability when actuating its flaps during flight.	Complete	I, A	The launch vehicle CP and relative ACS position will be simulated using RockSim and OpenRocket.	Upon visual inspection of completed launch vehicle, results will be verified.	3.2
LV.2	The launch vehicle must be able to overshoot the NDRT-determined target apogee.	The launch vehicle must be capable of reaching an apogee higher than the target in order for the ACS to influence its flight path and guide it towards the target.	Complete	A	The launch vehicle's maximum apogee without the activation of ACS will be simulated using RockSim and OpenRocket at varying launch angles and wind speeds.	The predicted apogees range from 4,601 ft to 5,167 ft, which are above the NDRT target apogee of 4,600 ft.	5.1.1

Table 100: NDRT Launch Vehicle Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
LV.3	No body tube shall include more than two squads' components.	Limiting the amount of components in a single body tube reduces physical and transmission-based interference between them.	Complete	I, A	The position of individual squads' internal components will be finalized using CAD and displayed using OpenRocket.	The nose cone contains only recovery components. The payload bay contains payload and recovery components. The ACS body tube contains ACS and recovery components. The launch vehicle's configuration will be visually verified to ensure compliance with this requirement upon final assembly in January.	3.4.1
LV.4	The launch vehicle design shall accommodate vehicle speeds that avoid fin flutter.	Designing to avoid fin flutter during flight will avoid resonance conditions for the fins and increase the stability of the launch vehicle.	Complete	A	Velocities at which fin flutter bcomes a risk given construction materials and launch conditions will be calculated by hand. RockSim and OpenRocket will be used to generate velocity data for a range of flight conditions to compare expected velocities and velocities with a risk of fin flutter.	Any component of the final launch vehicle that influences velocity will be designed such that stable speeds will not be speeds that induce fin flutter. Analysis shows that the launch vehicle will not reach velocities where fin flutter is a risk under any reasonable flight conditions.	5.3.0.1
LV.5	Payload and recovery system components shall not come in physical contact with each other during any point of the mission.	Modules must be properly secured and retained within the body tube to reduce damage during flight.	In Progress	I, T	Mount security of payload and recovery system components will be inspected upon completion of launch vehicle and verified using vibrational testing.	High-strength epoxy, bolts, and other methods of attachment will be used to secure components. Vibrational testing is scheduled to occur in Spring 2023.	4.5.1, 4.5.2, 6.4
LV.6	All launch vehicle airframe components shall be designed with a factor of safety of 1.5 above predicted forces inflicted.	A factor of safety of 1.5 prevents failure and accounts for unanticipated forces during flight and landing. Additionally, it contributes to the reusability of the launch vehicle.	In Progress	A, T	Simulations and analysis with ANSYS will confirm that all airframe components are capable of withstanding predicted forces with a factor of safety of 1.5.	FEA has demonstrated that the planned bulkheads and eye bolts exceed the required strength of predicted forces. Static loading tests will determine the specific point of failure and factor of safety. Tests are scheduled to occur in February 2023.	3.3.5, 5.3
LV.7	All body tubes containing electronic components used for communication shall be constructed using material that does not obstruct RF transmission.	Sensor communication is critical to mission success and must not be obstructed by airframe material that blocks RF transmissions to or from sensors.	Complete	I	Inspection of materials for body tubes containing electronic components will verify that they do not obstruct RF transmission.	The team is using G12 Fiberglass to construct the body tubes that contain electronic components, particularly for the payload bay body tube and coupler. G12 Fiberglass does not obstruct RF transmission.	3.3.3, 3.4.1
LV.8	All launch vehicle airframe components shall be designed to withstand cyclical loading and additional causes of fatigue.	The launch vehicle must be able to withstand loading associated with multiple flight demonstrations that occur throughout the competition season.	In Progress	T	Reusability will be verified by demonstrating launch vehicle flight and recovery multiple times in a 24-hour time period.	Full-scale flight demonstrations are scheduled for Spring 2023.	test

9.2.4 NASA Recovery Requirements

Table 101: NASA Recovery Requirements

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
3.1.	The full scale 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 . . .	In Progress	I, D	Inspection will verify the use of a drogue parachute deployed at apogee, and a main parachute deployed at a lower altitude. Demonstration of these deployments will be verified in the vehicle demonstration flight.	The FED will trigger the apogee deployment event of the drogue parachute, and the PED will initiate the main parachute deployment event at an altitude of 584 feet. This will be verified in the full-scale demonstration flight in Spring 2023.	4.2, test
3.1.1.	The main parachute shall be deployed no lower than 500 feet.	In Progress	D	The deployment of the main parachute above 500 feet will be verified at the full-scale demonstration flight.	The PED will initiate the main parachute deployment process at an altitude of 584 feet. The full-scale demonstration flight is scheduled for Spring 2023	4.2, test
3.1.2.	The apogee event may contain a delay of no more than 2 seconds.	In Progress	T, D	The delay of less than 2 seconds will be demonstrated through tests conducted with sample data on the altimeters as well as through a demonstration flight.	The three altimeters' triggering of the event will contain delays of 0, 1, and 2 seconds for redundancy. Flight data simulating the vehicle flight will be ran through the altimeters to test their ability to trigger the apogee event after no more than 2 seconds. Launch vehicle demonstration flights are scheduled for Spring 2023.	4.3.1, test
3.1.3.	Motor ejection is not a permissible form of primary or secondary deployment.	Complete	I	Inspection will verify that the team is not using motor ejection as a form of primary or secondary deployment.	All ejection events will be performed by the NED, PED, and FED recovery modules, which utilize black powder charges.	4.3
3.2.	Each team will perform a successful ground ejection test for all electronically initiated recovery events prior to the initial flights of the subscale and full scale vehicles.	In Progress	T	A ground ejection test will verify the successful electronic initiation of recovery events, and the team will not proceed with initial flights until a successful test is performed.	The ground ejection test will be supervised by the team mentor and conducted before the full-scale demonstration flight.	test
3.3.	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing. Teams whose heaviest . . .	In Progress	A, D	The kinetic energy of each independent section of the launch vehicle will be calculated by hand and software. Values will be verified during the full-scale demonstration flight.	Predicted kinetic energies of all four independent sections are below 65 lb-ft using MATLAB, OpenRocket, and RockSim.	5.2.1, test
3.4.	The recovery system will contain redundant, commercially available barometric altimeters that are specifically designed for initiation of . . .	Complete	I	Inspection will ensure that redundant, commercially available barometric altimeters will be selected for initiation of rocketry recovery events.	The PED and FED recovery modules each utilize one Raven4 and one Stratologger SL100 altimeter. The NED recovery module utilizes two Stratologger SLCF altimeters.	4.6.1
3.5.	Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.	Complete	I	Inspection will verify that each altimeter has a dedicated, commercially sourced power supply. The voltage of these power supplies, which will be batteries, will be verified as the correct amount with a multimeter.	Each altimeter will be powered by a single, unique battery that is commercially available.	4.6.1
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.	Complete	I	Inspection will confirm that dedicated mechanical arming switches will be used to arm the altimeters, and that the switches are accessible from the exterior of the rocket airframe when the rocket is on the launch pad in the launch configuration.	Keyed switches were chosen to ensure accessibility and reliability.	4.2, Section 4.4.3 of PDR

Table 101: NASA Recovery Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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).	In Progress	I	Inspection will prove that the arming switches will be capable of being locked in the ON position for launch.	Keyed switches were chosen due to the low likelihood of them being armed or unarmed unintentionally.	Section 4.4.3 of PDR
3.8.	The recovery system, GPS and altimeters, electrical circuits will be completely independent of any payload electrical circuits.	Complete	I	Inspection will verify the independence of the recovery system, GPS and altimeters, and electrical circuits from all payload electrical circuits.	All recovery components and circuits are completely contained within the individual PED, NED, and FED modules and do not interface with payload circuits.	4.5.1
3.9.	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	Complete	I	Inspection will confirm the use of removable shear pins for the main parachute compartment and the drogue parachute compartment.	Five 4-40 nylon shear pins will be used at each separation point in the launch vehicle.	4.3.1
3.10.	The recovery area will be limited to a 2,500 ft. radius from the launch pads.	In Progress	A, D	Analysis performed in simulations will confirm that the recovery area will be limited to a 2,500 ft radius from the launch pads, and will be backed up by demonstration flights.	Drift radius calculations using multiple apogees and OpenRocket, RockSim, and MATLAB show a maximum drift radius of 2,260 ft. The full-scale demonstration flight is scheduled for Spring 2023.	5.2.3, test
3.11.	Descent time of the launch vehicle will be limited to 90 seconds (apogee to touch down). Teams whose launch vehicle descent, as verified by vehicle demonstration flight data, . . .	In Progress	A, D	Simulations performed will demonstrate that the descent time of the launch vehicle will be less than 90 seconds. Launch vehicle demonstration flights will verify that the descent time is less than 90 seconds.	Descent time calculations using multiple apogees and OpenRocket, RockSim, and MATLAB show a maximum time of 79 s. The full-scale demonstration flight is scheduled for Spring 2023.	5.2.2, test
3.12.	An electronic GPS 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.	In Progress	I, D, T	Inspection will confirm the installation of a GPS device, and tests and demonstration will verify the accurate transmission of the postion of the tethered vehicle or any independent sections to a ground receiver.	Before installation into the vehicle, the position given by the GPS will be tested in multiple spots with known distances between them. This will also confirm the successful transmission of GPS data to the ground receiver.	4.6.2, test
3.12.1.	Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active . . .	Complete	I	Inspection will ensure that any rocket section or payload component that lands untethered will contain an active electronic GPS tracking device.	No rocket section or payload component will land untethered, so no additional GPS tracking devices are required.	4.6.2, 3.2
3.12.2.	The electronic GPS tracking device(s) will be fully functional during the official competition launch.	In Progress	D, T	The functionality the GPS device used will be verified in testing and the full-scale demonstration flight before the official competition launch.	The GPS devices will be subjected to shake and functionality tests to prove their effectiveness in flight conditions, and full-scale demonstration flights are scheduled for Spring 2023.	test
3.13.	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	In Progress	T	RF isolation testing will verify that recovery system electronic devices will not be adversely affected by additional on-flight devices.	Sample flight data will be run through the devices in the assembled vehicle to ensure that their performance is not impacted by other devices.	test
3.13.1.	The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.	Complete	I	Inspection will show that the recovery system altimeters are located in separate comparments from other radio frequency transmitting or magnetic wave producing devices.	The StratoLogger CF, Featherweight Raven 4, and StratoLogger 100 altimeters will be located within the respective recovery modules, and signals from other devices will be blocked by the carbon fiber bulkheads.	4.6.1
3.13.2.	The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.	Complete	I	Inspection will verify the presence of proper shielding to prevent excitation of recovery electronics caused by on board transmitting devices.	Recovery system electronics will be shielded with their modules using carbon fiber bulkheads and carbon fiber body tubes, which block transmissions.	3.4.1, 4.5.1

Table 101: NASA Recovery Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
3.13.3.	The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves . . .	Incomplete	T	Magnetic wave isolation tests will be conducted to verify that recovery system electronics are shielded from inadvertent excitation.	Sample flight data will be input into the devices in the assembled vehicle to test the shielding. This test is scheduled for Spring 2023.	test
3.14.4.	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery . . .	Incomplete	T	Electronics interference tests will be conducted to verify that the recovery system electronics are shielded from remaining causes of inadvertent excitation.	Sample flight data will be input into the devices in the assembled vehicle to test the shielding. This test is scheduled for Spring 2023.	test

9.2.5 NDRT Recovery Requirements

Table 102: NDRT Recovery Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
R.1	Heat-sensitive laundry items included in each recovery module shall have sufficient thermal protection.	Laundry items such as parachutes and shock cords are critical flight components and must be protected from damage during black powder charge detonation.	Complete	I	Inspection will verify that all heat-sensitive items within the recovery system are secured with thermal protection tools.	Each parachute will be covered by a fire-retardant Nomex blanket, which will provide protection against heat created by black powder charge detonations.	4.2
R.2	Load-bearing components necessary for in-flight separation shall have a factor of safety of 1.5 beyond projected loads.	The recovery system must be able to withstand loads of greater magnitude than expected to increase the reliability of the system and chances of reusability per NASA Requirement 2.3.	In Progress	A, T	Conducting FEA on load-bearing components such as bulkheads for each recovery module will yield estimated factors of safety. Components will then be tested using a load frame. Compressive forces will be applied and gradually increase until component failure occurs.	FEA results for predicted loads have been calculated using Fusion360. Static loading tests that utilize load frames are schedule to take place in February 2023.	4.5.1, 5.3

9.2.6 NASA Payload Requirements

Table 103: NASA Payload Requirements

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
4.1.	College/University Division—Teams shall design a payload capable upon landing of autonomously receiving RF commands and performing a series of tasks with an on-board camera system . . .	In Progress	I, D	Inspection will verify that all methods and designs utilized to complete the payload mission adhere to the standards listed in the requirement. The full-scale demonstration flight will verify the payload and additional experiment conduct the mission successfully.	The team has designed a payload that is capable of extending out of the launch vehicle after sensors determine it has landed, then taking and storing high-quality images. The payload full-scale demonstration flight is scheduled to occur in Spring 2023.	6.1, test

Table 103: NASA Payload Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
4.2.	Radio Frequency Command (RAFCO) Mission Requirements	In Progress	I	Inspection will verify that all listed RAFCO Mission Requirements are met through their respective verification plans.	The team will verify all RAFCO Mission Requirements through appropriate verification methods and plans.	6.1.1
4.2.1.	Launch Vehicle shall contain an automated camera system capable of swiveling 360º to take images of the entire surrounding area of the launch vehicle.	In Progress	D, T	Testing of the payload system will verify that the camera system is automated and capable of swiveling 360º to take images. This function will also be verified through the full-scale demonstration flight.	The 360º rotation capabilities of the telescoping camera arm will be tested and demonstrated in Spring 2023.	6.5.1, 6.5.2, test
4.2.1.1.	The camera shall have the capability of rotating about the z axis. The z axis is perpendicular to the ground plane . . .	In Progress	D, T	Testing of the payload system will verify its ability to identify and rotate about the defined z axis.	The accelerometer in the payload system will define the correct z axis. Its capabilities will be tested and demonstrated in Spring 2023.	6.6.1.4, test
4.2.1.2.	The camera shall have a FOV of at least 100º and a maximum FOV of 180º	Complete	I	Inspection will verify that the camera lens has a FOV within the acceptable range.	A 140º wide-angle lens will be used for the Arducam OV2640 camera in the payload system.	6.6.2
4.2.1.3.	The camera shall time stamp each photo taken. The time stamp shall be visible on all photos submitted to NASA in the PLAR.	In Progress	D, T	Testing of the camera subsystem will verify that on-board sensors successfully provide accurate time stamps on images. Pictures taken during the full-scale demonstration flight will also verify the result.	A real-time clock will be integrated into the ESP32-CAM camera subsystem to enable time stamps. Testing of its capabilities will occur in Spring 2023.	6.6.1, test
4.2.1.4.	The camera system shall execute the string of transmitted commands quickly, with a maximum of 30 seconds between photos taken.	In Progress	D, T	Payload system testing and the full-scale demonstration flight will verify that the camera system is capable of executing commands quickly. Time stamps will be used to determine the amount of time elapsed between photos.	Communication between electronics in the payload system will have negligible latency. Testing to verify the design will occur in Spring 2023.	6.7.2, test
4.2.2.	NASA Student Launch Management Team shall transmit a RF sequence that shall contain a radio call sign followed by a sequence of tasks to be completed. The list of potential commands to be given on launch day along with their . . .	Complete	D, T	Transmission testing will verify that the payload system is able to receive RAFCO and translate subsequent signals into camera commands.	Various commands were transmitted to the RF system using a HAM radio ground station. The system successfully utilized a TNC to output RAFCO commands to the ESP32 camera system. This process will be repeated during the full-scale demonstration flight in Spring 2023.	6.7.4, test
4.2.1.1.	An example transmission sequence could look something like, "XX4XXX C3 A1 D4 C3 F6 C3 F6 B2 B2 C3." Note the call sign that NASA will use shall be distributed to teams at a later time.	Complete	D, T	Transmission testing will verify that the payload system is able to receive RAFCO and translate subsequent signals into camera commands.	Various commands were transmitted to the RF system using a HAM radio ground station. The system successfully utilized a TNC to output RAFCO commands to the ESP32 camera system. This process will be repeated during the full-scale demonstration flight in Spring 2023.	6.7.4, test
4.2.3.	The NASA Student Launch Management Panel shall transmit the RAFCO using APRS.	In Progress	D, T	Radio transmission testing using HAM radio will verify that the RF subsystem operates successfully using APRS.	HAM radio ground station testing of APRS capabilities will take place in Spring 2023.	6.6.3, test
4.2.3.1.	NASA will use dedicated frequencies to transmit the message. NASA will operate on the 2-Meter amateur radio band between the frequencies of 144.90 MHz and 145.10 MHz. No team . . .	In Progress	D, T	Radio transmission testing using HAM radio will verify that the RF subsystem has receiving capabilities and does not transmit between the listed frequencies.	Various wiring configurations within the RF subsystem enable adjustment of transmitting and receiving capabilities. Additional testing and the full-scale demonstration flight are scheduled to occur in Spring 2023.	6.6.3, test

Table 103: NASA Payload Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
4.2.3.2.	The NASA Management Team shall transmit the RAFCO every 2 minutes.	In Progress	D, T	The RF subsystem will be tested to verify that it is able to receive RAFCO transmitted by the NASA Management Team by simulating various commands.	The RF subsystem is designed to receive RAFCO on the frequency range designated by NASA. Testing to verify this capability is scheduled for Spring 2023.	6.6.3, test
4.2.3.3.	The payload system shall not initiate and begin accepting RAFCO until AFTER the launch vehicle has landed on the planetary surface.	In Progress	D, T	Testing various landing sequences using the payload body tube and TROI sensor suite will verify that the payload system does not initiate and begin accepting RAFCO after landing. This result will be verified by the full-scale demonstration flight.	The ESP32 Main subsystem within the TROI payload system includes an acclerometer that determines when the launch vehicle has landed. The state that the accelerometer records determines whether the RF command capabilities of the payload system are activated. Testing and the full-scale demonstration flight are scheduled for Spring 2023.	6.6.1, 6.7.5, test
4.2.4.	The payload shall not be jettisoned.	In Progress	D	The payload full-scale flight demonstration will verify that TROI will not be jettisoned at any point.	The payload is retained within its body tube using airframe interface blocks that are bolted to the payload body tube, preventing in-flight jettison. Payload full-scale flight demonstration is scheduled to occur in Spring 2023.	6.4, test
4.2.5.	The sequence of time-stamped photos taken need not be transmitted back to ground station and shall be presented in the correct order in your PLAR.	In Progress	I	Inspection will verify that the sequence of time-stamped photos are presented in the correct order in the PLAR.	Students responsible for including time-stamped photos in the PLAR will include them in the correct chronological order. Technical editors will verify the chronological order and adjust the order of photos if necessary.	N/A
4.3.	General Payload Requirements	Complete	I	Inspection will verify that all listed General Payload Requirements are met through their respective verification plans.	The team will verify all General Payload Requirements through appropriate verification methods and plans.	N/A
4.3.1.	Black Powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Energetics shall not be permitted for any surface operations.	Complete	I	Inspection will verify that TROI does not utilize energetics for any of its surface operations.	The team will utilize a stepper motor-powered lead screw and telescoping camera arm to deploy the camera system, verifying that no energetics will be used for TROI surface operations.	6.5.1
4.3.2.	Teams shall abide by all FAA and NAR rules and regulations.	Complete	I	Inspection will verify that the team abides by all FAA and NAR rules and regulations.	The safety officer will apprise all team members of FAA and NAR rules and regulations that are applicable to the launch vehicle and launch.	8
4.3.3.	Any secondary payload experiment element that is jettisoned during the recovery phase …	Complete	I	The team does not intend to jettison the secondary payload experiment.	The team does not intend to jettison the secondary payload experiment.	N/A
4.3.4.	Unmanned aircraft system (UAS) payloads, if designed to be deployed during descent …	Complete	I	The team does not intend to utilize a UAS payload.	The team does not intend to utilize a UAS payload.	N/A
4.3.5.	Teams flying UASs will abide by all applicable FAA regulations …	Complete	I	The team does not intend to utilize a UAS payload.	The team does not intend to utilize a UAS payload.	N/A
4.3.6.	Any UAS weighing more than .55 lbs. shall be registered with the FAA …	Complete	I	The team does not intend to utilize a UAS payload.	The team does not intend to utilize a UAS payload.	N/A

9.2.7 NDRT Payload Requirements

Table 104: NDRT Payload Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
TROI.1	Subsystem movement and displacement shall not result in contact with the payload body tube or recovery system interface.	Contact between the TROI system and the payload body tube may inflict damage upon any components involved, which is highly undesirable.	Complete	A, T	The camera system will be treated as a beam for initial deflection calculations and comparison against the size of the payload body tube. Tests involving camera system rotation and deployment will be conducted.	The maximum deflection of the system is approximately 0.0675 inches, which means it is not predicted to come into contact with the payload body tube. Testing of the camera system will be conducted in Spring 2023.	6.5.3, test
TROI.2	All load-bearing payload system components shall have a factor of safety of 1.5 with regards to calculated forces exerted upon them during the mission.	Designing load-bearing components to withstand additional forces reduces the likelihood of failure, accomodates for unpredicted forces, and improves reusability.	Complete	A, T	FEA will be conducted on load-bearing components and yield estimated factors of safety.	The factor of safety of the lead screw cover is approximately 6.0.	6.5.3
TROI.3	The camera shall be capable of capturing images with an acceptably high resolution and quality.	Cameras with an appropriate resolution will take clear images and fit within the body tube.	Complete	I, T	Inspection will verify that the selected camera has an acceptable resolution rating provided by the manufacturing. Pictures taken by the camera during camera system testing will be inspected for their quality.	The selected camera has a resolution of two megapixels, which is an acceptable rating. Further testing of the camera system is scheduled for Spring 2023.	6.6.2
TROI.4	The payload deployment mechanism shall function properly for launch vehicle landing positions from -15 to +45 degrees relative to the horizontal axis.	The deployment mechanism must be functional for all probable angles the launch vehicle will come to rest at.	In Progress	T	The payload body tube will be placed in various landing angles to simulate camera system deployment.	Testing of various landing angles to verify the system's ability to deploy under various landing conditions is scheduled to occur in Spring 2023.	6.5.1, test
TROI.5	The payload will have an alloted tube length of 12 in. and an inner diameter of 6 in.	The payload system must fit within the body tube dimensions and accomoate for additional systems retained.	Complete	I	Inspection and measurement will verify that the TROI system fits within the alloted dimensions.	The design of the TROI system intended for full-scale launch vehicle use fits within the allotted space of the payload body tube.	6.3
TROI.6	The payload system shall be able to extend out of the body tube of the launch vehicle.	NDRT is designing a payload system that requires the camera to extend out of the body tube to take images.	In Progress	A, T	Hand calculations using the maximum length of deployment components will verify that the camera system is able to extend out of the payload body tube. Additional testing of the TROI system will verify the results of the hand calculations.	The total length of deployment subsystem components enables the TROI camera to extend 1.5 inches above the payload body tube. Testing to verify the calculations will occur in Spring 2023.	6.5, test

9.2.8 NDRT Non-Scoring Payload (ACS) Requirements

Table 105: NDRT Non-Scoring Payload (ACS) Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
ACS.1	The ACS shall be capable of actuating solid drag flaps to induce additional drag to aid in achieving the team's apogee estimates.	Basic functionality of the system ensures it can aid in slowing the launch vehicle below any apogee above the team's predicted, necessitated by NDRT Requirement LV.2.	In Progress	D, A	The team's full-scale demonstration flight will show that the ACS is capable of producing immediate drag. Analysis using RockSim and in-flight data will evaluate ACS impact on apogee.	The ACS utilizes a sensor suite that interfaces with flap pusher and lever arms in order to actuate drag flaps in-flight. Simulations and descriptions of results from the full-scale demonstration flight will be made available on the team's FRR on March 6th.	7.2, 7.4, test
ACS.2	The ACS drag flaps shall be capable of withstanding the maximum projected static loading force with a factor of safety of 1.5.	Basic functionality of the system ensures that the flaps can remain actuated during flight.	In Progress	T, A	The drag flaps will be constructed out of carbon fiber. FEA will verify that the material is capable of withstanding the maximum drag force with a factor of safety of 1.5. Estimated forces will be used as a benchmark for static loading tests conducted with a load frame.	The static loading test for load-bearing ACS components is scheduled to occur in February 2023.	7.2.7, 7.2.8, test
ACS.3	Sensors shall sample at a minimum rate of 10 Hz.	Provides basic functionality and timely responsiveness for the system during flight.	Complete	T	Data acquisition testing of the sensors will verify that they have a minimum sampling rate of 10 Hz.	The ACS 3-axis accelerometer has a sample rate above 100 Hz, and the two altimeters have sample rates of approximately 50 Hz. The high sample rates will ensure timely data collection and drag flap adjustments in-flight.	7.4.1, 7.4.2
ACS.4	The ACS shall log each sampled data point and state changes in a CSV formatted file for analysis.	The ACS functionality must be able to be verified upon returning to base station.	In Progress	D	The team's full-scale demonstration flight will include recording all sampled data points and state changes for the ACS. The data will be logged into a CSV formatted file and be made available to all team members.	The ACS will utilize a microprocessor and control software to process and record data points collected by the sensor suite. The results of the logged data will be made available on the team's FRR submission on March 6th.	7.5
ACS.5	The ACS shall be capable of determining and changing the launch vehicle's current stage of flight using the flight parameters of altitude, linear acceleration, angular acceleration, and magnetic field.	Basic functionality of the system is confirmed by this requirement.	In Progress	D	The team's full-scale demonstration flight will verify the ACS's functionality, including its ability to identify the current flight stage using appropriate flight parameters. A full-system demonstration test will verify this functionality prior to the full-scale demonstration flight.	The ACS utilizes a sensor suite consisting of a 3-axis accelerometer, an IMU, and two altimeters to measure all relevant flight parameters. The full-scale demonstration flight where ACS functionality will be assessed is scheduled to occur in Spring 2023.	7.4
ACS.7	The stall current of the servo motor shall be minimized.	Currents that exceed the stall current lead to insufficient voltage allocated to batteries and risk overheading of the system.	Complete	I	Inspection of the servo motor will verify that the motor has an acceptably low stall current value.	The DS5180 servo motor selected for use in the ACS has a stall current of 5 Amps, which will not significantly harm the servo motor battery life.	7.2.10

9.2.9 NASA Safety Requirements

Table 106: NASA Safety Requirements

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	I	Inspection will verify that the team uses a launch and safety checklist, the final checklists will be included in the FRR report, and will be used during relevant launch events.	The safety officer will be responsible for writing Standard Launch Operating Procedures to use on any Launch Day and used in the FRR and LRR.	8.1
5.2.	Each team shall identify a student safety officer who will be . . .	Complete	I	Inspection will verify that the team has identified a student safety officer.	The team has identified Christopher Fountain as the 2022-2023 NDRT safety officer.	8
5.3.	The role and responsibilities of the safety officer will include, but are not limited to:	Complete	I	Inspection will verify that the safety officer assumes all roles and responsibilities associated with safety of various team events.	The safety officer is cognizant of the following listed responsibilities of the role and will adhere to them.	8
5.3.1.	Monitor team activities with an emphasis on safety during:	Complete	I	Inspection will verify that the safety officer will monitor relevant team activities with an emphasis on safety.	The safety officer will maintain awareness of all team activities and be proactive in managing safety risks associated with them.	8
5.3.1.1	Design of vehicle and payload	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will be responsible for creating failure modes that mitigate the risks associated with the design of the launch vehicle and payload system.	8
5.3.1.2	Construction of vehicle and payload components	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will be responsible for updating Standard Workshop Operating Procedures to use during fabrication/construction. The safety officer will also ensure that all team members are certified to operate the machinery used during construction.	8
5.3.1.3.	Assembly of vehicle and payload	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will be responsible for writing Standard Launch Operating Procedures that will guide the team through assembly of the launch vehicle and its subsystems.	8.2, 8.3, 8.4, 8.5
5.3.1.4.	Ground testing of vehicle and payload	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will work with the Systems Lead to ensure proper PPE is worn during testing of the launch vehicle.	8
5.3.1.5	Subscale launch test(s)	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will work with the Systems Lead to ensure proper PPE is worn during testing associated with the subscale launch vehicle.	8.1
5.3.1.6	Full-scale launch test(s)	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will work with the Systems Lead to ensure proper PPE is worn during testing associated with the full-scale launch vehicle.	8.1
5.3.1.7.	Competition Launch	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will be responsible for writing Standard Launch Operating Procedures that will guide the team through assembly of the launch vehicle and its subsystems.	8.1
5.3.1.8.	Recovery activities	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will write failure modes as they relate to recovery activities as well as methods to mitigate those risks.	8.2

Table 106: NASA Safety Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
5.3.1.9.	STEM Engagement Activities	Complete	I	Inspection will verify that the safety officer monitors and manages all safety-related aspects of such activities.	The safety officer will write failure modes and safety considerations as they relate to STEM engagement activities as well as methods to mitigate those risks.	8
5.3.2.	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	Complete	I	Inspection will verify that the safety officer implements Standard Operating Procedures for all listed activities.	The safety officer will be in consistent communication with the design leads to ensure that construction, assembly, launch, and recovery activities are accurately represented in the FMEA tables and Standard Launch Operating Procedures.	8
5.3.3.	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	Complete	I	Inspection will verify that the safety officer manages and maintains team information concerning hazard and failure mode analyses, procedures, and relevant inventory data.	The safety officer will continually update Standard Workshop Operating Procedures, Standard Launch Operating Procedures, FMEA tables, MSDS/chemical inventory data and communicate these updates to the entire team as needed.	8
5.3.4.	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	Complete	I	Inspection will verify that the safety officer assists in the writing and development of FMEA tables for analyses and SOPs.	The safety officer will be responsible for constructing FMEA tables to sufficiently assess and mitigate various risks the team may face throughout the year.	8, 8.10
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 ...	Complete	I	Inspection will verify that the team abides by the rules and guidance of the local rocketry club's RSO and communicate their intentions to leadership.	NDRT will only launch at official NAR/TRA launch sites on official NAR/TRA launch days. The RSO will give the team final approval on if the vehicle can be launched. The local rocketry club has been identified as Michiana Rocketry.	8.7
5.5.	Teams will abide by all rules set forth by the FAA.	Complete	I	Inspection will verify that the team abides by all FAA rules.	The team will only launch at official NAR/TRA or NASA SLI launch sites on official launch days. The team will be made aware of FAA rules and will be conscious of them during relevant team activity.	8

9.2.10 NDRT Integration Requirements

Table 107: NDRT Integration Requirements

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
IN.1	Batteries for all launch vehicle systems must be sized for three hours of operation in temperatures ranging from 0F to 100F.	Three hours of operation is a factor of safety of 1.5 above the two hours listed by NASA Requirement 2.6. This accounts for systems that continue to function mid- or post-flight. The batteries must also function across all flight conditions.	In Progress	T	The team will conduct a battery duration test to verify that all system batteries function properly for at least three hours in cold weather conditions.	The battery duration test is scheduled to take place in Spring 2023.	TEST
IN.2	All electronic components involved in transmission or reception of data and/or magnetic activities shall be properly shielded.	Shielding will prevent interference with sensors located across separate systems and within each system of the launch vehicle. This ensures accurate reading and storage of data.	In Progress	I, T	The team is utilizing carbon fiber for many launch vehicle components due to its RF-shielding capabilities. Additionally, the team will conduct an electronics shielding test to verify that shielding methods are successful in preventing interference between electronic components.	The electronics shielding test is scheduled to take place in Spring 2023.	3.4.1, 4.5.1, TEST
IN.3	Electronics that are critical to flight and/or the mission shall have redundancy in their respective systems.	Redundancy creates systems that are more reliable and can function with component failure. This increases the likelihood of mission success.	Complete	I	Inspection will verify that each system and subsystem with flight and mission critical electronics will have redundancy.	Each design squad has included redundancy of electronics, including altimeters and other sensors, in the design and construction of its subsystems.	4.6.1, 7.4.2
IN.4	Each system and/or module retained within the launch vehicle shall not exceed their mass as allocated by the mass budget.	Accurate mass and weight values are necessary to determine launch vehicle components and meet the 5.0 : 1.0 thrust to weight ratio listed in NASA Requirement 2.15..	Incomplete	A	A mass budget has been created for all launch vehicle systems and their respective components. All members of the team have access to the mass budget and will be able to verify that designs are compliant with the mass budget.	All systems and respective components that will be included in the full-scale launch vehicle are of equal or less weight than the weight allocated to them in the mass budget.	3.4.2, 4.7, 6.9
IN.5	Sensitive components (ie. camera) in any system shall be protected from black powder charges.	Sensitive components require protection from particulate matter or forces caused by black powder charge detonation.	In Progress	T	TROI is protected from black powder charge detonation by a removable wall and Al ring. The effectiveness of these components will be tested by simulating charge detonations at this location. The TROI system will be replaced by a material that will indicate the presence of black powder residue during the test.	The TROI protection test is scheduled to occur in Spring 2023.	6.8.1, TEST
IN.6	Adhesives used near high-heat components (ie. motors and black powder charges) shall be rated to withstand the maximum temperature of those components.	Epoxy used in joints and connections must be heat-resistant to maintain strong bonds to reduce the risk of bond failure and loose components during flight.	Incomplete	I, D	Inspection will verify that heat-resistant epoxy and JB Weld will be used for attachment near high-heat components. Demonstration will verify that bonds hold through in-flight events.	The full-scale demonstration flight is scheduled to take place in Spring 2023.	3.5.1.5, TEST

9.3 STEM Engagement General Update

NDRT has already completed several successful STEM Engagement events. The team has served 188 participants, all of which were served through direct engagement. The team has many more events scheduled for the second semester of the school year with organizations such as the Girl Scouts, the St. Joseph County Public Libraries, and various schools within the South Bend community. The team collected feedback from both the partner organizations and NDRT volunteers. This feedback included more one-on-one time between volunteers and participants as well as adjusted levels of difficulty for different age groups. The STEM Engagement co-leads have worked to implement that feedback into future events. NDRT is looking forward to more opportunities to share the team's resources with the surrounding community.

9.4 Budget

Table 108 shows funding contributions both on hand and expected with high confidence. The team received generous donations from the Boeing Company, Blue Origin, and Northrop Grumman. Old NDRT merchandise that had been in storage was sold to members as a fundraiser after PDR. Also, the Michiana Rocketry Association's traditional contribution of $200.00 is expected again this year, and the New Team Merchandise Sales prediction is based off of revenue from similar sales in previous years. Further donations from alumni and friends of the University of Notre Dame beyond those included in Table 108 are common but unreliable so are not included.

Table 109 gives an overview of the team's allocations by category and actual or budgeted spending within each category. It should be noted that the launch vehicle budget has exceeded its original allotment due to motor and airframe material costs inflated beyond early predictions. However, the vehicle in conjunction with its subsystems as well as the project overall are within budget. With full-scale vehicle procurements near completion, the remaining funds are expected to be sufficient for project completion.

Tables 110 through 115 provide detailed line item budgets for each squad and category. All materials were and will be sourced by trustworthy vendors with which the team has had previous success. New items on hand – whether delivered, picked up, or 3D printed – have a green status field; items being sourced from the team's inventory are marked with blue; items currently en route to the team are shown in yellow; and items planned but not yet ordered have a red-colored status.

Table 108: NDRT 2022-23 Funding Sources

Allocation	Amount	Status
Carry-Over (2021-22)	$22,805.00	Received
Boeing Donation	$10,000.00	
Blue Origin Donation	$2,000.00	
EE Senior Design	$500.00	
Old Team Merchandise Sales	$500.00	
Northrop Grumman Donation	$100.00	
New Team Merchandise Sales	$900.00	Predicted
Michiana Rocketry Donation	$200.00	Expected
Total	**$37,005.00**	

Table 109: NDRT 2022-23 Budget Summary

Category	Allocation	Actual & Budgeted Spending	Margin
Launch Vehicle	$4,200.00	$4,958.66	118.06%
Recovery System	$1,500.00	$500.96	33.40%
Apogee Control System	$1,200.00	$283.64	23.64%
360° Rotating Optical Imager	$1,700.00	$591.70	34.81%
Vehicle Subtotal	***$8,600.00***	***$6,334.96***	***73.66%***
Safety	$200.00	$47.01	23.51%
Educational Outreach	$200.00	$18.29	9.15%
Huntsville Travel	$11,000.00	$11,000.00	100.00%
Miscellaneous	$1,000.00	$281.85	28.19%
Total	**$21,000.00**	**$17,682.11**	**84.20%**
Total Available	$37,005.00	$37,005.00	
Remaining Funds	$16,005.00	$19,322.89	

Table 110: Launch Vehicle Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
Licenses					$85.60	
RockSim Licenses	Apogee Rockets	4	$20.00	$5.60	$85.60	Delivered
Subscale Vehicle					$515.09	
3" G12 Fiberglass Airframe (Thin Wall), 5' length, Blue	Composite Warehouse	1	$98.00	$44.95	$252.95	Delivered
3" G12 Fiberglass Coupler Tube, 12" length, Blue		1	$30.00			
G10 Fiberglass Sheet, 12"x48"x3/32"		1	$68.00			
38 mm G12 Fiberglass Motor Mount Tube (Standard Wall), 12" length, Blue		1	$12.00			
Aero Pack 38mm Motor Retainer	Apogee Components	1	$29.17	$26.40	$82.56	Delivered
G5000 RocketPoxy, 8-oz Package		1	$26.99			
Aerotech I357T-14A Blue Thunder Rocket Motor	Countyline Hobbies	2	$60.00	$10.00	$130.00	Delivered
J-B Weld Professional Size, 10 oz	J-B Weld	1	$19.99	$10.85	$30.84	Delivered
1010 Rail Buttons, Pack of 4	Chris' Rocket Supplies	1	$2.50	$9.24	$11.74	Delivered
J-B Weld 5 Minute Set Epoxy Syringe, 25 ml	Amazon	1	$6.54	$0.46	$7.00	Delivered
Nose Cone	N/A	1	$0.00	$0.00	$0.00	3D Printed
Full-Scale Vehicle					$4,357.97	
6.0" Filament Wound Nose Cone, 4:1 Ogive, Metal Tip, White	Composite Warehouse	1	$149.99	$84.60	$1,315.37	Delivered
6.0" G12 Fiberglass Body Tube (Standard Wall), 3' length, White		1	$135.00			
6.0" G12 Fiberglass Coupler Tube (Standard Wall), 12" length, White		1	$60.00			
G10 Fiberglass Sheet, 12"x24"x3/16"		1	$74.00			
G10 Fiberglass Sheet, 12"x48"x3/16"		1	$137.00			
Carbon Fiber Sheet, 15"x19"x1/8"		2	$199.99			
3" Carbon Fiber Tube (Standard Wall), 5' length		1	$275.00			
6.0" Carbon Fiber Airframe Tubing EXTREME, 5' length	LOC Precision	2	$641.95	$40.05	$1,479.05	Shipped
6.0" Carbon Fiber Coupler, 5' length		1	$155.10			
Aerotech L2200G Rocket Motor Reload	Impulse Buys	4	$350.00	$84.00	$1,484.00	Delivered
Aero Pack Motor Retainer Assembly, 75mm (L)	Chris' Rocket Supplies	1	$51.00	$9.24	$60.24	Delivered
Large Airfoiled Rail Buttons (1515 Rail), Pack of 2	Apogee Components	1	$11.73	$7.38	$19.11	Delivered
				TOTAL	**$4,958.66**	
				Budget Allocation	**$4,200.00**	
				Remaining	**-$758.66**	

Table 111: TROI Payload Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
Electronics					$82.09	
Baofeng UV-5R Two-Way Radio	Amazon	2	$21.90	$3.06	$46.86	Delivered

Tiny Premium Breadboard	Adafruit	1	$3.95	$11.32	$15.27	Delivered
HAM Amateur Radio Module DRA818V	Tindie	2	$9.98	$0.00	$19.96	Delivered
Hardware					$102.19	
304 Stainless Steel Corner Bracket	McMaster-Carr	4	$2.59	$21.63	$421.69	Delivered
Stainless Steel 8-32 Thread Screws and Nuts		1	$7.84			
Compression Springs, 90.5mm length, Pack of 3		1	$12.48			
NEMA 17 Stepper Motor w/ Linear Actuation, 0.00125" travel distance, 11.2" travel length		1	$188.84			
NEMA 8 Stepper Motor, 2.8 in.-oz. Maximum Holding Torque		1	$115.14			
Flange-Mounted Shaft Support for 10mm Shaft Diamter, 1060 Aluminum		2	$20.42			
Female 4-40 Threaded Hex Standoff (18-8 Stainless Steel, 1/4" hex, 2-3/4" length)		4	$4.59			
Passivated 18-8 Stainless Steel Pan Head 4-40 Thread Phillips Screw, Pack of 100		1	$6.20			
PCB Mount 3-pin Straight RF Coaxial Adapter	Amazon	1	$9.72	$31.82	$58.02	Delivered
USB to Audio Jack Adapter		1	$7.99			
6063 Aluminum Tube, 10mm OD x 8mm ID x 250mm L, 2 Pcs		1	$8.49			
Enameled Copper Magnet Wire, 11 AWG	Digi-Key	1	$0.95	$28.95	$29.90	Delivered
				TOTAL	**$591.70**	
				Budget Allocation	**$1,700.00**	
				Remaining	**$1,108.30**	

Table 112: Recovery Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
Electronics					$0.00	
Featherweight Raven4 Altimeter	N/A	2	$0.00	$0.00	$0.00	Inventory
PerfectFlite StratoLoggerCF Altimeter		2				
PerfectFlite StratoLogger SL100 Altimeter		2				
Lithium Polymer Battery for GPS - 400 mAh		2				
Lithium Polymer Battery for Altimeter - 380 mAh		6				
Lithium Polymer Battery for Altimeter - 150 mAh		6				
Featherweight GPS Stability Tracker		1				
Hardware & Laundry					$500.96	
Braided Kevlar Shock Cord, 25 ft, 950 lb	Rocketman Parachutes	1	$16.00	$0.00	$16.00	Delivered
304 Stainless Steel Corner Bracket	McMaster-Carr	4	$2.59	$5.15	$23.25	Delivered
Stainless Steel 8-32 Thread Screws and Nuts		1	$7.84			
Powerline Micro USB Cable	Amazon	1	$15.99	$1.12	$17.11	Delivered
Rocketman Elliptical Parachute (Drogue), 2 ft, 1.6 C_d	N/A	1	$0.00	$0.00	$0.00	Inventory
FruityChutes Elliptical Parachute (Pilot), 2 ft, 1.6 C_d		1				
3000 lb Stainless Steel Swivel		1				
24" Nomex Blanket		1				
Steel Quick Link, Threaded (Various Sizes)		8				
Tubular Nylon Webbing (4400 lb), 1.25" thickness, 10' length	Rocketman Parachutes	1	$26.50	$0.00	$205.50	Budgeted
Tubular Nylon Webbing (4400 lb), 1.25" thickness, 15' length		1	$31.50			
Tubular Nylon Shock Cord, 5/8" thickness, 10' length		1	$28.00			
Tubular Nylon Shock Cord, 5/8" thickness, 15' length		1	$33.00			
Kevlar Shock Cord, 0.19" thickness, 5' length		1	$20.00			
Kevlar Shock Cord, 0.19" thickness, 25' length		1	$45.00			
12" Square Nomex Blanket		1	$21.50			
SkyAngle CERT 3 XXL Parachute	Wildman Rocketry	1	$239.00	$0.00	$239.00	Budgeted
				TOTAL	**$500.96**	
				Budget Allocation	**$1,500.00**	
				Remaining	**$999.04**	

Table 113: ACS Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
BNO055 IMU	Adafruit	1	$29.95	$20.34	$102.44	
ADXL343 Accelerometer		2	$5.95			
MPL3115A2 Altimeter		2	$9.95			
PWM Servo Driver		1	$14.95			
Piezo Buzzer		1	$1.50			

Delivered

RGB LED		1	$2.00			
Power Switch		2	$0.95			
YDL 3.7V 5000 mAh LiPo Battery	Amazon	2	$15.99	$10.33	$157.86	Delivered
PowerBoost 1000 Basic		1	$14.59			
Ovonic 7.4V LiPo Battery		1	$17.39			
ZOSKAY 80 kg Digital Servo Motor		1	$49.99			
Alien 7.4V 3000 mAh 2S LiPo Battery		1	$24.99			
4 Pc XT30 Plug Connector		1	$8.59			
304 Stainless Steel Corner Bracket	McMaster-Carr	4	$2.59	$5.14	$23.34	Delivered
Stainless Steel 8-32 Thread Screws and Nuts		1	$7.84			
				TOTAL	**$283.64**	
				Budget Allocation	**$1,200.00**	
				Remaining	**$916.36**	

Table 114: Safety, Educational Outreach, Miscellaneous Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
Safety					$47.01	
N95 NIOSH Certified Respiratory Masks, Pack of 20	Amazon	1	$16.99	$3.08	$47.01	Delivered
Med PRIDE NitriPride Nitryl Gloves, Pack of 100		1	$9.99			
KN95 Face Masks, Pack of 50		1	$16.95			
Educational Outreach					$18.29	
Silver Metallic Paper Sheets	Amazon	1	$17.09	$1.20	$18.29	Delivered
Miscellaneous & Shared Resources					$281.85	
Steel Eyebolt with Shoulder, 1/4"-20 Thread Size, 1" Thread Length	McMaster-Carr	5	$3.37	$15.86	$130.69	Delivered
Steel Eyebolt with Shoulder, 7/16"-14 Thread Size, 3" Thread Length		6	$16.33			
3" G12 Fiberglass Coupler Tube (Subscale backup), 6" length	Madcow Rocketry	1	$18.30	$24.65	$42.95	Delivered
6 Large Pizzas (PDR Team Writing Event)	Domino's Pizza	1	$73.14	$5.12	$78.26	Delivered
Snacks & Paper Plates (PDR Team Writing Event)	Martin's Supermarket	1	$29.75	$0.20	$29.95	Delivered
				COMBINED TOTAL	**$347.15**	
				COMBINED Budget Allocation	**$1,400.00**	
				COMBINED Remaining	**$1,052.85**	

Table 115: Competition Travel Expenses

Item	Total Cost	Status	Description
Team Lodging	$2,739.00	Budgeted	Team Airbnb (4 nights)
Team Mentor Lodging	$600.00		Hotel for $150/night (4 nights)
Van Rental	$1,450.00		5 rented vans @ $58.00/day (5 days)
Trip Gas	$1,200.00		5 vans, 23 MPG @ $3.50/gal (1500 mi)
Food Per Diem	$4,500.00		$30/person/day for 30 people (5 days)
Other Food & Misc.	$511.00		Remaining funds
TOTAL	**$11,000.00**		
Budget Allocation	**$11,000.00**		
Remaining	**$0.00**		

9.5 Timeline

The team is on track with the project schedules set out in Proposal and included in PDR. Since PDR submission, two subscale test flights have been completed and all CDR deliverables have been submitted on time. Upcoming timeline items include full-scale vehicle construction, Vehicle Demonstration Flight, FRR submission, and Payload Demonstration Flight. Full-scale parts and materials are ready for vehicle construction to commence upon NDRT members' return to campus on January 17th. The first full-scale flight attempt is scheduled for February 4th with backup dates planned for February 11th and February 25th. In the event that the team requires a re-flight but is unable to complete a re-flight before the Vehicle Demonstration Flight deadline on March 6th, a backup launch day is scheduled for March 11th to accommodate for time to submit a FRR Addendum by April 3rd. The team plans on attending competition in Huntsville, AL for completion of the Payload Demonstration Flight. Figures 117 through 123 provide Gantt charts outlining project timelines by squad.

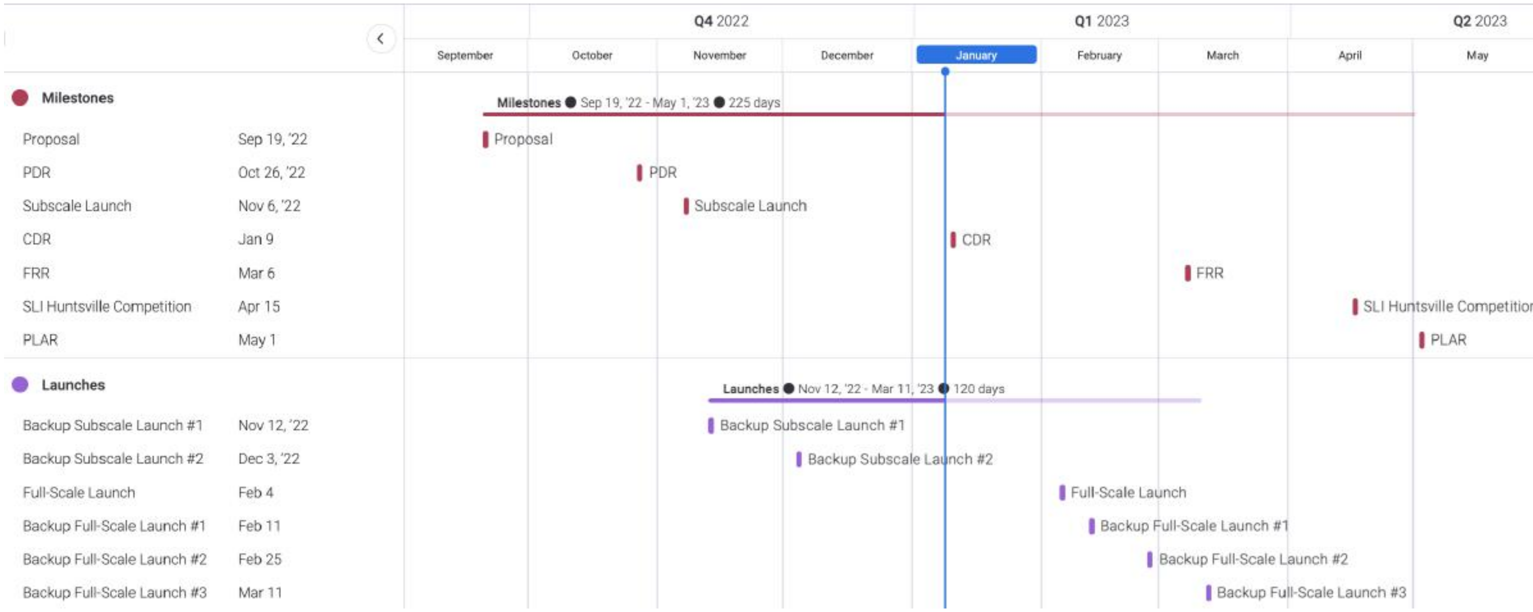


Figure 117: Gantt chart schedule for major project milestones.

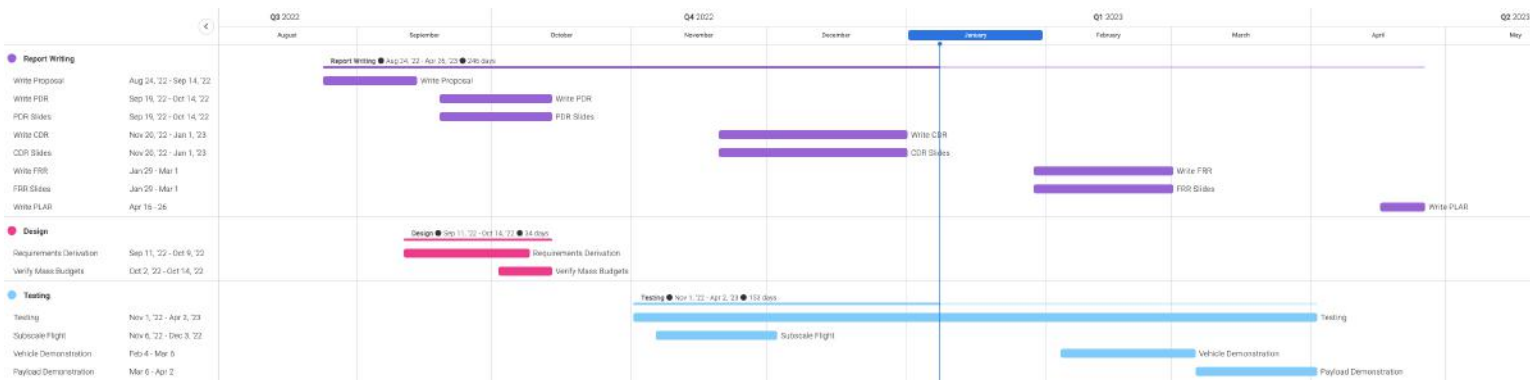


Figure 118: Gantt chart schedule for the Systems Squad.

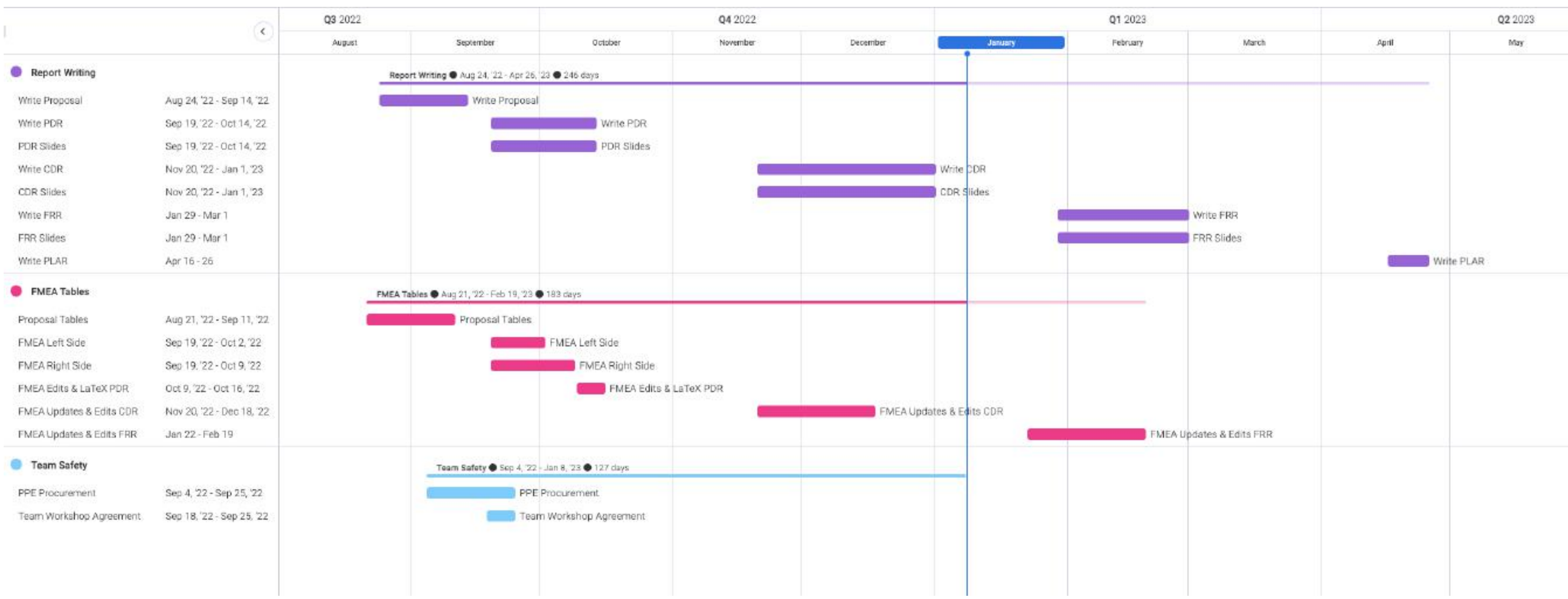


Figure 119: Gantt chart schedule for the Safety Squad.

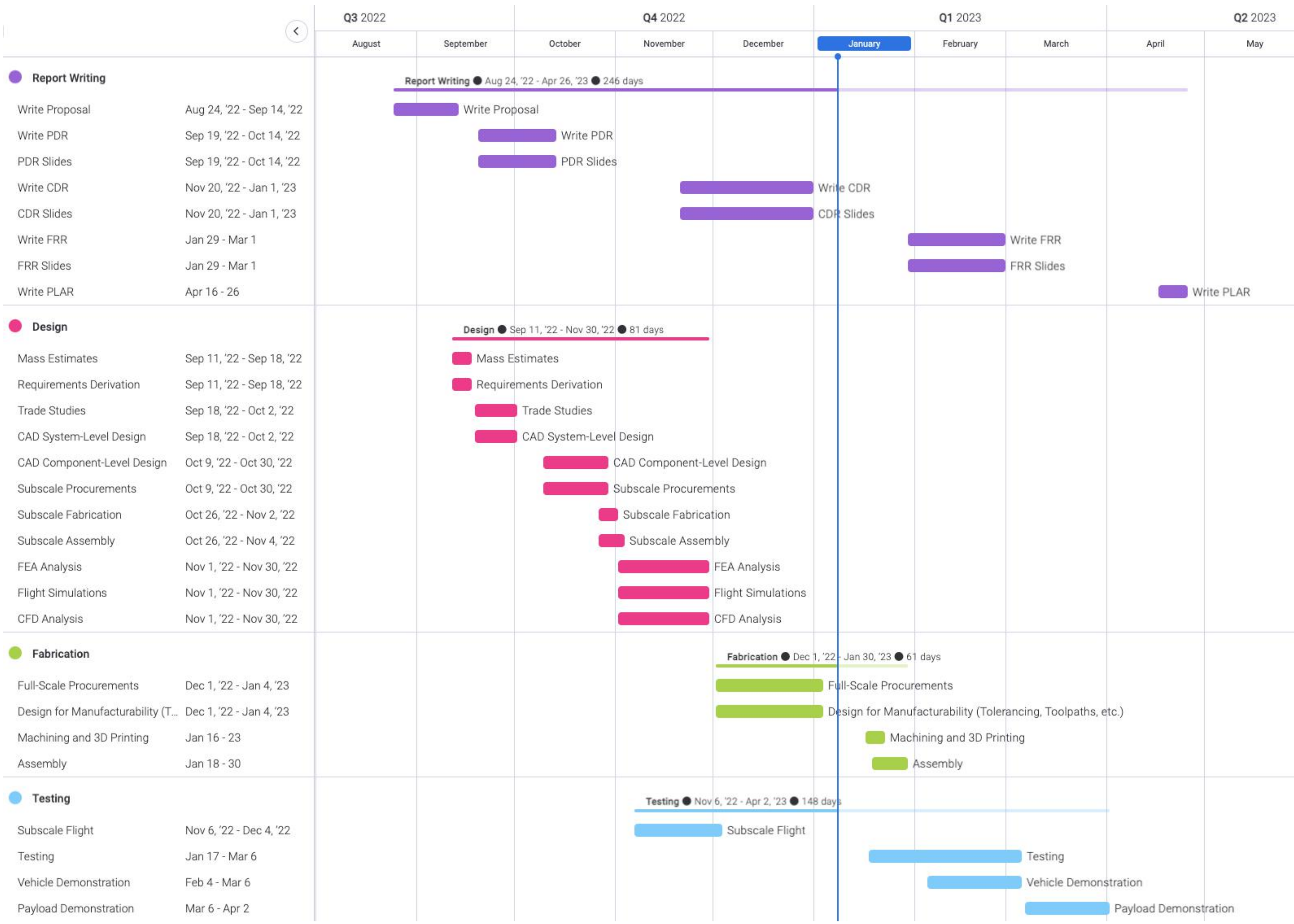


Figure 120: Gantt chart schedule for development of the launch vehicle.

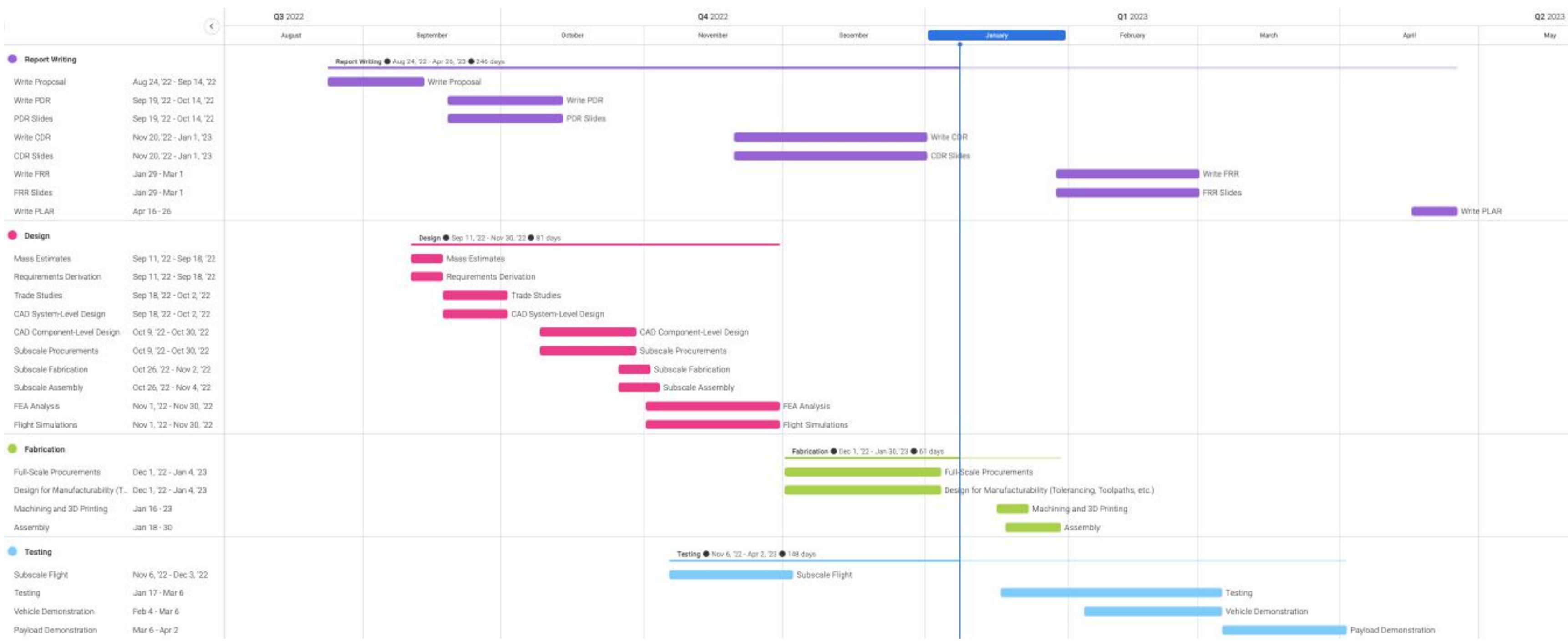


Figure 121: Gantt chart schedule for development of the recovery system.

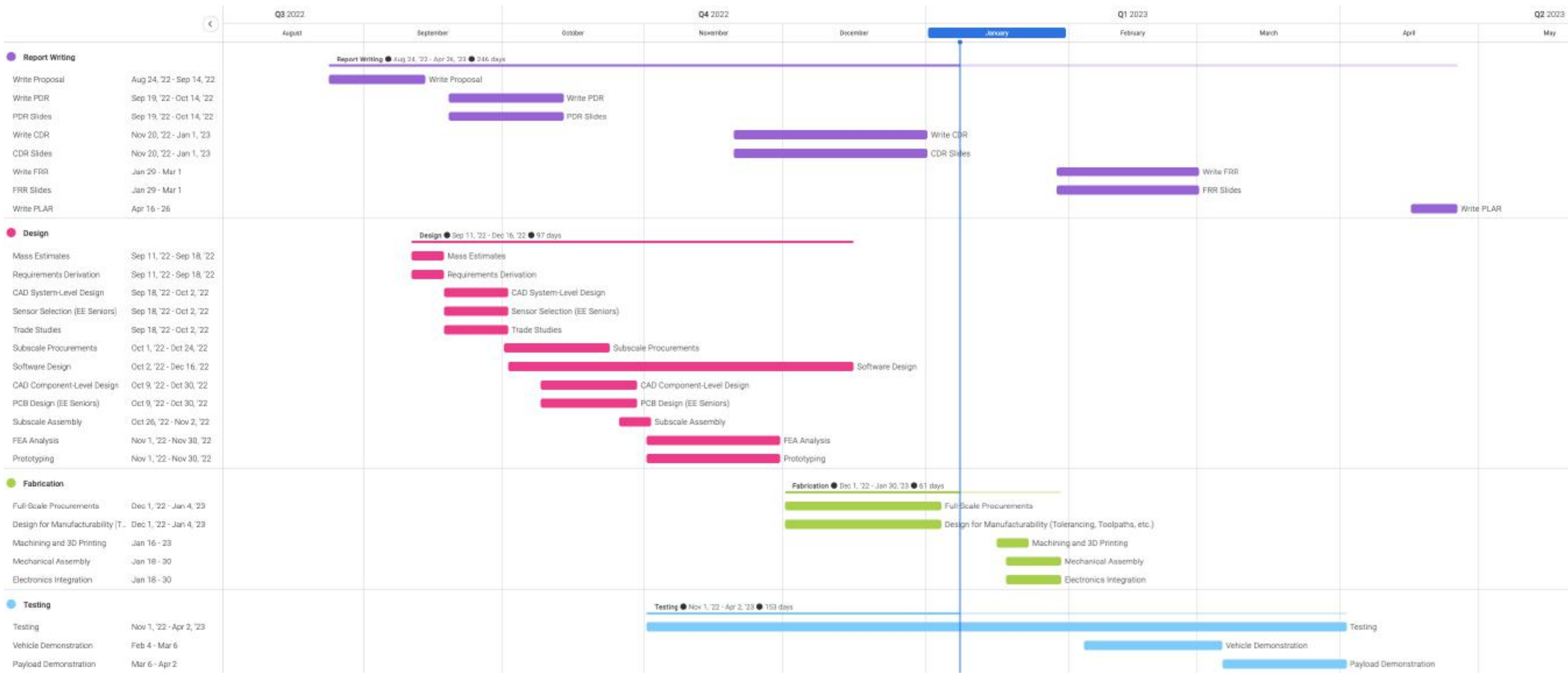


Figure 122: Gantt chart schedule for development of the TROI Payload.

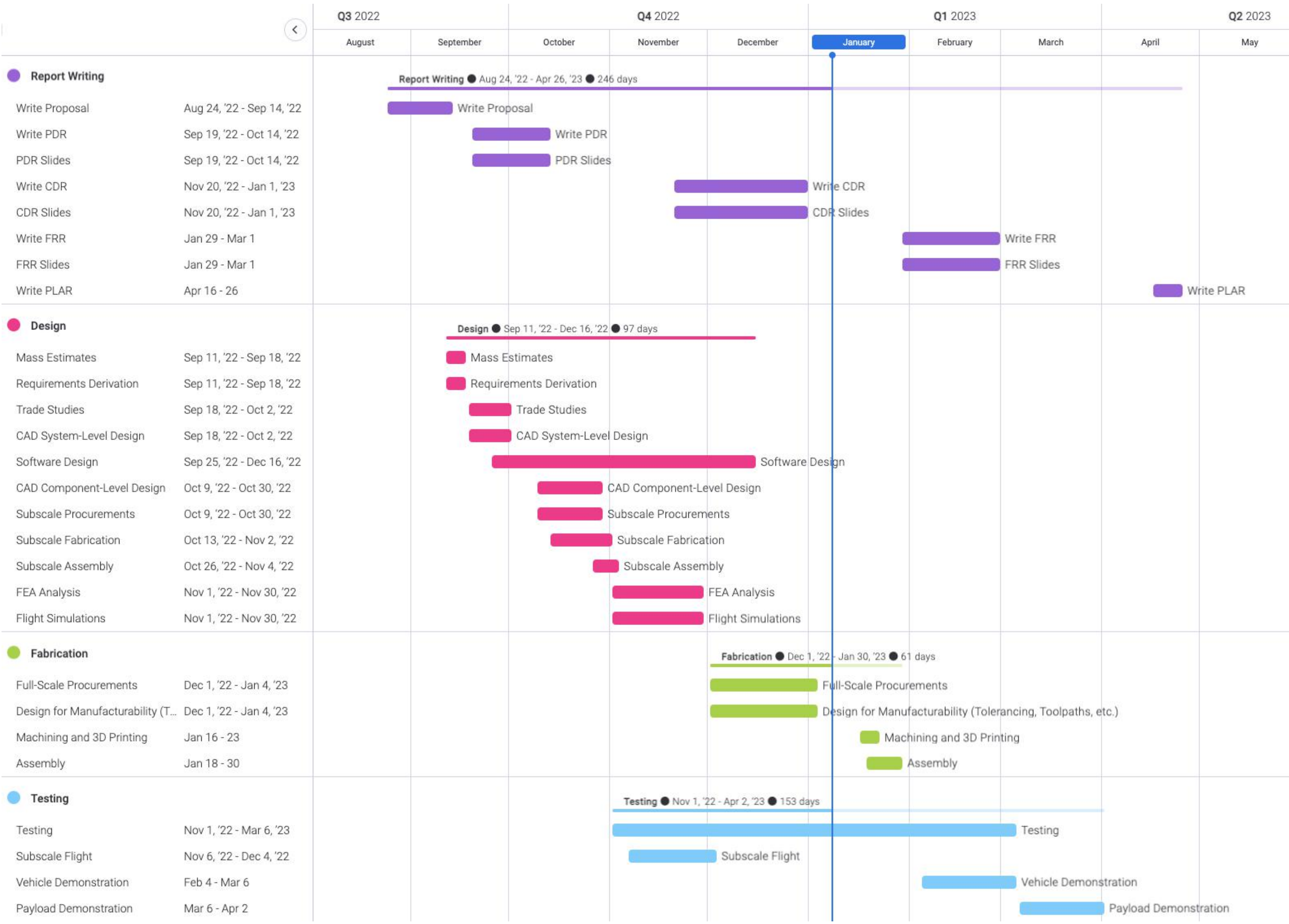


Figure 123: Gantt chart schedule for development of the apogee control system (ACS).

A MATLAB Hand Calculations Scripts

The following scripts were made by the team to automate the hand calculations necessary for the purposes of parachute selection and preliminary descent calculations. The `Input_Mass.m` and `Input_Parachutes.m` functions are used by the `full_vehicle_descent_calc.m` script to import the vehicle mass and parachute information in an organized manner. All of the scripts used for the CDR portion of the parachute selection/confirmation can be viewed below.

```
function [M, M_unsep, M_heaviest, M_mainchute, M_droguechute, ...
    M_noseshock, M_drogueshock, M_mainshock] = Input_Mass()
% Imports Vehicle Masses in standard english units (slugs, lbf, etc)
% Created by Paul du Vair, 12/27/2022
%% Unit Conversions
oz2slug = 0.00194256; % Conversion

%% Weight Inputs
% Total Masses (no laundry or prop)
M(1) = 72.447; % Nosecone Mass (oz)
M(2) = 203.212; % Payload Tube Mass (oz)
M(3) = 177.816; % Recovery Tube Mass (oz)
M(4) = 204.699; % Fin Can Mass (oz)
M = M.*oz2slug; % slugs
M_heaviest = max(M);
%% Adding Laundry and Prop
% Additional Mass Info
% mainchute_only = 25;
% mainchute_harnessql = 25; % Harness, bag, 2 QLs and Swivel
M_mainchute = 87.58; % oz, includes everything for main except shock cord
M_mainshock = 33.88;
% droguechute_only = 2.1;
% droguechute_harnessql = 28.9; % Harness, blanket, 2 QLs and Swivel
M_droguechute = 2.48;% oz, includes everything for drogue except shock cord
M_drogueshock = 16.73;% oz
M_noseshock = 10.2; % oz
M_prop = 90.984; % oz
% Convert oz to slugs
M_mainchute = M_mainchute*oz2slug; % slugs
M_mainshock = M_mainshock*oz2slug; % slugs
M_droguechute = M_droguechute*oz2slug;% slugs
M_drogueshock = M_drogueshock*oz2slug;% slugs
M_noseshock = M_noseshock*oz2slug; % slugs
M_prop = M_prop*oz2slug; % slugs
% Total Masses (with laundry & no prop)
M_unsep(1) = M(1) + M_noseshock; % Nosecone Mass (oz)
M_unsep(2) = M(2); % Payload Tube Mass (oz)
M_unsep(3) = M(3) + M_mainchute + +M_mainshock + ...
    M_droguechute + M_drogueshock; % Recovery Tube Mass (oz)
M_unsep(4) = M(4); % Fin Can Mass (oz)
end
```

```
function [CdA_main, CdA_drogue, CdA_main_chute] = Input_Parachutes()
% Imports Parachute Parameters in standard english units (ft2, etc)
% Created by Paul du Vair, 12/27/2022

%% Tumbling Drag Calcs
include_tumb = 1; % Yes 1, No 0;
CdA_tumb = 0;
if include_tumb == 1
    d_vehicle = 6.16/12; %  Diameter of vehicle, ft
    l_vehicle = 121/12; % Length of vehicle, ft
    Cd = 0.393 + 0.178*(d_vehicle/l_vehicle);
    % https://www.osti.gov/servlets/purl/4630398
    xA_vehicle = d_vehicle*l_vehicle;
    CdA_tumb = Cd*xA_vehicle;
end
%% Main Descent CdA Calcs
% Cd_main = 2.92;
% d_o_main = 12;
% d_i_main = 0;
% A_main = (pi/4)*(d_o_main^2-d_i_main^2);
% CdA_main_chute = Cd_main*A_main;
CdA_main_chute = 174.75; % SkyAngle provided CdA Override
CdA_main_chute = CdA_main_chute*0.9; % Worst Case Flag Adjustments
Cd_pilot = 1.6;
d_o_pilot = 2;
d_i_pilot = 4.22/12;
A_pilot = (pi/4)*(d_o_pilot^2-d_i_pilot^2);
CdA_pilot = Cd_pilot*A_pilot; % Hand-Calced CdA
CdA_pilot = CdA_pilot*0.87; % Worst Case Flag Adjustments
CdA_main = CdA_main_chute + CdA_pilot + CdA_tumb;
%% Drogue Descent CdA Calcs
% Cd_drog = 1.6;
% d_o_drog = 2;
% d_i_drog = 4.33/12;
% A_drog = (pi/4)*(d_o_drog^2-d_i_drog^2);
% CdA_drog_chute = Cd_drog*A_drog;
CdA_drog_chute = 4.62; % Rocketman provided CdA Override
CdA_drog_chute = CdA_drog_chute*0.87; % Adjustment for known performance
CdA_drogue = CdA_drog_chute + CdA_tumb;
end
```

```
%% full_vehicle_descent_calc.m
% Calcs descent time from apogee to ground
% Author: Paul du Vair
clear
clc
%% Inputs
% Total Mass Inputs
[M, M_unsep, M_heaviest, M_mainchute, M_droguechute, M_noseshock, ...
    M_drogueshock, M_mainshock] = Input_Mass();
```

```
[CdA_main, CdA_drogue, CdA_main_chute] = Input_Parachutes();

dep_bag = 1; % Yes 1, No 2
Max_KE = 65; % ft-lb (Set by Competition)
v_wind = 20; % mph (Set by Competition)
h_charge_min = 500; % ft (Set by Competition)
h_ned_max = 900; % ft
h_apo = 4600; % ft
v_wind = 1.46666667*v_wind; % ft/s (Set by Competition)
%% Unit Conversions
oz2slug = 0.00194256; % Conversion
g = 32.17; % ft/s^2
rho = 0.0023769; % slug/ft^3
%% Drogue Calculations
M_tot_final_desc = sum(M_unsep); % Total Mass of Vehicle less propellant
v_descent_drogue = sqrt((2*M_tot_final_desc*g)/(rho*CdA_drogue)); % ft/s
%% Charge Altitude Calculations
h_main_charge1 = h_charge_min + v_descent_drogue*1; % ft
h_main_charge2 = h_charge_min + v_descent_drogue*0.5; % ft
h_main_charge3 = h_charge_min; % ft
h_ned_charge3 = h_ned_max - v_descent_drogue*2; % ft
h_ned_charge2 = h_ned_max - v_descent_drogue*1; % ft
h_ned_charge1 = h_ned_max; % ft
%% Main Deployment Calcultions
if dep_bag == 1
    t_dep_bag = 3; % Delay for main deployment using bag (s)
   h_main_dep = h_main_charge1 - v_descent_drogue*t_dep_bag;
else
    t_dep_nobag = 1; % Delay for main deployment without bag (s)
    h_main_dep = h_main_charge1 - v_descent_drogue*t_dep_nobag;
end
%% Drogue Calcs, continued
t_descent_drogue = (h_apo-h_main_dep)/v_descent_drogue; % seconds
drift_drogue = t_descent_drogue*v_wind; % ft
%% Main Calculations
v_descent_main = sqrt((2*M_tot_final_desc*g)/(rho*CdA_main)); % ft/s
t_descent_main = h_main_dep/v_descent_main; % s
drift_main = t_descent_main*v_wind; % ft
%% Final Calcs
t_total = t_descent_drogue + t_descent_main; % s
drift_total = drift_drogue + drift_main; % ft
%% KE Calcs
KE1d = .5.*(M(1)).*v_descent_drogue.^2; % ft-lb
KE2d = .5.*(M(2)).*v_descent_drogue.^2; % ft-lb
KE3d = .5.*(M(3)).*v_descent_drogue.^2; % ft-lb
KE4d = .5.*(M(4)).*v_descent_drogue.^2; % ft-lb
KE1m = .5.*(M(1)).*v_descent_main.^2; % ft-lb
KE2m = .5.*(M(2)).*v_descent_main.^2; % ft-lb
KE3m = .5.*(M(3)).*v_descent_main.^2; % ft-lb
KE4m = .5.*(M(4)).*v_descent_main.^2; % ft-lb
```

```
%% Main Deployment Acceleration
acc = (0.5*rho*v_descent_drogue^2*CdA_main_chute)/(sum(M_unsep)) - g; % ft/s2
accg = acc / g; % gs
%% Forces at Main Deployment
F_MSH = (sum(M) + M_noseshock +  ...
    M_drogueshock + M_droguechute)*(acc + g); % lbs
F_PEDEYE = (M(1) + M(2) + M_noseshock)*(acc + g); % lbs
F_ACSEYE = (M(3) + M(4) + M_drogueshock + M_droguechute)*(acc + g); % lbs
F_NSH = (M(1) + M_noseshock)*(acc + g); % lbs
F_DSH = (M(4) + M_drogueshock + M_droguechute)*(acc + g); % lbs
%% Displays
disp('Drogue Details')
disp(['Drogue Descent Velocity: ', num2str(v_descent_drogue), ' ft/s'])
disp(['Drogue Descent Time: ', num2str(t_descent_drogue), ' s'])
disp(['Drogue Drift: ', num2str(drift_drogue), ' ft'])
disp(' ')
disp('Main Details')
disp(['Main Descent Velocity: ', num2str(v_descent_main), ' ft/s'])
disp(['Main Descent Time: ', num2str(t_descent_main), ' s'])
disp(['Main Drift: ', num2str(drift_main), ' ft'])
disp(['Main Charge Altitudes: ', num2str(h_main_charge1), ', ', ...
    num2str(h_main_charge2), ', ', num2str(h_main_charge3)])
disp(' ')
disp('NED Details')
disp(['NED Charge Altitudes: ', num2str(h_ned_charge1), ', ', ...
    num2str(h_ned_charge2), ', ', num2str(h_ned_charge3)])
disp(' ')
disp('Overall Time and Drift')
disp(['Total Descent Time: ', num2str(t_total), ' s'])
disp(['Total Drift: ', num2str(drift_total), ' ft'])
disp(' ')
disp(['KE Calculations'])
disp(['Fore Section KE during Drogue Descent: ', num2str(KE1d+KE2d+KE3d), ' ft-lb'])
disp(['Aft Section KE during Drogue Descent: ', num2str(KE4d), ' ft-lb'])
disp(['Nose Cone KE at Landing: ', num2str(KE1m), ' ft-lb'])
disp(['Payload KE at Landing: ', num2str(KE2m), ' ft-lb'])
disp(['ACS KE at Landing: ', num2str(KE3m), ' ft-lb'])
disp(['Fin Can KE at Landing: ', num2str(KE4m), ' ft-lb'])
disp(' ')
disp(['Global Acceleration at Main Deployment: ', num2str(accg), 'g'])
disp(['Force on Main Shock Cord: ', num2str(F_MSH), ' lbs'])
disp(['Force on Nosecone Shock Cord: ', num2str(F_NSH), ' lbs'])
disp(['Force on Drogue Shock Cord: ', num2str(F_DSH), ' lbs'])
disp(['Force on PED Eyebolt: ', num2str(F_PEDEYE), ' lbs'])
disp(['Force on ACS Eyebolt: ', num2str(F_ACSEYE), ' lbs'])
```

B Explanation of Mass Growth Allowance Method Used

The ANSI/AIAA standard method for mass growth allowance was utilized in order to determine the predicted mass of all design components. Specifically, the AIAA S-120A-2015 and SAWE RP A-3 methods were implimented. Further information on the methods can be found at the following link. In short, each component was given a maturity value, was categorized into a component type, and, given a basic — or current design— mass, the mass growth algorithm was able to calculate the predicted mass. Table 116 lists all the maturity values and an explanation of when to chose them. Table 117 lists all the component types and when to chose them. The mass growth allowance percentage is the intersection of each component's maturity value and component type, as seen in Table 118. The mass growth allowance percentages were adjusted from the source material based on a greater understanding of the team's historical trend of mass growth.

Table 116: Maturity Values and Their Description

Maturity Value	Description
Estimated	Extremely rough understanding of the component's mass; critical aspects of design are still unknown
Layout	Mass estimation based on conceptual design; major modifications of the design are still in the works
Preliminary Design	Mass estimation based on modified design; minor modifications of the design are still in the works
Critical Design	Mass estimation based on final design; parts for final design are not ordered yet, so masses may still change
Existing Hardware	Known mass based on prior experience on exact part or accurate distributor-given details
Actual Mass	Mass of in-person weighed components

Table 117: Component Type and Their Description

Component Type	Description
Primary Structure	Body tubes, bulkheads, parachutes, centering rings, etc.
Secondary Structure	Epoxy, non-critical support, screws, nuts, etc.
Mechanism	Moving component involved with the launch vehicle
Batteries	Devices that store electrical energy
Instrumentation/Sensors	Devices used to detect and/or store data during launch
Wiring	Electrical wiring
Other Electronics	Electrical devices, such as black powder or non-scoring cameras, that do not fit in the other categories

Table 118: Mass Growth Allowance Percentages

	Estimated	Layout	Preliminary Design	Critical Design	Existing Hardware	Actual Mass
Primary Structure	19%	10%	6%	4%	2%	0%
Secondary Structure	21%	12%	8%	7%	3%	0%
Mechanism	22%	16%	10%	4%	2%	0%
Batteries	23%	17%	11%	5%	2%	0%
Instrumentation/ Sensors	55%	25%	14%	3%	2%	0%
Wiring	80%	32%	17%	5%	2%	0%
Other Electronics	27%	22%	13%	7%	3%	0%

B.1 OpenRocket Setup for Subscale Launch Data

Figure 124 lists all the specific inputs used when simulating the subscale launch vehicle on OpenRocket. The wind conditions at launch were 12 mph, and the standard deviation was set to 0 mph. While it would be slightly more accurate to have a nonzero standard wind deviation, the wind conditions were taken immediately before launch, and the launch duration was short enough — less than a minute — to justify a constant wind speed approximation. It is beneficial to have no standard deviation so the collected flight simulation data is the same for every time the system is re-ran. Launch site Latitude, Longitude, and altitude were taken from the location of the launch site: Three Oaks, Michigan. Temperature and Pressure were taken at the launch field immediately before the launch occurred.

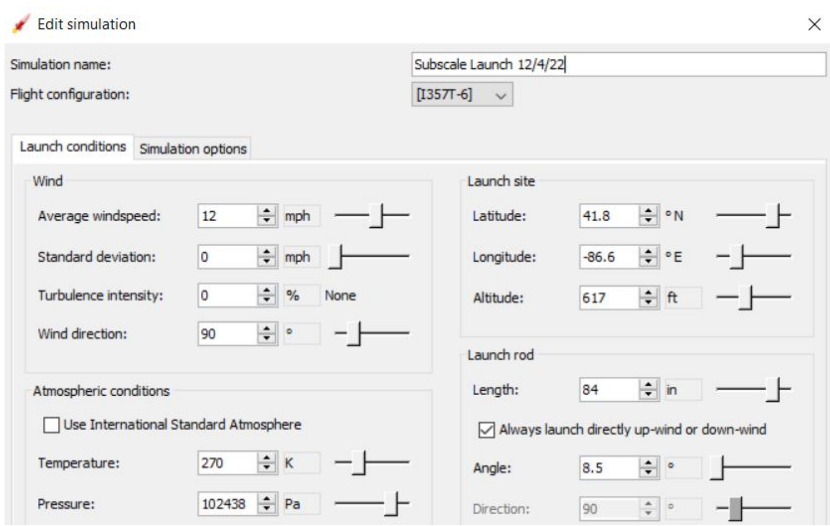


Figure 124: OpenRocket Flight Initialization Steps

B.2 RockSim Setup for Subscale Launch Data

Figures 125, 126, 127, 128, and 129 list all the specific inputs used when simulating the subscale launch vehicle on RockSim. Notably, as seen in Step 1, the parachute comes out 9 seconds after motor ignition. This is the same for both the OpenRocket and RockSim model. This number was determined, based on the fact that the I357 motor has a 1.0 second burn time, per the manufacturer AeroTech, and Team Mentor Dave Brunsting inserted an 8 second delay charge. Step 2 was left at all the default variables. Step 3 shows that the launch rail length and angle was held constant between the OpenRocket and RockSim versions. Step 4 demonstrates that all the same conditions — wind, altitude, temperature, pressure — were held constant between OpenRocket and RockSim. Step 5 demonstrates that the default conditions were modified in order to have zero probability of failure modes during flight.

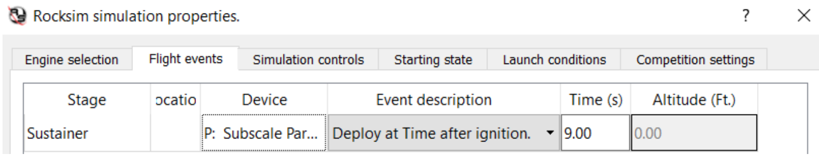


Figure 125: RockSim Flight Initialization, Step 1

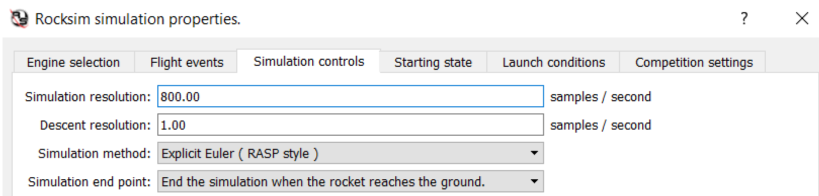


Figure 126: RockSim Flight Initialization, Step 2

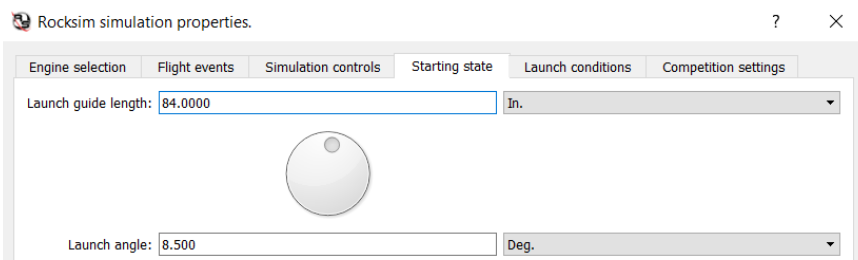


Figure 127: RockSim Flight Initialization, Step 3

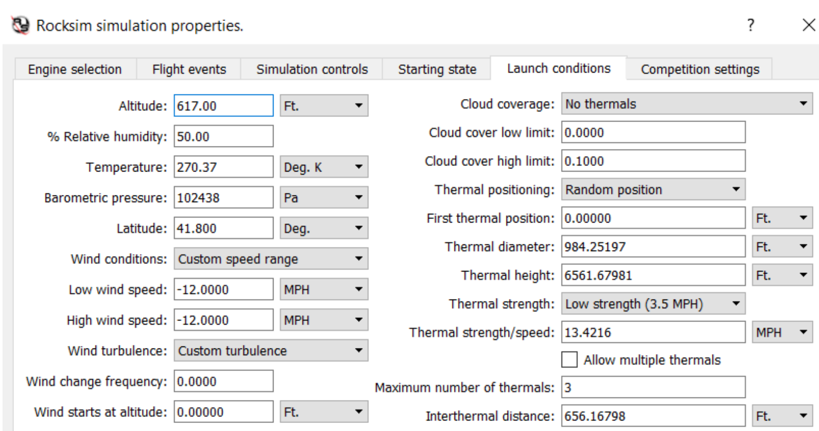


Figure 128: RockSim Flight Initialization, Step 4

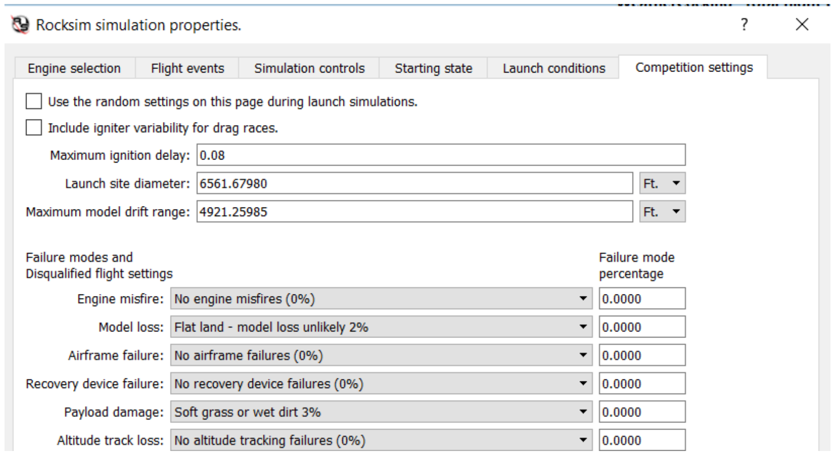


Figure 129: RockSim Flight Initialization, Step 5

C Vehicles MATLAB

C.1 MATLAB Fin Flutter Calculations

```
%% Notre Dame Rocketry Team - Fin Flutter - OpenRocket
% Created 1/8/2023
clc
close all
clear
% Setup Figure
figure;
hold on
xlabel('Time (s)')
ylabel('Velocity (ft/s)')
title('Fin Flutter Calculations: OpenRocket')
%% Input OpenRocket Flight Data
w0a10 = readtable('0w_10a.csv'); % Flight Condition For Max Velocity in OpenRocket
t_OR = rmmissing(w0a10.x_Time_s_); % Time
vel_OR = rmmissing(w0a10.TotalVelocity_ft_s_); % Velocity
alt_OR = rmmissing(w0a10.Altitude_ft_); % Altitude
a_OR = rmmissing(w0a10.SpeedOfSound_ft_s_); % Speed of Sound
P_OR = rmmissing(w0a10.AirPressure_Pa_); % Pressure [Pa]
P_OR = P_OR/6894.76; % Convert [Pa] --> [psi]
%% Set up Parameters
% Span
b = 6; %[in]
% Root Chord
cr = 6; %[in]
% Area of elliptical fin
S = (1/4)*pi*b*cr; %[in^2]
% Aspect Ratio
AR = (b^2)/S;
% Taper Ratio
Lambda = 0.44; % Based on Wing Taper Ratio of Wing, given the Aspect Ratio
```

```
% Flexural Modulus
G = 2400000; %psi
% Thickness
t = 3/16; %[in]
%% Calculate Fin Flutter
h = alt_OR; % Height during flight
% Temperature
T = 59 - (0.00356.*h); % [Deg f]
% Pressure
P = 2116.* ((T + 459.7)/518.6).^5.256; %[lbs/ft^2]
P = P/144;
% Speed of sound
a = sqrt(1.4*1716.59.*(T+460)); %[ft/s]
% Solve Fin Flutter Equation based on assumed temperature, pressure, and
% speed of sound
c1 = G;                                  % First part of flutter equation
c2 = 1.337 * (AR^3) * P * (Lambda + 1); % Second part of flutter equation
c3 = 2*(AR+2)*((t/cr)^3);                % Third part of flutter equation
V_OR = a.*sqrt(c1./(c2./c3));            % Full Flutter Equation
% Find Values based on RockSim Data of Tempertaure and Speed of Sound
c1 = G;                                     % First part of flutter equation
c2 = 1.337 * (AR^3) * P_OR * (Lambda + 1); % Second part of flutter equation
c3 = 2*(AR+2)*((t/cr)^3);                   % Third part of flutter equation
V_OR_Real = a_OR.*sqrt(c1./(c2./c3));       % Full Flutter Equation
plot(t_OR, V_OR,t_OR, vel_OR,t_OR,V_OR_Real,'LineWidth',1.5)
%% Finish Plot
set(gca, 'TickLabelInterpreter', 'latex', 'FontSize', 14);
axis([-0.5 18 -10 6000])
legend('Flutter Threshold: OpenRocket Height Data','Flutter Threshold:...
OpenRocket "P" and "a" Data','OpenRocket Velocity: 0 mph Wind, 10^o Angle')
x2 = xline(2.40,':','DisplayName','Burnout/Max Velocity', 'LineWidth',1.5);
hold off
%% Find FoS
Factor_Of_Safety =  min(V_OR)/max(vel_OR)
```