University of Notre Dame

2022-2023

Notre Dame Rocketry Team
Flight Readiness Review

NASA Student Launch 2023

360° Rotating Optical Imager and Apogee Control System

Submitted March 6, 2023

365 Fitzpatrick Hall of Engineering
Notre Dame, IN 46556

Contents

Table 1: Commonly-Used Acronyms

Acronym	Meaning
ACS	Apogee Control System
AIB	Airframe Interfacing Block
AGL	Above Ground Level
CDR	Critical Design Review
CG	Center of Gravity
CP	Center of Pressure
CPU	Central Processing Unit
EE	Electrical Engineering
FEA	Finite Element Analysis
FED	Fin Can Energetic Device
FMEA	Failure Modes and Effects Analysis
FPS	Frames Per Second
GPS	Global Positioning System
FRR	Flight Readiness Review
LED	Light Emitting Diode
LiPo	Lithium Polymer
NAR	National Association of Rocketry
NDRT	Notre Dame Rocketry Team
NED	Nose Cone Energetic Device
PCB	Printed Circuit Board
PDF	Payload Demonstration Flight
PDR	Preliminary Design Review
PED	Payload Energetic Device
PID	Proportional-Integral-Derivative
PWM	Pulse-Width Modulation
RF	Radio Frequency
SOP	Standard Operating Procedure
TRA	Tripoli Rocketry Association
TROI	360° Rotating Optical Imager
VDF	Vehicle Demonstration Flight

1 Team Summary

Team Info:	Notre Dame Rocketry Team (NDRT) University of Notre Dame 365 Fitzpatrick Hall of Eng. Notre Dame, IN 46556	**NAR/TRA Sec:**	TRA #12340 Michiana Rocketry
		Final Launch Plan:	Huntsville, AL April 15, 2023
Mentor:	Dave Brunsting Level 3 – NAR #85879, TRA #12369 e: dacsmema@gmail.com p: (269) 838-4275	**Backup Final Launch:**	Three Oaks, MI April 15, 2023 Michiana Rocketry, TRA #12340 Dave Brunsting, Prefect
FRR Hours:	1286		e: dacsmema@gmail.com

STEM Engagement: 21 Events, 1121 Participants Reached (1113 Direct Educational)

Activities:
Engineering Design Challenge: Tackle simplified version of SLI payload design challenge
Mars and Rovers: Complete rover puzzle, make paper helicopter, learn about Mars & NASA rovers
Paper Helicopters: Make paper helicopter, learn about forces that impact rotor blades
Paper Straw Rockets: Learn about key parts of a rocket, make a paper straw rocket
Space Kaleidoscopes: Learn about James Webb Space Telescope, create a space kaleidoscope
Q & A: Learn about NDRT and this year's launch vehicle and payload design challenge

1.1 Launch Vehicle Summary

Tables 2 and 3 give key features of the launch vehicle design. The recovery system comprises three separation events including two parachute deployments. At apogee, The **F**in Can **E**nergetic **D**evice (**FED**) deploys the drogue parachute, a 2 ft diameter, 1.6 C_d Rocketman elliptical parachute tethered by a 5/8 in. tubular nylon shock cord rated for 3,200 lb. At 900 ft AGL, the **N**ose Cone **E**nergetic **D**evice (**NED**) separates from the payload tube, remaining tethered to the launch vehicle via a kevlar shock cord but releasing no parachute. The **P**ayload **E**nergetic **D**evice (**PED**) deploys the main parachute at 608 ft AGL. The main parachute is a 12.8 ft diameter, 2.92 C_d SkyAngle XXL parachute connected to a 25 ft tubular nylon shock cord rated for 4,400 lb.

Table 2: Launch Vehicle Summary

Feature	Value
Target Apogee (ft)	4600
Competition Motor	Aerotech L2200G-P
Outer Diameter (in.)	6.17
Rail Size	12 ft, 1515
Dry Mass (w/o Ballast) (oz)	773.95
Dry Mass (w/ Ballast) (oz)	773.95
Wet Mass (oz)	852.75
Burnout Mass (oz)	773.95
Landing Mass (oz)	606.62

Table 3: Launch Vehicle Summary, *continued*

Section	Length (in.)	Mass (oz)
Nose Cone	25.5	81.013
Payload Bay	27.0	189.208
ACS Tube	39.0	271.808
Fin Can	38.25	310.720
Total	**129.25**	**852.75**

1.2 Payload Summary

The **360° R**otating **O**ptical **I**mager (**TROI**) utilizes an active lead screw, passive rotational bearing, and an active spring-based telescoping camera arm to deploy a rotatable camera outside the payload body tube and orient it parallel to the z-axis (NASA Reqs. 4.2.1.1, 4.2.1.2, 4.2.4, 4.3.1). TROI remains rigidly retained throughout flight, landing, and deployment. TROI receives and demodulates commands via APRS to take and store the requested images on the main ESP32 microcontroller once landed (NASA Req. 4.2.2).

2 Changes Made Since CDR

2.1 Vehicle Changes

There are three vehicle changes from CDR. The previous year's nose cone was initially used for the first vehicle demonstration flight, but it was damaged (See Section 8.6.1). Afterwards, the nose cone from another previous year was chosen for the final nose cone design. The nose cone alternatives had the same key dimensions — 4:1 ratio, ogive, 6.17 in. base diameter — but they were substantially lighter than the originally purchased nose cone for this year's competition, and mass was the driving force in the decision.

Second, the nose cone ring changed length. The first nose cone change resulted in a shoulder length reduction from 6.00 in. to 5.25 in. To abide by NASA Req. 2.4.2, the nose cone ring decreased from 3.00 in. to 2.25 in. When the nose cone changed for a second time, the shoulder length went from 5.25 in. to 4.5 in. Again, to abide by NASA Req. 2.4.2, the nose cone ring shrank from 2.25 in. to 1.5 in. These modifications were thoroughly investigated by the recovery squad to ensure the decrease in volume would not negatively impact the section separation. Changes to the nose cone ring were subsequently deemed safe for launch. For more information on the final nose cone and nose cone ring design, see Sections 3.3.1 and 3.3.2, respectively.

Third, the vehicle demonstration flight demonstrated that the launch vehicle was greatly over stable (See Section 8.4.1.5, and efforts to reduce the stability would only benefit the performance while still abiding by NASA Req. 2.14. For the final vehicle design, the span of the fins shrank from 6.00 inches initially to a final span of 5.00 inches. See Section 5.1.5 to see the mission performance of the new fin design.

2.2 Recovery Changes

There were only a few recovery changes from CDR based on construction and assembly. The altitude inputs for the Raven4 altimeters can only be entered in increments of 32 ft. As such, the precise deployment altitudes calculated during CDR could not be inputted, and instead altitudes close to those numbers had to be inputted for the Raven4 altimeters. This is further outlined in Section 4.3.1.Next, the SL100 and SLCF altimeters used fewer e-matches than anticipated in each charge well, as described in Section 4.6.1. Additionally, the screw that held each PVC pipe to its 3D-printed holder was deemed redundant and JB Weld was used instead. Next, several of the quick link sizes were changed from 3/16 in. to 3/8 in. as the 3/16 in. quick links could not fit on the 7/16 in. eye bolts on the bulkheads. This is further discussed in Section 4.5.3. Finally, the size of the black powder charges was optimized after ground ejection testing informed the team that some charges should be enlarged.

2.3 Payload Changes

Table 4 provides a short description of the TROI Changes since CDR. A more depth description of the changes is described in Section 6.2.

Table 4: Summary of changes made since CDR

Section	Change	Justification
PCB and Power Distribution 6.4.1	Battery and battery case is moved from aft to fore bulkhead.	Battery case did not fit on the aft bulkhead.
Telescoping Camera Arm 6.3.2	Telescoping arm is inverted so that the smallest link connects to the camera stepper motor	Will allow for more room for the electronics as well as a more reliable deployment piece

Vehicle Demonstration Flight 6.7	Longitudinal stepper motor and lead screw component replaced.	The original part was damaged beyond repair during the vehicle demonstration flight.
Telescoping Camera Arm 6.3.2	Camera stepper motor changed from a NEMA-8 to a NEMA-14	The NEMA-8 stepper motor did not provide enough torque to deploy the telescoping camera arm.
Payload Changes Since CDR 6.2	The orientation about the longitudinal axis changed from an active to a passive system through the use of a bearing.	The passive system is more reliable than the active system. The active system was not able to be implemented successfully.
Payload Changes Since CDR 6.2	The number of wooden mounting boards decreased from two to one.	Only one wooden mounting board is required, and this saves space and mass.
Payload Changes Since CDR 6.2	Antenna location was changed to be parallel to the telescoping camera arm on the lead screw cover.	This ensures that the antenna will be oriented parallel to the z-axis and thus able to receive from a z-axis antenna.

3 Launch Vehicle Design

3.1 Mission Statement and Success Criteria

The mission of the launch vehicle is to enable the functions of the payloads. The design of the vehicle was determined by NASA and NDRT Requirements to ensure the launch vehicle is safe and can integrate with the payload and recovery systems.

The NASA Requirements dictating vehicle design were reaching an apogee between 4,000 and 6,000 ft (NASA Req. 2.1), creating a reusable launch vehicle (NASA Req. 2.3), having a motor impulse of no more than 5,120 N-s (NASA Req. 2.12), achieving a static stability margin of at least 2.0 (NASA Req. 2.14) and reaching a minimum velocity of 52 ft/s (NASA Req. 2.17). The launch vehicle was also designed for this specific competition (NASA Req. 2.19.1.2.

The team requirements dictating the vehicle design are made to increase the functionality of the TROI and the ACS. The TROI requires that the launch vehicle stay within the electronics' range of the ground system so it can receive instructions (not drift or be too sensitive to gusts of wind). The ACS requires that launch vehicle overshoots its target apogee so that it can deploy and reach the desired one. Every component of the vehicle must retain structurally intact during launch, recovery events, and landing.

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

- The launch vehicle shall be in the pre-determined apogee range.
- The launch vehicle shall be return to the ground safely and be able to be launched again.
- The launch vehicle shall achieve the desired static stability margin.
- The body tubes of the launch vehicle shall separate for recovery events.

- The launch vehicle shall reach the minimum velocity.

3.2 Launch Vehicle Design Overview

The layout of the fully constructed launch vehicle showing all subsystems, sections, and separation points is shown in Figure 1.

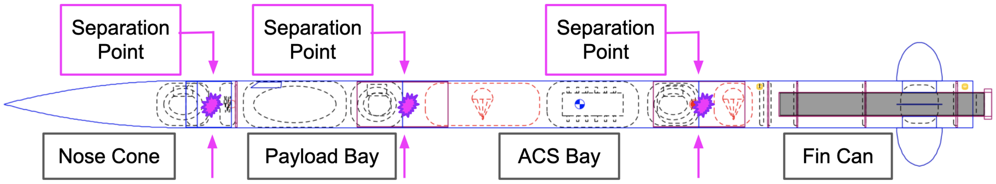


Figure 1: Launch Vehicle CAD Model

Table 5 shows the airframe material and subsystems within each section of the launch vehicle.

Table 5: Breakdown of launch vehicle components with materials and internal systems

Section	Material	Contents
Nose cone section	G12 Fiberglass	NED
Payload Bay Section	G12 Fiberglass	PED, TROI
ACS Bay Section	Carbon Fiber	ACS, FED, Main Parachute
Fin Can Section	Carbon Fiber	Motor, Drogue Parachute

Table 6 shows the launch vehicle major specifications. Note that the static stability value exceeds the required minimum static stability margin of 2.0 cal (NASA Req. 2.14.), and the thrust-to-weight value exceeds the minimum required value of 5.0:1.0 (NASA Req. 2.15.). Also of importance is the team's selected motor, the AeroTech L2200G-P, which has remained consistent since CDR (NASA Req. 2.10.1).

Table 6: Launch Vehicle Specifications

Parameter	Value
Stability (cal)	2.67
Center of Mass (in. from tip of nose cone)	75.21
Center of Pressure (in. from tip of nose cone)	91.69
Airframe outer diameter (in.)	6.17
Thrust-to-Weight Ratio	9.47:1
Total Length (in.)	129.75
Overall Mass (oz)	852.75
Motor	AeroTech L2200G-P

3.3 Component Design

3.3.1 Nosecone

The team originally purchased a 4:1 ogive fiberglass nose cone with a metal tip from Composite Warehouse. However, the mass exceeded its expected value by a factor of three and therefore could not be used in the launch vehicle. This discrepancy was due to a lack of a definitive mass value on the supplier's product page and the inaccurate assumption that the tip of the nose cone would be hollow. With NASA's permission, the team is reusing the nose cone from two years prior, which has the dimensions seen below in table 7. The only change between the two was a 1.5 in. difference in the shoulder length from 6.00 in. to 4.5 in. The nosecone is a FNC-6.0 Fiberglass nose cone purchased from Public Missiles LTD. The tangential ogive shape will allow the launch vehicle to lead with a low-drag leading edge at subsonic speeds. A nose cone "ring" will be installed, and details can be seen in section 3.3.2. An image of the nose cone can be seen in Figure 2. A CAD model of the nose cone assembly can be seen in Figure 3.

Table 7: Nose Cone Dimensions

Nose Cone Characteristic	Value
Exposed Length (in.)	24
Shoulder Length (in.)	4.5
Shape Parameter	4:1 Ogive
Material	G12 Fiberglass
Total Mass (oz)	23.3

Figure 2: Nose Cone

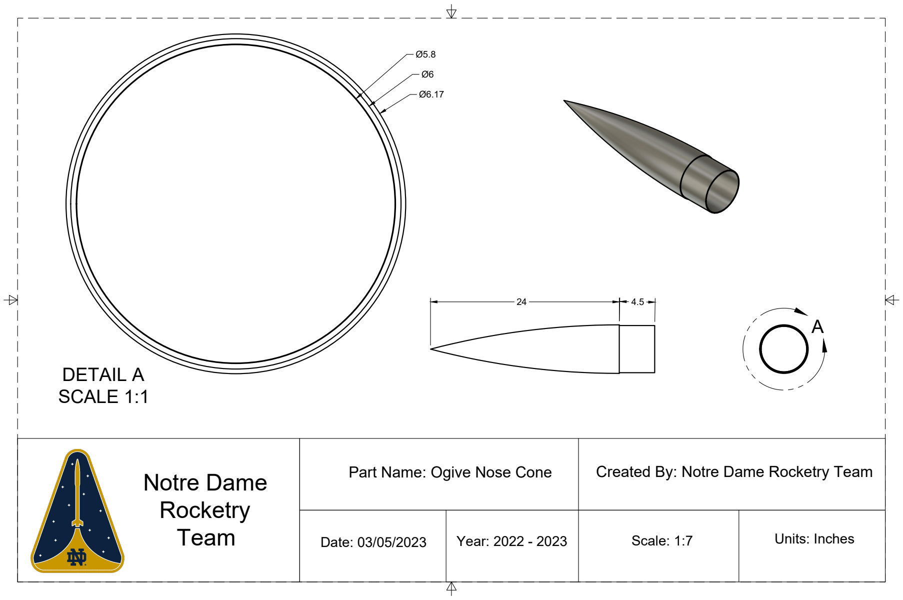


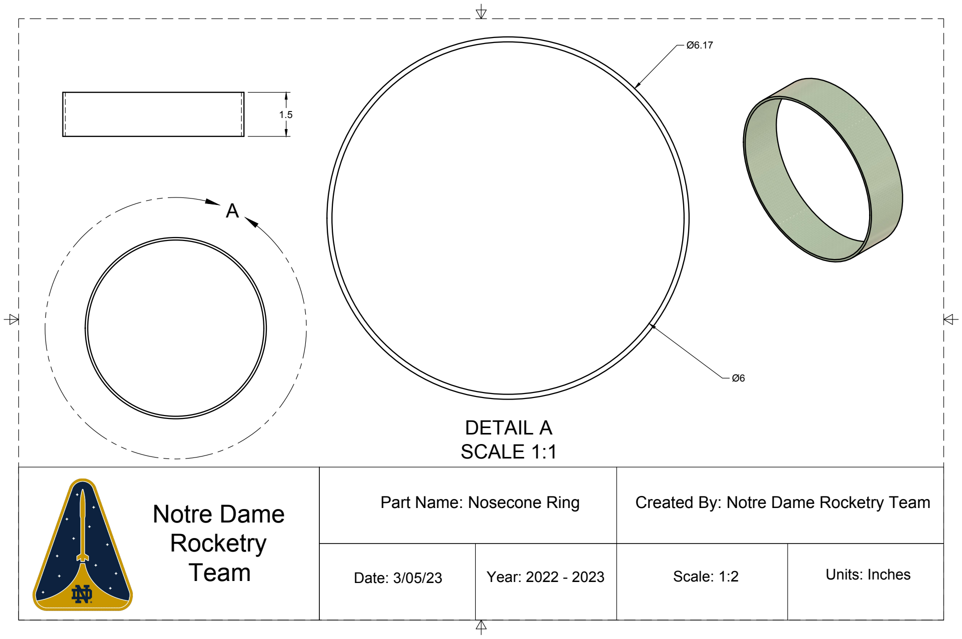
Figure 3: Nose Cone Drawing

3.3.2 Nosecone Ring

The nose cone “ring” allows the shock cord to have sufficient volume within the body tube for black powder ignition, without extending the length of the payload bay body tube. The nose cone “ring” was changed from a 3.00 in. long tube in CDR to now 1.50 in. long tube of G12 Fiberglass. This is due to a change in nose cone shoulder length (see section 3.3.1). Since the overall shoulder length changed from 6.00 in. in CDR to 5.25 in. and now 4.5 in., by attaching a 1.5 in. body tube "ring", it will satisfy NASA requirement 2.4.2. for the nosecone shoulder to be one half the body tube diameter. Table 8 lists the specifications of the nose cone ring. Figure 4 displays the CAD drawing for the nose cone ring.

Table 8: Nose Cone Ring Dimensions

Parameter	Value
Length (in)	1.5
Ring Outer Diameter (in)	6.17
Ring Inner Diameter (in)	6.00
Material	G12 Fiberglass
Mass (oz)	3.167



Notre Dame Rocketry Team
Part Name: Nosecone Ring
Created By: Notre Dame Rocketry Team
Date: 3/05/23
Year: 2022 - 2023
Scale: 1:2
Units: Inches

Figure 4: Nose Cone Ring Drawing

3.3.3 Airframe Sections

The launch vehicle design incorporates three independent airframe tubes. The aft-most body tube makes up the fin can assembly, the center airframe tube houses the ACS, and the foremost body tube houses the payload.

The fin can section of the airframe is carbon fiber due to its strength, low relative mass, and heat resistance, due to it being near the L2200G-P motor. It houses the motor retention assembly, drogue parachute, and fixed bulkhead. The specifications of the fin can can be seen in Table 9, and a CAD model of the fin can body tube can be seen in Figure 5.

Table 9: Fin Can Body Tube Specifications

Parameter	Value
Mass (oz)	40.992
Length (in)	36
Inner Diameter (in)	6.00
Outer Diameter (in)	6.144
Material	Carbon Fiber

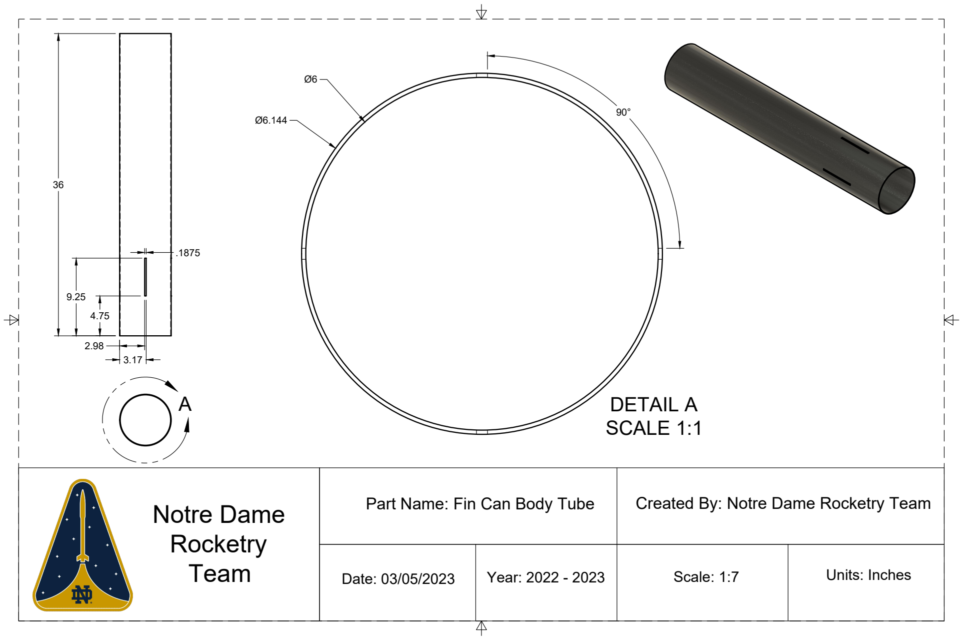


Figure 5: Fin Can Body Tube CAD Drawing

As well, the ACS bay airframe is made of carbon fiber due to its low mass relative to its strength. The ACS bay houses the ACS, main parachute, and FED. It interfaces with the fin can using a carbon fiber coupler, which is bonded to the tube using RocketPoxy. The overall specifications of the Recovery/ACS bay are shown in Table 10. A CAD model of the ACS bay body tube is shown in Figure 6.

Table 10: ACS Bay Body Tube Specifications

Parameter	Value
Body Tube Mass (oz)	35.998
Length (in)	39
Inner Diameter (in)	6.00
Outer Diameter (in)	6.144
Body Tube Material	Carbon Fiber
Coupler Mass (oz)	9.05
Coupler Inner Diameter (in)	5.88
Coupler Outer Diameter (in)	5.99
Coupler Length (in)	12
Coupler Material	Carbon Fiber

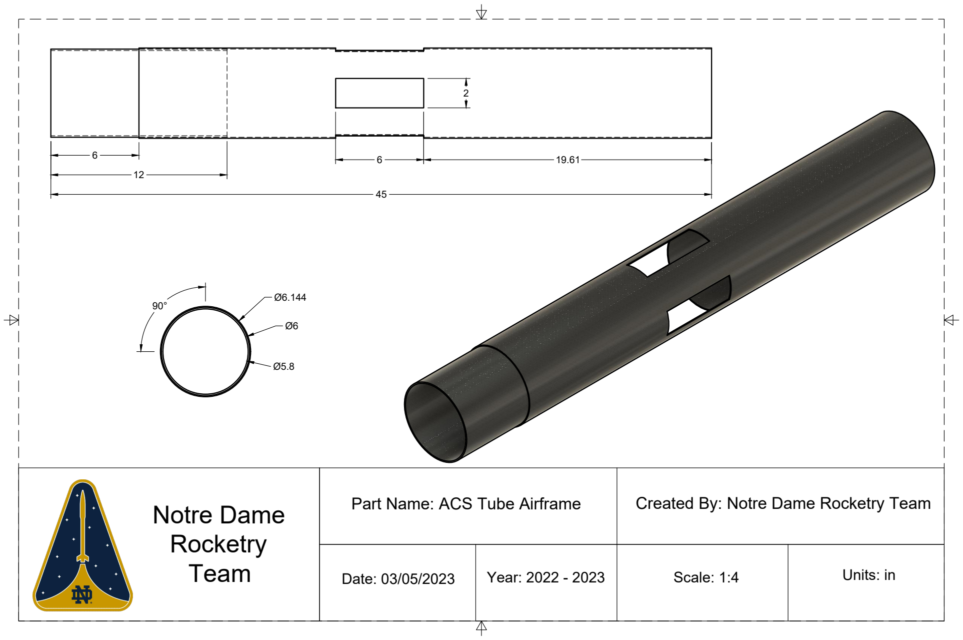


Figure 6: Recovery/ACS Body Tube CAD Drawing

The payload section of the airframe is constructed from G12 fiberglass to allow RF transmission via radio, necessary for payload actuation. It interfaces with the ACS bay section using a G12 fiberglass coupler, which is bonded to the payload tube using RocketPoxy. The specifications of the Payload Bay and coupler are shown in Table 11. A CAD model of the Payload Bay body tube can be seen in Figure 7.

Table 11: Payload Bay Body Tube Specifications

Parameter	Value
Body Tube Mass (oz)	57.048
Length (in)	34
Inner Diameter (in)	6.00
Outer Diameter (in)	6.17
Body Tube Material	G12 Fiberglass
Coupler Mass (oz)	13.532
Coupler Inner Diameter (in)	5.8
Coupler Outer Diameter (in)	5.99
Coupler Length (in)	12
Coupler Material	G12 Fiberglass

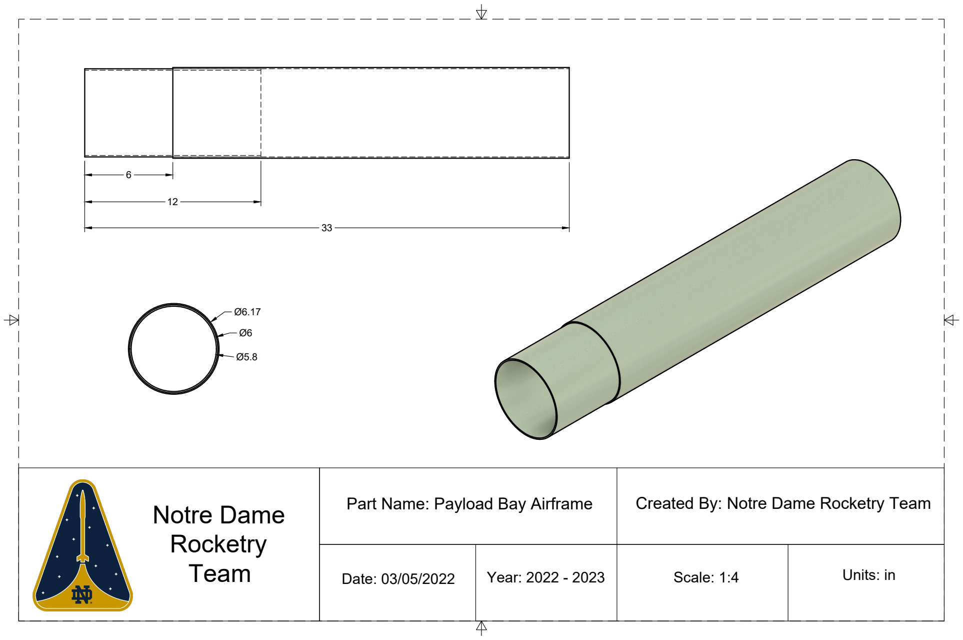


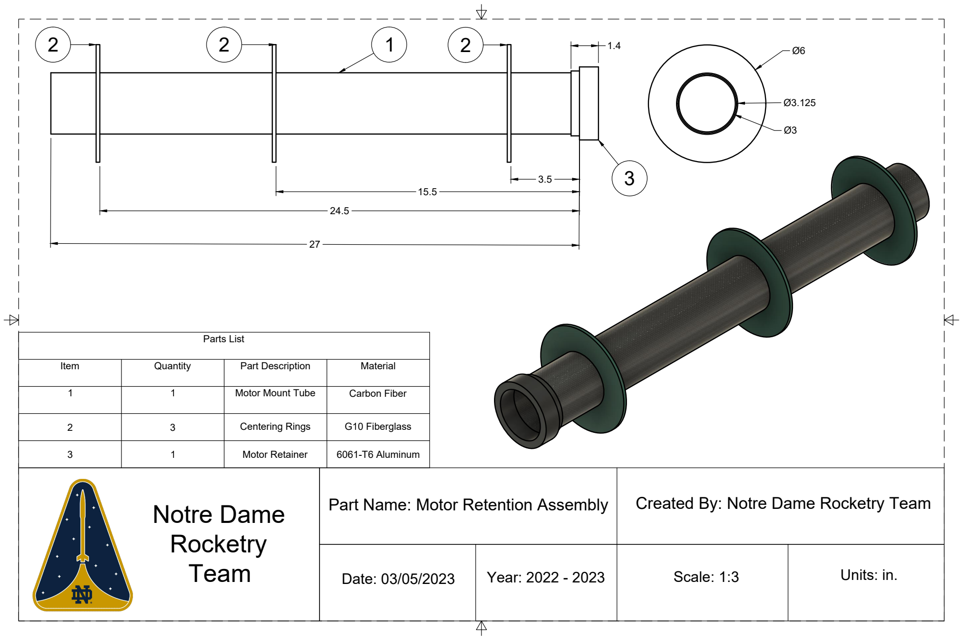
Figure 7: Payload Body Tube CAD Drawing

3.3.4 Motor Retention Assembly

The motor retention assembly consists of the motor mount tube, three G10 fiberglass centering rings, and the motor retaining ring. The purpose of the motor retention is to secure the motor during launch and direct the thrust of the motor through the center of mass of the launch vehicle. It also secures the motor to the fin can after burnout. The masses of each component can be seen in Table 12, and drawings of the assembly can be seen in Figure 8.

Table 12: Motor Retention Component Masses

Component	Mass (oz)
Motor Mount Tube	14.127
Centering Rings (3)	12.35
Motor Retainer	3.4
Epoxy	0.5
Total	30.377



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

Notre Dame Rocketry Team
Part Name: Motor Retention Assembly
Created By: Notre Dame Rocketry Team
Date: 03/05/2023
Year: 2022 - 2023
Scale: 1:3
Units: in.

Figure 8: Motor Retention Assembly CAD Drawing

3.3.5 Fins

Elliptical fins were chosen for the launch vehicle due to the minimized lift-induced drag, mass, and center of pressure characteristics in OpenRocket flight simulations. The fins were constructed from fiberglass due to its relatively low cost, ease of manufacture, and high durability compared to other options. Since the fins largely affect the location of the center of pressure, they are important for the stability of the launch vehicle. The shape and dimensions of the fins help achieve the static stability margin of 3.16 cals. Initially, the fins measured 6.00 inches in height and width. However, this contributed to a large stability value which caused a large amount of weather cocking during the first test launch. Therefore, with the permission of NASA, the fin size was then has been reduced with the permission of NASA to the values seen below in Figure 9. This moved the center of mass and the center of pressure, resulting in a new static stability margin of 2.49 cals. The other fin characteristics can be seen below in Table 13.

Table 13: Fin Characteristics

Characteristic	Value
Number of Fins	4
Cross-section	Elliptical
Height (in)	5.00
Root Chord (in)	6.00
Material	Fiberglass
Measured Total Weight (oz)	24.968

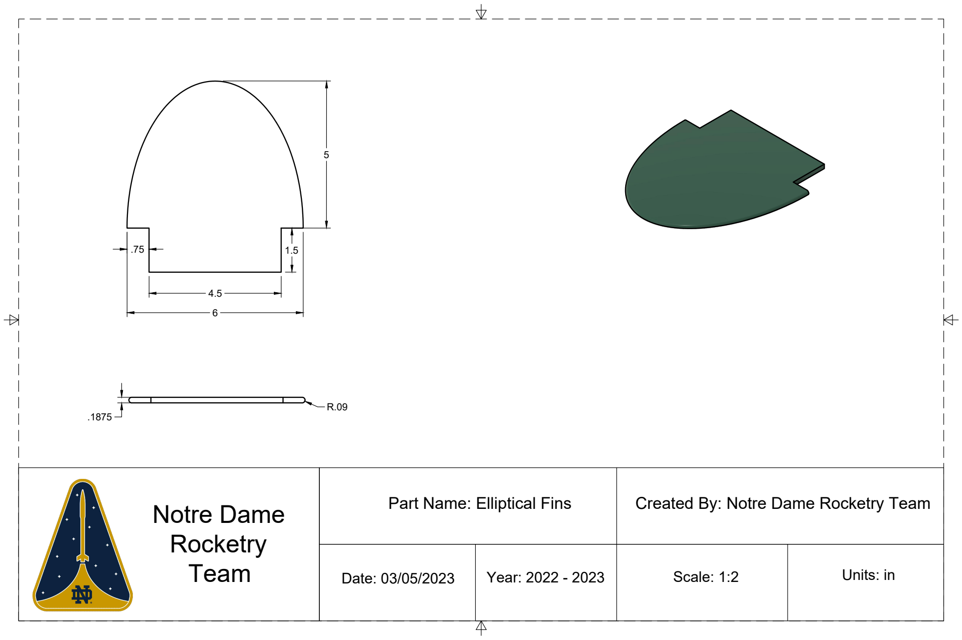


Figure 9: Fin CAD Drawing

Due to the change in fin size, the fin flutter predictions needed to be re-evaluated too. Figure 10 shows the vehicle demonstration flight velocity and the fin flutter threshold values. The figure clearly shows that, despite the reduction in fin size, flutter is not a concern for the fin design.

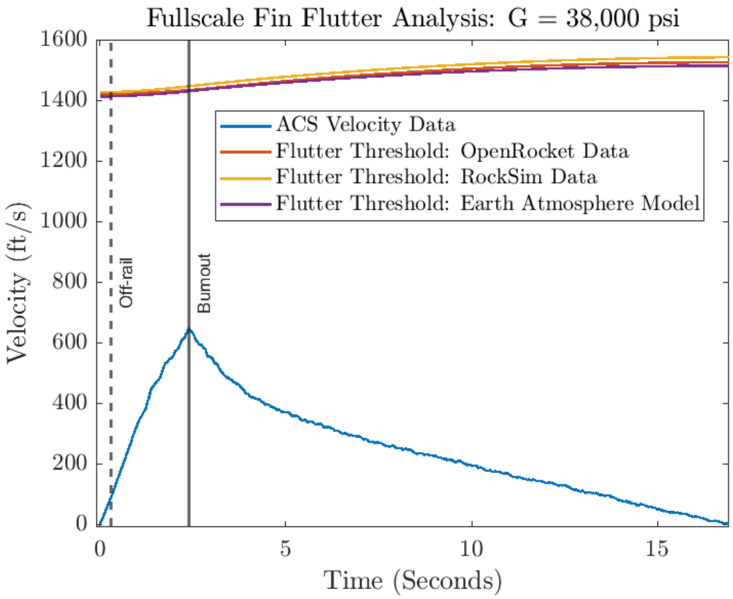


Figure 10: Fin Flutter Analusis of 5.00 in Height Fins

3.3.6 Fixed Bulkhead

The launch vehicle utilizes a fixed bulkhead in the Fin Can section of the airframe. This bulkhead serves as a pressure wall for the FED separation event. An eyebolt is mounted to the bulkhead as an attachment point for the recovery shock cord and drogue parachute. The bulkhead specifications can be seen in Table 14, and Figure 11 shows the bulkhead installed in the launch vehicle.

Table 14: Fixed Bulkhead

Parameter	Value
Outer Diameter (in.)	6.00
Inner Diameter (in.)	0.50
Thickness (in.)	0.187
Material	G10 Fiberglass
Eyebolt Eye Diameter (in.)	1.0625
Eyebolt Shank Diameter (in.)	0.4375
Eyebolt Shank Length (in.)	3.00
Eyebolt Material	Steel
Eyebolt Vertical Loading Capacity (lb)	2000
Overall Mass (oz)	5.60

Figure 11: Fixed Bulkhead Assembly

3.3.7 Camera Shroud

The camera shroud secures the camera onto the airframe while minimizing drag. The size of the shroud was based off of the Mobius 2 Action Cam. The overall design consists of two components: the camera holder and the shroud cap. The shroud has holes on the outside to allow access to the camera buttons when secured inside the holder. The shroud cap is attached onto the holder with two screws. The entire design is also at a 3 degree angle for a larger field of view for the lens. A drawing of the design is seen in Figure 12.

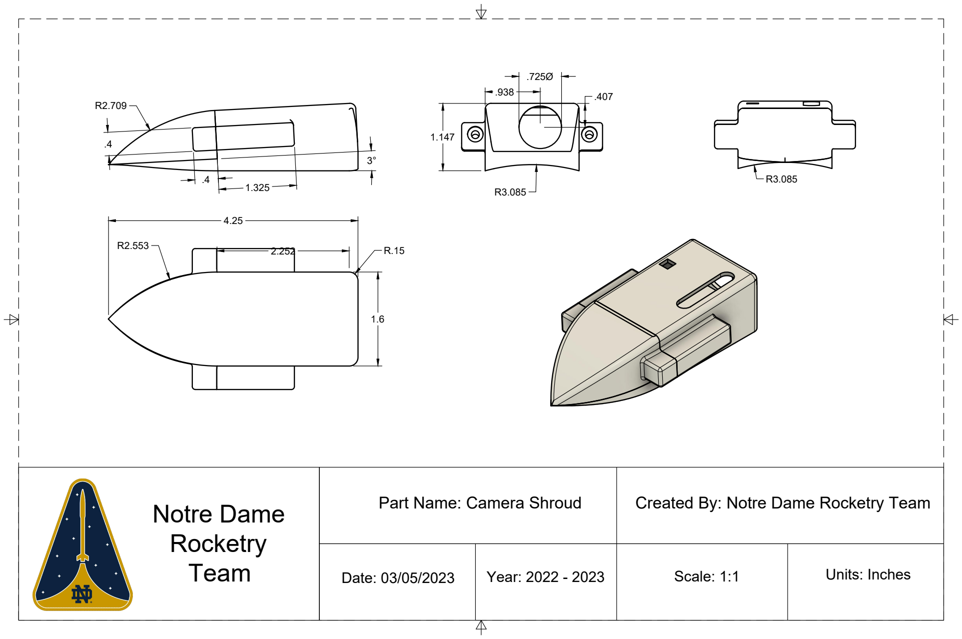


Figure 12: Camera Shroud Drawing

3.4 Construction

3.4.1 Body Tubes and Couplers

The body tubes were first measured and marked for cutting using tape and markers. The body tubes were cut using a bandsaw in the EIH. All team members wore face masks and all dust was vacuumed as the tubes were cut. According to the EIH workshop rules, all members present wore full length pants, close toed shoes, and short sleeves. Figure 38 show how the cuts were made in the workshop on certain body tubes.

(a) Carbon Fiber Body Tube Being Cut

(b) Fiberglass Body Tube Being Cut

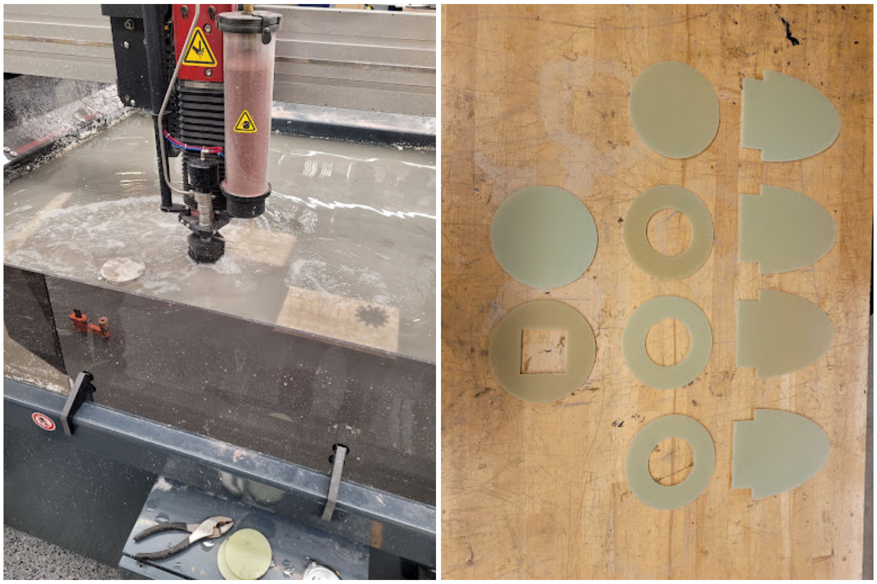
Figure 13: Body Tube Construction

Finally, construction on the body tubes concluded with hand sanding the areas where a cut was made. Face masks were worn during this process by all team members. Figure 14 shows the final image of the now cut body tubes. The couplers were attached to their respective bays and the nose cone ring to the nose cone shoulder using RocketPoxy. For each of this processes, safety glasses and gloves were worn to minimize exposure to epoxy resin.

Figure 14: Finished and Cut Body Tubes

3.4.2 Fiberglass and Carbon Fiber Sheets

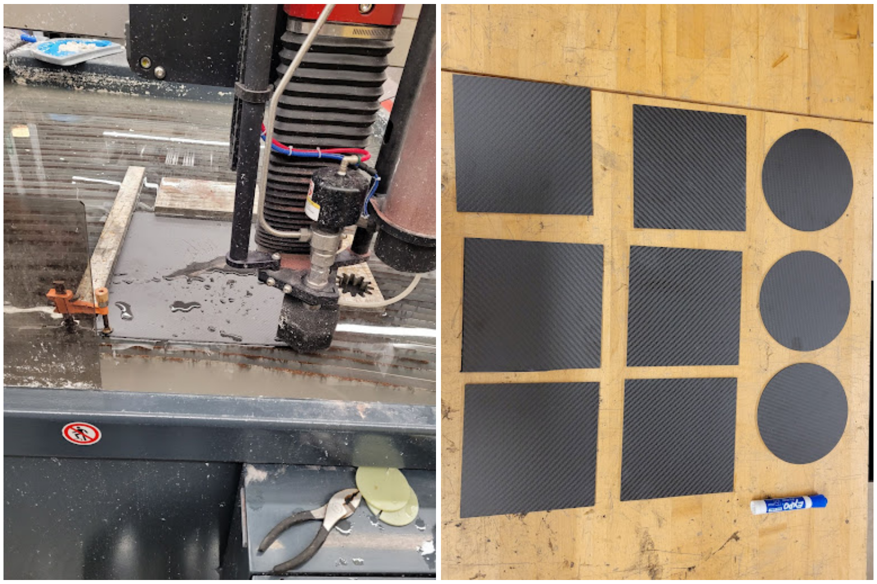
The fins, centering rings, fixed bulkhead, and Payload sled walls were constructed from G10 fiberglass sheets and were cut using the water jet in the EIH. All team members present during cutting wore safety glasses, full length pants, close toed shoes, and short sleeves in accordance with EIH regulations. Additionally, splash guards were used on the waterjet to reduce the risk of exposure to water-garnit-mixture. The DXF files used to cut the components were made in Autodesk AutoCAD using dimensions from the original CAD designs produced using Fusion 360. After being cut in the waterjet, parts were sanded to achieve final tolerance. Additionally, the profile of the fins were sanded into an airfoil shape to minimize drag. Since the fins were sanded by hand, the team used wet sanding to minimize the health risks incurred by fiberglass dust inhalation. Figure 15 shows the sheet during the cutting process and all of the components cut from the fiberglass sheets.



(a) Fiberglass Sheets Cut on Waterjet (b) Pieces cut from Fiberglass Sheet

Figure 15: Construction of Fiberglass Components

The carbon fiber sheets used to construct the remainder of the bulkheads as well as the removable bulkhead were initially cut out as squares using a water jet in the EIH. This was done to provide a clamping area for precise work using the CNC mill. All team members present during cutting wore safety glasses, full length pants, close toed shoes, and short sleeves in accordance with EIH regulations. The DXF files used to cut the components were made in Autodesk AutoCAD using dimensions from the original CAD designs produced using Fusion 360. Figure 16 shows one of the sheets mounted in the water jet prior to being cut and all of the components cut out of the sheets prior to milling.



(a) Carbon Fiber Sheet Cut on Waterjet (b) Pieces Cut from Carbon Fiber Sheet

Figure 16: Construction of Carbon Fiber Components

3.4.3 Fin Tab Slots and ACS Flaps

The ACS flaps and the slots for the fin tabs were cut in the CNC mill in the EIH. The Fin Can and ACS Bay were held in 3D printed jigs that the team designed in Fusion 360. This allowed for perfect 90° spacing for the flaps and fins. The team created a tool path and used an 1/8 in. end mill to cut the ACS flaps out of the ACS body tube. An 1/8 in. end mill was also used to cut the fin tab slots. The jigs and the process of cutting the slots and flaps can be seen in Figure 17.

(a) Body tube jigs (b) CNC milling

Figure 17: Cutting ACS Flaps and Fin Slots

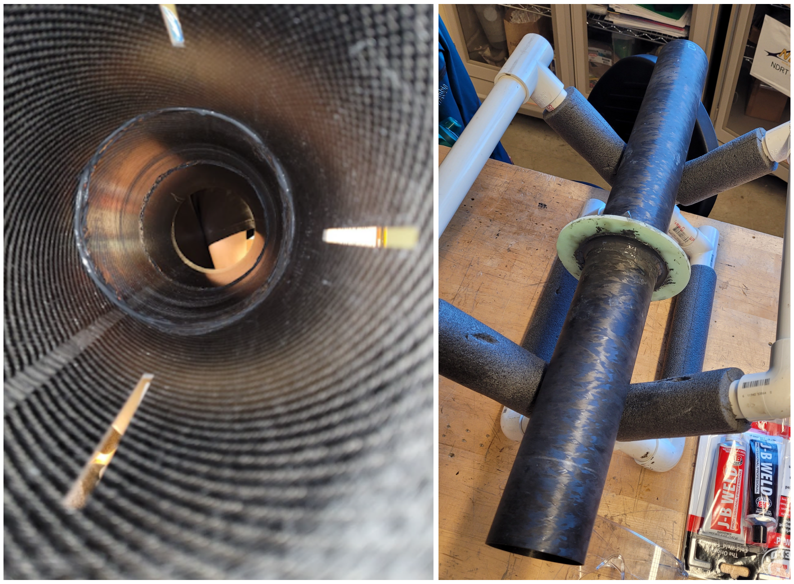
3.4.4 Centering Rings and Fixed Bulkhead

The team cut the fixed bulkhead out of a fiberglass sheet using the waterjet in the EIH, then used sandpaper to achieve a final tolerance for ease of construction. The drill press was then used to drill a mounting hole for the eyebolt, and the eyebolt was torqued in place. JB Weld was added to the nut to prevent it from loosening. Figure 18 shows the constructed bulkhead assembly as installed.

Figure 18: Constructed and Installed Fixed Bulkhead Assembly

3.4.5 Motor Retention Assembly

The motor mount tube was installed into the fin can with only the middle centering ring installed. JB Weld fillets were added to both sides of this middle centering ring, then the other two centering rings were installed by sliding them through JB Weld lines. JB Weld fillets were then added to the other side of these centering rings, ensuring that each centering ring has structural epoxy fillets on either side of it, and on both the motor mount tube and fin can. The motor retainer ring was then epoxied onto the end of the motor mount tube using JB Weld. Figure 19 show the installation of the motor retention assembly.



(a) Motor Mount Tube Inner Epoxy (b) Motor Mount Mid-Construction

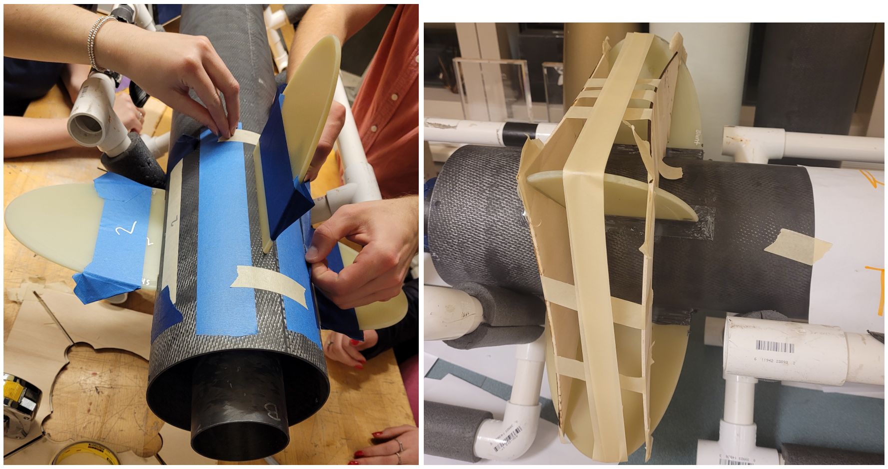
Figure 19: Installation of Motor Retention Assembly

3.4.6 Fin Can Assembly

The Fin Can assembly consists of the Fin Can tube, fins, motor retention assembly, and fixed bulkhead assembly. The motor retention assembly was installed into the fin can using JB Weld to ensure structural integrity at high operating temperatures, due to the proximity to the motor. The details of the motor retention assembly and its installation can be found in section 3.4.5. The bulkhead was then epoxied in place using West System epoxy. West System 406 Colloidal Silica was added to the epoxy to achieve the desired viscosity, and epoxy fillets were applied to both sides of the bulkhead to airframe joint.

3.4.7 Fin Alignment

The fins were then installed into the fin can. JB Weld was applied to the fin tab of each fin and the motor mount tube before each fin was installed into the fin can slots to create an epoxy joint between each fin and the motor mount tube. Epoxy was applied to the root chord of each fin, securing the fin to the exterior of the body tube. Painter's tape was used to create even fillets on all sides of the fins. A wooden jig made on the laser cutter was used to keep the fins at 90° angles as the epoxy cured. Figure 20 shows the fins being prepared for epoxy on the left and the fins curing in the alignment jig on the right.



(a) Epoxy Fillet Masking Lines (b) Fin Jig

Figure 20: Fin Alignment

Tape was wrapped around the jig to keep it in place. After the JB Weld dried, a final coating of West Systems epoxy was added to increase the structural strength of the epoxy fillets. Extra epoxy was removed later with sandpaper to minimize drag.

3.4.8 Rail Buttons and Camera Shroud

To attach the airfoil-shaped rail buttons, holes were drilled at the fore and aft of the fin can. The rail buttons were then screwed into the fin can. The holes were aligned to the vehicle body using a string to ensure vertical alignment with the central axis of the launch vehicle, and the rail buttons were then rigidly attached using epoxy as shown in Figure 21. Safety glasses and gloves were worn for all rail button construction work.

Figure 21: Rail Buttons Epoxied to Fin Can

The camera shroud assembly was 3D printed utilizing ABS plastic. The camera holder was epoxied to the Payload Bay with West Systems epoxy. The camera shroud is not aligned with rail buttons and fins. It is also 7 inches down from the front of the payload tube to prevent interference with the payload's integration or performance as shown in Figure 22. The shroud cap fits over the camera holder and is bolted together with two screws.

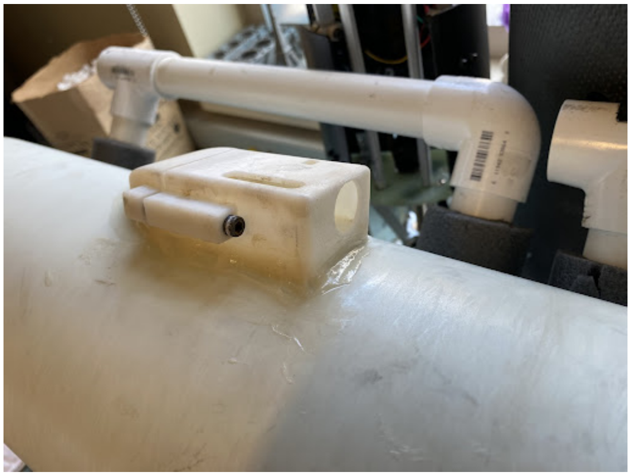
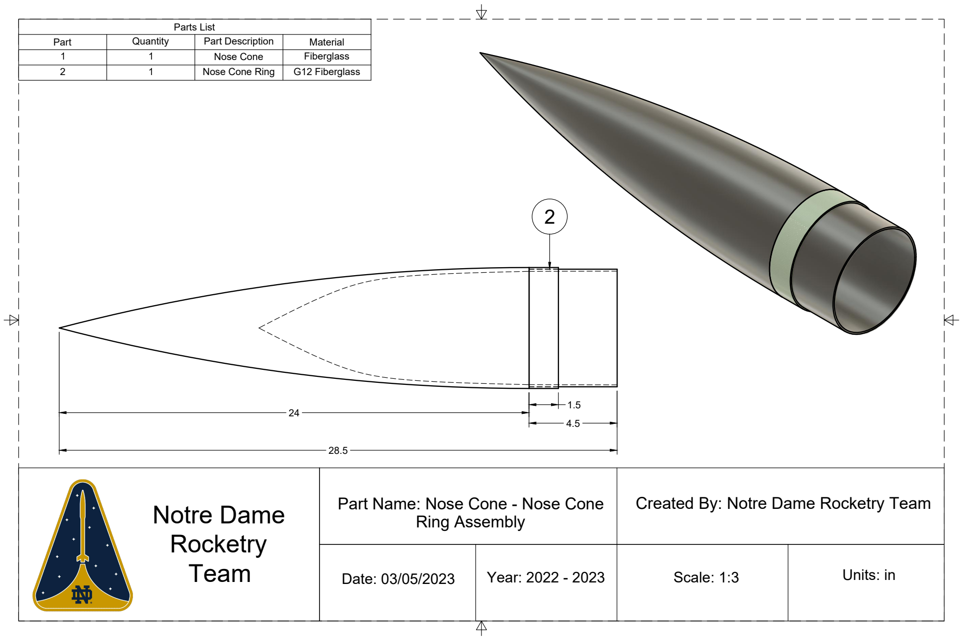


Figure 22: Camera Shroud Epoxied to Payload Tube

3.5 Launch Vehicle Detailed Design

3.5.1 Constructed Vehicle

After each individual section of the launch vehicle was constructed, the overall launch vehicle could be assembled. The nose cone CAD model can be seen below in Figure 23, and the as-constructed nose cone assembly can be seen in Figure 24.



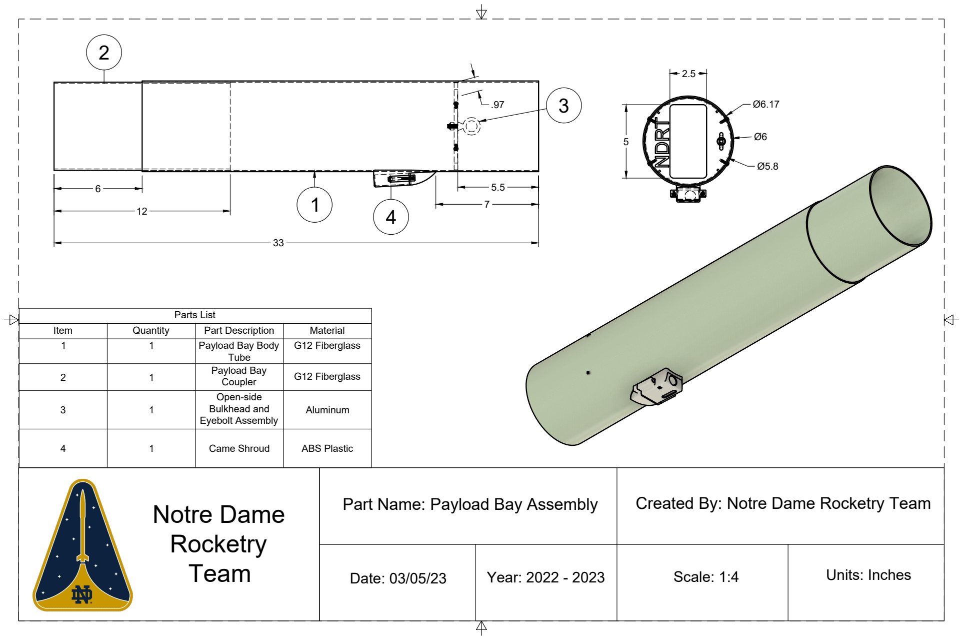
Parts List

Part	Quantity	Part Description	Material
1	1	Nose Cone	Fiberglass
2	1	Nose Cone Ring	G12 Fiberglass

Figure 23: Nose Cone Assembly Drawing

Figure 24: Nose Cone Assembly

The CAD for the Payload Bay Assembly is shown in Figure 25, and the fully constructed Payload Bay can be seen in Figure 26.



Parts List			
Item	Quantity	Part Description	Material
1	1	Payload Bay Body Tube	G12 Fiberglass
2	1	Payload Bay Coupler	G12 Fiberglass
3	1	Open-side Bulkhead and Eyebolt Assembly	Aluminum
4	1	Came Shroud	ABS Plastic

Notre Dame Rocketry Team

Part Name: Payload Bay Assembly

Created By: Notre Dame Rocketry Team

Date: 03/05/23

Year: 2022 - 2023

Scale: 1:4

Units: Inches

Figure 25: Payload Bay CAD Model

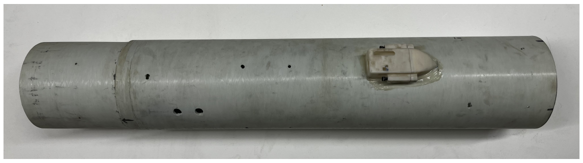


Figure 26: Constructed Payload Bay

The CAD model of the ACS Bay is shown in Figure 27, and the constructed ACS Bay is shown in Figure 28.

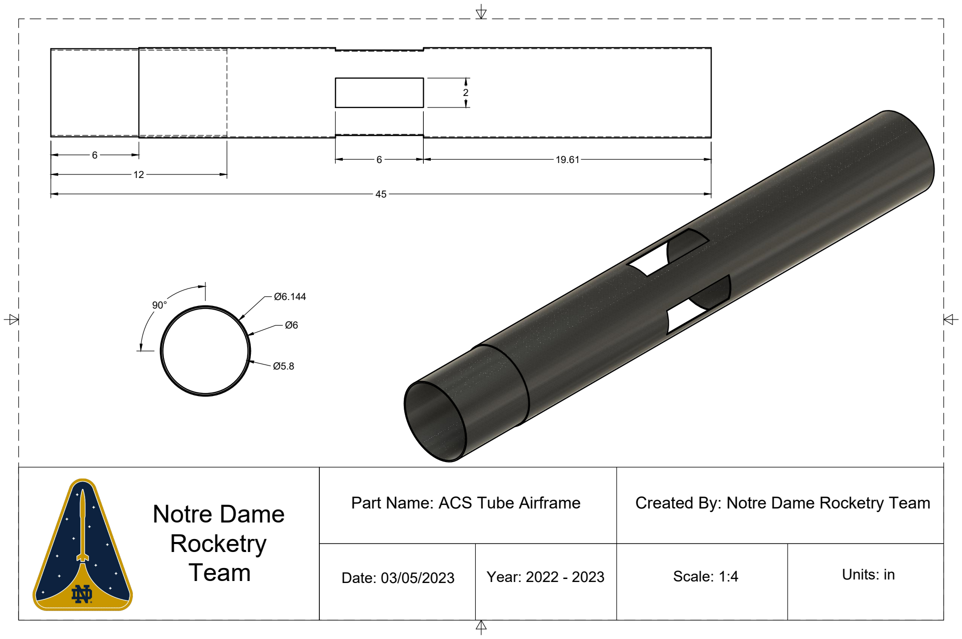


Figure 27: ACS Bay CAD Model

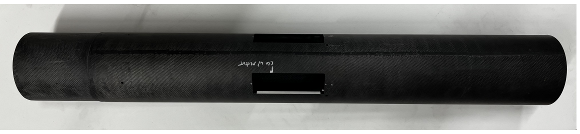
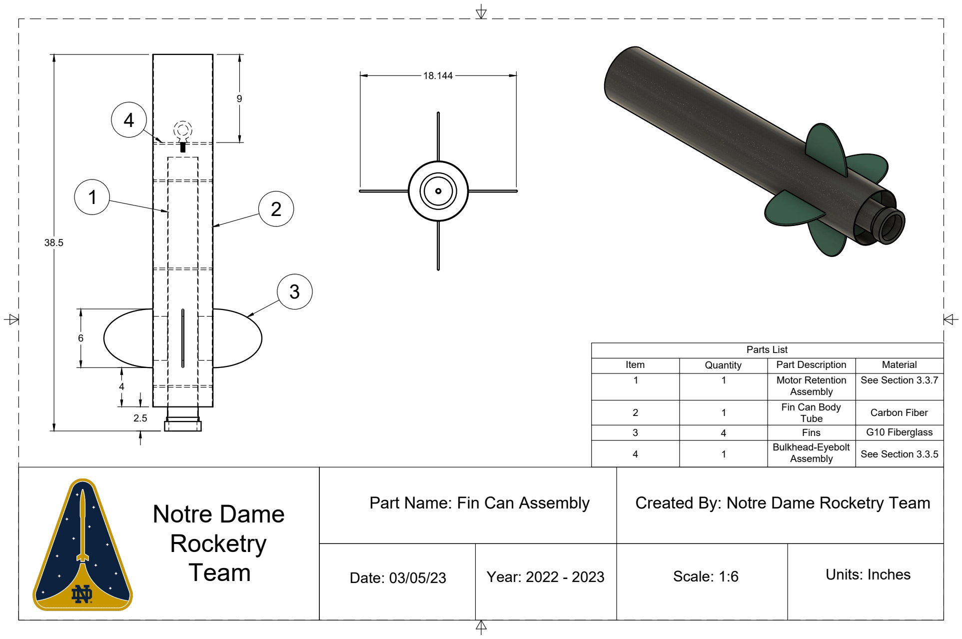


Figure 28: Constructed ACS Bay

Figure 29 shows the Fin Can CAD model, and Figure 30 shows the fully constructed Fin Can.



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 29: Fin Can CAD Model

Figure 30: Constructed Fin Can

The CAD for the overall launch vehicle is shown in Figure 31. Figure 32 shows the as-constructed fully assembled launch vehicle airframe.

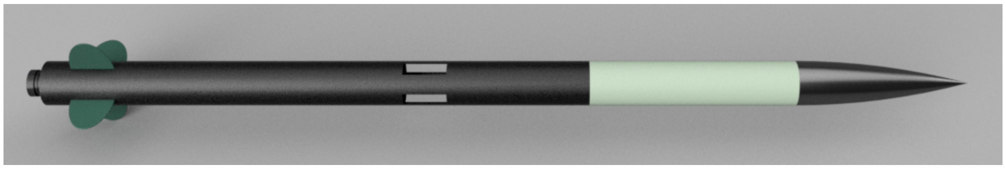


Figure 31: Launch Vehicle CAD Model

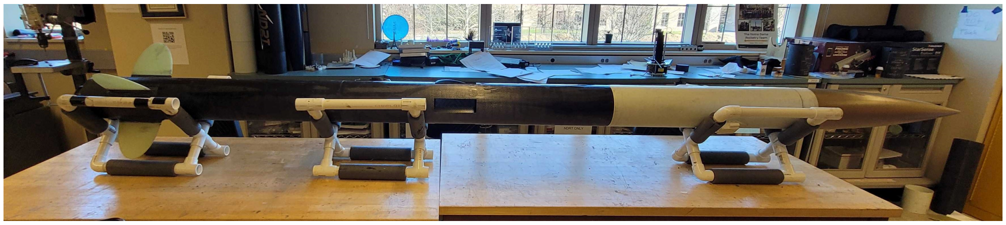


Figure 32: Photo of Fully Assembled Launch Vehicle

3.5.2 Mass Statement

Table 15 lists the detailed mass breakdown of the launch vehicle. Notably, the change in mass from CDR is due to the purchased items weighing out differently from the estimated values. Overall, a lighter launch vehicle is better for the overall mission performance, for it gives a wider range of options for apogee. To continue, Table 16 lists the section mass breakdown. Again, the lighter sections is better for kinetic energy purposes.

Table 15: Launch Vehicle Mass Breakdown

Component	CDR Predicted Mass Estimate (oz)	FRR Measured Mass (oz)	Allowable Mass (oz)	Margin (%)
Launch Vehicle	475.120	439.489	485.00	9.384
Recovery Device (PED)	33.932	38.900	115.00	1.826
Recovery Device (NED)	33.932	38.200		
Recovery Device (FED)	38.764	35.800		
Shock Cord	10.00	18.60	10.00	-86.000
Main Parachute	119.08	106	115.00	7.826
Drogue Parachute	18.83	26.20	20.000	-31.000
ACS	76.733	79.960	80.000	0.050
Payload	68.863	69.600	75.000	7.200
Total	875.257	852.749	900.00	5.250

Table 16: Launch Vehicle Independent Section Mass Breakdown

Section	Predicted Ascent Mass (oz)	Final Ascent Mass (oz)	Predicted Descent Mass Estimate* (oz)	Final Descent Mass* (oz)
Nose cone	79.691	81.013	69.689	63.507
Payload Bay	195.920	189.208	195.920	189.208
ACS Bay	309.676	271.808	171.766	158.582
Fin Can	289.970	310.720	200.770	195.320
Total	875.257	852.749	638.144	606.618

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

4 Technical Design and Construction: Vehicle Recovery System

4.1 Mission Statement and Success Criteria

The primary objective of the recovery system is to ensure the launch vehicle and the payload are not damaged during the descent of the vehicle. The system is also design to ensure the safety of any spectators watching the launch. The vehicle is required to be reusable per NASA Req. 2.3. which is largely dependent on the successful execution of the planned recovery events that slow the descent rate of the vehicle.

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 75 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 90 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

The launch vehicle will have three separation events and one recovery module for each event. The FED will deploy the drogue parachute immediately at apogee. The FED will trigger its event at 900 ft to separate the nose cone from the Payload Bay. No parachutes will deploy during this event and the nose cone will remain tethered to the vehicle via a shock cord. The purpose of this separation is to allow the payload to deploy out of the tube to complete its mission. The PED will deploy the main parachute at 608 ft which will slow the descent of the launch vehicle so that kinetic energy at impact is less than 75 ft-lb for any given section. The FED and PED modules are nearly identical with the only difference being the size of the bulkheads. The NED is also very similar in design but has a GPS on the top and the bulkheads are also different sizes. The detailed structures of the recovery modules can be found in Section 4.5.1.

4.3 Separations and Deployments

The separation and deployment of the stages of the launch vehicle are controlled by the recovery system's three modules. Black powder charges will be used to separate the body tubes and thus trigger the separation events. Ejection charges coupled to the motor will not be used for any of these events (NASA Req. 3.1.3). The decision to use black powder was made during CDR and remains valid due to black powder's low cost and high reliability.

4.3.1 Separation and Deployment Sequence

The first separation event will occur at apogee when the FED deploys the drogue parachute. The FED is situated in the ACS Bay with the charge wells oriented towards the fin can. The primary charge will detonate at apogee with backup charges 1s and 2s afterward in case of a charge misfire (NASA Req. 3.1.2). The second separation event will occur at 900 ft AGL. The NED will eject the nose cone from the Payload Bay while keeping it attached with a shock cord to allow the TROI to deploy. A backup charge will fire at 733 ft AGL (2 seconds after the primary charge given the predicted rate of descent). The final separation event is the deployment of the main parachute at 608 ft AGL. The PED module responsible for this event is situated between the Payload Bay and the ACS Bay. The backup charges were set to 560 ft AGL and 512 ft AGL. These values were picked due to technical limitations on the Raven4 that require altitudes to be selected in 32 ft intervals. The first and third charges are triggered by the Raven4 while the second charge is situated equidistant in altitude from both of Raven4 charges. This is possible because the SL100 responsible for triggering the second charge is not subject to the 32 ft selection limitation. The selected altitude values ensure that the main parachute will deploy above 500 ft and that at least 0.5 seconds exist between each detonation (NASA Req. 3.1.1). The ideal charge altitudes for the main parachute were calculated using the equation

$$h_{Ncharge} = 500 + \frac{1}{2}(3 - N)\, v_{drogue} \tag{1}$$

where N is the charge number (1 for first charge, 2 for secondary, 3 for tertiary), v_{drogue} is the descent rate of the vehicle under drogue (42 ft/s as of the time these altitudes were selected), and $h_{Ncharge}$ is the ideal height of the charge detonation. After these charge altitudes were tabulated, the nearest values that were available to be selected on the Raven4 that were above 500 ft and ensured at least 0.5 seconds of separation were selected as can be seen in Table 17, below.

Table 17: Main Parachute Charge Altitude Selection

Charge	Calculated Altitude (ft)	Selected Altitude (ft)
1	584	608
2	542	560
3	500	512

Figure 33 shows the sequence of separation events and the heights these will occur.

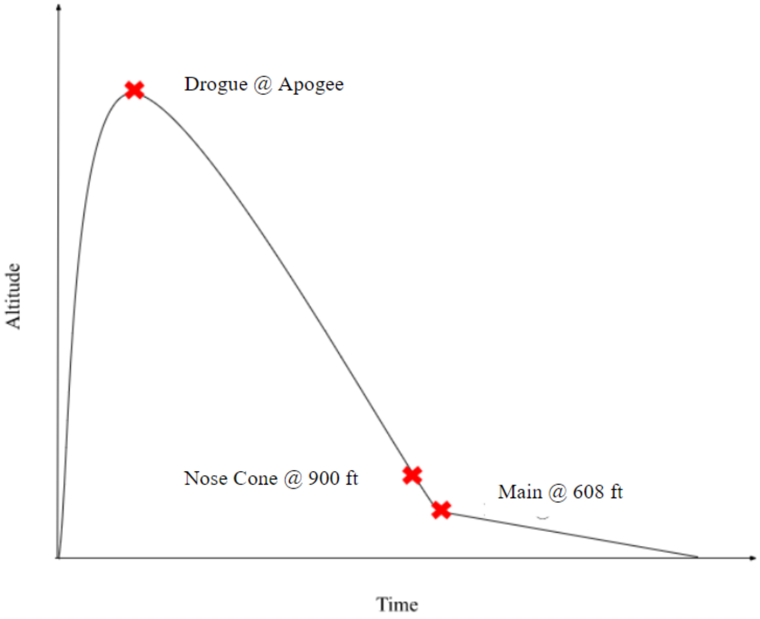


Figure 33: Descent Sequence

4.3.2 Ejection Charge Sizing

Figure 34 shows the locations of the black powder charges within the launch vehicle. The dimensions of each section are listed in Table 18

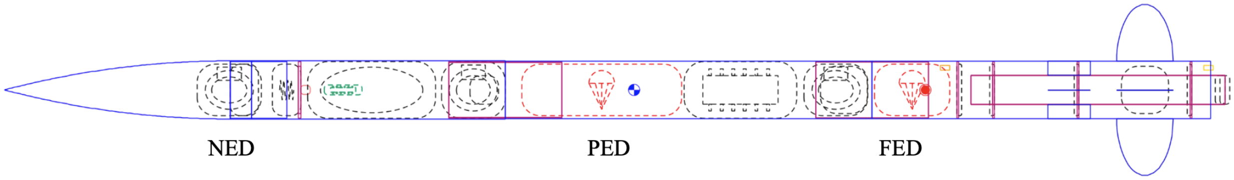


Figure 34: Location of Charges

Table 18: Dimensions of Pressurized Sections

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

Five 4-40 nylon shear pins will be used at each separation point satisfying NASA Req. 3.9. A factor of safety of 2 was applied when selecting the size and number of the shear pins to ensure the drag created as a result of ACS actuation would not prematurely separate the vehicle. Table 19 gives a description of the shear pins.

Table 19: Shear Pin Parameters

Parameter	Value
Size	#4-40
Length (in)	0.75
Diameter (in)	0.096
Material	Nylon
Shear Strength (psi)	10,000

The amount of black powder for the primary ejection charges, g_{bp}, that would be needed was calculated with the following equations:

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

$$\text{Moles of Gas Needed}: \; n_{\text{gas}} = \frac{F_{\text{shear}} L_{\text{sect}}}{RT}$$

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

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

$$\text{Grams of Potassium Nitrate Needed}: \; g_{\text{KNO}_3} = \frac{2}{4} n_{\text{gas}} \times \frac{101.1 \text{ g KNO}_3}{\text{mol KNO}_3}$$

$$\text{Grams of Black Powder Needed}: \; g_{\text{bp}} = g_{\text{C}} + g_{\text{S}} + g_{\text{KNO}_3}$$

After completing ground ejection testing, it was determined that additional black powder was needed to ensure successful separation events. 2 grams of black powder were added to each charge for the main deployment after the calculated sizes were insufficient to separate the tubes during a static ground test. This resulted in 6-gram charges that effectively separated the tubes without excessive force. Table 20 shows the final ejection charge sizes, as well as the final ejection altitudes for each charge.

Table 20: Summary of Separation Events

Separation Event	Altimeter Location	Parachute Deployment	Ejection Altitude	Ejection Charge Size (g)
Drogue Deployment	FED	✓	Apogee	3
			Apogee + 1 s	3
			Apogee + 2 s	3
Main Parachute Deployment	PED	✓	608 ft	6
			560 ft	6
			512 ft	6
Nose Cone Separation	NED		900 ft	2
			733 ft	2

4.4 Recovery Laundry

The team selected a main parachute and a drogue parachute to slow the vehicle to a safe rate of descent for recovery. A 2 ft Rocketman Elliptical Parachute was selected for its ability to slow the descent vehicle to a descent velocity optimized to reduce drift while also allowing the main parachute to deploy without exerting excessive force on the vehicle. The team selected a 12.8 ft SkyAngle XXL as the main parachute due to its ability to slow the descent vehicle to a rate of descent that yields a predicted kinetic energy under 75 ft-lb without excessive drift. Both are the same parachutes selected during CDR and details of each parachute and the associated laundry components will be discussed further in this section.

4.4.1 Main Parachute Assembly

The black powder charges in the PED are set to deploy the main parachute at 608 ft (complying with NASA Req. 3.1). This parachute will ensure that each section of the launch vehicle has a kinetic energy of no more than 75 ft-lb and a decent time of fewer than 90 seconds (NASA Reqs. 3.3 and 3.11, respectively). Figure 35 shows the main parachute with its specifications listed in Table 21.

Table 21: Main Parachute Description

Parameter	Main
Drag Coefficient, C_d	2.92
Brand	SkyAngleXXL
Diameter (ft)	12.8
Canopy Material	1.9 oz Silicon Coated Balloon Cloth
No. Shroud Lines	4
Weight (oz)	64
Packing Volume (in^3)	452

Figure 35: Main Parachute

The main parachute is stored in a 20-in. length, 6-in. diameter deployment bag from Fruity Chutes. The purpose of the deployment bag is to protect the main and pilot parachutes from any heat from the black powder detonations while also guiding it out of the body tube in an organized manner. A pilot parachute will also be used to ensure the main parachute is pulled out of the deployment bag. The use of a deployment bag also allows the main parachute to be packed in a controlled environment before arriving at the launch field reducing potential sources of inconsistencies. Figure 36 shows the pilot parachute included in the main parachute assembly with its specifications listed in Table 22.

Table 22: Pilot Parachute Description

Parameter	Pilot
Drag Coefficient, C_d	1.6
Brand	Fruity Chutes
Diameter (ft)	2
Canopy Material	1.1 oz Ripstop Nylon
No. Shroud Lines	8
Weight (oz)	2.2
Packing Volume (in^3)	12.2

Figure 36: Pilot Parachute

The main parachute is connected to the rest of the vehicle via two, 1.25 in. width tubular nylon shock cords rated for 4,400 lb from Rocketman Parachutes. There is a steel swivel attaching the parachute to the quick links at the center of the shock cords allowing the parachute to rotate freely during descent. The 10 ft cord is attached to the ACS Bay and the 15 ft cord is attached to the Payload Bay. Sizing and load rating justifications for the hardware can be viewed in Section 5.3.2. Table 23 displays the specifications for the main parachute shock cords that can be viewed in Figure 37. Table 24 describes the specifications of the fire-retardant blanket that will be used to protect the main parachute shock cords from singeing.

Table 23: Main Recovery Shock Cord

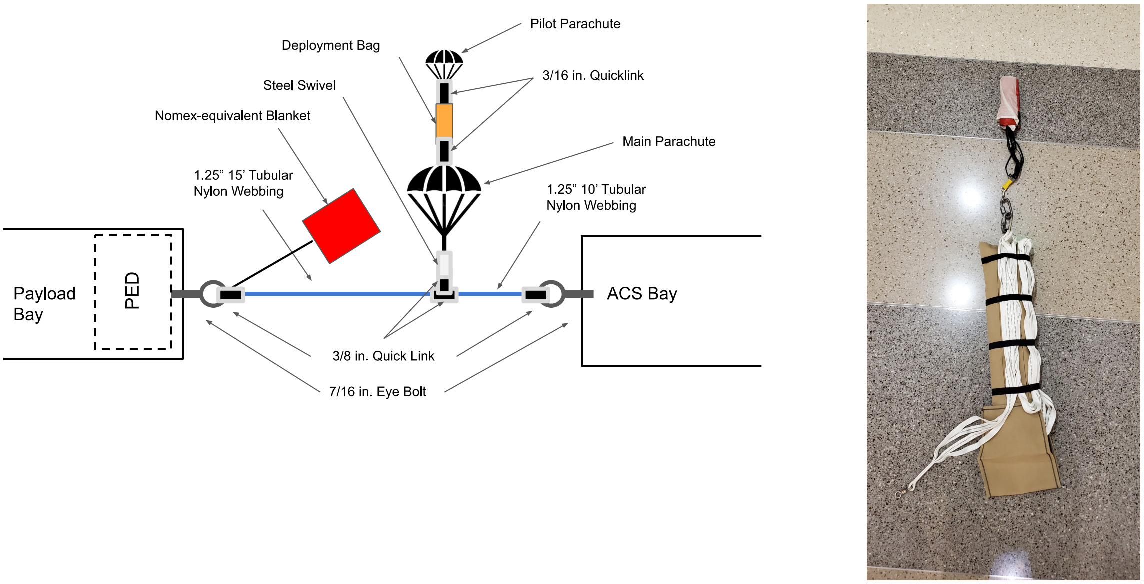
Parameter	Cord 1	Cord 2
Brand	Rocketman	Rocketman
Material	Tubular Nylon	Tubular Nylon
Width (in)	1.25	1.25
Length (ft)	15	10
No. Loops	2	2
Breaking Strength (lbs)	4400	4400
Weight (oz)	10.5	7.0

Figure 37: Main Shock Cord Assembly

Table 24: Main Shock Cord Protection Parameters

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

Figure 38 shows the main parachute schematic on the left and the folded main parachute as it will be put into the launch vehicle on the right. The pilot parachute will be tucked under the flap of the deployment bag that also covers up the shroud lines.



(a) As-Designed (b) As-Built

Figure 38: Main Parachute Assembly

4.4.2 Drogue Parachute Assembly

The drogue parachute deploys at apogee to initially slow the descent of the launch vehicle. A description of the drogue parachute can be seen in Table 25 and an image of it with its Nomex blanket can be seen in Figure 39.

Table 25: Drogue Parachute Parameters

Parameter	Value
Canopy Material	1.1 oz Ripstop Nylon
Brand	Rocketman
No. Shroud Lines	8
C_d	1.6
Diameter (ft)	2
Weight (oz)	2.1
Packing Volume (in^3)	12.16

Figure 39: Drogue Parachute

The drogue parachute is attached to both bulkheads with 5/8 in. thick tubular nylon shock cords each rated for 3200 lb. The 15 ft one will be attached to the ACS bay and the 10 ft one will be attached to the fin can. The specifications of the drogue shock cords can be viewed in Table 26 while the cords themselves can be seen in Figure 40. The drogue parachute and shock cords will be protected from the effects of the black powder with a fire retardant blanket which has specifications listed in Table 27.

Table 26: Drogue Recovery Shock Cord

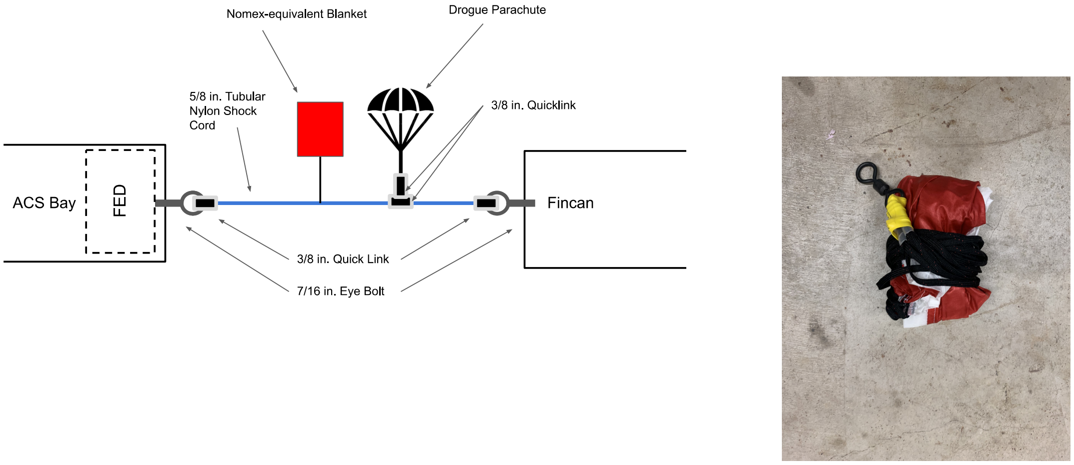
Parameter	Cord 1	Cord 2
Brand	Rocketman	Rocketman
Material	Tubular Nylon	Tubular Nylon
Width (in)	0.625	0.625
Length (ft)	15	10
No. Loops	2	2
Breaking Strength (lbs)	3200	3200
Weight (oz)	2.46	3.69

Figure 40: Drogue Shock Cord

Table 27: Drogue Parachute Protection Parameters

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

Figure 39 shows the drogue deployment diagram on the left and the drogue parachute as it will be folded before being put its blanket on the right. The size of the quick links used for the drogue shock cord has increased since CDR. Although the initial quick links were strong enough to handle the main deployment load, they were too small to fit around the 7/16 in. eye bolt on the bulkheads. The new 3/8 in. zinc quick links are large enough to fit aro



(a) As-Designed

(b) As-Built

Figure 41: Drogue Parachute Assembly

4.4.3 Nose Cone Ejection Assembly

The nose cone separation event will occur at 900 ft. The nose cone will remain tethered to the body tube for the duration of the flight with a 0.19 in. thick 25 ft long Kevlar shock cord. This shock cord will be connected to both the NED and PED eye bolts. A separate 0.19 in. Kevlar shock cord will connect the NED eye bolt to the carbon fiber removable wall in the payload body tube. This shock cord will be 5 ft long so that the force generated from the NED separation event pulls the removable wall from the aluminum ring it is mounted on. Due to continued supply chain issues with Rocketman, the intended shock cords to be used for this event that were ordered in January still have not been delivered to the team. As such, the first vehicle demonstration flight was attempted with alternate shock cords supplied by the team mentor. Pictures of the final shock cords to be used on the next vehicle demonstration flight will be included in the FRR Addendum report. Further analysis of the performance of the alternate shock cords will be discussed in Section 8.3. The specifications for the shock cords to be used once they arrive can be seen in Table 28. The NED deployment diagram is shown below in Figure 42.

Table 28: 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

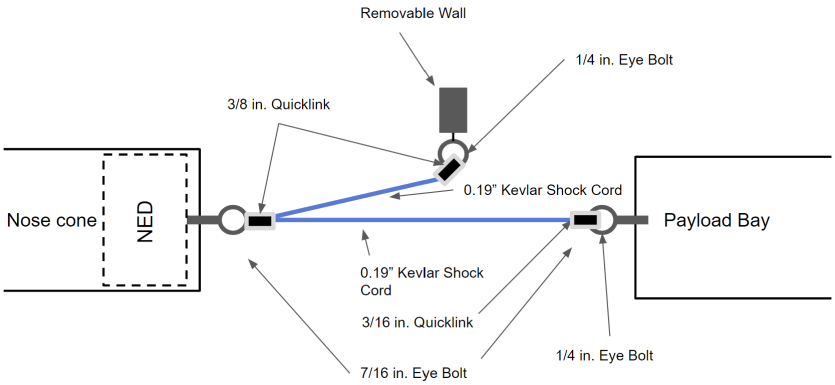
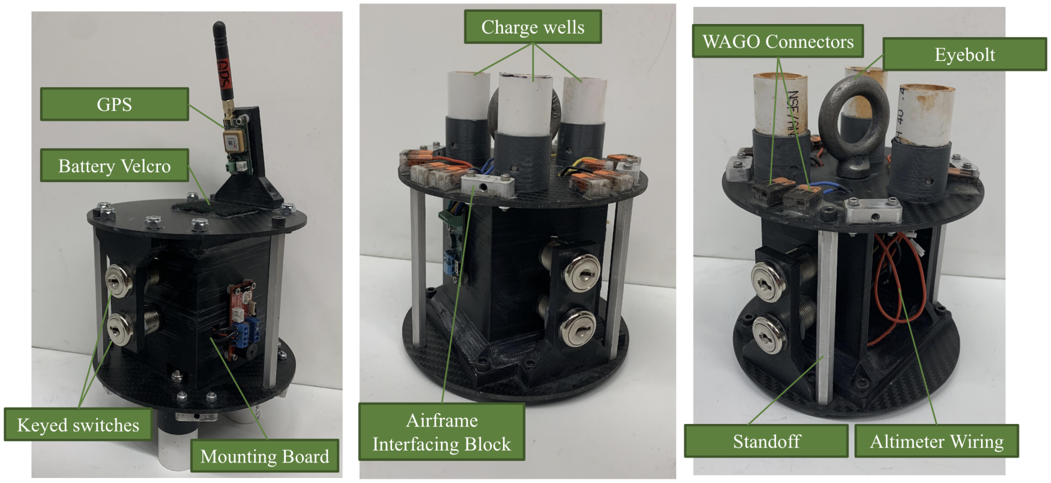


Figure 42: NED Deployment Diagram

4.5 Recovery Modules

The FED, PED, and NED are the three modules that provide black powder charge ignitions at desired altitudes. The structural elements of these modules were designed to withstand forces well beyond what they are expected to experience in flight. The altimeters, batteries, and wiring are protected within the modules to ensure that they safely separate the launch vehicle during flight. The following sections describe these modules in more detail. The final constructed modules are shown in Figure 43.



(a) NED (b) PED (c) FED

Figure 43: As-Built NED, PED, and FED Assemblies

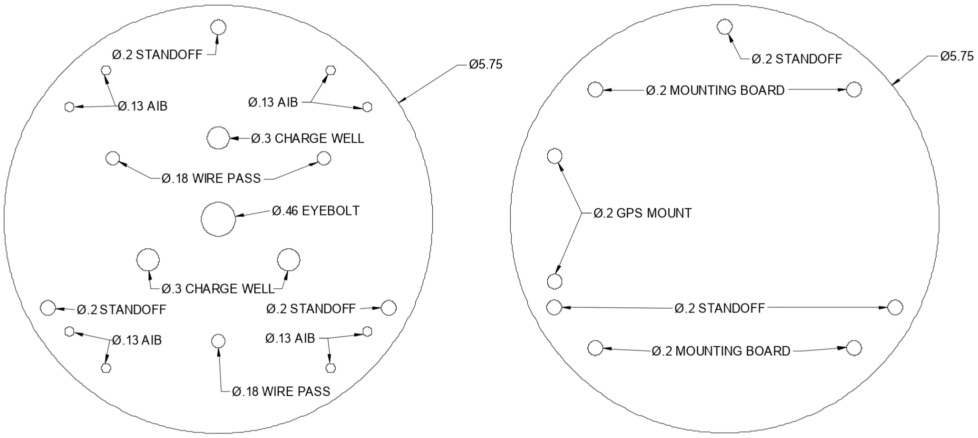
4.5.1 Primary Structural Elements

The largest loads the modules experience in flight is expected to occur during the main parachute deployment. The load from the main deployment travels through the shock cords to the eye bolts on each module. The properties of the eye bolts used are listed in Table 29.

Table 29: Eye Bolt Parameters

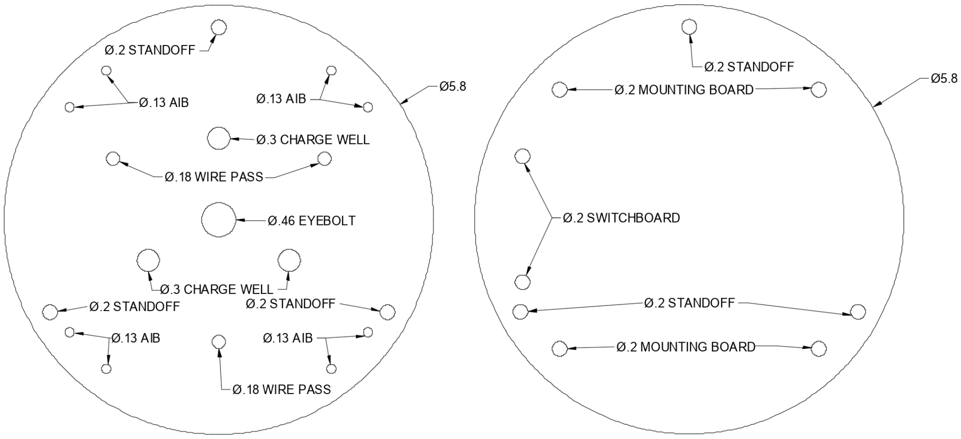
Parameter	Value
Material	Steel
Thread	7/16"-14
Breaking Strength (lbs)	2000

From there, the load is transferred to one of the two 1/8 in. thick carbon fiber bulkheads included on each module. All bulkheads were cut from the same carbon fiber sheet. The holes in the bulkheads were machined using a HAAS CNC mill to ensure they were in the correct locations and the correct size. The CNC mill also allowed the team to customize the outer diameter of each bulkhead which was useful as the modules are mounted in couplers and body tubes of differing inner diameters. The drill guides for the recovery module bulkheads can be viewed in Figures 44, 45, and 46, below. The machining process can be viewed in Figure 47, below.



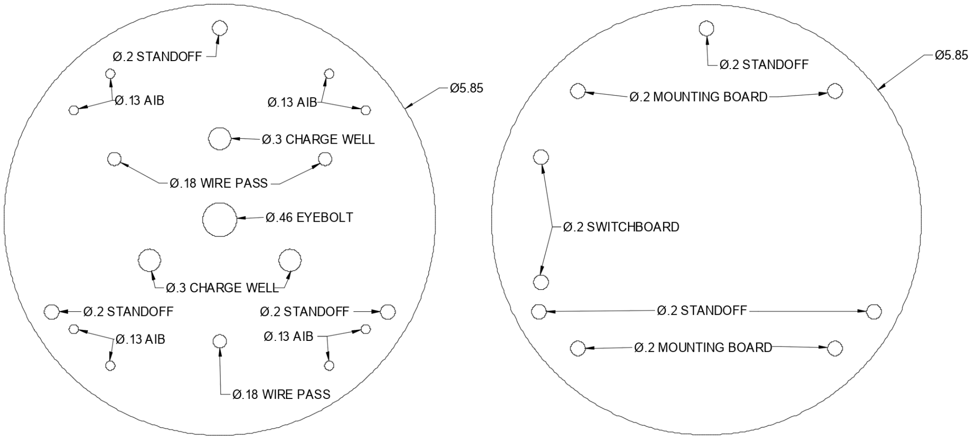
(a) NED (Top) (b) NED (Bottom)

Figure 44: Drill guide for NED bulkheads



(a) PED (Top) (b) PED (Bottom)

Figure 45: Drill guide for PED bulkheads



(a) FED (Top) (b) FED (Bottom)

Figure 46: Drill guide for FED bulkheads

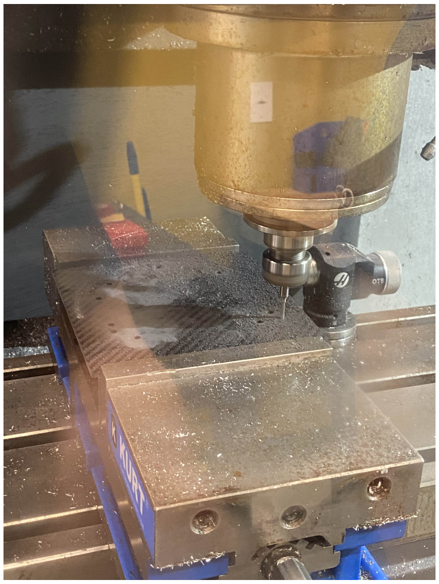


Figure 47: CNC Machining Process

Lastly, the bulkheads transfer the load to Airframe Interface Blocks (AIBs) that were cut and machined from aluminum stock using the same HAAS CNC mill. The AIBs then transfer the load to the body tube. Some AIBs were repurposed from last year to reduce the amount of new stock required. The AIBs interface with the bulkhead using 18-8 stainless steel socket head screws and with the body tube using 8-32 button-head screws. The drawings for the AIBs are shown below in Figure 48, below.

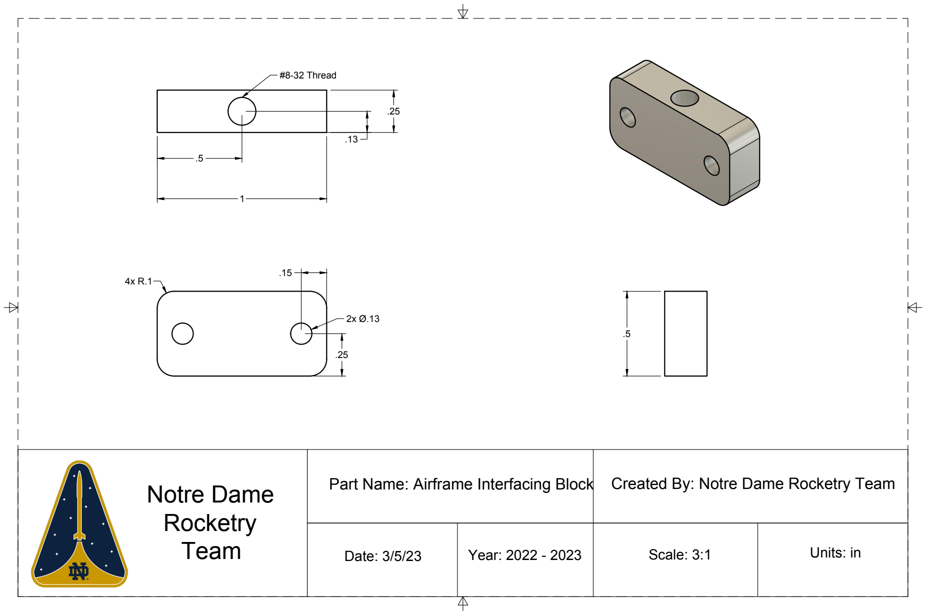


Figure 48: Airframe Interfacing Blocks

4.5.2 Secondary Structural Elements

The NED, PED, and FED contain several minimally load-bearing components in addition to 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 49, that are mounted on the face of the modules' aft bulkheads that face the separation end of the body tube. The charge wells are made of PVC and are secured to 3D-printed ABS end caps using epoxy. The previous design of the charge well from CDR included an 8-32 stainless steel screw mounted horizontally through the PVC and mount that affixed the PVC pipe to the ABS end cap. However, it has been determined that this was unnecessary as the heat-resistant JB Weld epoxy used to attach the components instead has been proven in previous years to be sufficient in holding end caps and PVC pipes together. The assemblies are attached to the aft bulkhead by bolting the end caps to the bulkhead with additional 8-32 stainless steel screws, lock nuts, and washers. In addition, the outer diameter of the PVC pipe has been downsized from the CAD presented in CDR to reflect the dimensions of the closest PVC pipe that was commercially available and was purchased for construction.

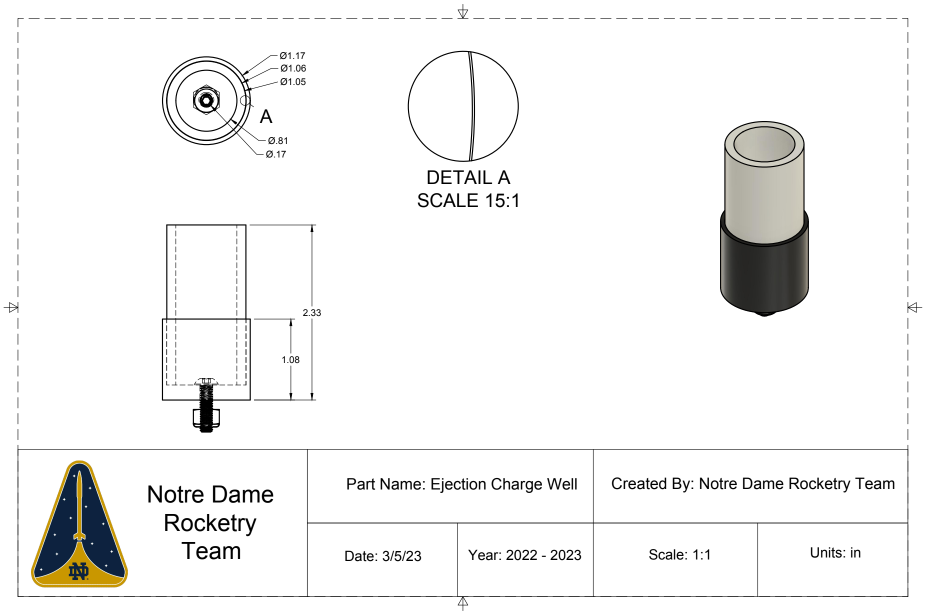


Figure 49: Ejection Charge Well

The altimeter mounting board and switchboard are enclosed between the bulkheads. Three aluminum turnbuckle standoffs are used to connect the fore and aft bulkheads in each recovery module. In the FED, PED, and NED, these standoffs are minimally load-bearing as the AIB 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 were 3D printed on a Stratasys F120 printer using ABS plastic and feature flanged 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. This allows for easy rewiring and fixes if necessary. The top of the mounting boards are free and not attached to the aft bulkhead to prevent loads from the aft bulkhead from accidentally passing through the piece. The altimeter mounting boards are U-shaped from above, like a rectangular prism missing one side and the top. This will allow them 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 flanged base during flight due to an inability to resist vibrations. The altimeter mounting boards for the PED and FED are identical while the NED has a modified version due to the fact that it has different altimeters. The drawing for the altimeter mounting boards can be viewed in Figures 50 and 51, below. The switchboard will not be U-shaped but will instead have chamfered walls near the flange to better resist vibrations that occur during flight. This can be viewed in Figure 52, below. The GPS mounting board was also designed to have chamfered walls near the flange to resist vibrations in flight. This can be viewed in Figure 53, below.

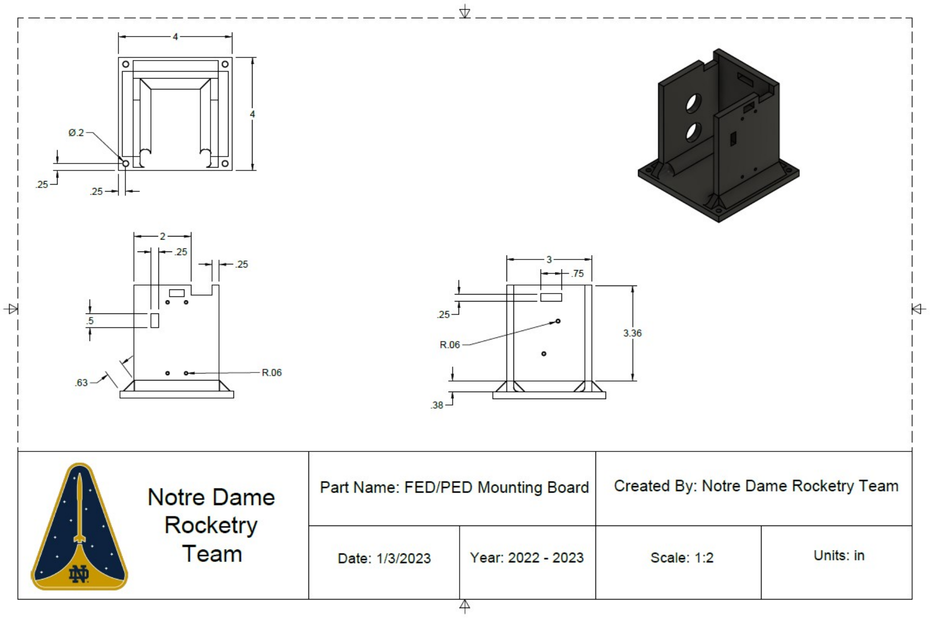


Figure 50: Altimeter Mounting Board for FED and PED

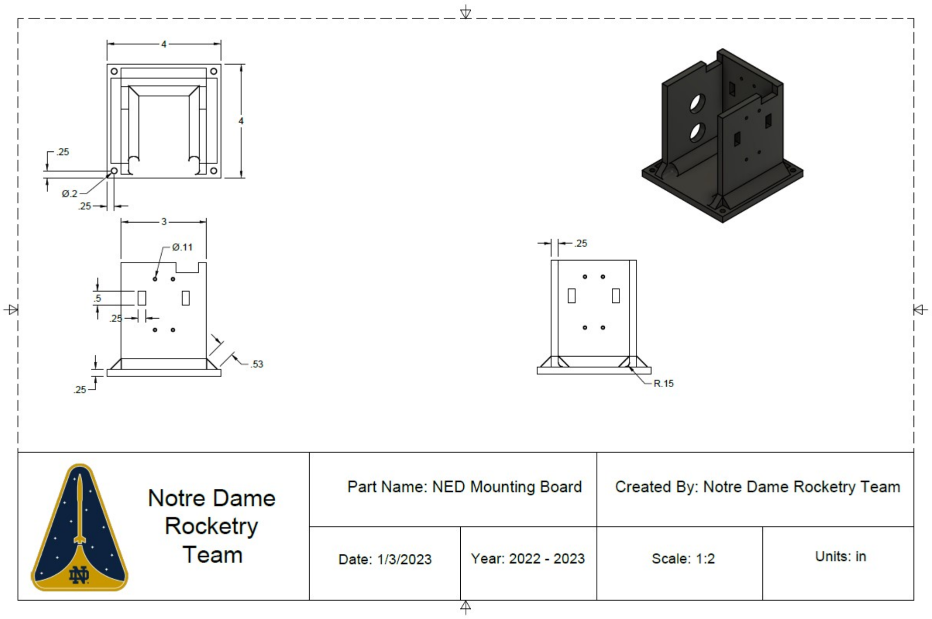


Figure 51: Altimeter Mounting Board for NED

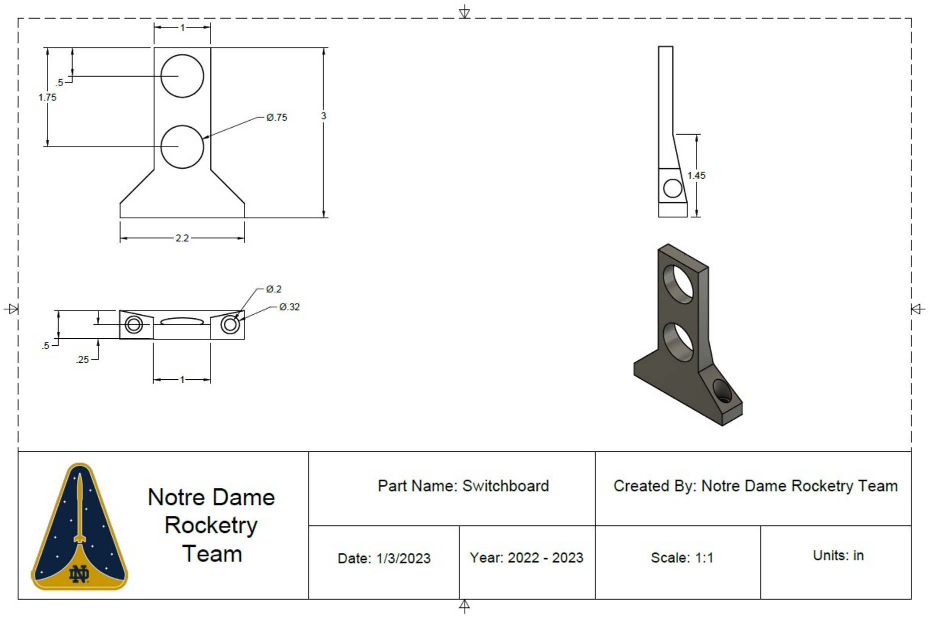


Figure 52: Switchboard

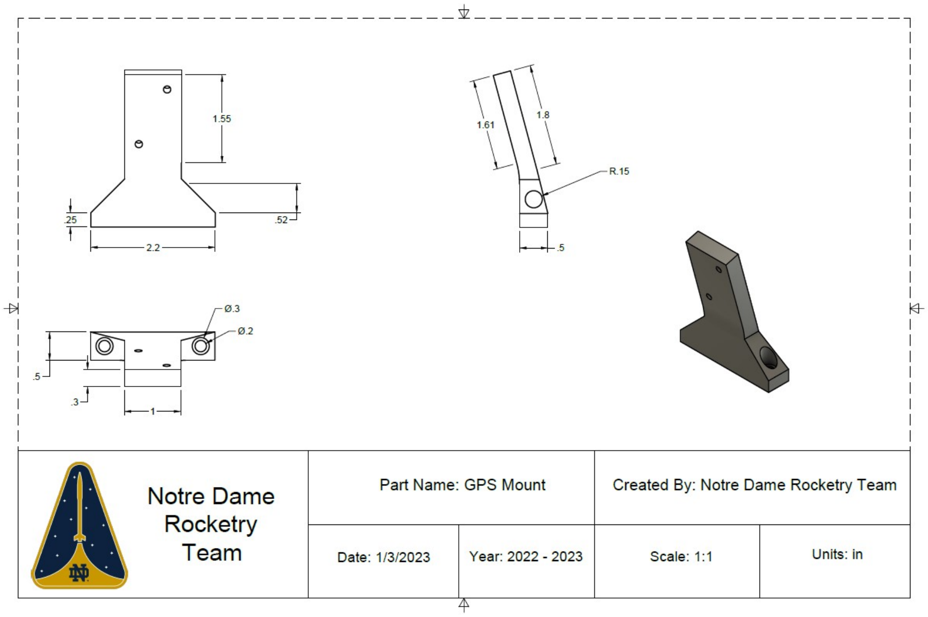


Figure 53: GPS Mounting Board

4.5.3 Hardware and Fasteners

The hardware and fasteners used to construct the modules remain largely unchanged from CDR. As noted in Section 4.5.2, charge well assembly screws were deemed unnecessary due to the sufficient strength of the epoxy connecting the 3D-printed charge well mount to the PVC well. None of the hardware and fasteners selected failed during the first VDF. The team standardized as many of the fastener sizes as possible for the modules to limit the number of unique components used in construction and make assembly easier. The full list of components and the number of them used in each module is shown in Table 30.

Table 30: Hardware and Fasteners on Each Recovery Module

Part	Frequency	
Module	NED	PED/FED
Aluminum Hex Standoff	3	3
Black-Oxide Alloy Steel Socket Head Screw	14	12
Airframe Interface Socket Head Screw	8	8
Large Nylon-Insert Lock-nut	11	9
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 Lock-nut	10	6
Stainless Steel Body Tube Screw	4	4
Chargewell Mounting Screw	3	3
Chargewell Assembly Nut	3	3

4.6 Avionics

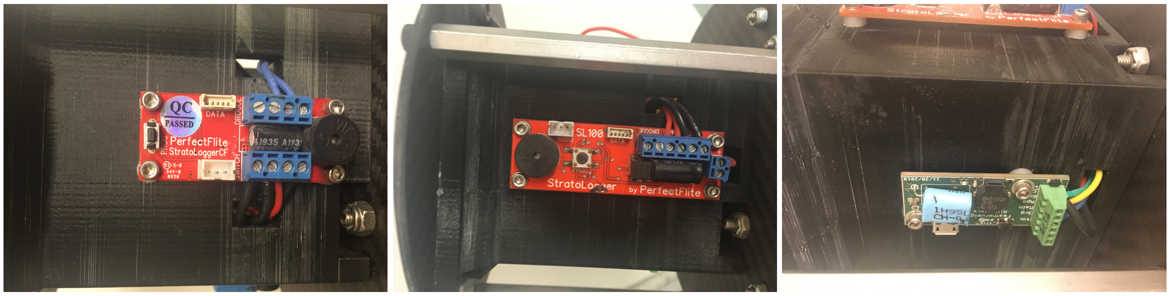
The electronics used in the recovery modules either catalyze recovery events or locate the vehicle during the descent. These systems operate independently of both other payloads onboard the vehicle (NASA Req. 3.8). These electronics are also shielded from interference from any of the other onboard electronics by the carbon fiber bulkheads which absorb and attenuate RF transmissions (NASA Req. 4.1). The detailed layouts and descriptions of the electronics selected for the recovery modules will be discussed in this section.

4.6.1 Altimeters

Each of the three recovery devices contains two altimeters for a total of six on the vehicle. The NED has two Stratologger SLCFs while the FED and the PED both have a Featherweight Raven4 and a Stratologger SL100. Having two altimeters on each module ensures the avionics are redundant decreasing the likelihood of a failed event (NASA Req. 3.4). Even if one altimeter on a module fails completely, the event should still occur without incident. The Raven4 altimeters have proven to be the most reliable in the past and have thus been assigned to complete the recovery events that deploy parachutes. Each altimeter was wired to an independent switch and battery (NASA Req. 3.5 and 3.6). Altimeters were tested before the launch by the team to ensure they were operational and undamaged. These tests can be referenced in Section 10. The specifications of the altimeters can be viewed in Table 31, below. Pictures of the altimeters integrated into the modules can be seen in Figure 54

Table 31: Specifications of Altimeters

Property	SL100	SLCF	Raven 4
Alt. Selection Interval (ft)	1	1	32
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
Measured Mass (oz)	0.45	0.40	0.30
Current Draw (mA)	1.5	1.5	<5

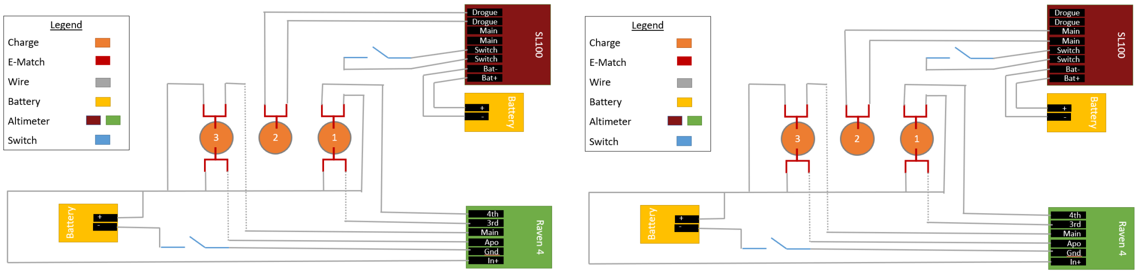


(a) StratologgerCF (b) Stratologger SL100 (c) Raven4

Figure 54: Altimeters Used in Launch Vehicle

The altimeters are shielded from the only transmitting device on the vehicle, the GPS, by the fore carbon fiber bulkhead on the NED. The closest altimeter to the GPS, one of the SLCFs on the NED, is 5 in. from the antenna. Through ground tests and the VDF flight it has been shown that the altimeters are not sensitive to this transmitter. All of the data from the SLCFs on the NED aligns with the altimeter readings from the PED and FED altimeters. Additionally, all the events were triggered at the correct altitudes further meaning the altimeters are not affected by the transmitter. Shielding and related topics and its associated tests are further discussed in Section 10.

Since CDR, the number of e-matches per charge well has been reduced due to unforeseen altimeter limitations. Each of the Raven4's event channels can be programmed to trigger an e-match at a specific altitude or time after apogee. For example, the "Main", "Drogue", "3rd", and "4th" channels can all be programmed to trigger an event at a specific altitude. As such, each Raven4 can trigger 4 e-matches as planned in CDR. However, the Stratologger SL100 and SLCF are not as flexible. The "Main" channel can only be programmed to trigger an event at a specific altitude and the "Drogue" channel can only trigger apogee events. As such, the Stratologgers can not be used to trigger two events at two different altitudes as intended during CDR. This has resulted in several wiring changes that can be viewed in the wiring diagrams viewable in Figures **??** and 56, below.



(a) FED Wiring (b) PED Wiring

Figure 55: PED/FED Wiring

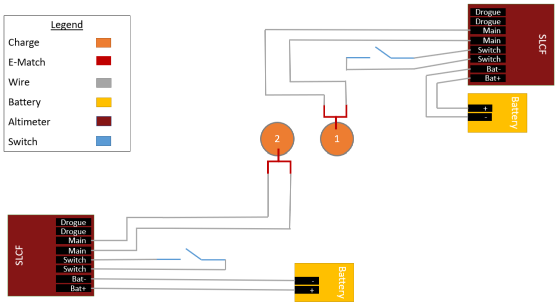


Figure 56: NED Wiring Schematics

Charges 1 and 3 on the PED and FED will have two e-matches in their charge wells. However, Charge 2 will only have one e-match to trigger it due to the SL100 limitations. On the NED, only one e-match will be wired to each of the two charges due to the limitations of the SLCF altimeters. While this is less redundant than planned during CDR, consultations with the team mentor have instilled confidence that the system is still redundant enough to ensure successful events. As is further discussed in Section 8.3, all charges were triggered as planned in the first VDF which suggests charge misfires in the future are unlikely. Additionally, the module with the least redundancy, the NED, is responsible for the least essential event for vehicle safety as it does not deploy a parachute.

The altimeters are attached to the recovery devices using steel 4-40 screws and lock nuts. Plastic spacers were placed between the altimeters and their mounting boards to prevent abrasion and short-circuiting. The 4 Stratologgers are powered by Tattu 1S Lithium Polymer batteries while the Featherweight Raven 4 is powered by an E-Flite 1S Lithium Polymer battery. These batteries have specifications listed in Table 32. Battery life will be tested in accordance with the test listed in test LVT.3, INT.1 as described in Section 10. These batteries are attached to the recovery device via velcro that has been proven to withstand in-flight vibrations.

Table 32: 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 is secured on the NED and is the only transmitting device on the vehicle. Only one GPS is necessary because all launch vehicle components will remain tethered together during descent. The Featherweight GPS Tracker allows the GPS to provide real-time altitude and location data directly to the team through the use of a ground station that transmits the data to an iPhone. The Featherweight GPS tracker specifications are detailed in Table 33. The range value was experimentally tested by the manufacturer and is dependent on a line-of-sight connection. The strength and range of the signal did not falter during either the subscale or the first VDF launch. The battery specifications for the GPS are detailed in Table 34.

Table 33: Featherweight GPS Specifications

Battery Parameter	Value
Frequency (MHz)	903-924.6
Average Wattage (kW)	20
Range (ft)	>145,000

Table 34: 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 located in the PED, FED, and NED will all be armed using McMaster-Carr keyed rotary switches. These will be located on the recovery modules and be accessible from the exterior of the launch vehicle. These switches are resistant to vibrations and will not be able to be deactivated in flight in accordance with NASA Req. 3.7. WAGO wire connectors are used throughout the modules in order to ensure ease of connection from the altimeters to the black powder charges. They allow the charges to easily be connected to the altimeters at the launch field by the team mentor. The wires used are stranded rather than solid core as it has a higher resistance to vibrations.

5 Mission Performance Predictions

5.1 Flight Ascent Analysis

5.1.1 Prelude: Initialization of Simulations

Flight conditions range from launch angles of 5, 7 and 10 degrees and for each launch angle, wind speeds are at 0, 5, 10, 15, and 20 mph. For initializing the data, the temperature and pressure was set to the standard temperature and pressure (STP) values of 59 F and 14.7 psi. For the wind direction, the launch vehicle is directed into the wind so it doesn't drift as far and is easier to retrieve.

5.1.2 Altitude

Table 37 lists the altitude flight profile for OpenRocket on the left side and RockSim on the right side.

Comparing the left and right side of the table, it is evident that the simulators line up closely to each other. In order to quantify their similarly, Table 35 lists the apogee values for OpenRocket for all flight conditions. Similarly, Table 36 lists the apogee values for RockSim for all flight conditions.

Table 35: OpenRocket Predicted Apogee for Various Flight Conditions, measured in feet

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	5403.6	5375.6	5333.4	5262.5	5234.2
7° Angle	5363.6	5319.8	5268.2	5212.2	5153.8
10° Angle	5267.7	5210.0	5145.5	5078.6	5010.6

Table 36: RockSim Predicted Apogee for Various Flight Conditions, measured in feet

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	5415.2	5389.1	5353.8	5313.7	5270.1
7° Angle	5372.7	5334.6	5291.1	5243.8	5194.0
10° Angle	5277.7	5226.8	5172.3	5115.4	5057.4

Table 37: OpenRocket (Left) and RockSim (Right) Predicted Altitude for Various Flight Conditions

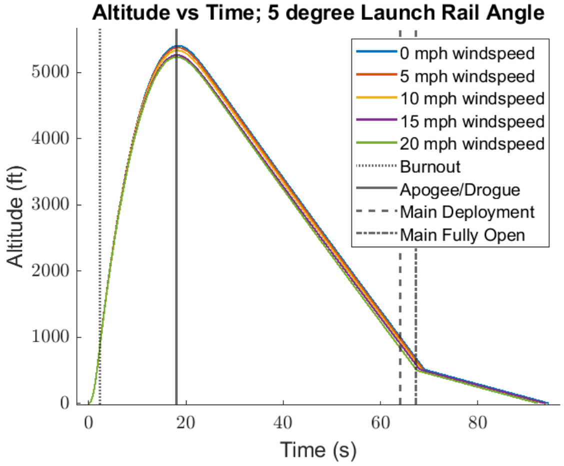
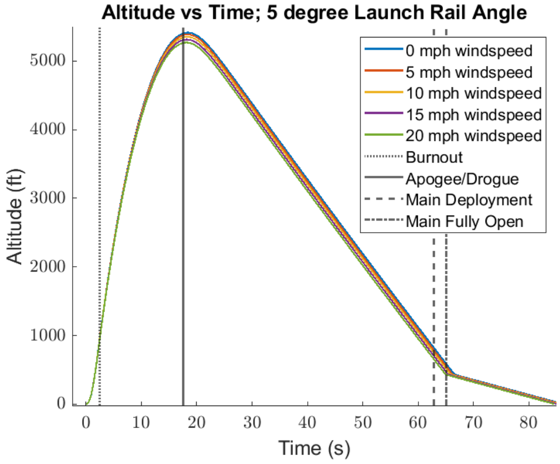
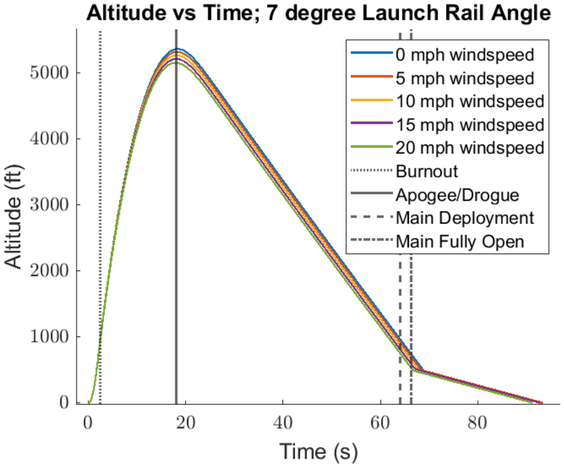
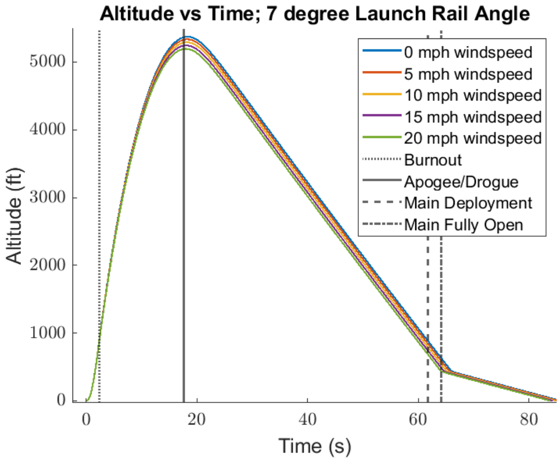
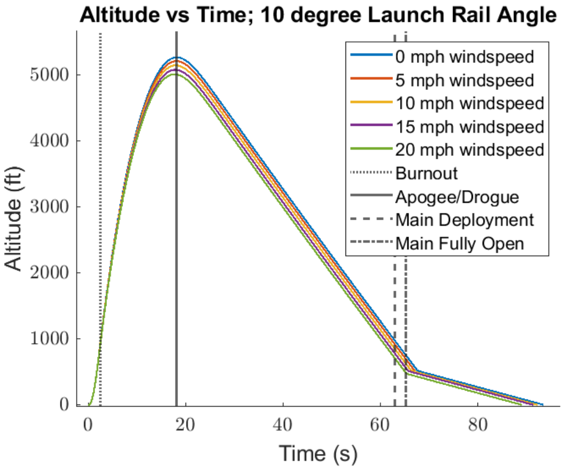
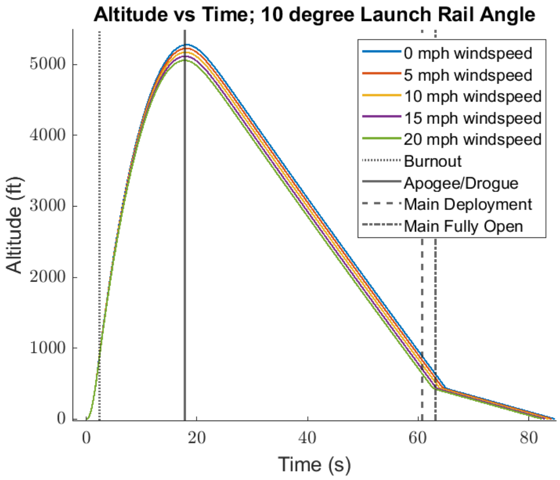
OpenRocket	RockSim
 Altitude vs Time; 5 degree Launch Rail Angle 	 Altitude vs Time; 5 degree Launch Rail Angle
 Altitude vs Time; 7 degree Launch Rail Angle 	 Altitude vs Time; 7 degree Launch Rail Angle
 Altitude vs Time; 10 degree Launch Rail Angle 	 Altitude vs Time; 10 degree Launch Rail Angle

Table 38 lists the difference between the OpenRocket and RockSim apogee values. From the table, it is evident that there is a positive trend between the wind speeds and the difference between apogee values. This information is important to keep in mind for the next vehicle flight. Given that the OpenRocket was more accurate to the vehicle demonstration flight's apogee than RockSim and the wind conditions during such flight were on the upper echelon of flight conditions, RockSim Apogees are not to be trusted in higher wind speeds; it is unknown at the moment how RockSim holds up at lower wind speeds.

Table 38: Difference in Apogee Values Between OpenRocket And RockSim, measured in feet

	0 MPH Winds	**5 MPH Winds**	**10 MPH Winds**	**15 MPH Winds**	**20 MPH Winds**
5° Angle	11.6	13.5	20.4	51.2	35.9
7° Angle	9.10	14.8	22.9	31.6	40.2
10° Angle	9.98	16.8	26.8	36.8	46.8

5.1.3 Velocity

Table 41 lists the vertical velocity flight profile for OpenRocket on the left side and RockSim on the right side.

Comparing the left and right side of the table, it is evident that the simulators line up closely to each other. There is one striking difference at apogee, where only RockSim has a spike in velocity when the drogue comes out. In order to quantify the similarly in vertical velocity overall, Table 39 lists the maximum vertical velocity values for OpenRocket for all flight conditions. Similarly, Table 40 lists the maximum vertical velocity values for RockSim for all flight conditions.

Table 39: 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	629.5	627.8	625.3	622.2	619.3
7° Angle	627.1	624.3	621.2	617.9	614.2
10° Angle	621.0	617.3	613.5	609.4	605.1

Table 40: 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	633.1	633.1	632.9	632.6	632.1
7° Angle	633.4	633.4	633.3	633.0	632.5
10° Angle	634.0	634.1	633.9	633.7	633.2

Table 41: OpenRocket (Left) and RockSim (Right) Predicted Vertical Velocity for Various Flight Conditions

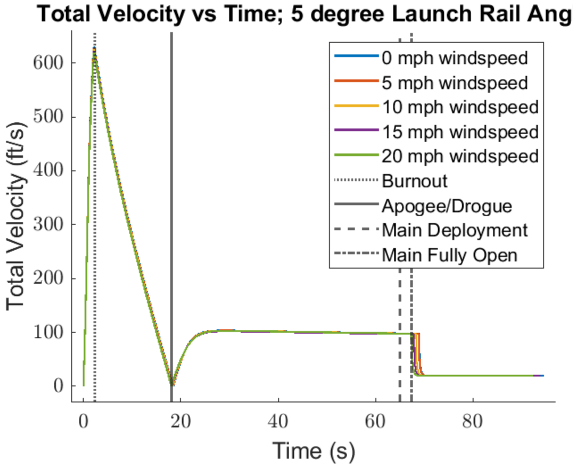
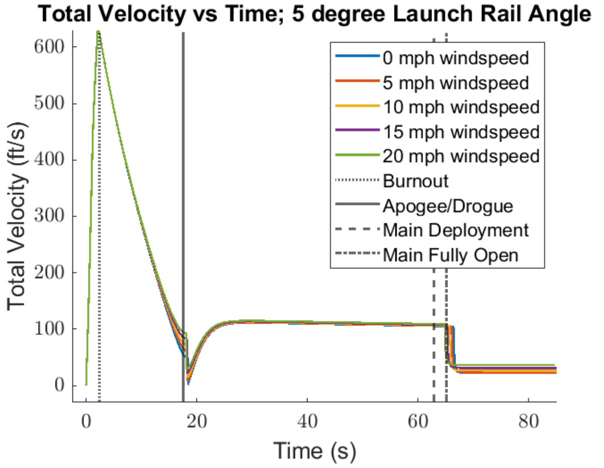
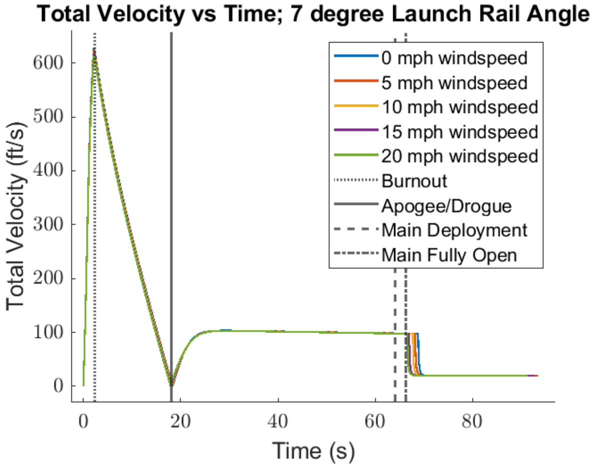
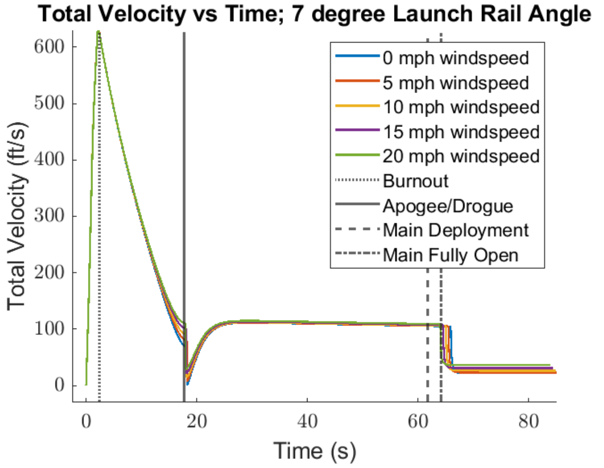
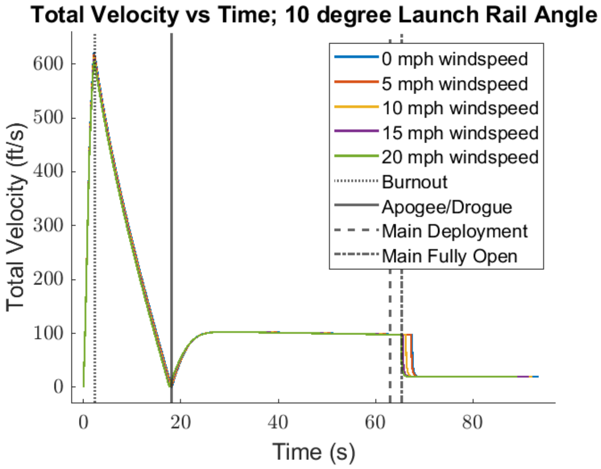
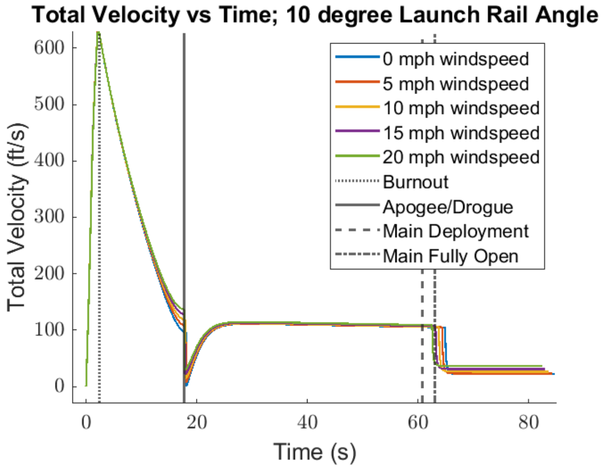
OpenRocket	RockSim
	
	
	

Table 42 lists the difference between the OpenRocket and RockSim maximum vertical velocity values. From the table, there is a positive trend between the wind speeds and the difference between maximum vertical velocity values; this trend was also seen with the apogee in Section 5.1.2. However, unlike apogee, Table 42 also shows that a positive trend between launch angles and the difference between maximum vertical velocity values. This information is important to keep in mind for the next vehicle flight. Given that the RockSim predictions were more accurate to the vehicle demonstration flight's velocity at key moments than OpenRocket predictions, and the wind conditions during such flight were on the upper echelon of flight conditions, RockSim is to be trusted more in higher wind speeds. It should be noted that the OpenRocket is not terribly off from the RockSim values, but OpenRocket was closer. However, it is unknown at the moment how either simulation holds up at lower wind speeds.

Table 42: Difference in Vertical Velocity Values Between OpenRocket And RockSim, measured in ft/s

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	3.632	5.351	7.652	10.407	12.793
7° Angle	6.337	9.13	12.078	15.1	18.267
10° Angle	13.014	16.74	20.484	24.316	28.077

5.1.4 Acceleration

Table 45 lists the vertical acceleration flight profile for OpenRocket on the left side and RockSim on the right side.

Comparing the left and right side of the table, it is evident that the simulators line up very closely to each other. In order to quantify the similarly in vertical velocity overall, Table 43 lists the maximum vertical acceleration values for OpenRocket for all flight conditions. Similarly, Table 44 lists the maximum vertical acceleration values for RockSim for all flight conditions.

Table 43: 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	403.105	401.595	400.3	399.086	398.059
7° Angle	401.822	399.431	397.941	396.504	395.153
10° Angle	397.928	395.363	393.396	391.525	389.779

Table 44: 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	405.3	405.4	405.6	405.8	406.2
7° Angle	405.4	405.6	406.0	406.3	406.5
10° Angle	405.9	406.2	406.4	406.7	406.6

Table 45: OpenRocket (Left) and RockSim (Right) Predicted Vertical Acceleration for Various Flight Conditions

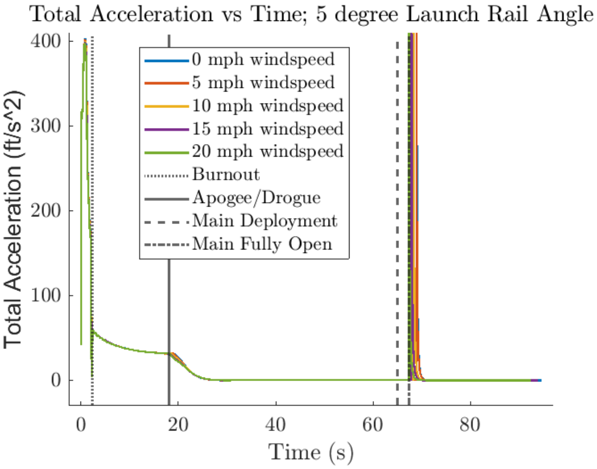
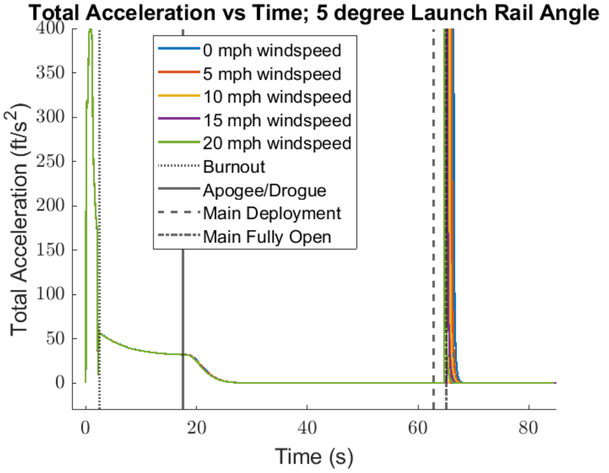
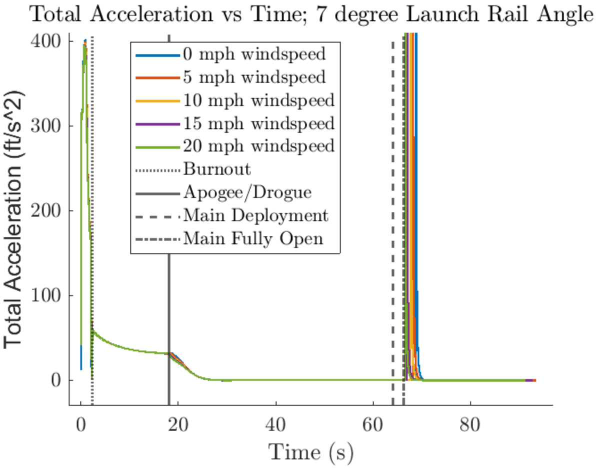
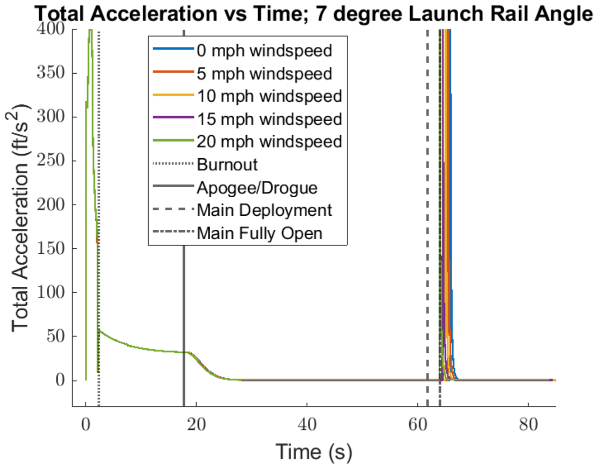
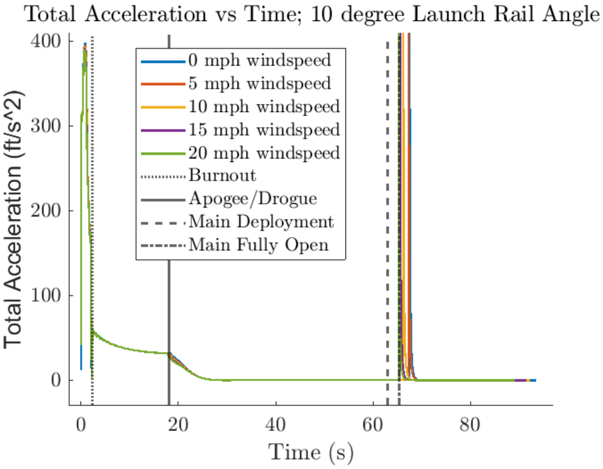
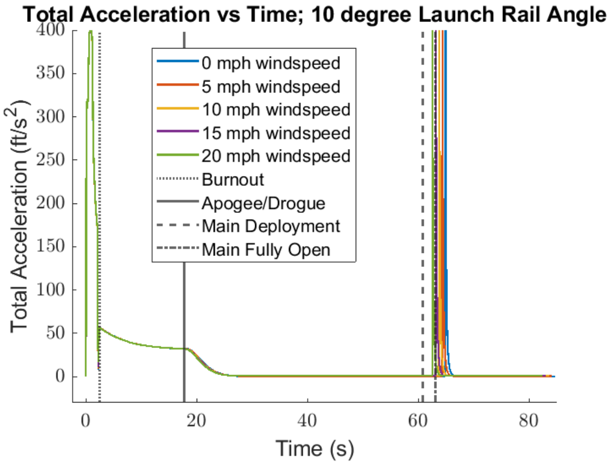
OpenRocket	RockSim
	
	
	

Table 46 lists the difference between the OpenRocket and RockSim maximum acceleration velocity values. From the table, there is a positive trend between the wind speeds and the difference between maximum vertical velocity values. Just like vertical velocity, Table 46 also shows that there is a positive trend between launch angles and the difference between maximum vertical acceleration values. This information is important to keep in mind for the next vehicle flight. As for which simulation is to be trusted more, there was no clear winner in the vehicle demonstration flight analysis, so for now either simulation is valid. However, it should be noted that is unknown at the moment how either simulation holds up at lower wind speeds.

Table 46: Difference in Vertical Velocity Values Between OpenRocket And RockSim, measured in ft/s

	0 MPH Winds	**5 MPH Winds**	**10 MPH Winds**	**15 MPH Winds**	**20 MPH Winds**
5° Angle	2.164	3.838	5.3	6.699	8.171
7° Angle	3.611	6.182	8.101	9.767	11.358
10° Angle	8.003	10.819	13.052	15.206	16.854

5.1.5 Stability

Table 47 lists the CG, CP and static stability margin values for the two simulators. The models were created to represent the vehicle's true CG value of 75.5 in., but the simulators differ in the motor mass; the dry mass of the simulators yields the same CG of 65.8 in.

Table 47: Static Stability Margin for Launch Vehicle

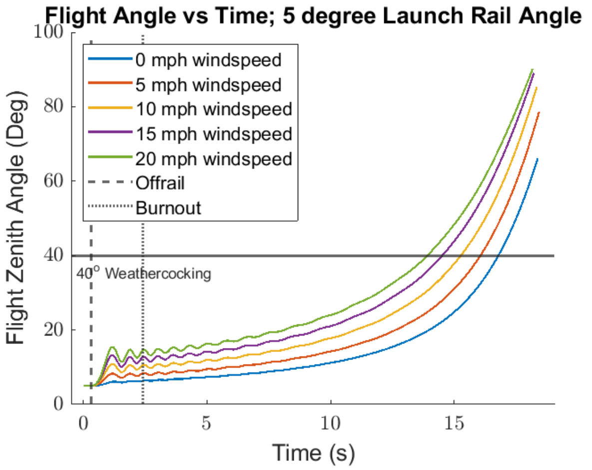
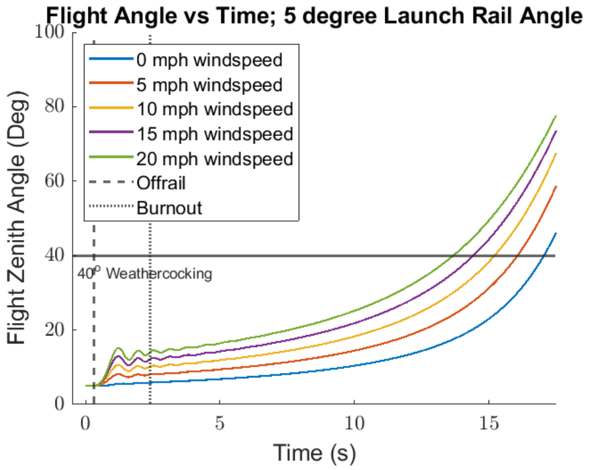
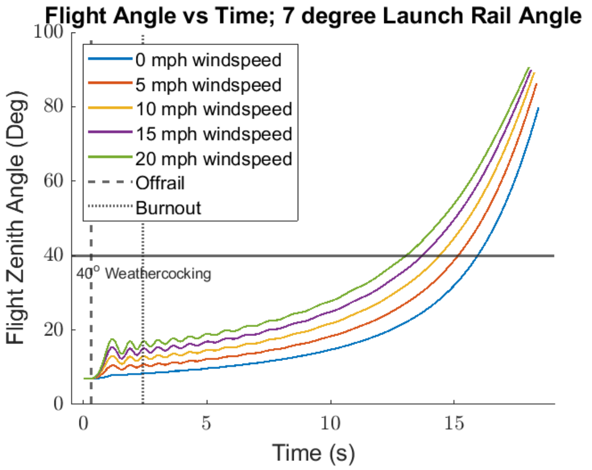
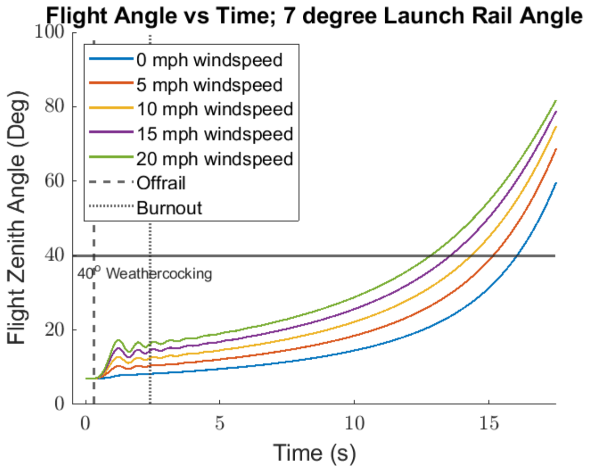
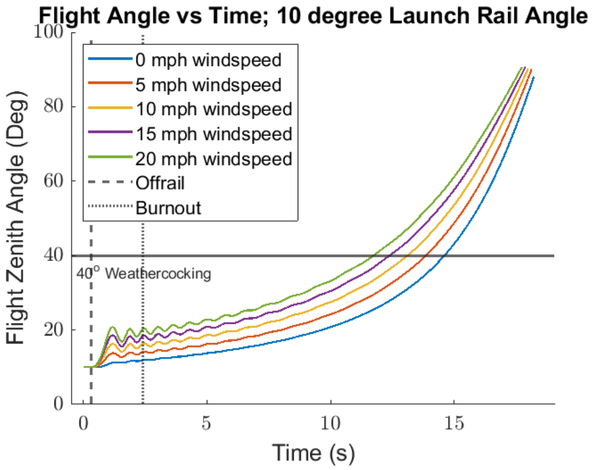
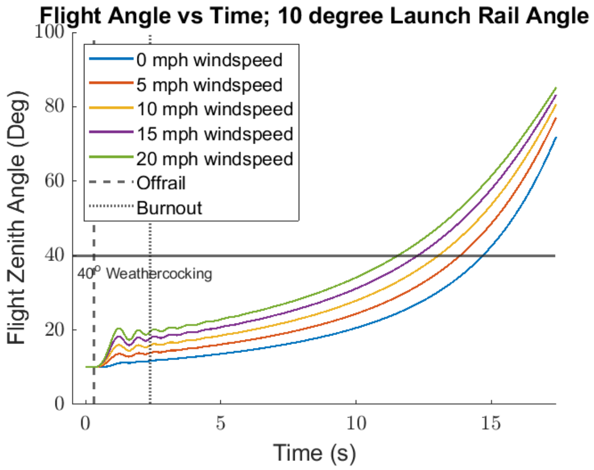
Method	**CG Location (in.)**	**CP Location (in.)**	**Static Stability Margin (cal)**
OpenRocket	75.525	90.826	2.49
RockSim (Barrowman Stability)	75.213	91.687	2.67
RockSim (RockSim Stability)	75.213	97.915	3.68

From the table and the analysis of the static stability in Section 8.4.1.5, the stability is greatly reduced from the previous design. Still, the static stability margin is greater than 2.00 cal, so the design abides by NASA Req. 2.14.

5.1.6 Flight Zenith Angle

An analysis of the flight zenith angle is imperative in the justification of the stability change. Table 48 lists the flight zenith angle for OpenRocket on the left side and RockSim on the right side.

Table 48: OpenRocket (Left) and RockSim (Right) Predicted Flight Zenith Angle for Various Flight Conditions

OpenRocket	RockSim
	
	
	

From Table 48 it is clear the the two simulators are similar to each other. Regarding weather-cocking analysis, Tables 49 and 50 show the simulators percent of altitude left to reach apogee, which is a good indication of how extreme the over-stability is; the less of apogee left, the better the stability margin is.

Table 49: 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	0.599	1.531	2.673	3.960	5.317
7° Angle	1.691	2.830	4.196	5.803	7.404
10° Angle	3.854	5.359	7.189	9.366	11.424

Table 50: 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	0.518%	1.498%	2.809%	4.327%	6.086 %
7° Angle	1.523%	2.837%	4.420%	6.221%	8.349 %
10° Angle	3.621%	5.467%	7.579%	9.913%	12.46709 %

Moreover, Section 8.4.1.6 shows that both simulators are very accurate in predicting the 40 weather-cocking location during flight of the demonstration flight. To prove this yet again, Table 51 shows the difference in the percent of altitude to reach apogee left at the 40 weather-cocking location for the two simulators. From the table's data, it is clear that at all flight conditions, the difference is extremely small, and thus, both simulators can be trusted to predict the weather-cocking of the launch vehicle. To reiterate, Tables 49 and 50 show that the weather-cocking is well improved from the previous design.

Table 51: Difference in Percent of Altitude to Apogee Left at the 40° Weather-cocking Location Between OpenRocket And RockSim

	0 MPH Winds	5 MPH Winds	10 MPH Winds	15 MPH Winds	20 MPH Winds
5° Angle	0.080817	0.032552	0.136192	0.367721	0.769083
7° Angle	0.167597	0.006384	0.224187	0.418091	0.945761
10° Angle	0.232766	0.107948	0.390183	0.546837	1.04291

5.2 Flight Descent

The descent of the full-scale vehicle moving forward is modeled using industry rocketry simulation software and an optimized MATLAB script created in-house during CDR. OpenRocket and RockSim 10 continue to be used by the team as they have proven to be reliable references in the past and provided reasonably accurate data during the subscale flight and VDF. The team's MATLAB script `full_vehicle_decsent_calc.m` (see Appendix) was previously developed based on the team's analysis of the descent physics to predict numerous parameters of the vehicle's descent. The `full_vehicle_decsent_calc.m` script still has numerous inputs about the vehicle and the environment which are provided by the `Input_Mass.m` and `Input_Parachutes.m` functions. Several of these values of been updated to better reflect the characteristics of the vehicle ascertained during the VDF. The input parameter fields remain identical to those presented in the CDR which are as follows:

- 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 20 mph) 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 rely on several assumptions that allow the system to be modeled by basic kinematic equations. 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 2.3 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 does not contribute 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).

All of the input parameters relating to the weather are adjusted for actual launch day conditions. However, for the general predictions that will be explored in this section, Standard Temperature and Pressure values will be used. The significant input values that have changed since the first VDF flight to improve future prediction accuracy relate to the expected parachute performance adjustment coefficients. Despite the team's prediction during CDR that the SkyAngle XXL parachute would provide drag forces closer to its advertised amount, the post-flight analysis further discussed in Section 8.4.2 has indicated otherwise. Analysis of the actual descent rate of the vehicle under the main parachute suggested the parachute instead provides 55% of the advertised amount. This expected parachute performance coefficient has thus been altered in the code for descent simulations moving forward. The mass inputs that reflect the current mass of the vehicle after several small changes after the first failed VDF and will now be used in the hand calculations moving forward can be viewed in Table 52, below. The "separated" mass values are useful for calculating the kinetic energy values of each section while the total mass of the vehicle is essential for calculating the descent velocity of the entire vehicle which will be discussed further later in this section.

Table 52: Vehicle Section Masses

Section	Weight (oz)
Nose Cone (Separated)	63.51
Payload Bay (Separated)	189.21
ACS Bay (Separated)	158.58
Fin Can (Separated)	195.32
Total Mass of Separated Sections	606.62
Mass of Laundry (Between Sections)	150.8
Total Mass of Vehicle During Descent	757.42

The main assumptions that have changed since CDR to improve prediction accuracy relate to the main parachute delay and pilot parachute drag. After analyzing the time it actually took for the main parachute to deploy after the separation event commenced, it was found that it takes 2.3 seconds for the main parachute to fully deploy as discussed further in Section 8.4.1.4. As such, the assumption for the main parachute delay time has been reduced from 3 seconds to 2.3 seconds to better model the actual performance of this specific parachute and deployment bag assembly. Additionally, a review of the photos of the vehicle under the main parachute descent suggested that the pilot parachute does not considerably contribute to the full vehicle drag as it does not fully inflate after the main parachute is deployed. This has now been reflected in the code.

The hand calculations that build the foundation of the code calculate the descent velocity using a force-balance equation between drag and weight (terminal velocity) that shows

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

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

$$v_{\text{descent}} = \sqrt{\frac{2 m_{\text{tot}} g}{\rho C_d A}} \tag{3}$$

is used to calculate the descent rate for both the main and drogue phases of descent. Table 53, below displays the calculated descent rates under STP using these hand calculations, OpenRocket, and RockSim.

Table 53: Predicted Descent Rates

Descent Phase	MATLAB v_{descent} (ft/s)	OR v_{descent} (ft/s)	RS v_{descent} (ft/s)
Drogue	78.89	95.67	109.23
Main	19.77	16.28	22.18

The following section will discuss the important descent parameters found using these rates as calculated via the `full_vehicle_decsent_calc.m` in the Appendix. The full `MATLAB Hand Calculations Script`, `Input_Parachutes.m`, and `Input_Mass.m` can be also be found in the Appendix to further clarify the exact methodology used for hand calculations and changes since CDR. The kinetic energy, decent time, and drift radius calculations are calculated using an identical method to that used during CDR. However, changes in the inputs such as mass alter these values and thus account for the difference in predictions between CDR and FRR.

5.2.1 Kinetic Energy

The team calculated the kinetic energy at the landing of each section of the launch vehicle to ensure that the section with the most mass adheres to NASA Req. 3.3 moving forward with the new inputs and assumptions. The equation used to calculate each section is

$$KE = \frac{1}{2} m_{\text{section}} v_{\text{main}}^2 \tag{4}$$

where KE is the kinetic energy of a given section, m_{section} is the mass of the section in its separated state (see Table 52), and v_{main} is the descent velocity of the launch vehicle. The calculated values for kinetic energy are shown in Table 54, below.

Table 54: Predicted Kinetic Energies at Landing

Section	MATLAB KE (ft-lb)	OR KE (ft-lb)	RS KE (ft-lb)
Nose Cone	24.12	16.76	31.10
Payload Bay	71.86	48.71	90.41
ACS Bay	60.23	40.82	75.77
Fin Can	74.19	51.05	94.76

OpenRocket predicts the smallest kinetic energies due to the low rate of descent the software predicts when the vehicle is descending under the main parachute. The RockSim software predicts the highest kinetic energy which exceeds the restrictions set forth in NASA Req. 3.3. However, this is likely due to the fact that RockSim consistently reports much higher descent rates than OpenRocket when provided with the same parachute and mass parameters. The RockSim predictions provided very high kinetic energy values bordering the 75 ft-lb requirement *before* the parachute performance adjustment was even added to the software. As such, this estimate is likely overinflated and does not concern the team. The MATLAB script predicts the most moderate kinetic energy prediction of just under 75 ft-lbs. While this is close to the limit, the team was conservative when estimating how much the main parachute underperforms during this round of simulations and thus does not expect the vehicle to descend faster than the calculated value. Additionally, this estimate is closest to the actual kinetic energy observed during the first VDF as discussed in Section 8.4.2.1. While the vehicle might be close to the kinetic energy requirement, the team is confident it will comply with NASA Req. 3.3 on launch day.

5.2.2 Descent Time

It is essential to calculate the total descent time of the vehicle to ensure it adheres to NASA Req. 3.11. The equation used to calculate the descent time during main or drogue descent is given by the equation

$$t_{\text{descent}} = \frac{\Delta h}{v_{\text{descent}}} \tag{5}$$

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. Identical to the calculations carried out in CDR, Δh is the difference between apogee and the main parachute's effective deployment altitude for the drogue phase. For the main descent time, Δh is the difference between the main parachute's effective deployment altitude and the ground (0 ft). The total vehicle descent time is the sum of these two values.

Table 55: Predicted Descent Times

Apogee (ft)	MATLAB t_{descent} (s)	OR t_{descent} (s)	RS t_{descent} (s)
4600	74.45	N/A	N/A
5252	82.14	82.96	N/A
5270	82.36	N/A	66.13

All of the predicted descent times fall below the 90 second limit set forth in NASA Req. 3.11. The RockSim simulations predicted the lowest descent time which aligns with its fast predicted rate of descent. The MATLAB and OpenRocket descent time predictions are within a second of each other suggesting they are likely the most accurate. This is also supported by the close proximity of the MATLAB predicted value to the actual descent time observed during the first VDF.

5.2.3 Drift

The calculation of the expected drift radius is essential to ensure the vehicle does not travel outside the immediate vicinity of the launch rail. The rudimentary method used to calculate drift in the `full_vehicle_decsent_calc.m` script utilizes the equation

$$D = v_{\text{wind}} t_{\text{descent}} \tag{6}$$

where D is drift, v_{wind} is the wind speed, and t_{descent} is the descent time calculated in 5.2.2. The calculated drift distances can be viewed in Table 56, below. It is worth noting the OpenRocket and RockSim simulations were conducted with a 5 degree launch angle and 20mph wind to simulate the worst-case drift scenario.

Table 56: Predicted Drift Distances

Apogee (ft)	MATLAB Drift (ft)	OR Drift (ft)	RS Drift (ft)
4600	2184	N/A	N/A
5252	2409	1623	N/A
5270	2416	N/A	1939

All of the predicted drift distances fall within the 2500ft limit set forth in NASA Req. 3.10. The OpenRocket simulations predicted the smallest drift which is counter-intuitive considering it predicts the longest descent time. However, the method OpenRocket accounts for the fact that the vehicle is traveling in the opposite direction of the way it will eventually drift when it reaches apogee as it is launched into the wind. This results in a smaller "net" drift from apogee. The MATLAB and RockSim drift predictions are both larger than the OpenRocket prediction but are within the requirements. The MATLAB script predicts the largest script which is likely due to the fact that it doesn't account for any initial horizontal velocity at apogee as it assumes apogee is reached at 0ft/s. As such, the OpenRocket and RockSim predictions for drift are likely more accurate. Another factor that reduces the accuracy of the drift predictions is the fact that wind varies with altitude. Moving forward, the team plans on using an average of the wind speed on the ground at the launch field with the wind speed at 3000ft provided by the Aviation Weather Center in Winds Aloft reports.

5.3 Structural Verification

5.3.1 Peak Thrust

Peak thrust FEA was performed during CDR and showed a factor of safety of 46.3, 185.0, 323.3, and 97.8 for the centering rings, motor mount tube, ACS body tube, and payload body tube, respectively. Recall that the peak thrust of the motor is predicted to be 697 lbf. During FRR, the centering rings were tested, given they had the smallest factor of safety, to find the failure point of the vehicle during ascent. See Section 10.1.1 for the full breakdown of the test. The results indicated that the epoxy would yield before the fiberglass at a factor of safety of 1.4. While this is below the desired factor of safety of 1.5, the motor thrust curves are relatively consistent for each flight: it is safe to assume that the peak thrust will stay within a reasonable range from the predicted peak thrust of 697 lbf. Therefore, vehicle air frame is safe from the L2200G-P's peak thrust forces.

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. The nose cone shock cord failure was attributed to this event and is further discussed during the analysis of the first VDF attempt. This highlights the importance of accurate main parachute deployment figures for the team moving forward. Figure 57, below, shows a simplified free-body diagram of the launch vehicle and its components during this event.

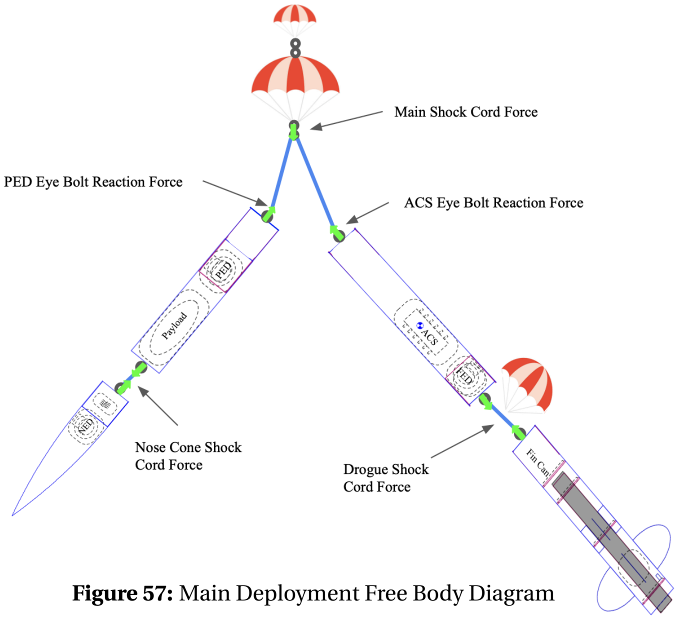


Figure 57: Main Deployment Free Body Diagram

The forces exerted on the vehicle were calculated in an identical manner to the method used during CDR. The global acceleration of the entire launch vehicle is first calculated before finding the force on each component. The first step to calculating this acceleration is setting up the mass balance equation

$$\sum F = D - W = ma \tag{7}$$

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 that

$$a = \frac{D}{m} - g \tag{8}$$

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

$$D = \frac{1}{2}\rho v_{\text{drogue}}^2 C_d A_{\text{main}} \tag{9}$$

where v_{drogue} is the descent rate under the drogue parachute and $C_d A_{\text{main}}$ is the effective coefficient of drag multiplied by cross-sectional area of the entire vehicle (reference area) under the main and pilot parachutes. After substitution, the final equation for the global acceleration is

$$a = \frac{\frac{1}{2}\rho v_{\text{drogue}}^2 C_d A_{\text{main}}}{m} - g = 468.60\text{ft/s}^2 = 14.56\text{g} \tag{10}$$

This global acceleration is significantly smaller than the load anticipated during CDR. The reduction in expected drag provided by the main parachute is largely responsible for this reduction in acceleration as less drag force is applied at the main parachute deployment. The force experienced on a given shock cord can be calculated using the equation

$$\sum F = T - W_{\text{supported}} = m_{\text{supported}} a \tag{11}$$

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. The force supported by any eye bolt and its respective bulkhead can be calculated by multiplying the sum of the global acceleration and the gravitational constant by the mass of the sections supported. The PED and ACS bulkhead force calculations should sum to the total force on the main shock cord assuming the mass of the shock cord is negligible in comparison to the rest of the supported mass. 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 once again assuming the mass of the shock cord is negligible for this calculation. Therefore, the masses used in Table 57 were used to calculate the forces on each component listed in Table 58. The listed weights are the sum of the weights of all the supported items which includes body tube sections, their contents, and all relevant laundry components.

Table 57: Weight Supported by Components

Component	Weight Supported (oz)
Main Shock Cord	651.34
PED Eye Bolt	271.28
ACS Eye Bolt	380.05
Nose Cone Shock Cord	82.10
Drogue Shock Cord	221.49

Table 58: Main Deployment Forces on Components

Component	Force Supported (lb)
Main Shock Cord	633.69
PED Eye Bolt	263.93
ACS Eye Bolt	369.76
Nose Cone Shock Cord	79.87
NED Eye Bolt	79.87
Aluminum Ring Eye Bolt	79.87
Drogue Shock Cord	215.49
FED Eye Bolt	215.49
Fin Can Eye Bolt	215.49

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

$$FoS = \frac{S}{F} \tag{12}$$

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

$$FoS = \frac{n\tau_{\text{shearmax}}\frac{\pi}{4}D^2}{F} \tag{13}$$

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 AIBs 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 369.76 lbs. For this screw, one can calculate the FoS to be 9.6 thus showing that these screws will be sufficient for all of the AIBs. The factor of safety for the full list of components in the primary load-bearing path can be viewed in Table 59, below.

Table 59: Factors of Safety for Load-Bearing Components

Component	Location	F Experienced (lb)	Breaking F (lb)	FoS
Main Shock Cord	Payload & ACS Bay	633.69	4400	6.9
3/8" Steel QL	Main Parachute	633.69	3600	5.7
3/8" Zinc QL	Payload Bay	263.93	2200	8.3
3/8" Zinc QL	ACS Bay	369.76	2200	5.9
3000lb Swivel	Main Parachute	633.69	3000	4.7
7/16" Steel Eye Bolt	PED	263.93	2000	7.6
7/16" Steel Eye Bolt	ACS	369.76	2000	5.4
Drogue Shock Cord	ACS Bay & Fin Can	215.49	3200	14.8
3/8" Zinc QL	Drogue Parachute	215.49	2200	10.2
3/8" Zinc QL	Payload Bay	215.49	2200	10.2
3/8" Zinc QL	Fin Can	215.49	2200	10.2
7/16" Steel Eye Bolt	FED	215.49	2000	9.3
7/16" Steel Eye Bolt	Fin Can	215.49	2000	9.3
NC Shock Cord	NC & Payload Bay	79.87	5300	66.4
3/8" Zinc QL	Nose Cone	79.87	2200	27.5
3/8" Zinc QL	Payload Bay	79.87	2200	27.5
7/16" Steel Eye Bolt	NED	79.87	2000	25.0
1/4" Steel Eye Bolt	Al Ring	79.87	500	6.3

The bulkheads were analyzed using the Ansys Discovery finite element analysis software. For the bulkheads with AIBs, fixed geometries were applied 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 through an 8-32 screw into the body tube. For the Fin Can bulkhead, the entire perimeter of the circle is fixed since this surface was epoxied into the Fin Can. Since CDR, the location of the AIBs on the NED has been altered as they are now located on the aft bulkhead. this eliminates the need for the aluminum standoffs to be load-bearing and instead means the force is transferred out of the bulkhead through the AIBs identically that the load path in the FED and PED. Lastly, it is worth noting the force applied to each bulkhead by its respective eye bolt is applied over the area of the associated washer since the eye bolt tries to pull said washer "through" the bulkhead. The stress and factor of safety results for each bulkhead are tabulated below in Table 60.

Table 60: Factors of Safety for Bulkheads based on FEA Analysis

Bulkhead	*F* Applied (lb)	Peak Resultant Stress (ksi)	Strength (ksi)	FoS
PED Bulkhead	263.93	19.8	290	14.6
ACS Bulkhead	369.76	35.00	290	8.3
FED Bulkhead	215.49	23.80	290	12.2
Fin Can Bulkhead	215.49	9.41	290	30.8
NED Aft Bulkhead	79.87	9.13	290	31.8
Al Ring	79.87	2.90	30	10.3

Overall, factors of safety increased universally as the force experienced at main deployment was determined to be less than previously anticipated. This is largely due to the fact that the main parachute does not provide as much drag as previously anticipated. This reduces the sudden force applied at main deployment and results in smaller loads on each component which is positive for the overall life of the vehicle and its components.

6 Technical Design: 360° Rotating Optical Imager

6.1 Mission Statement and Success Criteria

The **360º** **R**otating **O**ptical **I**mager (**TROI**) is the Notre Dame Rocketry Team's scoring payload for the 2022-2023 NASA Student Launch Initiative. The team independently designed, built, and tested a payload that detects landing and deploys a camera subassembly out of the body tube and passively orients the camera subassembly parallel to the z-axis. The payload demodulates RF communications into software commands, and takes and stores images as instructed. The payload must be successfully retained and deployed, while taking and storing images for a successful mission.

The following criteria will be used to evaluate the success of the payload:

- The TROI shall be rigidly retained in the launch vehicle during flight and system deployment (NASA Req. 4.2.4).
- The TROI shall deploy after landing is detected (NASA Req. 4.2.3.3.), orient parallel to the z-axis (perpendicular to the ground) and rotate about the z-axis (NASA Req. 4.2.1.1).
- The TROI shall receive RF commands sent by NASA's ARPS protocol, properly demodulate them to software commands, and take clear images without obstruction according to the commands (NASA Req. 4.2.2.).
- The TROI shall digitally timestamp all images, applies filters as commanded, and save them on an onboard microSD card for later recall (NASA Req. 4.2.1.3).
- The TROI and internal components shall be accessible during tests and competition to make repairs and modifications as needed.
- The TROI shall be protected from residue from recovery systems.
- The TROI shall operate in variable weather conditions and temperatures.

6.2 Changes Since CDR

Elaborating on the summary table provided in Section 1.2, several changes have been made to TROI.

The lead screw cover was changed from one structural component to two components which interface together with a ball bearing. This allows for half of the cover to rotate after exiting the guide rails while the other stays stationary. The rotation is a passive, gravitationally controlled rotation using the telescoping camera arm as a counterweight as opposed to using accelerometer data to turn the lead screw a prescribed amount. When the lead screw was a single component, there was a deflection of 15° from the horizontal axis. Adding a bearing made this deflection negligible. Additionally, the active system for rotating the telescoping camera arm to the z-axis could not reliably complete the mission due to lack of standardization of initial starting conditions including initial placement of the hub link. The passive system operates much more reliably as it does not rely on initial conditions.

The location of the battery changed from the aft bulkhead to the fore bulkhead due to space constraints. The electronics were moved from two wooden mounting boards to one wooden mounting board in order to save space on the aft bulkhead as well as cut down on the total mass. The antenna mounting location was changed from the top of the fore bulkhead to embedded in the lead screw cover in order to always orient the antenna to the z-axis to ensure it receives communication from the NASA ground station.

During the full scale vehicle demonstration flight attempt, the TROI deployed prematurely and the lead screw bent on landing as further explained in Section 6.7. The lead screw was damaged beyond use and the lead screw and stepper motor were replaced. The primary axis stepper motor was replaced with a NEMA 17 stepper motor.

The telescoping camera arm concentric cylinder components were continuously iterated after CDR, creating a final design which includes four triangular interfacing tracks as opposed to one rectangular track for motion control. The inner cylinder material was changed to 3D printed resin from ABS-M30 plastic to increase the strength of this part.

As per CDR, the telescoping mechanism was retained by a thin locking arm that extended from the innermost cylinder to the outside of the mechanism with the outermost cylinder being fixed to the stepper motor. Because of concerns of the thin locking arm breaking due to the strength of the spring, for the final design, the telescoping mechanism has been inverted such that the telescoping mechanism is retained by a thick block on the outermost cylinder and the innermost cylinder is fixed to the stepper motor.

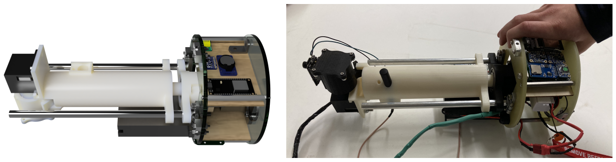
To prevent premature or improper deployment of the telescoping camera arm, the locking mechanism on the lead screw cover was designed to constrain the stopper mechanism on the telescoping camera arm on three sides, as opposed to the one side constrained in CDR. This ensures that before and during deployment the system can only rotate in the desired direction to unlock, but not move in any other direction.

Upon constructing the telescoping camera arm, the team realized that the NEMA-8 stepper motor was unable to provide enough torque to overcome the locking mechanism. As a result, the NEMA-8 was replaced by a NEMA-14 stepper motor which provides enough torque.

6.3 Mechanical Design

The TROI consists of two concentric tiered bulkheads and is rigidly retained to the payload body tube throughout all aspects of flight, landing, and operation. The payload structure is further described in Section 6.3.3. The payload camera subassembly features four components of motion. These components include the longitudinal lead screw deployment, passive bearing orientation, telescoping camera arm, and camera stepper motor rotation. The steps of deployment and the telescoping camera arm are further described in Sections 6.3.1.1 and

6.3.2, respectively. Each section describes the manufacturing, assembly, and integration of the respective components. The TROI CAD model and as-constructed photo are shown side by side in Figure 58.



(a) CAD (b) As-Constructed

Figure 58: TROI Retained Configuration

6.3.1 Camera Deployment

To fulfill the payload mission, the camera subassembly must deploy and orient itself outside of the payload body tube. Successful deployment allows for the TROI to take unobstructed images and execute received radio commands. The team designed and built the camera subassembly to deploy through four components of motion in a four step process. The final, fully deployed location of the camera subassembly features the telescoping camera arm extended and oriented parallel to the z-axis. A picture of the as-constructed TROI in the fully deployed state is shown in Figure 63.

6.3.1.1 Steps of Deployment

It is necessary to describe the camera subassembly and how it is retained before the deployment sequence. The as-built, labeled retained payload is labeled in Figure 59.

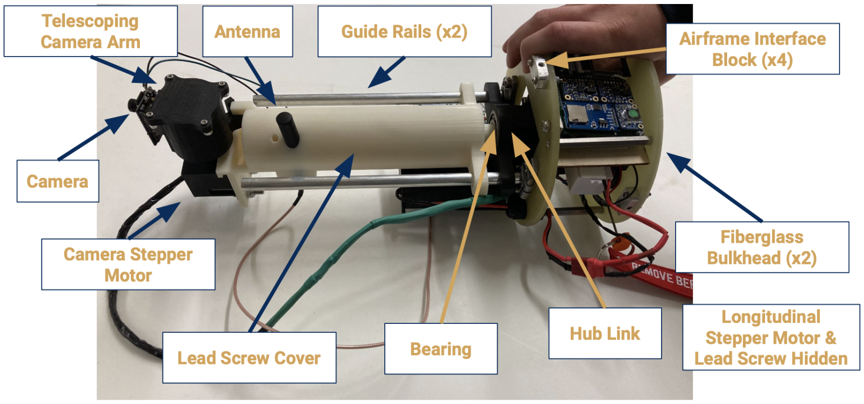


Figure 59: Labeled As-built Retained Payload

The camera subassembly is deployed in the following sequence. The TROI begins in its retained configuration as shown in Figure 59. After launch and then landing is detected (as described in Section 6.5.3), the longitudinal axis stepper motor is activated to rotate the lead screw and hence translate the camera subassembly forwards since rotational motion is constrained by the guide rails. The longitudinal translation continues for a set distance of 8.5 inches. The longitudinal translation is the first component of motion and is shown in Figure 60.

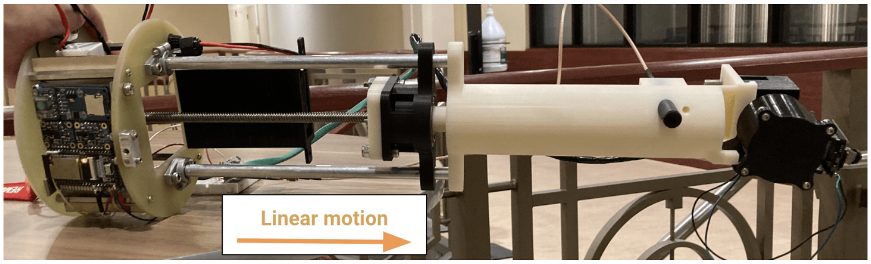


Figure 60: TROI Deployment Step 1: Longitudinal Translation

At the conclusion of the longitudinal translation, the camera subassembly exits the guide rails. The aft lead screw cover remains on the guide rails, and the camera subassembly is now free to rotate relative to the aft lead screw cover through the use of the bearing. The camera stepper motor of the camera subassembly acts as a counterweight when the camera subassembly is free to rotate. This passive system orients the camera subassembly to be parallel to the z-axis through the use of the camera stepper motor acting as a counterweight. The bearing rotation is the second component of motion. The camera subassembly is then deployed and oriented outside the payload body tube, and it is shown in Figure 61.

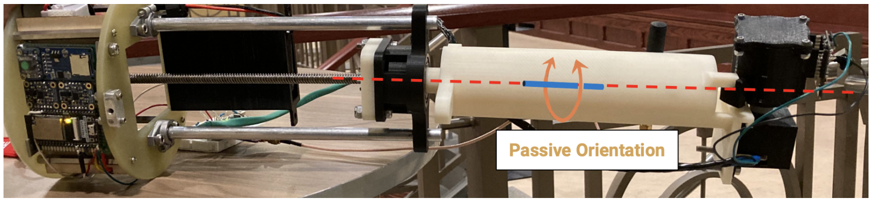


Figure 61: TROI Step 2: Bearing Rotation

The telescoping camera arm remains in its retained configuration through the first two deployment steps. Two seconds after the longitudinal translation is completed, the camera axis stepper motor activates and rotates, deploying the telescoping camera arm. The telescoping camera arm is further explained in Section 6.3.2. The telescoping camera arm raises the camera above the payload body tube. The telescoping camera arm is the third component of motion, and it is shown in its deployed, integrated state in Figure 62.

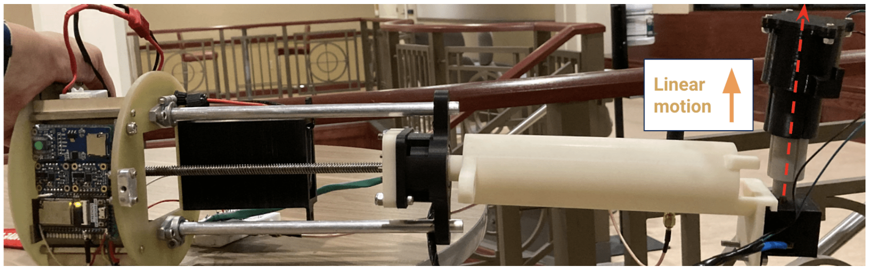


Figure 62: TROI Step 3: Telescoping Camera Arm Deployment

The camera axis stepper motor can rotate the camera by rotating the telescoping camera arm about the z-axis and provide for 360° rotation as per received commands (NASA Reqs. 4.2.1., 4.2.1.1.). This is the fourth component of motion, and it is shown in Figure 63.

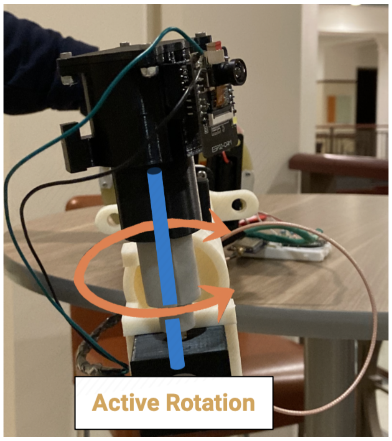


Figure 63: TROI Step 4: Camera Rotation

The manufacturing and assembly/integration of the camera deployment mechanisms is described in Sections 6.3.1.2 and 6.3.1.3, respectively.

6.3.1.2 Deployment Manufacturing

The TROI deployment mechanism was created using a combination of 3D printing, rapid prototyping, and cutting of commercial parts to length. Table 61 provides a list of all the TROI deployment components and the respective manufacturing method used to create or purchase the part. The telescoping arm is described separately in Section 61.

Table 61: TROI Main Deployment Components and Manufacturing Methods

Deployment Component	Subsystem	Manufacturing Method	Material
Stepper Motor Covers	Deployment	3D Printing & Rapid Prototyping	ABS M-30
NEMA 17 & Lead Screw	Deployment	Purchased & Cut to Length	-
NEMA 14 & Shaft	Deployment	Purchased	-
Ball Bearing	Deployment	Purchased	Steel
Lead Screw Cover	Deployment	3D Printing & Rapid Prototyping	ABS M-30
Guide Rails	Deployment	Purchased & Cut to Length	Aluminum

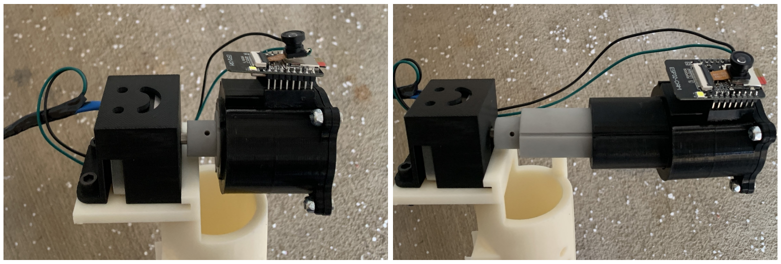
6.3.1.3 Deployment Assembly and Integration

The lead screw stepper motor cover retains the stepper motor in place and is screwed into the aft bulkhead. The lead screw extends through the fore bulkhead. The aft portion of the lead screw cover screws into the lead screw hub link and the fore portion of the lead screw cover integrates with the aft portion via a ball bearing. The guide rail flange supports are screwed into the fore bulkhead as specified in the retention section and the guide rails are clamp into the supports with M4 screws. The antenna to receive the radio communication is fixed in the lead screw cover to ensure it remains in the proper configuration to receive the communication after deployment. The camera stepper motor cover is screwed into the lead screw cover with two 18-8 socket head screws.

Additionally, the lead screw cover integrates with the telescoping camera arm by containing the locking mechanism which keeps the camera arm in its retained configuration during flight and prior to deployment. The holes drilled manually for all screw holes often did not interface with other parts with workable tolerances. To account for this, the 3D printed parts were iterated until the tolerance discrepancies were negligible. Additionally, the holes were sanded manually. In the future, the holes will be machined with a CNC machine to ensure exact tolerances.

6.3.2 Telescoping Camera Arm

To capture a clear image of the landing site, the camera extends above the payload body tube atop the telescoping camera arm. The camera arm features three nested cylinders that are deployed with an internal spring. The cylinders are retained during flight by a stopper located on top of the lead screw cover. After the lead screw deploys and the telescoping camera arm aligns with the z-axis, the camera arm stepper motor initiates a turn, moving the mechanism past the stopper and deploying the spring mechanism in the telescoping arm. The telescoping arm extends upward to capture high quality photos of the terrain. The camera, including its electronics, is attached to the side of the outermost cylinder. The telescoping arm can be seen in its retained and deployed states in Figure 64.



(a) Retained (b) Deployed

Figure 64: Telescoping Camera Arm

6.3.2.1 Telescoping Camera Arm Manufacturing

The three nested cylinders and spring cap were 3D printed on a Stratasys F123 series printer and sanded such that they slide and interface smoothly. Originally all three cylinders were made out of ABS-M30 plastic, but when one of the cylinders broke prematurely, the team tested two different material blends. A carbon fiber infused plastic and 3D printed resin were constructed, and ultimately the team chose the 3D printed resin part when the carbon fiber cylinder broke again. 3D printing was chosen to manufacture these parts because this experimental mechanism required rapid prototyping with repeated testing and iteration. The spring inside of the camera arm was purchased and stretched to necessary length by pulling it apart by hand.

6.3.2.2 Telescoping Camera Arm Assembly and Integration

The three cylinders interlock with each other via four interfacing tracks along the sides of each cylinder. The interlocked mechanism attaches to the stepper motor with a 4-40 set screw in the innermost cylinder. The set screw was machined to a shorter length with a dremel to mitigate part interference. The interface between the lead screw cover and the telescoping camera arm locks the telescoping camera arm in its retained configuration. An extruded portion on the outermost cylinder of the camera arm interfaces with an extruded portion on the lead screw cover. The stepper motor rotates the camera arm assembly free of the stopper mechanism to deploy. The camera and its electronics board is mounted on the outermost cylinder with super glue. The spring is contained within the innermost cylinder to deploy the system and is retained by a cap secured with four 4-40 screws.

6.3.3 Retention

The TROI is retained in the launch vehicle with two fiberglass bulkheads, each matching the three inch inner radius of the payload section of the launch vehicle. Each bulkhead is outfitted with two aluminum airframe interface blocks to ensure the TROI is retained safely within the payload bay. The tight fit of the TROI within the payload bay in addition to four 8-32 screws which screw the airframe interface blocks into the airframe of the launch vehicle ensure the rigidity of TROI within the payload bay. The electronics are also retained in place on a wooden mounting board positioned between the two bulkheads. The lead screw stepper motor is fixed in place on the aft bulkhead with a 3D printed lead screw cover and extends through a hole in the fore bulkhead. On the leading face of the fore bulkhead, a 3D printed battery case retains the battery in place and both aluminum guide rails are screwed into the bulkhead with guide rail flange supports. The rigid retention of the payload was verified in the vehicle demonstration flight attempt as described in Section 6.8.

6.3.3.1 Structural Manufacturing

The two fiberglass bulkheads were cut from fiberglass using a water jet, each having a thickness of 1/8 in. and diameters of 6 in. The fore bulkhead additionally had a 2.6 in. by 2.6 in. hole machined with the water jet centered on the bulkhead. This hole allows the lead screw to extend beyond the retention system of the payload. Additional sanding with the belt sander was used to fit the bulkheads within the body of the rocket. Most electronics as specified in Section 6.4.1 are housed on a wooden board machined using the laser cutter and fitted between the two bulkheads. The holes and other cutouts on the bulkheads were measured using actual component measurements and machined using a drill press. These holes include screw holes for the four standoffs, the lead screw motor cover, the guide rail flange supports, the electronics board, the battery cover, the wire tunnel, and the retention blocks. Some holes were not machined to workable tolerances and the 3D printed parts were re-machined to the desired specifications. The lead screw cover and battery case were rapidly prototyped multiple times until they met the desired specifications. The machined bulkheads are shown in Figure 65.

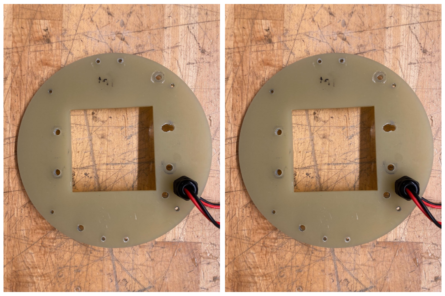

(a) Fore Bulkhead (b) Aft Bulkhead

Figure 65: TROI Machined Bulkheads

6.3.3.2 Structural Assembly and Integration

Two airframe interface blocks were screwed into the top of the fore bulkhead and two were screwed into the bottom of the aft bulkhead using eight 4-40 screws and locknuts. Each airframe interface block is screwed into the outside of the payload bay with 8-32 screws to secure the TROI in place before flight. The four standoffs were fixed between the two fiberglass bulkheads with eight 18-8 Phillips pan head screws. The wooden electronics board is fixed between the fore and aft bulkheads with two steel corner brackets and four M8 hex drive flat head screws.

The stepper motor for the lead screw is retained within the payload with a 3D printed lead screw cover bolted to the aft bulkhead with four 18-8 stainless steel socket head screws. The lead screw extends beyond the fore bulkhead through a rectangular hole in the fore bulkhead. The battery is fixed to the top of the fore bulkhead with a 3D printed battery case which is bolted into the fore bulkhead with four 18-8 stainless steel socket head screws. The wires to connect the electronics between the two bulkheads to the battery on the fore bulkhead pass through a wire tunnel which is screwed through a hole machined in the fore bulkhead.

The retention system integrates directly with the launch vehicle to ensure that the TROI is retained in place. Additionally, it integrates with the camera deployment mechanism subsystem of TROI as the lead screw that controls the camera deployment is fixed within the retention subsystem.

6.4 Electrical Design

A summary of the various electronic components of the TROI are listed in Table 62.

Table 62: TROI Electronics Summary

Component	Purpose	Quantity
Inertial Measurement Unit (IMU)	Acceleration & Gyroscope Data	2
DS3231 Real Time Clock	Timestamping Images	1
OV2640 140° Camera Module	Taking Images	1
A4988 Stepper Motor Driver	Motion Control	2
11.1V 3000mAh Battery	Power	1
DRA818V RF Transceiver	RAFCO	1
Main PCB	Main Integration	1
RF PCB	RF Integration	1
ESP-WROOM-32E	PCB Microcontroller	1
ESP-32S	Camera Microcontroller	1
Pull Pin	System Activation	1

6.4.1 PCB and Power Distrubution

The TROI electronic components are divided across two PCBs: the RF PCB and the Main PCB. Neither PCB has arrived yet, and the team is currently using perfboards as a substitute. The main PCB includes the components listed in Table 63.

Table 63: TROI Major Main PCB Components

Part Name	Description	Quantity
ESP-WROOM-32E	Acceleration & 32 bit microcontroller	1
MPM3610	Synchronous rectified, step-down converter	1
XC6220	Voltage regulator	1
BNO055	Inertial measurement unit	2
DS3231	Real time clock	1
A4988	Microstepping motor driver	2

The main PCB is used to house the main microcontroller, various sensors, and stepper motor drivers, as well as regulate voltage. A custom PCB replaces the need for jumper cables and breadboards, allowing for a cleaner, more reliable design. Each sensor and driver will be powered by the regulators and controlled with the microcontroller on this main PCB. The PCB also hosts the pinouts to command and power the freestanding stepper motors and RF devices. The ESP-CAM is powered using cables connected to the PCB and communicates wirelessly with the main microcontroller through the ESP-NOW protocol described in Section 6.5.2. A diagram of the main PCB is provided in Figure 66.

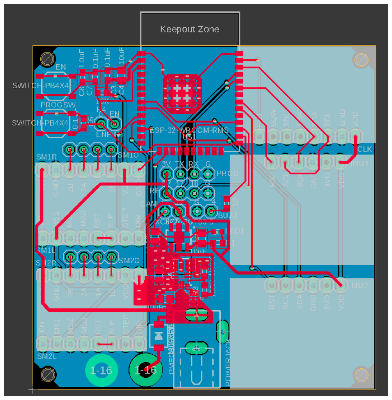
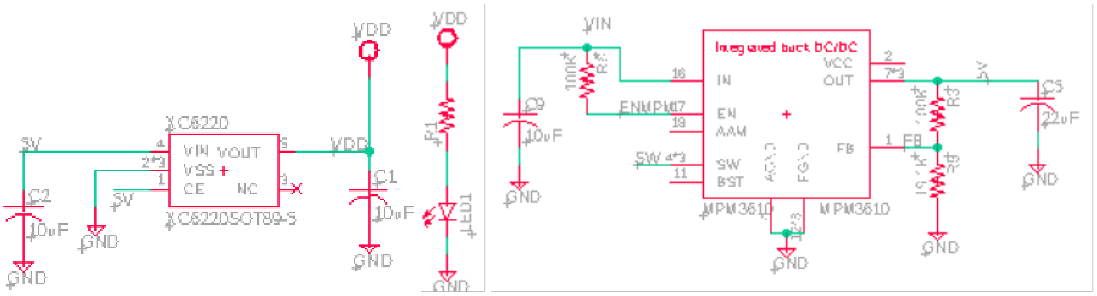


Figure 66: Main PCB Layout

The TROI battery is a 11.1 V 3000 mAh Li-Po battery. It is secured in a 3D printed case that is mounted on the fore bulkhead. It is wired to a pull pin that is then wired to the two PCBs. This 11.1 V voltage is required to properly supply the two stepper motor drivers with 11.1 V. As the TROI only uses one battery, it is necessary to step-down the voltage of the battery to 5 V and 3.3 V that can be used by the various microcontrollers and sensors of the payload. The main PCB is responsible for stepping down the voltage, and Figure 67 provides the step-down converters used.



(a) XC6220 (b) LED (c) MPM3610

Figure 67: Main PCB Step-down Converters

Figure a) is the XC6220 which is used to step 5 V down to 3.3 V. Figure b) is a simple LED used as a power indicator. Figure c) is the circuit schematic for the MPM3610 which is used to step down the 12 V battery supply to 5 V. For the RF PCB, it includes the components listed in Table 64.

Table 64: TROI Major RF PCB Components

Part Name	Description	Quantity
DRA818V	Transceiver for the 2 meter band	1
Arduino Nano	SUsed for demodulating AX.25 packets as part of the TNC	1
10K Resistor	Used to bias the voltage from the DRA818V AF$_{O}UTpin$	2
10nF Capacitor	Used to bias the voltage from the DRA818V AF$_{O}UTpin$	1
Bingfu Dual Band Antenna	Used for a 2 meter band antenna	1
Male to Male SMA Wire	Used to connect the antenna to the transceiver	1
SMA Female PCB Mount	Used to connect the SMA wire to the PCB	1

A diagram of the RF PCB is provided in Figure 68.

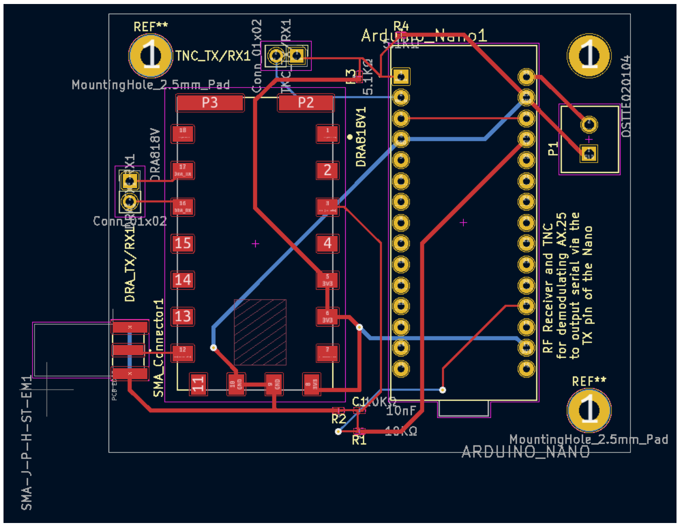


Figure 68: RF PCB Layout

6.4.2 Sensors

TROI sensors consist of two IMUs, a real time clock, a camera with a wide angle lens, and a HAM radio wireless voice transceiver module. For the two IMUs, the team selected the Adafruit BNO055 Absolute Orientation Sensor because of its small size, high accuracy and reliability, and low cost. Two IMUs were chosen for redundancy and accuracy. For the real time clock, the team chose the Adafruit DS3231 real time clock to properly timestamp every photo taken following RAFCO commands, satisfying NASA Req. 4.2.1.3.. This clock was selected because of its low power consumption, compact size, and ease of integration. The team chose the OV2640 camera integrated with an AI-Thinker ESP32-CAM because of their combined small size and easy integration. A replacement lens was added to the camera to provide a FOV of 140° satisfying 4.2.1.2.. Finally, a DRA818V ham radio module was chosen as the ham radio wireless transceiver because of its low power consumption and cost-effectiveness. For the ham radio wireless transceiver, an Arduino Nano will be used to demodulate the radio commands from the transceiver.

In order to gather and process the data from the sensors, the team chose to use two ESP32-based microcontrollers, an ESP-WROOM-32 for the main unit and an ESP32-S for the camera subassembly. The ESP-WROOM-32 microcontroller will receive and process data from the two IMUs and the real time clock. The ESP32-S integrated in the ESP32-CAM will receive and process the data from the camera.

6.4.3 Deployment Control

Utilizing two stepper motor drivers, the TROI is mechanically able to deploy its camera beyond the payload tube to take images of the area around the launch vehicle. Each stepper motor is controlled by an A4988 stepper motor driver and is provided with the full 11.1 V of the TROI's battery. The code on the ESP-Main microcontroller controls each stepper motor driver and commands the TROI stepper motors to operate. The two stepper motors are coded to never be moving at the same time.

The longitudinal axis stepper motor is a NEMA 17 stepper motor featuring an embedded 8 mm lead screw. The camera stepper motor is a NEMA 14 stepper motor. This motor controls the motion about the camera axis, responds to RAFCO commands, and interfaces with the telescoping camera arm. Instead of a lead screw, the NEMA 14 features a built-in keyed rod.

Both stepper motors are electronically locked under torque when they are fully powered on. This is especially relevant for the telescoping camera arm, which ensures that there is no premature deployment. The NEMA 14 stepper motor has a holding torque of 14 Ncm.

The longitudinal stepper motor must deploy a distance of approximately 8.5 in. in order to achieve step two of the deployment sequence as described in Section 6.3.1.1. The camera stepper motor will rotate following RAFCO commands it is given. For example, if the TROI is executing command A1, the camera stepper motor will rotate 60° to the right while B2 will rotate 60° to the left.

6.4.4 Camera

The TROI utilizes the Arducam OV2640 camera with the AI Thinker ESP32-CAM. This combination of camera and board was chosen primarily due to its adherence to NASA Reqs. 4.2.1.1. and 4.2.1.3., alongside native microSD compatibility, and accessibility of robust image processing libraries. A Treedix OV2640 camera module is used for the camera as it has a 140° FOV, satisfying NASA Req. 4.2.1.2. With these features in mind, the TROI is able to execute all the required image processing and capture commands as outlined by NASA Req. 4.2.2. The specific imaging commands and their implementation on the TROI are described in Section 6.5.5. In addition to these features, the camera subsystem will operate with minimal overhead, requiring only a 5 V and ground lead, and has a low-power sleep mode to allow for reduced power consumption prior to when the TROI deploys.

6.4.5 Radio Communication

The RF system is designed to strictly receive commands from NASA over an RF link during competition with frequencies between 144.90 MHz and 145.10 MHz and convert received radio packets into a form that can be relayed to the microcontroller and camera system. It consists of an antenna, DRA818V transceiver, a Mobilinkd TNC, and an ESP-WROVER-E microcontroller. The Mobilinkd is a breadboard-based TNC containing an Arduino Nano and several other electronic components. A breadboard configuration of this system is shown in Figure 69.

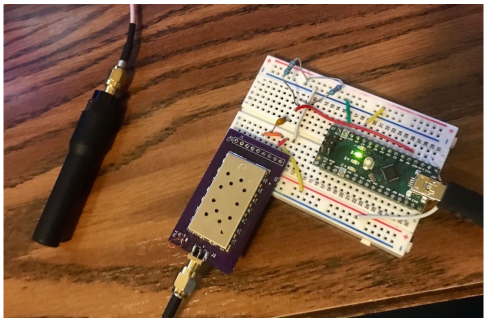
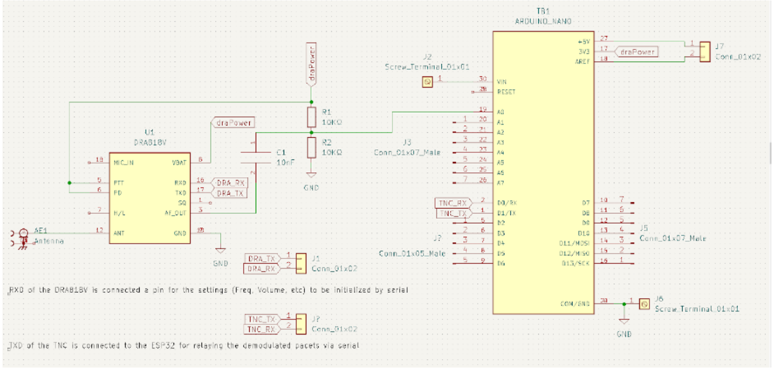


Figure 69: The Physical RF Subsystem including the DRA818V and TNC

This breadboard configuration was utilized for development and testing stages. The complete RF system is implemented on a custom-designed printed circuit board (PCB), which houses all electronic components in the RF system and voltage regulators to step-down from 11.1 V at the battery to 5 V required by the Arduino Nano as described in Section 6.4.1. A schematic of the RF system is included in Figure 70.



RXD of the DRA818V is connected a pin for the settings (Freq, Volume, etc) to be initialized by serial

TXD of the TNC is connected to the ESP32 for relaying the demodulated pacets via serial

Figure 70: RF Subsystem Schematic including the DRA818V and TNC

To prepare the system for RF reception, the DRA818V transceiver is initialized to the desired frequency ranges via the RXD pin using serial protocol. The DRA818V verified reception capabilities between 144.90 MHz and 145.10 MHz. This initialization method utilizes a modified version of the Arduino-DRA818V library. Radio packets are received via the antenna and transceiver, and then demodulated by the TNC, using APRS AX.25 AFSK 1200 baud packet demodulation. This process converts radio packets into signals that can be sent to the ESP32-WROVER-E via serial for parsing, after which the parsed commands are relayed to the camera system.

A set of initial tests were conducted using the DRA818V with software TNCs such as Direwolf and APRSdroid to verify that the RF system could receive signals with enough resolution to demodulate the AX.25 packets. These tests succeeded, and were followed by another round of tests integrating the Mobilinkd TNC, to verify that the embedded systems TNC could demodulate received radio packets. These tests were also successful. Lastly, a successful test was conducted to send the demodulated packets to the ESP32-WROVER-E via serial connection for interpreting commands. The mentioned sets of tests are described in greater detail in Section 6.5.4.

6.5 Software Design

6.5.1 Overall Control Flow

Once the TROI is activated after the pull pin is removed, the TROI initializes all its sensors and subsystems, waiting in standby mode on the launchpad for launch. During this standby phase, the TROI constantly takes accelerometer data from two sets of BNO055 IMUs in order to determine when the launch vehicle launches from the planetary surface. Once in flight, the TROI again enters a standby mode for landing. Here, the TROI takes filtered accelerometer and gyroscope sensor readings in order to determine when the launch vehicle re-encounters the planetary surface. The launch and landing detection control flow is described in further detail in Section 6.5.3. Once landing has been detected, the TROI gathers and filters absolute orientation data from the IMUs in order to ensure the payload is completely still.

Once a full landing with a still payload is detected, the ESP32-Main subsystem actuates the longitudinal stepper motor to rotate the lead screw and thus deploy the camera subassembly. Once the camera subassembly has been released from the guide rails inside the launch vehicle, the second component of motion, the camera subassembly passively orients itself through the use of a bearing and its own component weight. Once the camera subassembly is completely deployed, the camera stepper motor extends the telescoping camera arm on which the camera is mounted, completing the third component of motion. From that point, the RF receiver activates and begins to listen for and detect the RF commands.

Once a string of commands has been received, they are demodulated by an accessory Arduino. The Arduino then sends the full demodulated RAFCO command to the ESP32 Main microcontroller. The ESP32 Main then processes the commands one by one. If a command involves rotating the camera about the z-axis (A1 or B2 according to NASA Req. 4.2.2.), the ESP32 Main will actuate the stepper motor to achieve the rotation. However, if the command involves image capture or processing (C3, D4, E5, F6, G7 or H8 according to NASA Req. 4.2.2.), the ESP32 Main will send a packet to ESP32-CAM via ESP-NOW and enter a standby state. ESP32-CAM, which is in a default standby state, executes the command and sends a packet back to ESP32 Main to signal completion. This process ensures that all commands are executed in a linear and timely manner, with a maximum of 30 seconds between photos taken (NASA Req. 4.2.1.4.). The control flow for the TROI is shown in Figure 71.

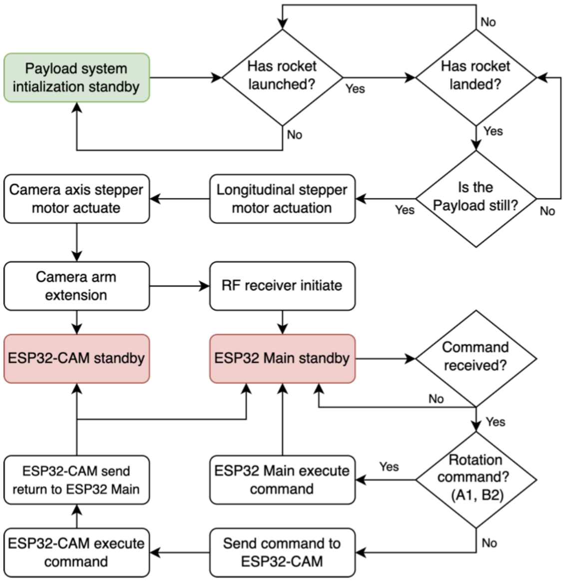


Figure 71: Overall Control Flow Diagram

6.5.2 ESP32 Communication

For the communication between the two ESP32 subsystems, the TROI uses ESP-NOW which is an Espressif Systems low-power 2.4 GHz wireless communication protocol similar to Bluetooth. ESP-NOW allows for two-way communication of packets with a payload of 250 bytes or fewer. The data communicated between the two subsystems includes a command indicator and a string containing the timestamp data which is well within ESP-NOW's communication packet constraints.

6.5.3 Launch and Landing Detection

In order to detect launch and landing, the TROI utilizes two Adafruit BNO055 9-axis IMUs to detect various accelerometer, gyroscopic, and angle values. Once the TROI has been fully initialized, launch is detected using acceleration data from the IMUs. The TROI detects whether the average rate of the last two readings of the main IMU is greater than 30 $\mathrm{m/s^2}$. If this is true, the TROI begins flight processing. For a fixed buffer of 90 seconds, the TROI passively records acceleration and gyroscopic motion, polling the accelerometer and gyroscope components of the main IMU. During the first 90 seconds of flight, the TROI only records data and does not search for landing in order to reduce the risk of premature deployment.

When the payload body tube has landed and is stationary, the only force acting on the onboard IMUs is gravity. The gyroscope component also checks to see if the TROI is moving. After 90 seconds of flight, utilizing these checks, the TROI begins averaging the last 10 accelerometer values and the last 10 gyroscopic values. If the average accelerometer value is within 0.3 $\mathrm{m/s^2}$ of standard gravity and the average gyroscopic motion is within 5 radians/s of movement, the TROI determines that it has landed. The launch and landing control flow is shown in Figure 72.

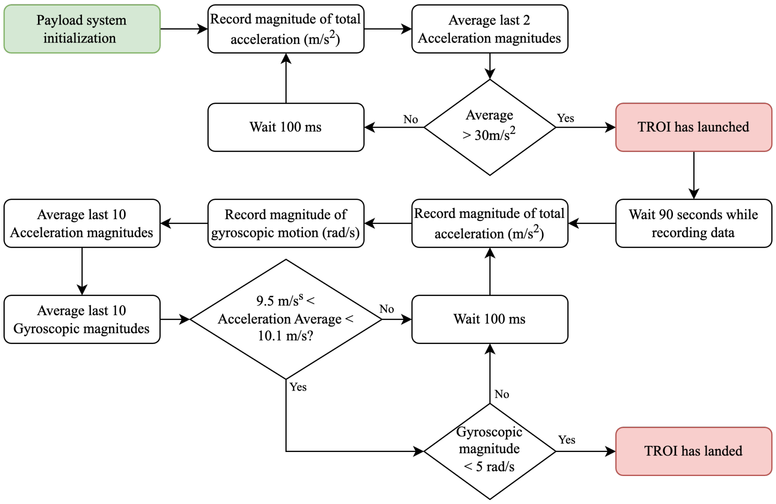


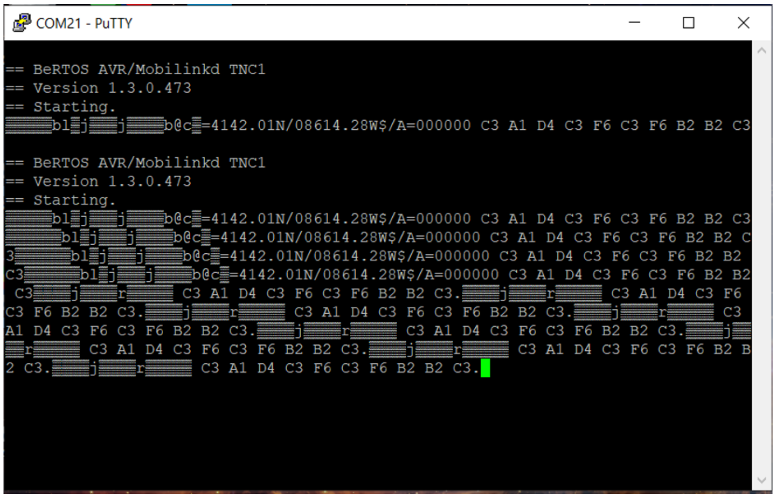
Figure 72: Launch and Landing Detection Diagram

6.5.4 RF Demodulation

As described in Section 6.4.5, the RF system consists of an antenna, DRA818V transceiver, Mobilinkd TNC, and ESP32-WROVER-E microcontroller. To prepare for RF reception, the DRA818V is initialized via a serial pin connection. Following initialization, RF transmissions in the form of AX.25 AFSK 1200 packets are demodulated using the onboard embedded systems TNC. The TNC design was a modified version of the Mobilinkd TNC1 that was simplified to only include the components needed for APRS demodulation. The modified TNC will integrate with the DRA818V on the RF PCB, minimizing the space required for demodulation hardware, and ensuring durable electrical connections. The RF PCB also minimizes interference and noise in the system as loose wires can act as small antennas disrupting the data collected from the main antenna. The embedded systems antenna was tested and verified by comparing the demodulated packets to software TNCs such as Direwolf and APRSdroid.

An initial test was conducted using the DRA818V transceiver and a software TNC on a laptop computer for demodulation. These tests verified that the antenna and transceiver function correctly, and that the DRA818V has enough resolution for AX.25 packet demodulation. For this test, the DRA818V settings and reception frequency were initialized via serial commands. Note that after initialization, the DRA818V will remain on the same settings and reinitialization is only required to change the reception frequency. Therefore, the serial connection is temporary to avoid added weight and components to the system. Additionally, the transceiver's AF_{OUT} pin was connected to the audio port of the laptop. This test succeeded in demodulating via a software TNC.

Tests have also been conducted to evaluate the Mobilinkd TNC's ability to demodulate packets for APRS AX.25 AFSK 1200 baud packet demodulation. They were also intended to verify that the embedded TNC can successfully integrate with the DRA818V transceiver. These tests followed a similar procedure to the previous set of tests, but incorporated the Mobilinkd TNC for demodulation in place of the laptop computer. A diagram for the test circuit is displayed in Figure 70. A licensed HAM radio Operator (KI5REN) tested 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. The RF system successfully received and demodulated both of the two AX.25 packet formats that were used for testing. Packet content was output to the COM port of the computer via the TX serial pin of the Arduino Nano and PuTTY computer software, after which it was successfully filtered and parsed. A serial terminal output produced during testing is displayed in Figure 73.



```
== BeRTOS AVR/Mobilinkd TNC1
== Version 1.3.0.473
== Starting.
▒▒▒▒▒bl▒j▒▒▒j▒▒▒▒b@c▒=4142.01N/08614.28W$/A=000000 C3 A1 D4 C3 F6 C3 F6 B2 B2 C3

== BeRTOS AVR/Mobilinkd TNC1
== Version 1.3.0.473
== Starting.
▒▒▒▒▒bl▒j▒▒▒j▒▒▒▒b@c▒=4142.01N/08614.28W$/A=000000 C3 A1 D4 C3 F6 C3 F6 B2 B2 C3
▒▒▒▒▒▒bl▒j▒▒▒j▒▒▒▒b@c▒=4142.01N/08614.28W$/A=000000 C3 A1 D4 C3 F6 C3 F6 B2 B2 C
3▒▒▒▒▒▒bl▒j▒▒▒j▒▒▒▒b@c▒=4142.01N/08614.28W$/A=000000 C3 A1 D4 C3 F6 C3 F6 B2 B2
C3▒▒▒▒▒▒bl▒j▒▒▒j▒▒▒▒b@c▒=4142.01N/08614.28W$/A=000000 C3 A1 D4 C3 F6 C3 F6 B2 B2
 C3▒▒▒▒j▒▒▒▒r▒▒▒▒▒ C3 A1 D4 C3 F6 C3 F6 B2 B2 C3.▒▒▒▒j▒▒▒▒r▒▒▒▒▒ C3 A1 D4 C3 F6
C3 F6 B2 B2 C3.▒▒▒▒j▒▒▒▒r▒▒▒▒▒ C3 A1 D4 C3 F6 C3 F6 B2 B2 C3.▒▒▒▒j▒▒▒▒r▒▒▒▒▒ C3
A1 D4 C3 F6 C3 F6 B2 B2 C3.▒▒▒▒j▒▒▒▒r▒▒▒▒▒ C3 A1 D4 C3 F6 C3 F6 B2 B2 C3.▒▒▒▒j▒
▒r▒▒▒▒▒ C3 A1 D4 C3 F6 C3 F6 B2 B2 C3.▒▒▒▒j▒▒▒▒r▒▒▒▒▒ C3 A1 D4 C3 F6 C3 F6 B2 B
2 C3.▒▒▒▒j▒▒▒▒r▒▒▒▒▒ C3 A1 D4 C3 F6 C3 F6 B2 B2 C3.
```

Figure 73: Serial Output Following Successful Embedded TNC Demodulation

Lastly, the complete RF subsystem was integrated with the ESP32-WROVER-E microcontroller. The TX pin of the TNC Arduino Nano was connected to the RX pin of the ESP32-WROVER-E. The microcontroller was initialized to the correct baud rate of 38400 and was able to successfully read the demodulated AX.25 packets via the serial interface and use them to send commands to the rest of the system. This test fulfills the RF Command Processing Test TROIT.8. The testing of the integrated TROI subsystems is described further in Section 6.5.6.

6.5.5 Camera Commands

The commands outlined by NASA Req. 4.2.2. that the TROI receives are divided between its two ESP32 subsystems as shown in Table 65. Commands are first received and interpreted by the ESP32 Main subsystem, which then either executes the command or sends it to the ESP32-CAM subsystem. The ESP32 Main subsystem handles commands which involve rotation about the z-axis, such as command A1. Otherwise, a packet is sent via ESP-NOW to the ESP32-CAM subsystem containing an integer flag indicating which command was received and the timestamp data. The ESP32-CAM subsystem executes all commands involving digital image processing or image capture, such as command C3. This process was chosen to separate the processing requirements of the system between two microcontrollers and to allow for the use of the prebuilt ESP32-CAM board.

Table 65: List of commands and the respective subsystem

Command	Microcontroller	Action Completed	Return Packet?
A1	ESP32 Main	Camera stepper motor rotated by 60° clockwise	N/A
B2	ESP32 Main	Camera stepper motor rotated by 60° counterclockwise	N/A
C3	ESP32-CAM	Picture taken and saved to onboard microSD card	Yes
D4	ESP32-CAM	Software changes next image from color to grayscale	Yes
E5	ESP32-CAM	Software changes next image from grayscale to color	Yes
F6	ESP32-CAM	Software flips image upside down	Yes
G7	ESP32-CAM	Software applies special effects filter	Yes
H8	ESP32-CAM	Software removes all filters	Yes

6.5.6 Software Testing

The team conducted several software-related tests. The Camera Unit Test verified the camera's basic ability to take images and apply filters, ensuring that the manufacturer sent a functional product to the team (TROIT.3). This test passed, and integration of the camera subsystem with the TROI was able to continue. The RF Command Processing Test verified the TNC's ability to demodulate RF commands and send them to the ESP-32 subsystem (TROIT.8). This test passed; the TNC was able to demodulate commands into those capable of being understood by the ESP-32. Successful demodulation verifies the RF system is fully functional and that integration with the camera subsystem may continue. The Camera Stepper Motor Test verifies the camera's ability to accurately respond to in-house code commands from the ESP-32 by rotating to the correct position (TROIT.9). This test passed. The Camera Baseline Imaging Test (TROIT.12) verifies the camera is able to capture high-quality images within 30 sections of each other while applying special effects as necessary, and these images are included in Figure 131. The TROI completed commands C3, D4, and F6 for this test. This test passed and allowed the team to continue integrating the camera subsystem. The Camera RF Integration Test verifies the RF subsystem can receive, demodulate, and transmit RAFCO to the camera subsystem, with the camera system accurately capturing images according to RAFCO (TROIT.13). Finally, the Payload State Identification Test verifies that in-house code successfully interfaces with the TROI electronic sensors to identify whether the launch vehicle is in a flying or landed configuration. This test passed; the TROI lead screw actuates only after the sensors have detected landing (TROIT.14). This test demonstrates nominal integration of the TROI mechanical and electrical subsystems.

6.6 Flight Reliability

It is essential that the TROI is reliable during flight for safety and achieving mission success. The following list of actions have been taken to verify payload safety:

- Multiple deployment tests have been performed on the ground, testing and verifying the system code as described in Section 6.5.6
- The launch and landing code includes a 90 second waiting period after launch is detected to start detecting landing as described in Section 6.5.3.
- The launch and landing code includes three redundant checks for landing, with a redundant IMU checking for the still, landed payload as described in Section 6.5.3.
- The camera stepper motor is powered during flight and hence is consistently providing a locking back torque to keep the telescoping camera arm from deploying prematurely as described in Section 6.3.2.2.
- The successful retention of the payload was verified in the vehicle demonstration flight attempt as described in Section 6.7.

6.7 Vehicle Demonstration Flight

The TROI flew in the vehicle demonstration flight attempt on February 18th. The team tested the retention, launch and landing code, and longitudinal stepper motor deployment subsystem through this launch. The TROI did not fly in its complete configuration nor was running the finalized code; hence, this flight does not qualify as a payload demonstration flight. Images of the TROI after landing are shown in Figure 74.

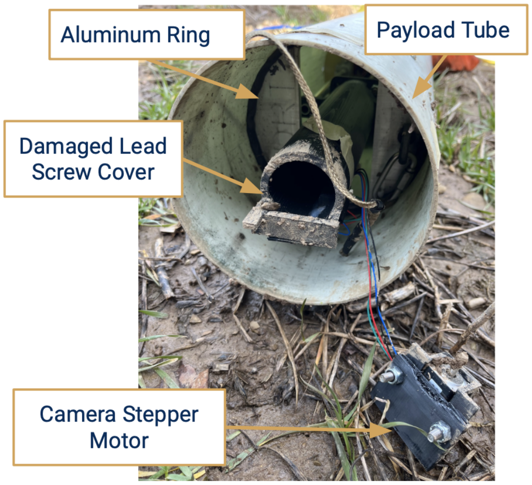


Figure 74: Payload after landing at VDF attempt

As demonstrated in Figure 74, the TROI was successfully retained in the vehicle demonstration flight attempt. There were a combination of successes, failures, and damages to the payload resulting from the flight.

The TROI was successfully retained in the vehicle demonstration flight attempt. All hardware remained intact and functioned as intended, and no electronic connections were disconnected. However, the TROI prematurely deployed about 60 seconds into the flight. This was determined to be due to a coding error in the launch and landing detection code. This error has since been corrected. Additionally, the TROI will wait 90 seconds after launch to start detecting landing as an additional redundancy considering flight length requirements (NASA Req. NASA 3.11. as specified in Section 6.5.3.

The premature longitudinal stepper motor deployment caused the lead screw cover and lead screw to sustain the force of the payload body tube landing. This caused the 3D printed lead screw cover to fail, and the 1/4 in. diameter 303 stainless steel lead screw bent. The damage to the lead screw is shown in Figure 75.

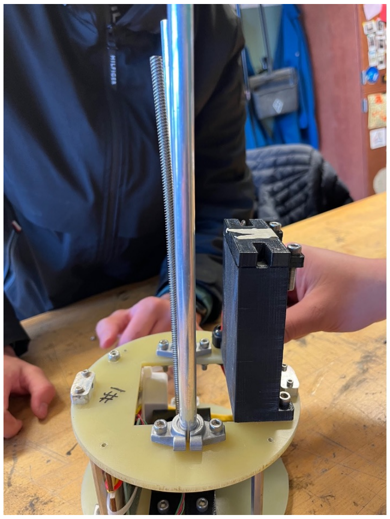


Figure 75: Lead Screw Damage after VDF Attempt

Figure 75 demonstrates the noticeable deformation in the lead screw. This damage required the replacement of the lead screw. Four options were considered: reorder the original part, replace the lead screw in the existing stepper motor, use a coupling nut to attach a new lead screw to the existing lead screw, or replace the total lead screw and stepper motor assembly. All four options were explored in parallel, causing the team to try to machine a custom coupling nut as described in Section 6.3.1.2. This effort failed, and the team decided not to disassemble the stepper motor. A replacement of the original part would not arrive in time for the FRR milestone, so that option was not considered. The team acquired a replacement lead screw and stepper motor assembly and chose this option to remediate the damage due to launch as the only available option. The team reconfigured the necessary parts of the payload to work with the new lead screw size. The available lead screw has a diameter of 8 mm (0.315 in.).

6.8 Payload Demonstration Flight

A payload demonstration flight is essential to confirm the safety and test the functionality of the TROI. March 10th and March 25th are possible dates currently in consideration for payload demonstration flight(s). In order to achieve a successful payload demonstration flight, the payload must be successfully retained and attempt to operate in its final configuration. The payload will achieve its mission if all the mission and success criteria are met from Section 6.1. As per Section 6.6, the team does not anticipate any retention or deployment errors after extensive ground testing. The team will change the series of RF commands to the TROI at each test to practice operating with any order of commands. The TROI will save all time-stamped images taken during operation for later retrieval and submission. The team will submit the FRR Addendum to include the results of the payload demonstration flight(s), including the sequence of time-stamped photos in the correct order.

7 Technical Design and Testing: Apogee Control System

7.1 Mission Statement and Success Criteria

The Apogee Control System is the team's non-scoring payload. ACS is an air braking system that consists of four hinged drag flaps that are symmetrically actuated between burnout and apogee to lower the launch vehicle's apogee to the 4600 ft. target. Its mechanism is driven by a standard high-torque servo motor that receives commands from a Raspberry Pi 4 microprocessor via a PWM servo controller board. The ACS sensor suite consists of an accelerometer, IMU, and two altimeters all mounted on a single PCB. The ACS software is written in Python 3 and includes a data filter as well as a proportional control algorithm to dynamically adjust flap extension in response to the launch vehicle's trajectory. Once burnout is detected, the servo motor rotates a central hub which pushes out a set of four pusher arms that are linked to four lever arms. The lever arms are directly attached to the flaps and enable hinged actuation. As soon as the system detects apogee, it commands the flaps to fully retract and they remain in that position for the remainder of the flight.

The ACS mission success criteria are as follows:

- The system must reduce apogee to within 25 ft. of the target apogee, 4600 ft.
- The ACS drag flaps must be located aft of the burnout CG (NASA Req. 2.16)
- The system must perform a successful power-on self-test before it is armed
- The system must not jeopardize the safety or stability of the launch vehicle
- The system must only actuate between burnout and apogee
- The system must extend and retract its flaps as commanded directly or according to a proportional control algorithm
- The system must accurately collect, filter, and record sensor data for in-flight use and post-flight analysis

7.2 Changes Since CDR

The design of the ACS was unchanged from CDR, with the exception of 2 minor alterations made to improve the structural integrity and operability of the mechanism. The material used for the flap lever arms was changed from aluminum to stainless steel. This was done to increase the strength of the high-load-bearing part and to simplify the manufacturing from a multi-step CNC milling process with complex geometry to a single metal 3D print for all four lever arms. A double pull pin switch was added, which disconnects the motor and Raspberry Pi 4 from their respective batteries when inserted. This change simplifies the troubleshooting and initialization processes, as well as the steps required to integrate the ACS into the launch vehicle.

7.3 Mechanical Design

The overall ACS mechanism consists of a central hub attached to a standard high-torque 80 kg-cm servo motor (DS5180) that is rotated according to commands from the ACS microprocessor. The central hub's rotation is coupled to the linear motion of four flap pusher arms via a set of linkages. Each pusher arm is attached to a hinged flap lever arm that rotates outward. Four drag flaps cut out from the body tube are rigidly attached to the lever arms and thus actuate accordingly. A slotted deck, several bulkheads, and threaded rod supports maintain the structural integrity of the entire system while permitting adjustments to be made during assembly.

The following sections describe how each of the key mechanical components were manufactured and their role within the ACS assembly.

7.3.1 Slotted Deck

The slotted deck is a thick bulkhead which houses the central hub, linkages, and flap pusher arms and guides the mechanism's motion during actuation. The slotted deck was manufactured out of 0.75 in. thick Nylon 6/6 using a CNC mill, with final adjustments made using a manual mill and belt sander. The CAD model compared to the constructed slotted deck is shown in Figure 76.

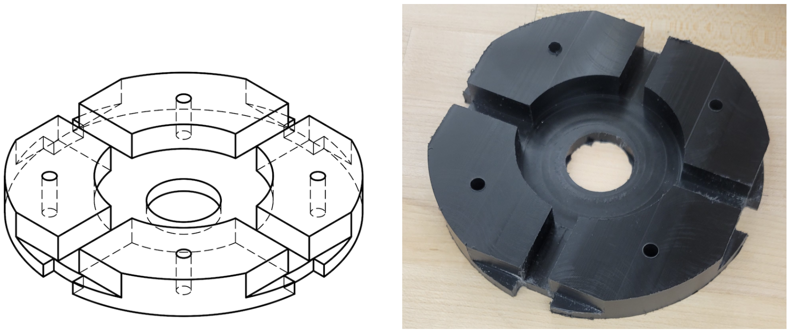


Figure 76: CAD Drawing (left) and as constructed (right) slotted deck

7.3.2 Central Hub

The central hub is a key component in the ACS flap deployment mechanism. It is located in the center of the mechanism on the slotted deck and is attached to a threaded servo disc using M2.5 screws. The servo disc splines directly to the servo motor output gear shaft. Four outer linkages hinge to the central hub using linkage bolts, allowing the motor to actuate all four drag flaps simultaneously, which avoids asymmetric actuation. The inner threads were created by first drilling and then manually tapping the holes with a 10-32 tap to fit the linkage bolts and linkages.

To ensure that the central hub meets all design requirements, it was cut out of 0.5 in. thick 6061 Aluminum sheet stock using a CNC mill, which ensured adequate precision during the manufacturing process. Figure 77 shows an isometric CAD drawing of the central hub alongside the manufactured part.

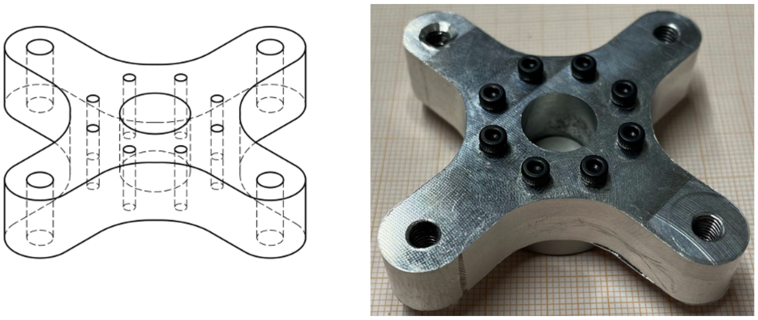


Figure 77: CAD Drawing (left) and as constructed (right) central hub

7.3.3 Linkages

Four identical linkages are responsible for connecting the flap pusher arms to the central hub and ensuring symmetric flap actuation. The linkages extend due to the rotation of the central hub by the servo motor, with each linkage being connected to both the flap pusher arms and the central hub by linkage bolts that enable linkage rotation about their own axes.

A waterjet cutting process was used as it provided the necessary precision to manufacture the component to the required specifications. This ensured that the linkages could smoothly interface between the central hub and pusher arms and could act as reliable secondary load-bearing structures. The material used for the linkage component was 0.25 in. thick 6061 Aluminum sheet stock, selected for its ability to sustain high torsion forces from the servo motor in both directions. Figure 78 shows the isometric CAD drawing of a linkage alongside the manufactured part.

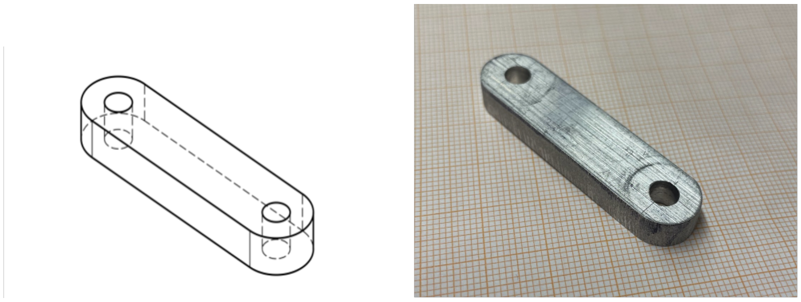


Figure 78: CAD Drawing (left) and as constructed (right) linkage

7.3.4 Flap Pusher Arms

The flap pusher arms interface with the central hub's linkages and the flap lever arm to enable flap actuation. Due to the design of the slotted deck, the flap pusher arms are only capable of motion along a single axis, enabling the hinged drag flaps to actuate at a specific angle relative to the body tube. Each flap pusher arm is secured to the central hub's linkage using a linkage bolt, while a sliding drive pin (4-40 shoulder screw and nut) secures it to the flap lever arm.

To ensure maximum precision during the manufacturing process, each pusher arm was cut out of 0.5 in. thick 6061 aluminum sheet stock using a waterjet. The curve on each arm allows it to slide along the path of the drive pin and was manually created using a belt sander, then hand fitted to minimize friction which avoids jamming the mechanism. The hole attaching the part to the central hub's linkages was drilled and then tapped so it could be secured using a linkage bolt. Figure 79 shows the isometric CAD drawing of a flap pusher arm alongside the manufactured part.

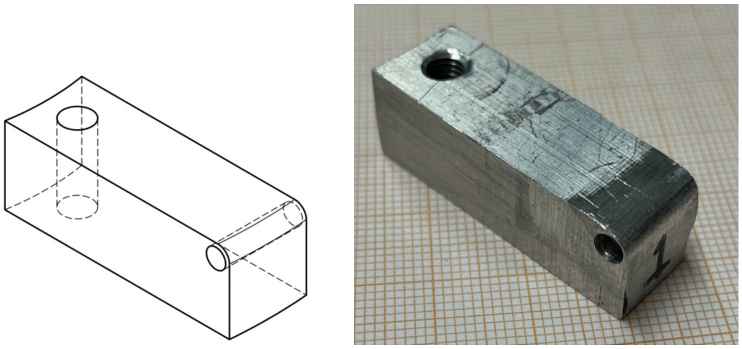


Figure 79: CAD Drawing (left) and as constructed (right) flap pusher arm

7.3.5 Flap Lever Arms

The flap lever arms are primary load bearing structures that are attached directly to the drag flaps. They also hinge on the flap pusher arms and fore bulkhead hinges via stainless steel shoulder screws and small pattern nuts. The flap lever arms were 316L stainless steel 3D printed on the GE Cusing M2 Dual Laser 3D printer to ensure that the point of attachment to the flap pusher arm (only 0.035 in thick) can sustain the expected aerodynamic loads because this part is a primary load bearing structure. The arms were printed upright using a 0.05 mm layer height with break-away supports that were removed using pliers. Although stainless steel is heavier than the Aluminum the team originally planned to use, the ACS is still within its allowable mass of 80 oz as the bulkhead masses had been significantly overestimated during CDR. After 3D printing, the flap attachment holes were drilled out to a larger size and then tapped to fit 8-32 screws used for drag flap attachment. An isometric CAD drawing alongside the 3D printed flap lever arms (different orientations) is shown in Figure 80.

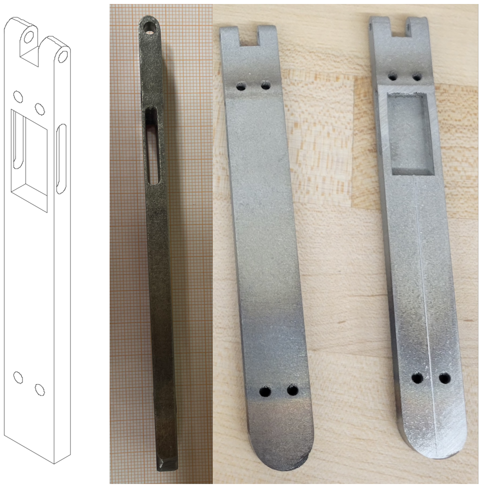


Figure 80: CAD Drawing (left) and as constructed (right) flap lever arms

7.3.6 Drag Flaps

The drag flaps are cut out from the carbon fiber ACS body tube using a CNC mill. To prevent interference between the drag flaps and ACS body tube during actuation and for tolerance, the drag flaps were fabricated to be slightly smaller than the original cut in the tube. Only about 0.125 in. of material was cut from all sides of each flap in order to ensure that external debris does not significantly impact ACS electronics and to avoid affecting the launch vehicle stability margin. To securely fasten the flaps to the lever arms, through holes were drilled at the appropriate locations. The as-designed CAD model for a drag flap is shown alongside the constructed flap in Figure 81.

Figure 81: CAD Drawing (left) and as constructed (right) drag flap

7.3.7 Bulkhead Hinges

The bulkhead hinges are aluminum components that interface between the ACS lever arms and fore bulkhead. They enable rotational flap actuation by acting as pivots for the flap lever arms via shoulder screws. The bulkhead hinges were cut out of 0.25 in. 6061 Aluminum stock with a CNC mill. Holes were then drilled on the top to allow a 4-40 screw, nut, and washer to secure each hinge to the fore bulkhead. Figure 82 shows the as-designed isometric CAD hinge drawing alongside the as-constructed bulkhead hinge.

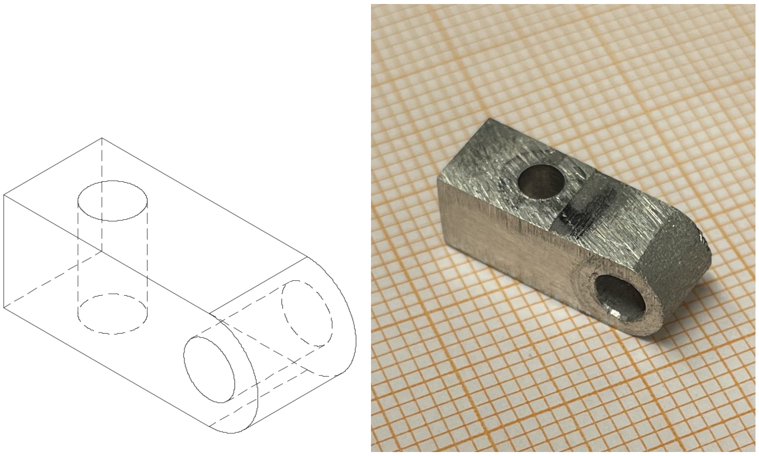


Figure 82: CAD Drawing (left) and as constructed (right) fore bulkhead hinge

7.3.8 Bulkheads and Supports

The ACS includes 3 bulkheads, in addition to the slotted deck, used to secure components in the correct locations relative to each other during assembly and to maintain overall ACS structural integrity. These bulkheads are the fore bulkhead, aft bulkhead, and motor mount bulkhead.

The fore bulkhead has four attached hinges for flap lever arm attachment. It also contains four threaded airframe interface blocks used to secure the ACS within the ACS body tube via 8-32 screws. An eyebolt is used to facilitate

ACS integration into the launch vehicle. The motor mount bulkhead is used to secure the servo motor and provides the first attachment point for the PCB mounting board, while the aft bulkhead serves as the second attachment point. Four 1/4 in.-20 threaded rods traverse the entire length of the system and enable adjustment of bulkhead positioning. Tightened 1/4 in.-20 nuts are used on both sides of each bulkhead to ensure structural integrity.

7.3.9 Mechanism Assembly and Integratiion

The ACS is assembled from base to top, as the bulkheads and corresponding components are fastened to the threaded rods in ascending order. Beginning at the base, four threaded rods are fastened to the aft bulkhead using tightened nuts on each side of the bulkhead.

All electronics are mounted to the PCB using soldered connections, which is in turn bolted to the electronics board along with the pull pin switch, microcontroller battery, and motor battery. The electronics board is attached to the aft and motor mount bulkheads with four L-brackets.

The motor mount bulkhead is held in place by nuts on the threaded rods and uses two L-brackets to attach to the electronics board. The motor is bolted to the motor mount bulkhead in four locations to keep the motor's shaft centered on the ACS.

The motor interface disk connects the motor to the central hub using a pattern of eights bolts, which form the center of the slotted deck assembly, shown in Figure 83. The central hub controls the motion of the flap pusher arms via linkages, which are connected using flanged socket head cap screws. These components are all located on the slotted deck, whose axial distance from the motor mount bulkhead is determined by nuts that hold it in place.

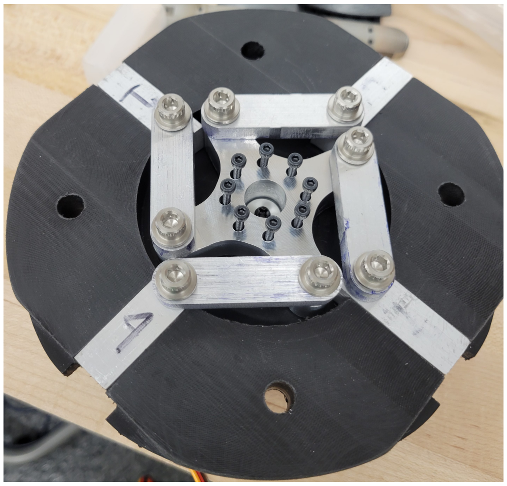


Figure 83: The ACS Slotted Deck Assembly

The four ACS flaps, located within cutouts in the ACS body tube, are each supported by a flap lever arm screwed to the backside of each flap. The flap lever arms are linked to the flap pusher arms using a pin and slot, which couple the flaps' motion to that of the motor. The flap lever arms also connect to the fore bulkhead via hinges which constrain the position of the lever arms while allowing for rotation in the desired direction.

The fore bulkhead contains the hinges, airframe interface blocks, and eyebolt, which is used for transportation and integration of the ACS into the launch vehicle. These components are all fastened to the fore bulkhead with tightened bolts. The fully assembled ACS compared to the CAD model is shown in Figure 84.

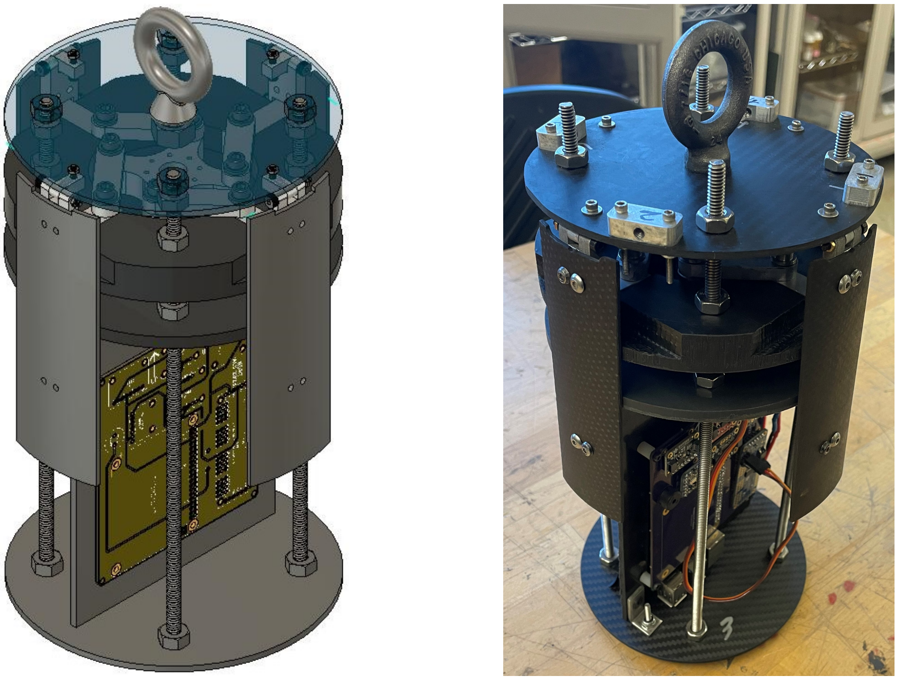


Figure 84: CAD model (left) and as constructed (right) Integrated ACS

7.4 Electrical Design

The following sections outline the electrical components of the ACS subsystem and the electronics tests that the team has performed.

7.4.1 Electronic Component Integration and Testing

The ACS electrical system is split into two independent circuits: a logic circuit and a servo motor circuit. Both circuits are included on a custom PCB as detailed in Section 7.4.2 and share a common ground plane on the PCB.

The logic circuit contains a DC boost converter, the Raspberry Pi 4 microprocessor, and four sensors. These sensors include an Adafruit ADXL343 3-axis accelerometer, a MPL3115A2 barometric altimeter, a BMP390 backup altimeter, and a BNO055 9-DoF Inertial Measurement Unit with absolute orientation measurement capabilities. This circuit is powered by a 3.7 V 5000mAh LiPo battery that is stepped up to 5 V by the Adafruit 1000 Basic PowerBoost. The Raspberry Pi 4 continuously collects data from its sensor suit via the I2C protocol, filters it, and sends the appropriate commands to the servo motor. The complete control flow design is described in Section 7.5.

The servo motor circuit is directly powered by a 7.4 V 2-cell 3000 mAh LiPo battery and is linked to the logic circuit by the PCA9685 PWM servo controller board that communicates with the Raspberry Pi via the I2C protocol and sends PWM signals to the servo motor. Both circuits are switched independently by SPDT double pull-pin switches.

The two most comprehensive electrical tests performed were a battery duration test and a ground test. The battery duration test was performed during the vehicle demonstration flight on February 18th and proved successful as the system remained active for well over 2 hours and still actuated in flight. The system was able to remain powered for another hour after launch before a low battery light was observed. Therefore, the team is confident that the ACS can remain armed on the launchpad for as long as is necessary on launch day. The ACS ground test was performed using legacy subscale data (as a .csv file) from the team's December 4th subscale launch and proved successful as the ACS correctly detected the launch vehicle's state and commanded servo actuation accordingly in real time. The flaps were also retracted after apogee. All electronic component unit tests were also passed with reliable data being recorded from each sensor that matched data collected by recovery/payload sensors and OpenRocket simulations. Refer Section 8.3.2 for further details regarding in-flight ACS testing.

7.4.2 PCB Design and Fabrication

The ACS electrical system is housed on a two-layer Printed Circuit Board (PCB) which was fabricated using OSH Park's 2 Layer Prototype Service. It was designed to ensure that all electronic components (with the exception of the servo motor) are mounted securely. The PCB also minimizes the system's total electrical footprint and minimizes the amount of external wiring necessary. This improves the reliability of the electrical system as compared to a perfboard. Moreover, the PCB includes a copper pour ground plane on both PCB layers, which acts as a form of electrical shielding and minimizes the risk of electromagnetic interference from external RF signals and from the servo motor (which may draw a large current while actively actuating).

The PCB was designed in Autodesk Fusion 360 Electronics with the following dimensions: 114.4 x 101.7 x 1.6 mm (4.50 in. x 4.00 in. x 0.063 in.). All electronic components were mounted using Through Hole Technology (THT) with header pins soldered to each breakout board and to the corresponding PCB pads. A piezo buzzer was also included to provide auditory feedback during ACS initialization and to alert the team if a software runtime error occurs. The PCB included component placeholders on the front and back silkscreens to ensure that components are placed in the correct location and orientation. The silkscreen also includes the names of a component's pins that must be soldered to ensure connectivity with other components. The team chose to use THT mounting rather than SMT (surface mount technology) because THT mechanical connections are superior to SMT, enabling the electrical connections to endure more mechanical stress, especially during launch and recovery. Figure 85 shows the designed PCB Layout diagram and the as-fabricated PCB (without mounted electronics).

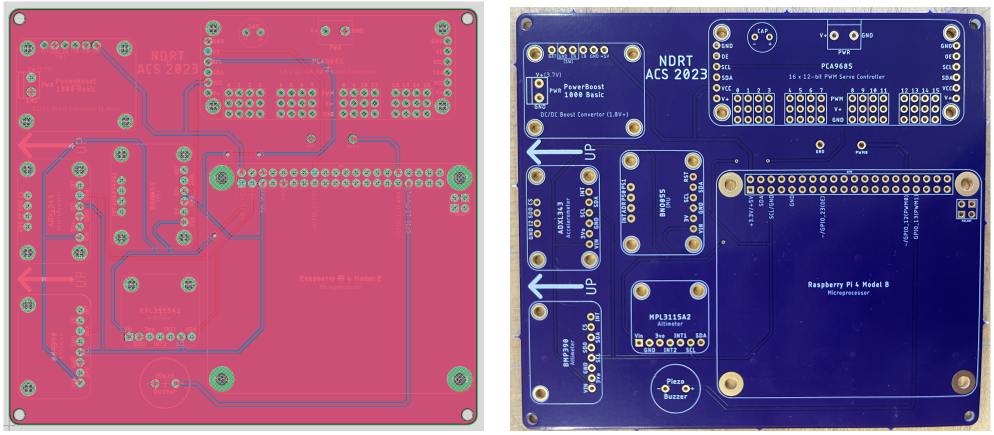


Figure 85: PCB Layout Diagram (left) and fabricated PCB (right)

The PCB was mounted with M2.5 screws/nuts and spacers on an HDPE board that was cut out (with a servo motor slot) from a larger stock using a waterjet. The PCB mounting board was secured to the motor bulkhead above and to the aft bulkhead below using an Aluminum L-bracket on each corner. Figure 86 shows the ACS PCB in its powered/armed state with all electronics mounted and fully integrated into the ACS assembly.

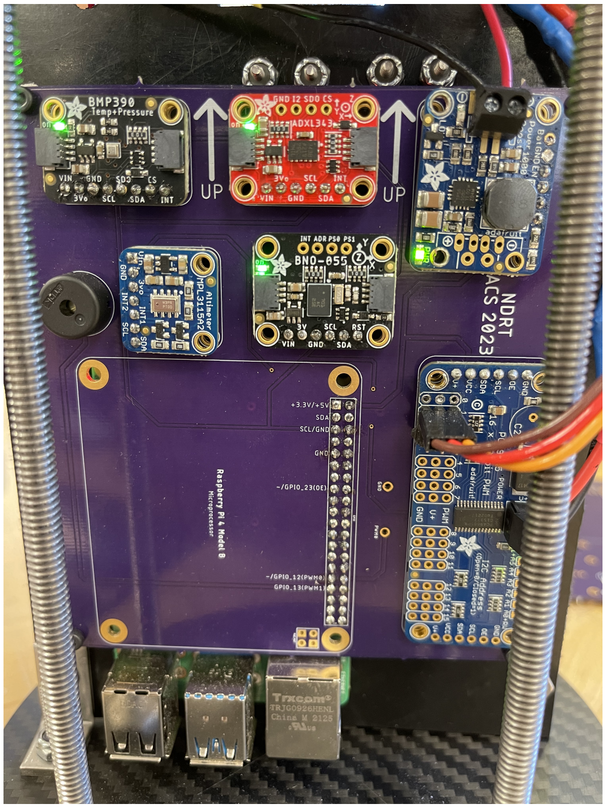


Figure 86: Battery-powered PCB with mounted electronics (armed)

7.5 Control Flow Design

The ACS control system consists of a microprocessor, PWM servo controller, and control software. All ACS code and their libraries are written in Python 3 and maintained by versioning on the ACS 2023 GitHub Repository. The ACS sensor suite inputs data to the control system, which is processed by the microprocessor. Then, according to a proportional control algorithm, the servo angle is relayed to the servo motor via the PWM servo controller. All processing runs in a closed-loop that cycles over 20 times per second as described in Figure 87.

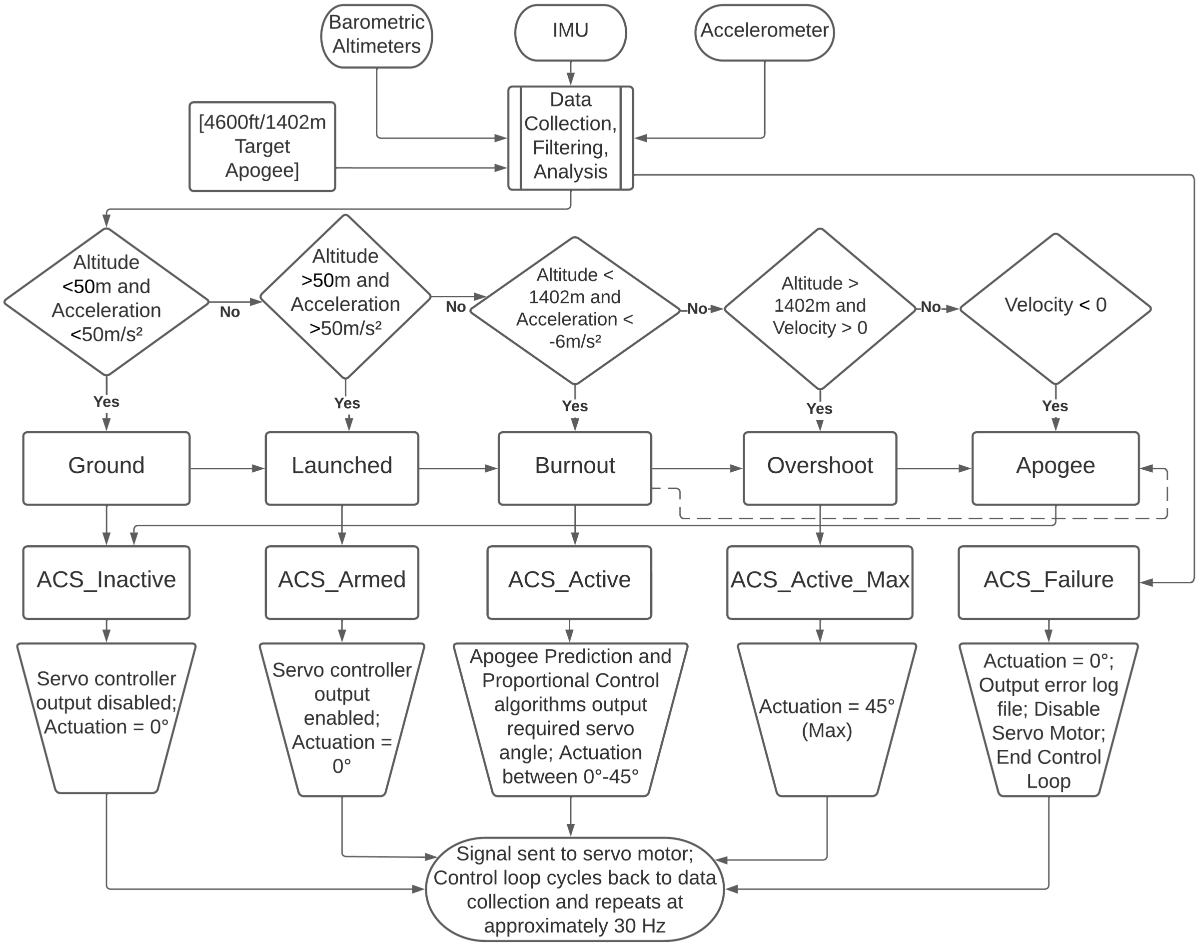


Figure 87: ACS Control Code Flowchart

The ACS microprocessor reads and Kalman filters sensor data to categorize the launch vehicle's state into one of five categories based on its altitude, velocity, and acceleration. Depending on the launch vehicle state, the ACS will itself be put into one of five states: Inactive, Armed, Active, Active_Max, and Failure. The Failure state is only triggered in the event of a runtime error; 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.

The following sections provide further information regarding the ACS implementation of two key algorithms: the Kalman Filter and Proportional Control.

7.5.1 Kalman Data Filter

In flight, the ACS control system dynamically determines when to actuate the mechanical flaps to airbrake the launch vehicle as it approaches target apogee. Thus, the system must accurately know the position, velocity, and acceleration of the launch vehicle. Although ACS is equipped with multiple sensors, the sensor values cannot be used directly because they contain noise and do not directly measure velocity.

To lessen the impact of inaccurate sensor output data, the ACS applies Kalman filtration to 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 to estimates a joint probability distribution for each time step to estimate future values, a more accurate approach 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 14.

$$H = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{14}$$

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 15.

$$\Phi = \begin{bmatrix} 1 & \Delta & \Delta^2/2 \\ 0 & 1 & \Delta \\ 0 & 0 & 1 \end{bmatrix} \tag{15}$$

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 14 may be tuned by hand for more accurate estimates after analyzing sensor readings. The Kalman filter has proven successful in previous test flights.

7.5.2 Proportional Control Algorithm Design

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 87. The apogee prediction algorithm continuously solves Equation 16 forward in time from burnout until apogee using a fourth order Runge-Kutta numerical approximation.

$$x'' = -\frac{1}{2m}\rho x'^2(C_{dl}A_l + C_{df}A_f) - g \tag{16}$$

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 17.

$$C_{df} = 1.28 sin(\alpha) \tag{17}$$

where α is the drag flap actuation angle. 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 4,600 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 18.

$$\theta(t) = K_P E(t) \tag{18}$$

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 Testing and Demonstration Flights

A comprehensive tests were conducted to ensure that all ACS mechanical, electrical, and software components meet NASA + team-derived requirements and are able to perform nominally during launch. With the exception of the apogee prediction and proportional control algorithm tests, all ACS tests were successfully carried out, which gave the team confidence regarding ACS functionality in-flight. Refer Section 10.1.4 for more details on all ACS ground tests.

The ACS was also active on the team's February 18th Vehicle Demonstration Flight. This test was partially successful as the ACS actuated as commanded at fixed pre-programmed angles of 20° and 30° over 5 seconds. However, the ACS actuated a few seconds after apogee (and drogue parachute deployment) instead of between burnout and apogee. This was caused by a software error related to sensor orientation and the team has taken steps to rectify the issue before the next demonstration flight. Further analysis of ACS in-flight performance may be found in Section 8.3.2.

8 Demonstration Flights

8.1 Demonstration Flight Overview

Table 66 describes the VDF completed on February 25th.

Table 66: Vehicle Demonstration Flight Information

Variable	Summary
Flight Type	Demonstration Flight 1
Date	2/18/23
Location	Three Oaks, MI
Wind Speed AGL (mph)	17
Atmospheric Pressure (inHg)	30.24
Air Temperature (°F)	39.2
Motor (NASA 2.19.1.5)	Aerotech L2200G-P
Ballast (oz) (NASA 2.19.1.6, NASA 2.23.7)	0
Final Payload (Y/N)	N
Apogee Control System Status	Unsuccessful but Operable
Official Target Altitude (ft)	4600
OpenRocket Trajectory Altitude (ft)	4757.9
RockSim Trajectory Altitude (ft)	4997.2
MATLAB Code Trajectory Altitude (ft)	4762.5
Measured Altitude (ft)	4729.3

8.2 Flight Profile

The flight profiles from the PED and FED altimeters are shown in Figure 88 below. The NED altimeters are shown in Figure 89 below. Note that the Raven4 altimeter in the FED did not record altitude data despite triggering its charges properly. The NED altimeter data is displayed separately because the nose cone descended independently of the full vehicle in an unplanned manner.

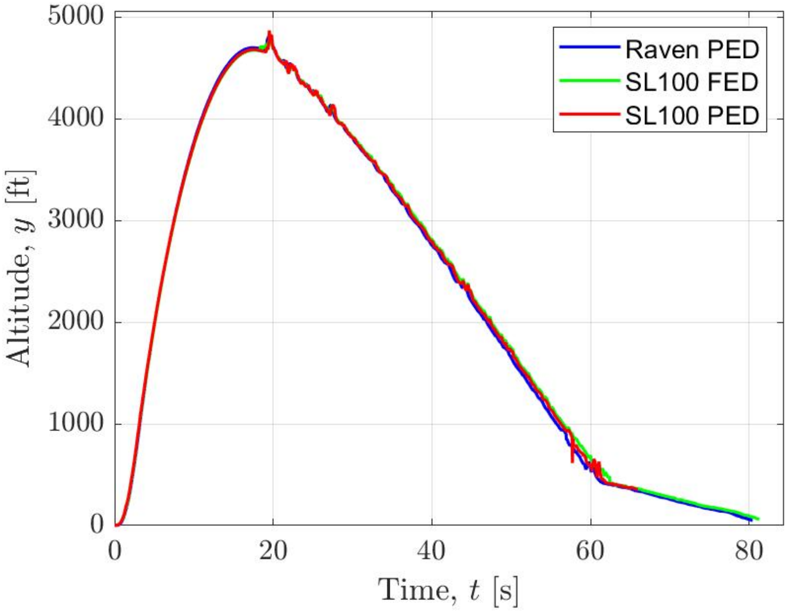


Figure 88: PED and FED Flight Profiles

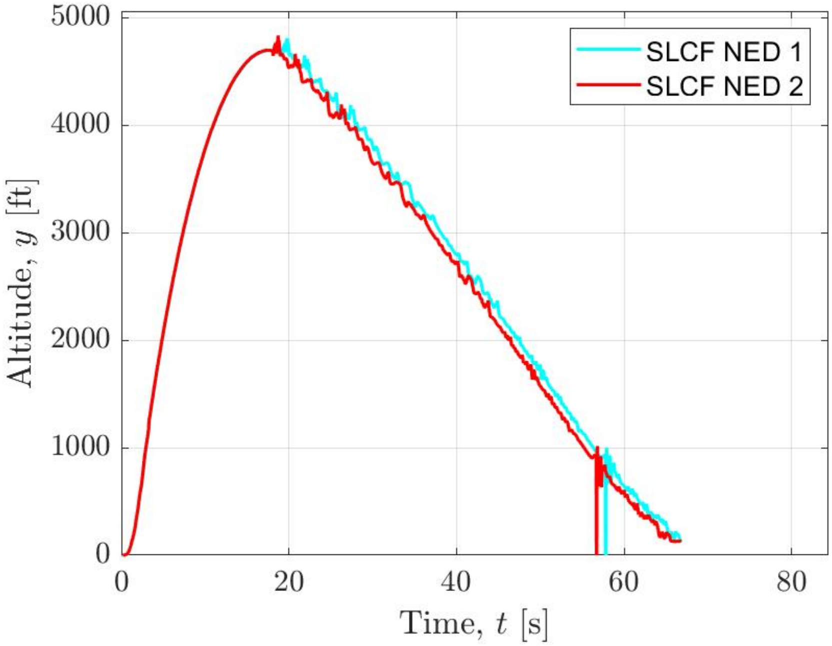


Figure 89: NED Flight Profiles

The above-ground GPS track of the vehicle during flight is shown in Figure 90, below.

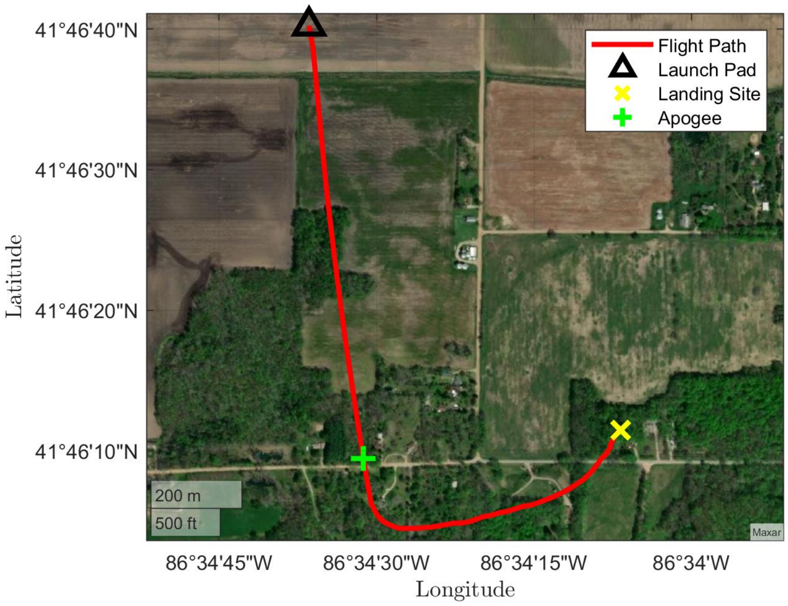


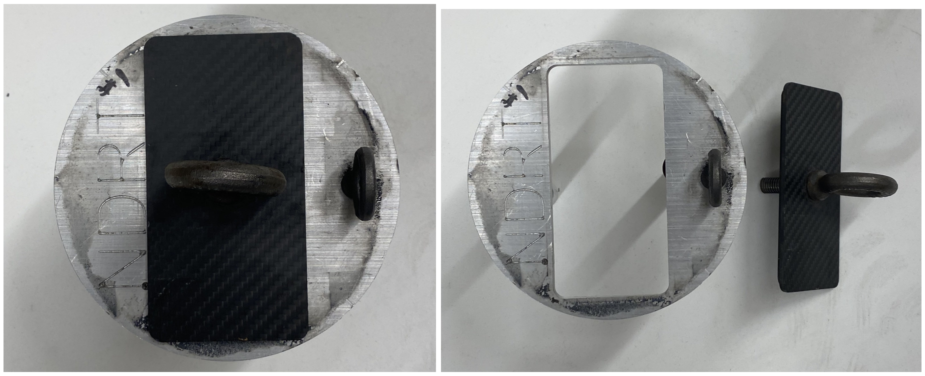
Figure 90: Vehicle GPS Track

8.3 Vehicle and Recovery System Verification

The launch vehicle performed close to what was intended for a majority of flight events. The vehicle's apogee was within the range of 4,000 - 6,000 ft, per NASA Req. 2.1. Specifically, the vehicle went up to an apogee of 4,729.3 ft.

Given a target apogee of 4,600 ft, and the fact that the ACS did not work during ascent, the launch vehicle has the potential to reach the target apogee with a fully functioning ACS in the next launch; even without ACS, this demonstration flight proved that all NASA altitude requirements are still satisfied. The OpenRocket predicted altitude for the flight conditions was 4,757.9 ft, which it's close proximity to the measured apogee is a clear indication in the simulations' ability to predict launch conditions. Moreover, the vehicle's ability to reach within the range of altitudes is a clear indication that the launch vehicle is not under-stable. While there may have been some over stability, as seen in the footage with a great deal of weather-cocking, (See Section 5), NASA Req. 2.14 only required a minimum stability margin, and the vehicle was well above that margin; the CG was measured at 77.25 in., and the CP was calculated on OpenRocket to be 96.775 in. With an outer diameter of 6.17 in., the static stability was 3.16 cal, which is well above the required 2.00 cals. By integrating the acceleration data and taking the derivative of the altimeter data, it was found that the off-rail velocity of the launch vehicle was 91.534 ft/s, which is well above the NASA Req. 2.17 of 52.0 fps. For more on ascent performance, see Section 8.4.1. Finally, every section of the launch vehicle that landed while tethered to a parachute had zero structural damage, which is a good indication that the material selection and all construction methods were done properly. The nose cone did sustain moderate damage to its shoulder due to its high rate of descent and impact with a tree after the nose cone shock cord snapped. There were some small scorch marks on the drogue parachute that occurred during the first separation event. This damage explains the increase in the vehicle descent speed. The drogue parachute will be folded more tightly to increase the distance between the parachute and the charge wells to remedy the issue.

The first separation event occurred at apogee and was triggered by the FED, which properly deployed the drogue parachute and separate the fin can from the rest of the vehicle. At the second separation event that occurred at 900 ft AGL, the NED successfully ejected the nose cone from the vehicle. However, the shock cord intended to hold the nose cone and the rest of the vehicle together snapped and the nose cone landed in a tree 60 ft AGL. Upon review of the onboard video footage, it is estimated that the nose cone shock cord snapped during the large accelerations caused by the main parachute deployment. The altimeter data of the nose cone altimeters also supports this theory. The third separation event that occurred at 612 ft AGL was successfully performed by the PED. The main parachute had a nominal deployment and the Payload bay and ACS Bay were separated while remaining attached through the main shock cord. Every charge successfully detonated upon review of the recovery modules after launch which instilled confidence that all of the avionics on the modules performed as designed. Additionally, the removable wall successfully protected the payload from the effects of the black powder ejection charges and was jettisoned successfully as evidenced by the lack of residue inside the Payload Bay. The removable wall and aluminum ring as flown can be viewed in Figure 91, below. The vehicle descending under the main parachute can also be viewed in Figure 92, below.



(a) Removable Wall and Aluminium Ring Top View

(b) Top View With Removable Wall Removed

Figure 91: Removable Wall as Constructed

Figure 92: Main Descent During VDF

The failure of the nose cone shock cord was partially due to the fact that the team did not have the shock cord it intended on using available at the time of launch. As discussed in Section 4.4.1, the supplier for the shock cords (Rocketman Parachutes) still has not delivered the shock cords intended for use on this section despite them being ordered in January. Instead, the team used a 25 ft kevlar shock cord rated for 950 lbs for the nose cone shock cord with a homemade 1/4 in. kevlar shock cord 5 ft in length for the removable wall. While the team calculated the predicted force on the nose cone shock cord should have been 115.14 lbs, the shock cord rated for 950 lbs still snapped. This could have been due to prior wear on the shock cord from previous launches. Regardless, the team hopes to use the Rocketman cord rated for 5300 lbs if it arrives before the next VDF attempt. If it does not arrive, a homemade kevlar shock cord will be constructed with the team mentor out of 1/4 in. kevlar to ensure a high load rating. The broken shock cord can be seen in Figure 93.

Figure 93: Broken Shock Cord

Figure 94 shows the landed Fin Can, and Figure 95 shows the landed ACS body ube and Payload Bay. Finally, Figure 96 shows the Nose Cone resting comfortably in a tree.

Table 67: Damage and Repairs to Vehicle from Flight 1

Vehicle Component	Damage	Repairs
Nose Cone	Cracked Shoulder	The nose cone will be replaced with a replica nose cone. See Section 8.6 for more details
Payload Bay	None	None
ACS Bay	None	None
Fin Can	None	None

Figure 94: Landed Fin Can

Figure 95: Landed ACS Body Tube and Payload Bay

Figure 96: Landed Nose Cone

8.3.1 TROI

See Section 6.7 for a detailed description of the performance of the TROI at the vehicle demonstration flight attempt.

8.3.2 Apogee Control System

ACS flight performance was evaluated based on the criteria from section 7.1. The ACS met 3 out of the 5 criteria, indicating partially successful mission performance. Specifically, the ACS had a successful power-on self-test, accurately actuated its flaps according to pre-programmed commands, and successfully collected raw and filtered data during flight. Figure 97 shows ACS drag flap deployment in flight and Figure 98 shows a plot of its Kalman-filtered altitude (in feet) over time.

Figure 97: In-flight ACS Drag Flap Deployment

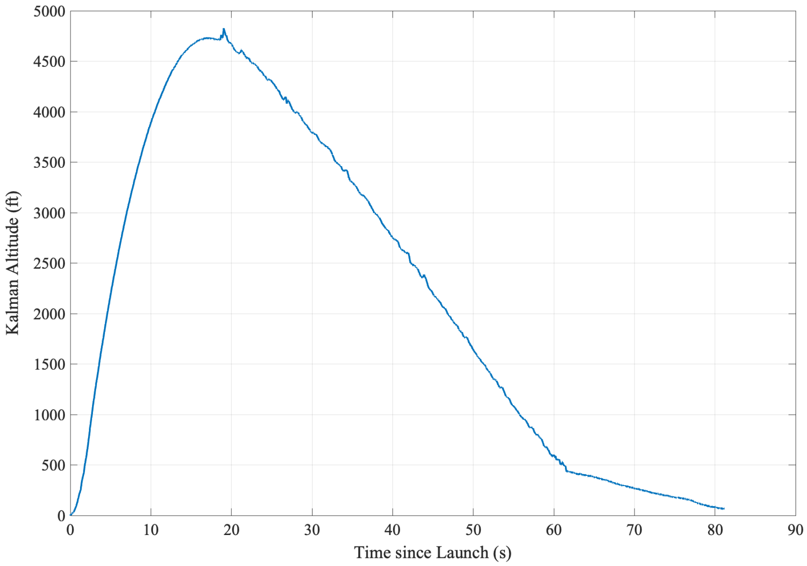


Figure 98: ACS Kalman Altitude vs Time since launch

ACS deployment occurred shortly after apogee rather than between burnout and apogee. After further investigation, the team found that a software error was responsible. The state manager algorithm depended on the Kalman acceleration (and altitude) to activate the ACS, but the Kalman acceleration used the accelerometer's z-axis to determine vertical acceleration. However, the accelerometer's y-axis was actually perpendicular to the ground due to its physical orientation after soldering it onto the PCB. This resulted in the system detecting burnout and actuating the flaps only after drogue parachute deployment when the launch vehicle was approximately horizontal to the ground and experienced a large acceleration as the parachute deployed. This software error was not detected during prior ground tests as the accelerometer was oriented differently (with with its z-axis pointing up) during the subscale launch. Section 7.5 contains further details regarding the ACS software control loop.

The team promptly fixed the aforementioned software error by correcting the vertical axis values used in the ACS control code. Another ground test was performed using data from the fullscale vehicle demonstration flight and the team observed that burnout was detected at the right time and accurate actuation took place between simulated burnout and apogee. This verified the ACS software bug had been fixed and that the system should perform successfully during the next demonstration flight.

8.4 Vehicle Demonstration Flight Analysis

8.4.1 Demonstration Flight Ascent Analysis

8.4.1.1 Prelude: Key Takeaway from CDR's Subscale Flight Analysis It is imperative that one re-reads the subscale flight analysis written in the CDR report before reading more of the fullscale mission performance. In short, the in-depth subscale analysis deduced that only the vertical velocity and vertical acceleration of the launch vehicle can be accurately predicted by the simulators — up to a certain zenith angle — due to the way the data is measured and the measurement devices used. Because of this, the fullscale analysis will only report vertical velocity and vertical acceleration. Finally, all flight measured data was taken from the ACS's measurement devices because the ACS measures the ascent of the launch vehicle as accurately as possible for the best performance during flight. It is important to understand how the simulators perform in reference to the actual flight performance; if the simulators are very accurate, their flight data can be given to ACS in the future to test the system's ability to reduce the altitude towards the target apogee.

8.4.1.1.1 Initialization For OpenRocket and Rocksim, the following assumptions were made. First, the winds were set to 35 mph given that the wind speeds on the ground were 17 mph and at 3000ft, the winds were 38 mph; it was assumed that the winds would be even greater at apogee, so 35 mph was a good average overall. The MATLAB code increases the wind speed as a function of the altitude already, but it was ensured that the winds reached 38 mph around 3000ft. Second, it was assumed that the parachutes had an efficiency of 90%, which assumes that the parachutes purchased do not work perfectly. Thus, it was inputted into the simulators that the Cd of the drogue and main was 1.44 and 2.628, respectively. Finally, the temperature and pressure on launch day was 4 C and 30.24 inHg.

8.4.1.2 Altitude Results Figure 99 displays both the measured altimeter altitude data and the simulated altitude data of the entire fullscale flight. As well, Figure 100 shows the same data as Figure 99, but it is only from ignition to apogee. The data was shortened to shown up to apogee in Figure 100 because that is the range that applies to the ascent analysis.

The blue "ACS Data" references the altimeter data located in the ACS. The Kalman filter was applied to "ACS Data" to remove outliers and reduce noise. The noise that exists in the data is a byproduct of the data collected. The red "MATLAB Simulation" references the new MATLAB flight simulator created by the team between CDR and FRR for the purpose of extending the range of simulations to work with. The code is still in a preliminary stage, but the team was interested in how it would perform against real data. The yellow and purple lines are the OpenRocket simulated data and the RockSim simulated data, respectively. As well, Table 68 lists the apogee of the measured and simulated flight and the simulators' percent error to the measured apogee. It should be noted that the apogee was taken where the minimum velocity was, not where the altitude was the highest in the data set. This was done because the data showed a sudden spike in altitude after the "true" apogee, caused by pressurization from the drogue parachute ejection charge. The spike better represents a measurement error than a sudden "jump" in altitude.

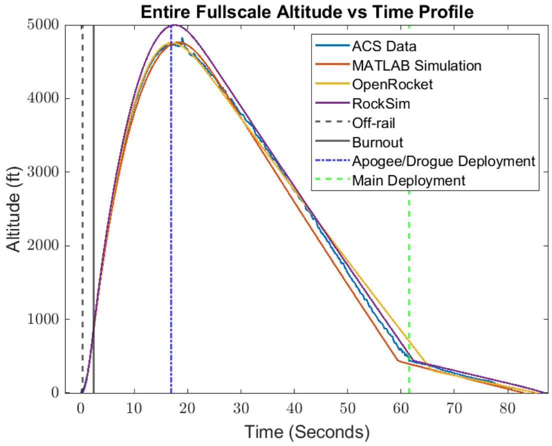


Figure 99: Entire Profile Fullscale Simulation and Flight Altitude Data

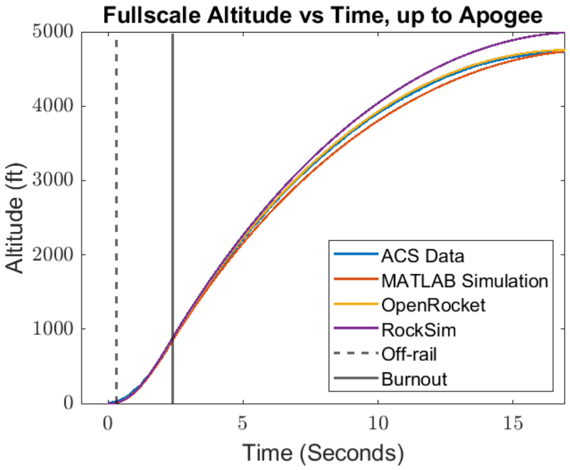


Figure 100: Profile of Fullscale's Simulation and Flight Altitude Data, up to Apogee

There are many key takeaways from the figures and table. First, Figure 99 clearly shows the full altitude flight profile, and that the drogue and main both deployed to decrease the descent velocity; thus NASA Req 2.19.1.8.1.

Table 68: Apogee Values for Fullscale Simulation and Flight Data

Method	Apogee (ft)	Percent Difference to Measured Data
Measured ACS Data	4729.3	N/A
MATLAB	4762.5	0.7%
OpenRocket	4756.0	0.56%
RockSim	4998.1	5.68%

is satisfied. Second, the measured apogee was within the required range of 4,000 to 6,000 ft, satisfying NASA Req. 2.1. Third, the MATLAB altitude profile matches up very close to the measured altitude during the entirety of flight. Even better, the MATLAB code's predicted apogee was only 0.7% off from the measured value. Thus, it can be deduced that the MATLAB code is effective at predicting flight conditions and can be used as a reliable source for simulating launch conditions. Fourth, the OpenRocket was the most accurate at predicting the launch apogee, with a percent error of only 0.56%. Just like the MATLAB code, the OpenRocket simulator can be treated as a reliable source for simulating launch conditions. Finally, the RockSim simulations was the least accurate, with a percent error of 5.68%. Compared to the other options, this is the least trustworthy. Still, it will be consulted in all mission performance simulations as a "factor of safety" to ensure that no simulations has the vehicle surpassing an apogee of 6,000 ft.

8.4.1.3 Velocity Results The ACS was equipped with an accelerometer and altimeter. By integrating the accelerometer (acceleration), differentiating the altimeter (altitude), and utilizing both data sets, one can derive the vehicle's velocity. Just as mentioned in Section 8.4.1.1 the vertical velocity will be the only measured component of the velocity.

Figure 101 displays both the measured vertical velocity data and the simulated vertical velocity data of the entire fullscale flight. As well, Figure 102 shows the same data as Figure 101, but it is only from ignition to apogee. The data was shortened to shown up to apogee in Figure 102 because that is the range that applies to the ascent analysis. More importantly, the velocity data after apogee cannot be fully reliable data due to the vehicle's tumbling in the air being difficult to accurately measure on the devices. Still, the figure clearly shows where the parachute deployed and there is clear evidence that the parachutes were successful in reducing the vehicle's descent speed.

The blue "ACS Data" references the measured vertical velocity, utilizing the methods mentioend above. The red "MATLAB Simulation" references the new NDRT MATLAB flight simulator. The yellow and purple lines are the OpenRocket simulated data and the RockSim simulated data, respectively. As well, Tables 69 and 70 lists the maximum and offrail velocity, respectively, of the measured and simulated flight and the simulators' percent error to the measured velocity. Table 71 displays the measured and simulated time to apogee; this was measured at the location where the vertical velocity is zero at the height of the altitude.

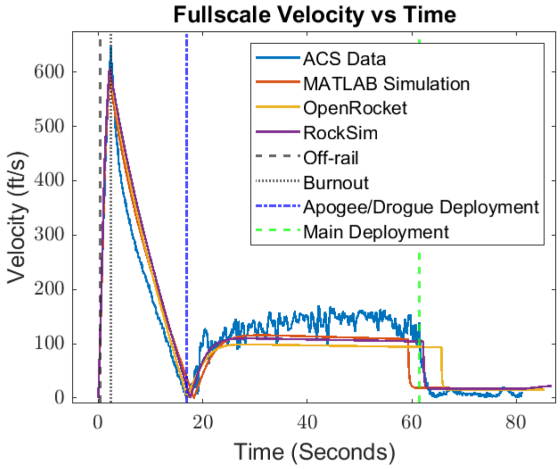


Figure 101: Entire Profile Fullscale Simulation and Flight Vertical Velocity Data

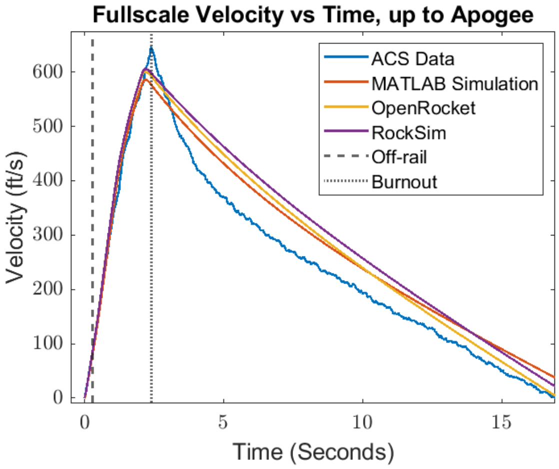


Figure 102: Profile of Fullscale's Simulation and Flight Vertical Velocity Data, up to Apogee

Table 69: Maximum Velocity Value for Fullscale Simulation and Flight Data

Method	Max Velocity (ft/s)	Percent Difference to Measured Data
Measured ACS Data	647.3	N/A
MATLAB	585.9	9.49 %
OpenRocket	600.4	7.25 %
RockSim	605.8	6.41 %

Table 70: Offrail Velocity Value for Fullscale Simulation and Flight Data

Method	Offrail Velocity (ft/s)	Percent Difference to Measured Data
Measured ACS Data	91.5	N/A
MATLAB	82.4	9.95 %
OpenRocket	87.6	4.26 %
RockSim	91.9	0.44 %

Table 71: Time to Apogee for Fullscale Simulation and Flight Data

Method	Time to Apogee(s)	Percent Difference to Measured Data
Measured ACS Data	16.9	N/A
MATLAB	18.3	8.28 %
OpenRocket	17.0	0.59 %
RockSim	17.6 s	4.14 %

From the figures, it is clear that the main discrepancy in velocity values comes from a difference in maximum velocity and a sharp decrease in velocity once the drogue parachute, something the simulators were unable to predict. Still, the simulators were able to converge to around the same apogee time as measured on launch day, seen in Table 71, with the MATLAB code being the only simulator with a noticeable error in time to apogee. Predicting time to apogee matters more in terms of mission performance than the curve to apogee, albeit the curve is within a reasonable range/shape. Still, MATLAB's error is not of terrible concern. Furthermore, While Rocksim's apogee prediction was the least accurate, Tables 69 and 70 show that, in fact, RockSim was the best simulator at predicting the vehicle's vertical velocity. This alone justifies the continued use of RockSim for mission performance. As for the other simulators, they were not as accurate but within a reasonable level of error. All three simulators were better at predicting the offrail velocity than the maximum velocity. Second, the measured velocity was well above the required minimum of 52 fps, satisfying NASA Req. 2.17.

8.4.1.4 Acceleration Results Figure 103 displays both the measured vertical acceleration data and the simulated vertical acceleration data of the entire fullscale flight. As well, Figure 104 shows the same data as Figure 103, but it is only from ignition to apogee. The data was shortened to shown up to apogee in Figure 104 because that is the range that applies to the ascent analysis. More importantly, the acceleration data's *magnitude* after apogee cannot be fully reliable data due to the vehicle's tumbling in the air being difficult to accurately measure on the devices. Still, one can look at the full flight acceleration to tell when the parachutes deployed.

The blue "ACS Data" references the measured vertical acceleration, utilizing the accelerometer data. The red "MATLAB Simulation" references the new NDRT MATLAB flight simulator. The yellow and purple lines are the OpenRocket simulated data and the RockSim simulated data, respectively. Table 72 lists the maximum acceleration of the measured and simulated flight and the simulators' percent error to the measured acceleration. In order to show that the simulators are accurate at predicting the acceleration from burnout to apogee, Table 73 lists the absolute value of acceleration of the measured and simulated flight at a flight time of 10 seconds and the simulators' percent error to the measured acceleration.

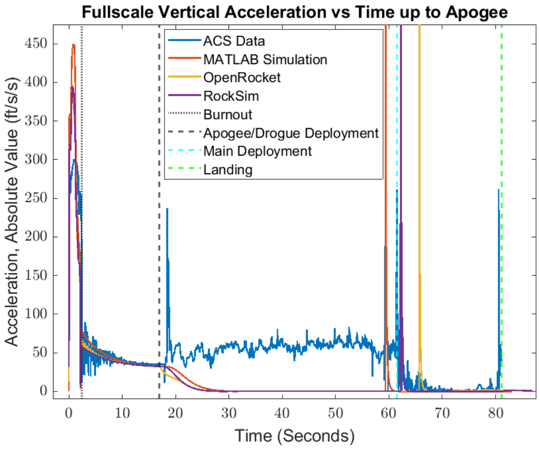


Figure 103: Entire Profile Fullscale Simulation and Flight Vertical Acceleration Data

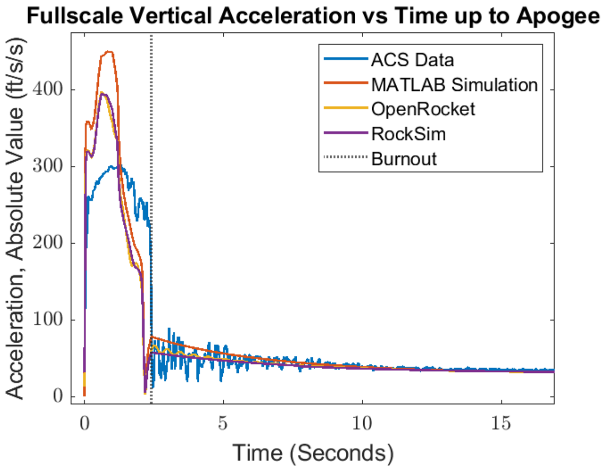


Figure 104: Profile of Fullscale's Simulation and Flight Vertical Acceleration Data, up to Apogee

Table 72: Maximum Acceleration Value for Fullscale Simulation and Flight Data

Method	Max Acceleration (ft/s/s)	Percent Difference to Measured Data
Measured ACS Data	303.4	N/A
MATLAB	450.1	48.4 %
OpenRocket	397.4	31.0 %
RockSim	394.6	30.1 %

From the figures and table, it is clear that the simulators are incapable at predicting the acceleration from ignition to burnout. The most obvious explanation comes from the motor's thrust. Most likely, the measured data was incapable at measuring the thrust given the device's data collection rate. As well, there is the possibility that the motor did not perform exactly as the producer's thrust curve would assume. Nevertheless, Table 73 demonstrates

Table 73: Acceleration Value for Fullscale Simulation and Flight Data at 10 Seconds into Flight

Method	Acceleration (ft/s/s)	Percent Difference to Measured Data
Measured ACS Data	38.3	N/A
MATLAB	40.1	4.70 %
OpenRocket	37.0	3.39 %
RockSim	36.7	4.18 %

the simulators are very accurate at predicting the acceleration from burnout to apogee; the percent error in acceleration at 10 seconds into flight was a very respectable level. In Table 73, OpenRocket was the most accurate to the measured acceleration, but MATLAB and RockSim are only slightly less accurate; all three simulators can be trusted to predict the acceleration after burnout.

While parachute deployment is relating to descent, not ascent, there are key takeaways to learn by looking at the acceleration profile of the launch vehicle. During CDR, it was predicted that the main parachute would take approximately 3.0 seconds to fully deploy and slow the launch vehicle down. Figures 105 and 106 show the timing between drogue and main deployment, respectively, and the parachutes inducing substantial drag on the system to slow it down. Table 74 list the time of deployment, the time when the parachutes are effective, and the time between such events. It also shows that the drogue parachute took 0.52 seconds to be effective, and the main parachute took 2.3 seconds to be effective. This parachute delay was accounted for in the mission performance in Section 5.

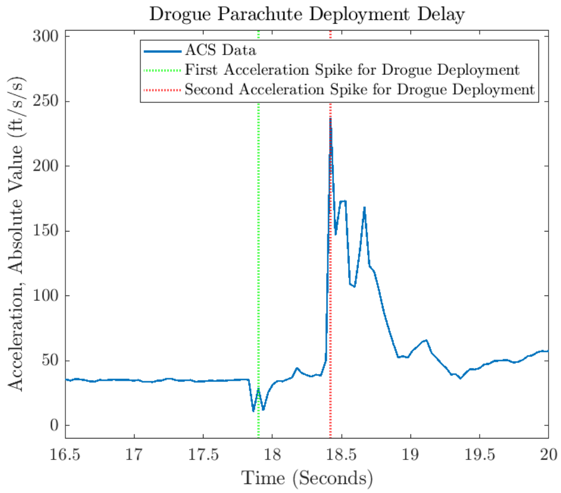


Figure 105: Acceleration vs Time, During the Range when the Drogue Parachute Deploys

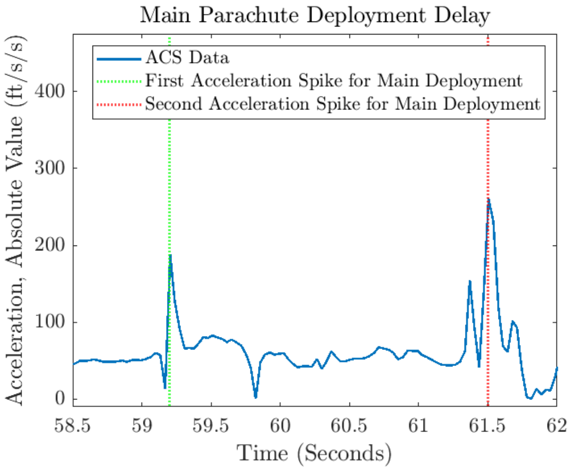


Figure 106: Acceleration vs Time, During the Range when the Main Parachute Deploys

Table 74: Time Between Parachute Deployment and Parachute Working to Reduce Vehicle Velocity

Parachute	Event 1, Time (s)	Event 2, Time (s)	Time To Effectiveness
Drogue Parachute	17.9	18.42	0.52
Main Parachute	59.2	61.5	2.3

Estimating Drag Coefficient The drag coefficient on the launch vehicle is essential for properly estimating the vehicle's apogee, especially for the ACS. The drag coefficient was calculated based on the data collected during the ascent of the launch vehicle. Section 8.4.1.4.1 explains how the drag coefficient was calculated, and Section 8.4.1.4.2 will list the results.

8.4.1.4.1 Drag Coefficient Derivation Equation 19 was used to calculate the drag force

$$F_d = \frac{1}{2}\rho C_d V^2 A, \tag{19}$$

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. Given the limitations of the measurement devices previously mentioned, only the force in the vertical direction is considered, and so only the vertical component of velocity was used. Additionally, Equation 20 computes the vehicle's cross sectional area, A, which was part of Equation 19:

$$A = \frac{\pi}{4}(d_{outer})^2 = \frac{\pi}{4}(6.17)^2 = 29.899 in^2 = 0.01929 m^2 \tag{20}$$

The ideal gas law, shown in Equation 21 was used to calculated the density of air.

$$\rho = \frac{P}{RT} \tag{21}$$

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 22 and 23 were used to determine the pressure and temperature. These equations are taken from the NASA Earth atmosphere model.

$$T = 39.2 - 0.00356 \times h \tag{22}$$

$$P = \frac{2116}{144} \times \left(\frac{T + 459.7}{518,6}\right)^{5.256} \tag{23}$$

where h is the height. Note, the value of pressure must be converted to Pascals from psi, and the number 59 was replaced with 39.2 in Equation 22 so that the height at the ground level was equal to the measured value, not the standard temperature and pressure (STP) values. The density equation used in the Earth atmosphere model was ignored, and instead the ideal gas assumption was used. Figures 107 and 108 prove that the use of the Earth Atmosphere model for temperature and pressure, respectively, will yield precise values in relation to the OpenRocket and RockSim simulations. Similarly, Figure 109 proves that the use of ideal gas for the air density will yield values precise to the OpenRocket and RockSim value. While the simulators' values are not guaranteed to be accurate, it is a good assumption of how the atmosphere works, especially in subsonic motion.

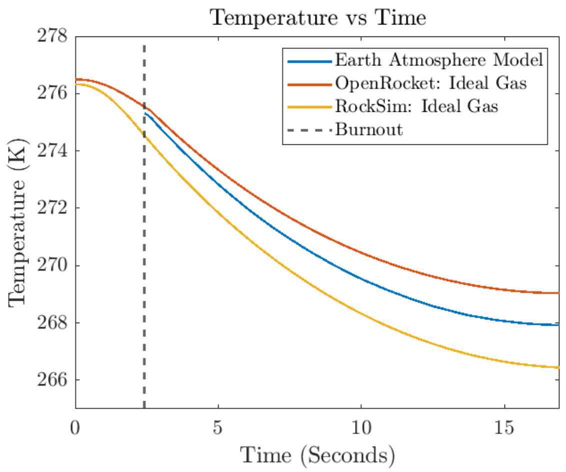


Figure 107: Temperature as a Function of Time, for the Experimental Method in Section 8.4.1.4 and the Simulations' Values

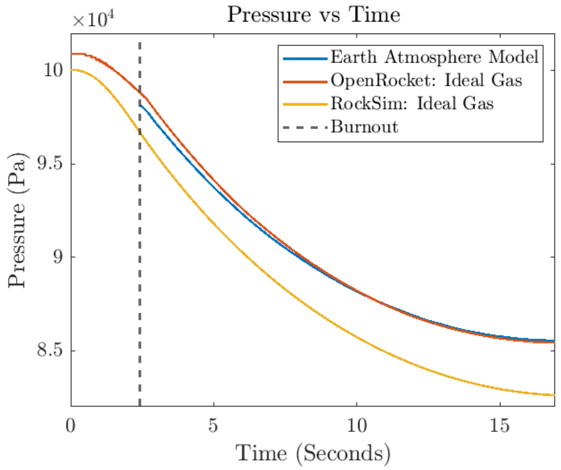


Figure 108: Pressure as a Function of Time, for the Experimental Method in Section 8.4.1.4 and the Simulations' Values

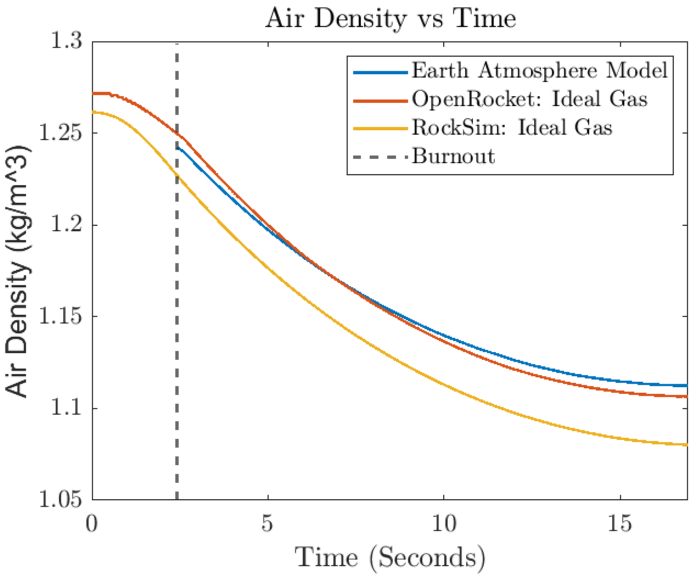


Figure 109: Air Density as a Function of Time, for the Experimental Method in Section 8.4.1.4 and the Simulations' Value

Equation 24 was used as the basis for determining the drag force on the vehicle. Given the only the vertical direction of measured velocity and acceleration data is used, Newton's 2nd Law, Equation 24, for only the vertical direction can be utilized:

$$\sum F_v = ma_v = T - F_d - mg \tag{24}$$

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, equal to 9.81 m/s^2. Only data before apogee is considered, given the discussion in Sections 8.4.1.4 and 8.4.1.3 on the unreliability of acceleration and velocity data, respectively, after apogee. Data from ignition to burnout is also ignored so the force of thrust does not need to accounted for, given how inaccurate that range of data was in Section 8.4.1.4. If only the time from burnout to apogee is considered, the only affects on the vertical acceleration is the gravitational force and drag force. This simplifies things greatly. Thus, Equation 25 can be used.

$$\sum F_v = ma_v = -F_d - mg \tag{25}$$

With Equation 26 rearranged, the equation to find the drag force is now:

$$F_d = -m(a_v + g) \tag{26}$$

A combination of Equations 21,24, and 26 were used to find the drag coefficient, as seen in Equation 27:

$$c_d = \frac{2F_d}{\rho V^2 A} = \frac{-2m(a_v + g)}{\rho V^2 A} = \frac{-2mRT(a_v + g)}{PV^2 A} \tag{27}$$

8.4.1.4.2 Drag Coefficient Results Figure 110 displays the fullscale drag coefficient as a function of time. Figure 111 displays the fullscale drag coefficient as a function of velocity, from burnout to apogee. In the figures, the blue "Estimated Value" data utilizes the measured data by the fullscale's accelerometer and altimeter and filtered through the Kalman filter.

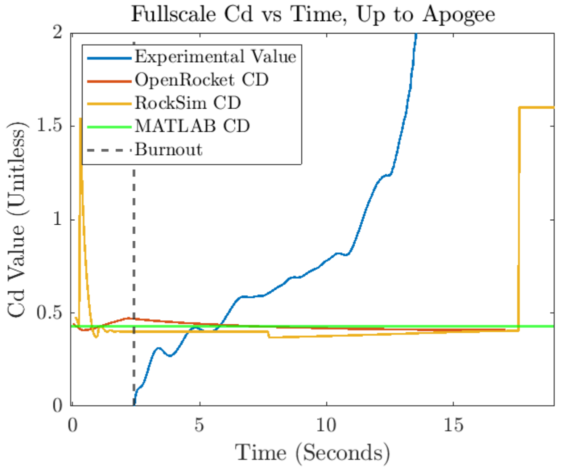


Figure 110: Fullscale Vehicle Coefficient of Drag as a Function of Time, up to Apogee

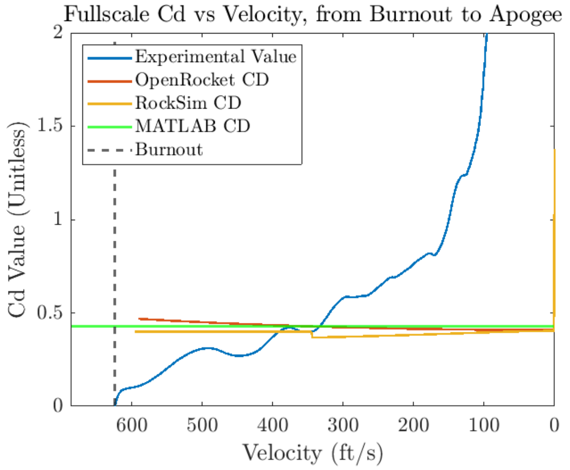


Figure 111: Fullscale Vehicle Coefficient of Drag as a Function of Velocity, From Burnout to Apogee

From the figures, it is evident that the drag coefficient is constant increasing throughout flight and never converging to any one value. To have a better sense of what a constant drag coefficient value would be, the mean value from burnout to the 9 second mark was taken and compiled in Table 77. 9 seconds was chosen given that the data starts to increase rapidly at that moment onward, due to the increasing flight zenith angle causing the vertical direction of flight to be increasingly inaccurate; this source of error was discussed in great detail in CDR, but more information can be found in Section 8.4.1.6.

Table 75: Mean Drag Coefficient Values for Flight Data and Flight Simulators' Cd Data, Measured from Burnout to the 9 Second Mark

Method	Cd	Percent Difference to Estimated Cd
Estimated Cd	0.448	N/A
OpenRocket Cd	0.442	2.68 %
RockSim Cd	0.434	0.893 %
MATLAB Cd	0.42*	6.25 %

* Constant number inserted into the MATLAB Code, chosen based on how the data lined up

Table 77's values indicate that the C_d value from the RockSim simulation is precise to the Fullscale measured value. On the other hand, OpenRocket and MATLAB were less accurate overall. It should be noted that the MATLAB code also accounts for the drag on the sides of the body tube, which was ignored in this section's calculations to simplify things immensely; this may be the cause of that method's level of error.

It should be noted that the flight conditions during the VDF was not ideal for calculating the Cd; the winds were 17 mph on the ground and over 37 mph at 3000 ft AGL, and the launch angle was set to 7.938 . Ideally, the Cd should be calculated with the smallest launch angle and the least amount of wind as possible; this is so that the *only* affect on the vehicle's apogee is drag. In reality, the drag coefficient is not equal to 0.448, but there is insufficient data to deduce the real Cd value until the next flight. Therefore, the coefficient of drag, C_d on the fullscale launch vehicle is 0.448 until further evidence says else wise.

8.4.1.5 Static Stability Margin Table 76 lists the CG, CP, outer diameter d_{outer}, and static stability margin of the launch vehicle. Recall, Equation 28 is used to compute the static stability margin.

$$StaticStablity = \frac{CP - CG}{d_{outer}} \tag{28}$$

Table 76: Static Stability Margin Values

Variable	Value
CG	77.25 in
CP	96.775 in
d_{outer}	6.17 in
Static Stability Margin	3.16 cals

From the table, it is clear that the measured stability value is greater than 2.00 cals. Thus the vehicle abides by NASA Req. 2.14. See Section 8.4.1.6 for the analysis of how the static stability margin performs, in reference to the weather-cocking.

8.4.1.6 Flight Zenith Angle Given the vehicle's high stability margin, it is imperative to analyze the flight zenith angle in order to determine if the vehicle is too over stable to launch; if so, the design can then become less over-stable by sanding down the fin size. Figure 112 displays the measured and simulated flight zenith angle, up to apogee; the data becomes immeasurable due to tumbling after apogee (and irrelevant to ascent performance).

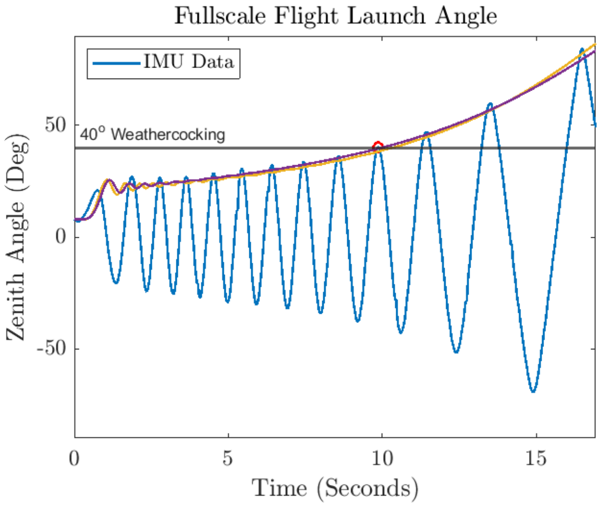


Figure 112: Profile of Fullscale's Simulation and Flight Zenith Angle, up to Apogee

Figure 112 shows that, while the simulators could not predict the extreme oscillatory nature, it was very precise in predicting the 40 weather-cocking threshold. Given that weather-cocking is the main concern when analysing the flight zenith angle, it is safe to say that the simulators can be trusted to predict the phenomena.

From Figure 112's weather-cocking, it appears that the vehicle is over-stable to the extent that it turns into the wind a substantial amount. To quantify how severe the situation is, Figures 113 and 114 impose the altitude and velocity, respectively, on top of the flight zenith angle so that one can visualise the point in flight where it occurs. Table 1 lists the altitude and velocity value at which the vehicle goes past 40.

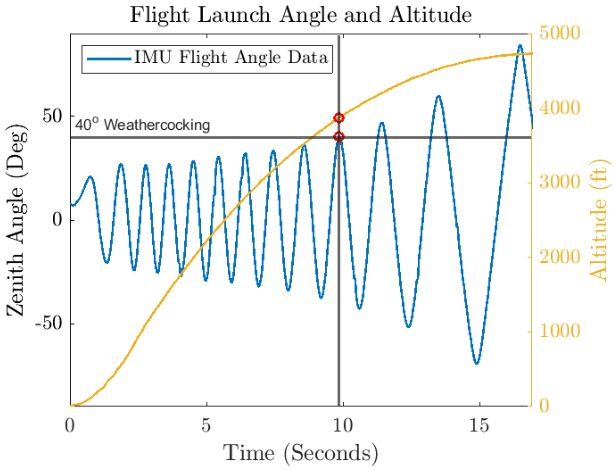


Figure 113: Flight Angle and Altitude

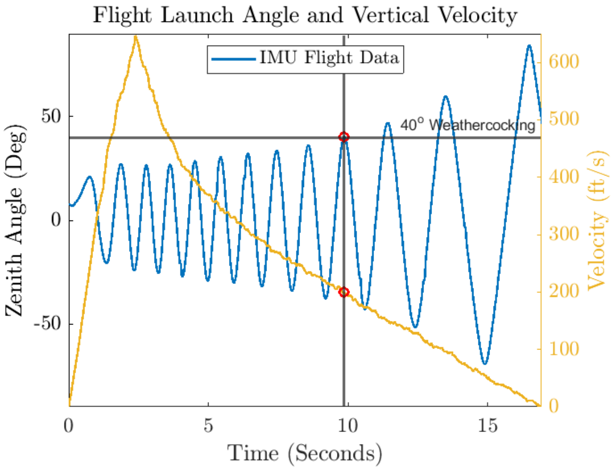


Figure 114: Flight Angle and Vertical Velocity

Table 77: Mean Drag Coefficient Values for Flight Data and Flight Simulators' Cd Data, Measured from Burnout to the 9 Second Mark

Variable	Value at 40 Weather-cocking	Percent left to apogee
Altitude	3871.1 ft	80.23%
Velocity	199.3 ft/s	

From Figures 113 and 114 and Table 77, it is clear that the weather-cocking can not be ignored, and the vehicle's stability is jeopardizing potential altitude; the design wants to overshoot by a substantial amount so there is clear trajectory data for ACS to properly reduce the apogee, and the vehicle's weather-cocking is complicating the device's ability to track and operate properly. To fix the stability, the elliptical fins will be cut from a 6.00 inch span to 5.00 inches. this will reduce the stability from 3.45 cal to 2.44 cal, in the final design. See Section 3.3.5 for visuals of the change and more information on the fins.

8.4.2 Demonstration Flight Descent Analysis

The demonstration flight provided valuable data regarding how the vehicle actually performs during the descent phase of flight. Several factors largely related to the main and drogue parachutes made the vehicle descend faster than predicted by the `full_vehicle_decsent_calc.m` hand calculations, OpenRocket, and RockSim. The actual descent rate of the vehicle was calculated using the Raven4's flight data. The following points shown in Figure 115 were selected from the Raven4's flight data to determine the apogee and descent rates during the drogue and main phases of the descent.

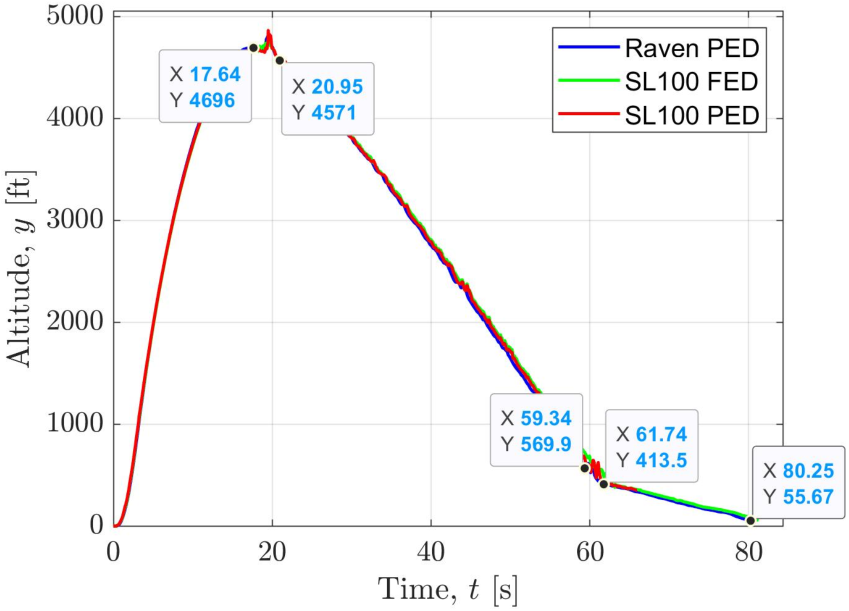


Figure 115: Raven4 Selected Data Points for Actual Descent Calculations

The points used to calculate descent rates were intentionally selected to be on relatively straight portions of the descent plot where recovery effects would not affect the altitude readings. These points were used to calculate the descent rates using the equation

$$v_{\text{descent}} = \frac{\Delta h}{\Delta t} \tag{29}$$

where v_{descent} is the descent rate, Δh is the difference in altitude between the two points, and Δt is the difference in time between the two points. After the actual descent rates were calculated, the team compared those values with the values predicted by the models presented during CDR (original `full_vehicle_decsent_calc.m` script, OpenRocket, and RockSim) with updated mass and ambient weather data. This comparison cam be viewed in Table 78, below.

Table 78: Actual Descent Rates

Descent Phase	Actual v_{descent} (ft/s)	MATLAB v_{descent} (ft/s)	OR v_{descent} (ft/s)	RS v_{descent} (ft/s)
Drogue	104.22	77.63	96.74	107.89
Main	19.33	15.16	15.46	17.19

The actual descent rate during the main descent phase was higher than all models predicted. This follows a trend similar to the team's discovery last year where the 12ft Rocketman Standard Parachute underperformed from its advertised drag values. The higher-than-expected descent rate suggests the SkyAngle XXL parachute also underperforms by a large margin. By calculating the amount of drag produced by the main parachute given the calculated actual descent rate, and the drag equation, an effective C_d value could be calculated that was compared to the advertised C_d value. The team's calculations found that the main parachute provided 55% of the drag that was expected based on its provided C_d numbers. As such, the effective parachute performance coefficient was altered for future MATLAB hand calculation predictions as discussed in Section 5.2. This lower C_d value will also be used in OpenRocket and RockSim for future calculations to better reflect the actual drag provided by the parachute.

The vehicle also descended faster than the MATLAB and OpenRocket models predicted. It was noted in Section 8.3 that the drogue parachute was singed and had several small holes in it after it was recovered. This reduced the amount of drag provided by the parachute and likely contributed to the higher-than-expected descent rates. While the RockSim value was close to the actual drogue descent velocity, the team expects this value to decrease in accuracy when an undamaged drogue parachute is used in the future. In the remainder of this section, other essential actual descent parameters of the vehicle will be compared to the predicted values.

8.4.2.1 Kinetic Energy Performance The kinetic energy of each section during the demonstration flight was calculated to ensure compliance with NASA Req. 3.3. The equation used to calculate the KE for each section is

$$KE = \frac{1}{2} m_{\text{section}} v_{\text{main}}^2 \tag{30}$$

where KE is the kinetic energy of a given section, m_{section} is the mass of the section in its separated state (see Table 52), and v_{main} is the descent velocity of the launch vehicle calculated in the previous section. The calculated values for kinetic energy are shown in Table 79, below.

Table 79: Actual vs. Predicted Kinetic Energies at Landing

Section	Actual KE (ft-lb)	MATLAB KE (ft-lb)	OR KE (ft-lb)	RS KE (ft-lb)
Nose Cone	23.62	14.53	15.11	18.68
Payload Bay	68.67	42.23	43.92	54.30
ACS Bay	57.55	35.40	36.81	45.51
Fin Can	71.97	44.27	46.04	56.92

The higher-than-expected kinetic energy is due to the higher-than-expected descent rate discussed in Section 8.4.2. While the kinetic energy is close to the limit specified in NASA Req. 3.3, the slight reduction in Fin Can weight due to the fin size reduction should help reduce this value in the future as the mass of the heaviest section will be smaller.

8.4.2.2 Descent Time and Drift Performance The actual descent time was calculated by taking the difference in time between when the apogee was reached and when the vehicle hit the ground. The predicted descent time was calculated identically to the method described in Section 5.2.2 except with the masses and weather conditions from the day of the first VDF attempt. The descent times can be viewed in Table 80, below.

Table 80: Actual vs. Predicted Descent Times

Apogee (ft)	Actual t_{descent} (s)	MATLAB t_{descent} (s)	OR t_{descent} (s)	RS t_{descent} (s)
4696	64.2	79.17	N/A	N/A
5006	N/A	87.58	84.40	N/A
5253	N/A	82.78	N/A	72.34

The descent time was slightly lower than expected which aligns with the observation that the descent velocity was higher than anticipated. This indicates the vehicle should have no problem complying with NASA Req. 3.11. While the vehicle may descend slightly slower if the drogue parachute is not singed, this will not add 16 seconds to the descent time and is therefore not a concern for compliance. The parachute performance coefficient adjustments discussed in Section 5.2 should reduce the predicted descent times to coincide with what is observed in flight.

The actual drift distance was calculated by finding the distance between the coordinates of the vehicle at apogee and its final landing location. The predicted drift was calculated identically to the method described in Section 5.2.3 except with the masses and weather conditions from the day of the first VDF attempt (the wind was measured to be the 17 mph measured at the field). The drift distances can be viewed in Table 81, below.

Table 81: Predicted Drift Distances

Apogee (ft)	Actual Drift (ft)	MATLAB Drift (ft)	OR Drift (ft)	RS Drift (ft)
4696	1865	1974	N/A	N/A
5006	N/A	1985	2104	N/A
5253	N/A	2184	N/A	1591

The actual drift was relatively close to the predicted values with the MATLAB script providing the nearest estimate. However, the drift was slightly lower than expected which coincides with the descent rate that was higher than expected. With less time in the air, the vehicle had less time to drift with the wind. The new parachute assumptions in predictions moving forward should predict lower drift distances which should be closer to the actual values observed during flight.

8.5 Comparison to Subscale

Table 82: Comparison of Full-Scale to Subscale Stability and Thrust-to-Weight Parameters

Parameter	Full-Scale	Subscale
CG location (in.)	77.25	35.28
CP location (in.)	96.775	46.226
Static stability margin (cal)	3.16	3.554
Off-rail stability (cal)	3.37	3.63
Off-rail velocity (ft/s)	91.5	65.3
Thrust-to-Weight	9.47:1*	9.34:1

* Greater than 5.00:1, so design abides by NASA Req. 2.15

Table 83: Dimensions of Full-Scale and Subscale Vehicle

Component	Full-Scale (in.)	Subscale (in.)	Scaling Error*
Nose cone exposed length	24.0	12.0	0%
Body tube total length	104.25	48.0	7.91%
Body tube diameter	6.17	3.086	0.03%
Fin root chord	6.00	3.00	0%
Fin height	6.00	3.00	0%

* Recall that the intended scaling factor was 50 %

8.6 Post-Flight Structural Integrity

8.6.1 Launch Vehicle

The nose cone descended without a parachute and landed in a tree. Due to unexpected high loads of landing without assistance, the shoulder sustained significant damage: chunks of the shoulder were found missing, and there are cracks throughout. Luckily, the NED, located inside the nose cone, sustained no damage, highlighting the vehicle's ability to protect all its internal modules.

There were two potential options to fix the nose cone. First, the nose cone shoulder could be reinforced with WestSystems epoxy, or a new nose cone could be used. Luckily, the team has another nose cone of the exact same dimensions — 4:1 ratio, ogive, 6.17 in. diameter — but the shoulder length is only 4.5 inches instead of the previous length of 5.25 in., resulting in the nose cone ring to shrink from 2.25 in. to 1.5 in. After a discussion with the recovery squad, it was deduced that the independent section could safely separate with less volume, so the change in nose cone ring was doable: See Section 3.3.2 for a more detailed explanation for the purpose of the nose cone ring.

8.6.2 Recovery

The recovery modules did not sustain any damage during the full-scale demonstration flight. Even though the nose cone descended without a parachute following main parachute deployment, the NED remained completely structurally intact and its internal electronics were not damaged. This result demonstrates the durability of the recovery modules and their ability to withstand worst-case scenarios. The nose cone shock cord failure discussed in Section 8.3 was the only recovery system to sustain damage.

8.6.3 ACS

The ACS remained structurally intact throughout the demonstration flight with no signs of damage. The system was successfully retained within the ACS bay using the four airframe interfacing blocks and 8-32 screws.

8.6.4 TROI

The TROI was successfully rigidly retained using four airframe interfacing blocks with 8-32 screws throughout the vehicle demonstration flight attempt. The system did detect landing prematurely and hence deployed prematurely. The system sustained damage to the lead screw upon landing as described in Section 6.7. The code has since been updated, and the damaged parts have been replaced. The retention subsystem did not sustain any damage.

8.7 Payload Mission Sequence

Neither the finalized payload hardware nor code was ran during the vehicle demonstration flight attempt. Future flights will serve as payload demonstration flights, and the payload will attempt to complete all mission success criteria listed in Section 6.1 with the finalized code and hardware.

8.8 Timeline Verification and Future Flights

As of FRR submission, the team plans to re-fly the finished launch vehicle to fulfill Vehicle Demonstration Flight and Payload Demonstration Flight requirements. Table 84 summarizes the launch opportunities and backup options scheduled for the remainder of the NASA Student Launch competiton. Weekday launches at NDRT's home field in Three Oaks, MI, and launches any day at the team's backup launch field in Tab, IN, are not listed but will be considered if necessary to complete flights on time.

Table 84: Future Flight Plans and Objectives

Launch	Location	Date	Objectives
Vehicle Demonstration Re-Flight & Payload Demonstration Flight	Three Oaks, MI	March 10, 2023	Satisfy NASA Req. 2.19.1 and 2.19.2
Vehicle Demonstration Re-Flight & Payload Demonstration Flight (Backup)	Three Oaks, MI	March 18/19, 2023	Satisfy NASA Req. 2.19.1 and 2.19.2
Vehicle Demonstration Re-Flight & Payload Demonstration Flight (Backup)	Three Oaks, MI	March 25/26, 2023	Satisfy NASA Req. 2.19.1 and 2.19.2
Competition Flight	Huntsville, AL	April 15, 2023	Fulfill conditions in NASA General Requirements Section 6
Competition Flight (Backup)	Three Oaks, MI	April 15, 2023	Fulfill conditions in NASA General Requirements Section 6

9 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.

9.1 Launch Concerns and Operating Procedures

9.1.1 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.

9.1.2 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.

9.1.3 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
- ☐ 16 short-length #8-32 screws
- ☐ 4 long-length #8-32 screws
- ☐ Cellular device of ACS lead
- ☐ 8 #4-40 shoulder screws
- ☐ 4 lever arms
- ☐ 8 #4-40 pattern nuts
- ☐ Pull-pin switch
- ☐ 3-32 Allen wrench
- ☐ Laptop with ACS code installed
- ☐ Extra SD cards
- ☐ Extra altimeters
- ☐ 1 nominal 3.7 V battery
- ☐ 1 nominal 7.4 V battery
- ☐ 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: ______________________________

9.1.4 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:_______________________________________

9.1.5 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, minimal wildlife 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:____________________________________

9.2 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

9.2.1 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: 2 g
- NED Ejection Charge: 2 g
- PED Parachute Charge: 6 g
- PED Parachute Charge: 6 g
- PED Parachute Charge: 6 g
- FED Parachute Charge: 3 g
- FED Parachute Charge: 3 g
- FED Parachute Charge: 3 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:__________________________________

9.2.2 Pre-Flight Checklist

9.2.2.1 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 Full-Scale 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.

Figure 117: Main Parachute Folding Guide

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:____

9.2.2.2 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.

Figure 118: Drogue Parachute Folding Guide

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:______________________________________

9.2.2.3 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:______________________________________

9.2.2.4 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:______________________________________

9.2.2.5 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:______________________________________

9.2.2.6 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: 2 g
- NED Ejection Charge: 2 g
- PED Parachute Charge: 6 g
- PED Parachute Charge: 6 g
- PED Parachute Charge: 6 g
- FED Parachute Charge: 3 g
- FED Parachute Charge: 3 g
- FED Parachute Charge: 3 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:____

9.3 TROI Preparation

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

Required PPE: None

9.3.1 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.

☐ Ensure that the TROI in its entirety is void of scratches, cracks, or any other damage. Repair as necessary.

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

Safety Officer Signature:____

Payload Lead Signature:____

9.3.2 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 is operational, verify that the correct code is loaded onto the ESP WROVER and the ESP32-CAM.

☐ Ensure that updated, launch day NASA radio frequency is uploaded to transceiver. Note: Failure to complete this procedure will result in the payload not responding to the commands upon landing and a complete mission failure.

☐ With the battery status verified, connect the TROI to the battery and remove the pull pin.

☐ Once the battery connection is made, the whole system initializes. If the system does not initialize, it will restart automatically. The piezzo will buzz upon completion of initialization.

☐ **Note:** If the audio does not sound, obtain the Payload Squad Lead's laptop to ensure that the correct code is uploaded to the microcontroller. If the audio light still does not sound, turn the system off and restart this procedure.

☐ The piezzo will buzz for a second time upon the successful receipt of a test packet over ESP32-NOW.

☐ TROI is waiting for launch.

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

Safety Officer Signature:____

Payload Lead Signature:____

9.3.2.1 Mechanical Functionality 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.
- ☐ Simulate launch through the Payload Squad Lead's laptop and await landing detection by TROI.
- ☐ When the TROI detects landing, the system should detroy.
- ☐ Verify successful deployment. Note: If any individual component fails, isolate it from the system and trouble shoot until complete.
- ☐ Disconnect the TNC and send serial commands to put the TROI in its retained configuration.
- ☐ Verify that TROI is in retained configuration.
- ☐ Reconnect pull pin, disconnecting the system.
- ☐ Reconnect the TNC.
- ☐ Remove camera lens cap. Ensure the camera is rigidly attached.
- ☐ Note: If the mechanical functionality test fails, cut power to TROI by reinserting the pull pin. Assess TROI for any mechanical failures such as jamming, misalignment from the guide rails, or any unfasten connections. Once completed, complete the Pre-Flight Checklist and restart the Mechanical Functionality Test.

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:______________________________________

9.4 Apogee Control System Preparation

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

Required PPE: Safety Glasses

9.4.1 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.
- ☐ 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.
- ☐ Ensure that the wire connections between the two batteries and the servo motor connector are secure before proceeding. **Failure to do so may result in these connections becoming lose during flight and a complete or partial system failure.**

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:______________________________________

9.4.2 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.

- ☐ Pull the pin out of the assembled ACS on the rear side of the circuit board to start initialization of the batteries and system.
- ☐ Both ACS batteries will be activated. Once activated, the Raspberry Pi should sound a noise and display a light confirming its activity. All team members should listen for three consecutive noises. The first noise will confirm that the ACS code is running, the second will confirm that the sensors have initialized, and the third will confirm that the sensors have started to read data. If this activity does not occur, access the Raspberry Pi through the ACS code and analyze the error log. Once all identified errors have been addressed, reactivate the system and verify the consecutive noises. Failure to follow this procedure may result in unpredictable

behavior from the servo motor, or failure mode ACS.6.

- ☐ Between the second and third noises, ensure that the servo motor begins to rotate. Specifically, the motor will extend and retract as a basic functionality test. Confirmation of this action will verify that the system is mechanically functional.
- ☐ Ensure that the laptop is connected to the Raspberry Pi. This verification can be completed by checking the command log of the Raspberry Pi on the laptop.
- ☐ 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 one altimeter. If the light does not appear, turn off and reactivate the altimeter 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.
- ☐ Perform a final inspection on the low battery light on the circuit board to ensure it is not on. If it is, deactivate the system and replace the 3.7 V battery with a fully charged one. Repeat the previous Pre-Flight Checklist procedures once again.

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:______________________________

9.5 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

9.5.1 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:________________________________

9.5.2 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.

9.5.2.1 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. Pay careful attention to the orientation of the ACS; the airframe interfacing blocks have numbers marked on the top and must line up to the corresponding number on the ACS 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.**

☐ Command the ACS to extend the pusher arms.

☐ Before fastening the lever arm connections, match the numbers marked on the lever arms to the numbers marked on top of the pusher arms. **The lever arms have been cut to fit individually with each pusher arm, and failure to accurately follow this procedure may lead to the lever arms not properly working during**

flight due to differences in tolerance fit with the pusher arms.

☐ Obtain 8 shoulder #4-40 screws, 8 #4-40 pattern nuts, and the 4 lever arms. With the ACS pusher arms extended, attach the lever arms to the pusher arms. One connection will be made by inserting the shoulder screws to the top hinger below the top bulkhead and screwing a pattern nut to tighten the connection. A second conneciton will be made by attaching a shoulder screw through the lever arm and the extension arms that have been pushed out by the ACS code. This connection will also be tightened with a pattern nut.

☐ 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.**

☐ 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.**

☐ 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. Similar to the lever arms and airframe interfacing blocks, ensure that the number marked on the extension flaps matches that of the number on the lever arms. The matching scheme is detailed in Figure 119. Only attach extension flaps 1-3, leaving the fourth one off of the integrated system. In order to conserve the system's battery life, the push pin that was removed during the ACS Pre-Flight Checklist will be reinserted. This pin can not be inserted or removed with the fourth extension flap integrated into the system. The fourth extension flap, rather, will be installed before departing for the launch pad.

☐ Instruct the ACS to retract the extension arms so that the extension flaps are flush with the ACS body tube.

☐ Reinsert the push pin into the switch to deactivate the system and verify that no lights are on. **Failure to do so may result in the battery draining and a complete or partial system failure during launch.**

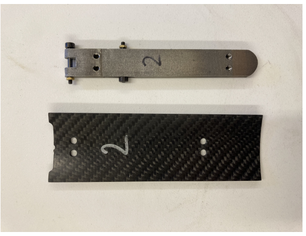


Figure 119: Matching ACS Flap and Lever Arm

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:______________________________________

9.5.2.2 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.

- ☐ Remove the pull pin from TROI.
- ☐ 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.
- ☐ Integrate the PED Recovery Module. Ensure the integration is according to the procedures outlined in PED Module Integration.
- ☐ integrate removable wall with airframe interfacing blocks

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:______________________________________

9.5.2.3 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:______________________________________

9.5.2.4 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:______________________________________

9.5.2.5 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:____

9.5.2.6 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:____

9.5.2.7 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:_______________________________________

9.5.2.8 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:______________________________

9.5.2.9 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:______________________________

9.5.2.10 ACS Fourth Extension Flap Integration

☐ **Be sure not to connect the laptop or the cellular device to the Raspberry Pi to avoid a time discontinuity in the data collection. To ensure this, verify that the hot spot of the cellular device is turned off before removing the pull pin.**

☐ Obtain the ACS Lead and the Safety Officer. Remove the pull pin from the ACS to reactivate all electronics.

☐ Repeat the procedures outlined in Pre-Flight checklist to ensure that the electronics are fully functional and that the low battery light is not on.

☐ Using the 8-32 screws, fasten the fourth extension flap to the lever arm. Ensure once again that the number on the lever arm matches the number marked on the extension flap.

ACS Extension Flap Integration Confirmation: I hereby certify that the fourth ACS extension flap has been properly attached and that the electronics are fully functional.

ACS Lead Signature:____

Safety Officer 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:____

9.6 Launch Pad Setup

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.**

☐ The Safety Officer must confirm that the launch pad is void of any flammable materials in the near surrounding area. **Failure to do so may result in failure mode VE.12.**

☐ 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:______________________________________

9.6.1 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 9.1.5 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 9.1.5 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:______________________________________

9.6.2 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 9.1.5. 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:____

9.6.3 Launch Rail Checklist

9.6.3.1 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:______________________________________

9.6.3.2 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 mode 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:____

9.6.3.3 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:____

9.6.3.4 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 pull pin 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:______________________________________

9.6.3.5 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 (NAR/TRA Level 3 certified) Dave Brunsting. Instruct him on the launch angle the team desires to launch at. Note: Only Dave Brunsting is authorized to set the launch angle for the team due to his NAR/TRA certification
- ☐ 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:______________________________________

9.6.3.6 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 certify that the igniter is live.

Team Mentor Signature:____

Safety Officer Signature:____

RCO Signature:____

LSO Signature:____

9.7 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: ____

9.8 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

9.8.1 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.

☐ Identify the location of the TROI. Obtain one team member to take the system back to the launch site. Ensure that this team member is wearing heat resistant gloves when picking up TROI, as the telescoping arm may still be hot. **Failure to complete this procedure may result in failure mode TROI.9.**

☐ 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 ejection charges are still active?

- Determine which ejection charges are still active.
- Only Team Mentor (NAR/TRA Level 3 certified) Dave Brunsting is allowed to complete these next procedures, and they must be wearing nitrile gloves and safety glasses. **Failure to allow Dave Brunsting to handle these energetics may result in an ejection charge firing around team members, resulting in failure mode L0.1.**
- 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, located in 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:______________________________________

9.9 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, with their cellular device, can reactivate their hotspot to connect with the ACS.

☐ The ACS will stop data collection by, after connecting, commanding a halt on data collection. They will then pull the flight data from the microcontroller.

☐ Remove the fourth extension flap on the ACS and verify that the low battery light is not on. Reinsert the pull pin to deactivate the system.

☐ 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, with their cellular device, can reactivate their hot spot to connect with the ACS.
- ☐ The ACS will stop data collection by, after connecting, commanding a halt on data collection. Reinsert the pull pin into the ACS to deactivate the system.
- ☐ Command the ACS to extend the extension arms and remove the extension flaps and lever arms. Command the ACS to retract once these parts are removed to allow for full disassembly.
- ☐ Unscrew all airframe interfacing blocks to allow for disassembly of the launch vehicle.
- ☐ Once the ACS is removed, disconnect the 3.7 V and 7.4 V batteries.
- ☐ 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 general waste 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.** Team members should check the area where the launch vehicle was inspected, integrated, launched, and retrieved for any and all general and launch vehicle equipment waste.

☐ 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:______________________________________

9.10 Project Concerns

9.10.1 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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive	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. These documents are available in the team Google Drive 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 members in the team Google Drive	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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive	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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive	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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive	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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive 4. Safety glasses will be worn for all construction in addition to any other necessary PPE. Necessary PPE can be found in the Standard Workshop Operating Procedures, made available in the team Google Drive	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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive 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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive	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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive 4. Safety glasses will be worn for all construction in addition to any other necessary PPE. Necessary PPE can be found in the Standard Workshop Operating Procedures, made available in the team Google Drive	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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive 4. The Workshop Standard Operating Procedures, which are available for all team members in the team Google Drive, include detailed procedures on how to safely use epoxy with appropriate PPE	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. These documents are available in the team Google Drive 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 are available for all members in the team Google Drive 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	1. A link to appropriate to an MSDS sheet with appropriate disposal procedures for relevant chemicals is found in section 3 of the Safety Handbook. The Safety Handbook is located in the team Google Drive 2. At least one team lead will be present at any official NDRT function or meeting in order to, among other tasks, provide additional guidance on proper safety disposal methods	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. These procedures are outlined more specifically in section 9.8.1	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 relevant 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 relevant 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 at the launch site 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, denoted in section 9.6.3.6 of the team's Launch Procedures and Operations 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, outlined in section 9.7 of the team's Launch Procedures and Operations	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, denoted on the team packing list in section 9.1.3 of the team's Launch Procedures 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 as denoted in the packing list of section 9.1.3 of the team's Launch Procedures	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 as denoted in the packing list in section 9.1.3 of the team's Launch Procedures 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 denoted in the packing equipment list in section 9.1.3 of the team's Launch Procedures 3. The Project Manager and Safety Officer will continually assess the weather and determine if the temperatures are safe to launch in, made clear in step 2 of section 9.1.5 in team's Launch Procedures 4. The team will send announcements further reminding the entire team about the cold temperatures	2	4	8

9.10.2 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 an 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, made clear in all relevant launch procedures concering energetics 2. The team is using a AeroTech L2200G-P motor as denoted in section 3.2. The motor is a trusted product from a reputable 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. The launch vehicle's bulkheads passed the static loading test and exceeded the team-derived goal of a 1.5 factor of safety. Results of this test are located in section 10.1.1 under LVT.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. The launch vehicle's fiberglass bulkhead passed the static loading test with a factor of safety over 1.5. Results of this tests are found in section 10.1.1 under LVT.5. The carbon fiber bulkhead static loading test, located in section 10.1.2 under RT.5 and ACS.14, also was performed with the bulkheads exceeding 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, outlined in section 9.1.5 of the team's Launch Procedures	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 is made of carbon fiber, a high quality material that cna withstand considerable force 2. 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 as denoted in section 9.1.5 and throughout the team's Launch Procedures 2. The carbon fiber for the body tube is from a trusted vendor and was approved by the Project Manager and Vehicles Squad Lead prior to purchase 3. The body tube was be tested with the black powder charges to ensure, upon inspection, that the combustion reaction does not damage the body tubes. Results of this test are found in section 10.1.2 under RT.3 4. The procedures for inserting the separation charges are outlined in Launch Operating Procedures under section 9.2.2.6, which is made available to all team members in the team Google Drive. 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 proved successful in the sub-scale launch, outlined in section 10.1.1 under LVT.2	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 body tube is made of carbon fiber, a strong material that can withstand considerable blunt force during launch 2. Recovery system has been verified through a subscale launch before a full-scale launch. Results of this demonstration flight are made available in section 10.1.2 under LVT.2	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 are purchased from a respected and trusted vendor and were 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 as denoted in all relevant launch procedures 3. The team will utilize five 4-40 nylon shear pins at each separation point, which demonstrate a factor of safety of 2 with respect to shear failure. Detailed information on this selection is available in section 4.3.2	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	Coupler material will be verified to be able to withstand the force and combustion experienced from the separation charges	The coupler was not damaged during the ground ejection test. Results of this test are found in section 10.1.2 under RT.3 and INT.3	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 will be from a trusted and respected vendor and approved by the Project Manager and the Vehicles Squad Lead prior the purchase	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. These steps are denoted in all relevant launch procedures 2. The team is using an Aerotech L2200G-PS motor, a high quality product that was approved by the Vehicles Squad Lead and Project Manager prior to 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. Only team mentor Dave Brunsting (NAR/TRA Level 3 certified) will be authorized to install the centering rings	1. The Launch Operating Procedures clearly note that team mentor Dave Brunsting is the only individual authorized to install the centering rings 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 as denoted in section 9.5.2.7 3. Procedures for installing centering rings are available for all team members and are outlined in the Launch Operating Procedures, which are available in the team Google Drive	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. These procedures are outlined in step 5 of section 9.6.2 of the team's Launch Operating Procedures	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	1. All vehicle components will be securely fastened during integration and verified by the Safety Officer and Vehicles Squad Lead 2. The launch vehicle will pass a vibration test when fully assembled to ensure that internal components do not become dislodged when the vehicle is fully integrated	1. 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 as denoted in section 9.5.2.5 of the team's Launch Operating Procedures 2. The launch vehicle passed the vibration test during the vehicle demonstration flight. Results of these test are available in section 10.1.1 under LVT.4	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 a launch 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. This procedure is located in section 9.5.2.8 under the Stability Test	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. The Project Manager and Vehicles Squad Lead must agree to the shape and size of the fins before proceeding in their construction	Four elliptical fins are used in the full-scale launch vehicle, a design choice that was approved by both the Vehicles Squad Lead and the Project Manager prior to purchase of the materials. Further detail on the fins can be found in section 3.3.5	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, denoted on all relevant launch procedures 2. Standard Launch Operating Procedures for installing the centering rings properly are available on step 3 of section 9.5.2.7 in the team's 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.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, as denoted on all relevant launch procedures 2. Standard Launch Operating Procedures for installing the centering rings properly are available on step 3 of section 9.5.2.7 in the team's 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 5. Troubleshooting steps for assessing and readjusting the launch vehicle should it not leave the launch rail are made available under section 9.7 of the team's Launch Operating Procedures	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 team's Launch Operating Procedures under section 9.6.3.5	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. This design choice is further explained in section 4.6.1 3. Procedures for installing the main parachute will are clearly written out in the Standard Launch Operating Procedures under section 9.2.2.1 and will be reviewed during the launch rehearsal the day before the launch 4. Main parachute shock cord purchase choices are explained in detail in section 4.4.1	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 5. High winds	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 5. The team will not launch in winds exceeding 20 mph	1. Both the Recovery Squad Lead and Safety Officer will monitor the main parachute installation and sign off on the Standard Launch Operating Procedures under section 9.2.2.2 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. This design choice is further explained in section 4.6.1 3. Drogue parachute shock cord purchase choices are explained in detail in section 4.4.2 4. The Safety Officer will continually monitor the wind and postpone or cancel the launch should winds exceed 20 mph. This check is outlined in section 9.1.5 of the team's 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. Such steps are denoted on all relevant launch procedures 2. The black powder charges performed a successful test, with detail provided in section 10.1.2 under RT.3 and INT.3	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. Any altimeter present in the system will be properly shielded by an appropriate shielding material	1. Each recovery device will feature at least two altimeters which will be verified by inspection. Further detail on the altimeter design choice is provided in section 4.6.2 2. A successful electronics shielding was performed and is available in section 10.1.2 under RT.4 and INT.2 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. Further detail is provided in section 4.6.2 2. Shear pin design choices are made available in section 4.3.2 3. A successful black powder charge ejection test and electronics shiedling test was performed. Results are available under section 10.1.2 under RT.3, INT.3 and RT.4, INT.2, respectively	2	3	6
R.6	Drogue parachute shroud lines tangle	1. Improper packing of drogue parachute 2. High winds	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 4. The team will not launch in winds exceeding 20 mph	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. Drogue parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures under section 4.4.2 3. Successful demonstration of the parachute unfolding test is available under section 10.1.2 under RT.8 This check is outlined in section 9.1.5 of the team's Launch Operating Procedures	1	3	3

R.7	Main parachute shroud lines tangle	1. Improper installation of main parachute 2. High winds	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	1. Main parachute installation will be closely monitored by the Recovery Squad Lead and Safety Officer 2. The team will not launch in winds exceeding 20 mph	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. Main parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures under section 4.4.1 3. Successful demonstration of the parachute unfolding test is available under section 10.1.2 under RT.8 4. The Safety Officer will continually monitor the wind and postpone or cancel the launch should winds exceed 20 mph. This check is outlined in section 9.1.5 of the team's 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 under sections 4.4.1 and 4.4.2 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. Further detail on altimeter redundancy is available under section 4.6.2	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. Design choices for the parachute are available under section 4.4.1 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. Further detail on altimeter redundancy is available under section 4.6.2	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. 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. Drogue parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures under section 4.4.2	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 is included on the team's Launch Operating Procedures under section 9.2.2.1 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	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	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. This step is listed under section 9.6.3.2 in the team's Launch Operating Procedures	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 4. High winds	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 3. The team will not launch in winds exceeding 20 mph	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. Further detail on this design choice is provided in section 4.6.2 2. Parachute installation procedures are readily available for all team members on the Standard Launch Operating Procedures under sections 4.4.1 and 4.4.2 3. 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 under section 9.2.2.1 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 analyzed prior to integration into the launch vehicle to verify that no fraying is present	Step 6 of section 9.2.1 in the team's Launch Operating Procedures verify that the shock cords are not frayed or ripped 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. Further detail on this design choice is provided in seciton 4.6.2	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 this test are provided in section 10.1.3 under TROIT.1	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, in conjunction with the full-scale battery duration test, is in progress. Details of the test can be found in section 10.1.1 under LVT.3	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. This placement will be verified by section 9.5.2.1 in the team's Launch Operating Procedures	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	The servo motor will be capable of performing accurate actuation under predicted maximum static loading	The ACS passed the dynamic flap actuation test, with results found under section 10.1.4 under ACST.2	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 team's Launch Operating Procedures in section 9.5.2.1 and 9.5.2.10 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. Details of this design decision are found in section 7.4.2 2. Heat shrink will be used to cover any frayed wires 3. Section 9.4.1 of the team's Launch Operating Procedures ensures wires are checked for any fraying	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 is 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	Three altimeters will be present with appropriate electromagnetic shielding in the ACS to ensure redundancy, with details further explained in 7.4.1	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 PWM controller will be present in the ACS to prevent noisy signal to the servo motor, which is further detailed in section 7.4.1	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, further detailed in 7.4.2 2. Wires will be checked to fraying as part of the initial inspection sequence in section 9.4.1 of the team's Launch Operating Procedures	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	1. 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, verified in sections 9.5.2.2 and 9.5.2.8 of the team's Launch Operating Procedures 2. TTROI has yet to pass TROIT.11, verifying that it is able to operate at various angle placements relative to the horizontal axis. Details of this test are available in section 10.1.3 under TROIT.11. The test will be completed before the FRR Addendum deadline	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	1. TROI has passed TROIT.3, verifying that the system is able to capture images. Details of this test are available in section 10.1.3 under TROIT.3 2. TROI has yet to pass TROIT.11, verifying that it is able to operate at various angle placements relative to the horizontal axis. Details of this test are available in section 10.1.3 under TROIT.11. The test will be completed before the FRR Addendum deadline	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 by the success of INT.1. Details of this test are available in section 10.1.1 under INT.1 2. The procedures for testing the payload battery are available to all team members in section 9.3.1 in the team's 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.	Section 9.3.2 on the team's Launch Operating Procedures ensures that the team sets the radio frequency to the value given by NASA SLI	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	The camera system will be securely fastened to the payload and approved by the Safety Officer and Payload Squad Lead prior to launch	Section 9.5.2.8 of the team's Launch Operating Procedures	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 team is using a OV2640 140° Camera Module, a purchase approved by both the Payload Squad Lead and the Project Manager 2. TROI has yet to pass TROIT.12, verifying that the camera is able to take pictures of nominal quality. Details of this test are available in section 10.1.3 under TROIT.12. The test will be completed before the FRR Addendum deadline	1	3	3
TROI.8	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	TROI will be confirmed to be functional at landing through a functionality test	TROI is currently in the process of completing TROIT.15, a functionality test that confirms the system will perform as expected after the launch vehicle lands. Details for this test are available in section 10.1.3 under TROIT.15	1	3	3
TROI.9	Telescoping arm generates heat	Continual power by the TROI battery generates heat	Team member is injured from touching the telescoping arm without proper PPE	3	2	6	1. Proper PPE will be brought when retrieving the launch vehicle 2. Team members will be reminded that, when retrieving the launch vehicle, they should be cautious of TROI and the heat that may have generated on the telescoping arm	A pair of heat resistant gloves will be brought and will be used by the team member that retrieves TROI. Heat resistant gloves are identified as a packing item in section 9.1.3 on the team's Launch Operating Procedures. The procedure to have the team member wear heat resistant gloves when retrieving TROI is identified in section 9.8	1	2	2

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	A bulkhead will be installed within the payload bay just above the electronics to prevent water presence in the electronics bay	TROI integration, as verified in section 9.5.2.2 of the team's Launch Operating Procedures, includes the system's bulkhead	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 be able to operate in various angle positions should it land in a disadvantageous position	TROI has yet to pass TROIT.11, verifying that it is able to operate at various angle placements relative to the horizontal axis. Details of this test are available in section 10.1.3 under TROIT.11. The test will be completed before the FRR Addendum deadline	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 Mechanical Functionality Test outlined in section 9.3.2.1 in the team's Launch Operating Procedures will be completed before launch	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 robust to ensure TROI is adequately protected during descent and landing	TROI is retained with two fiberglass bulkheads and four airframe interfacing blocks. Details of this retention system are further explained in section 6.3.3	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 are done thoroughly	The team is using a A4988 Stepper Motor Driver, a reputable product that was approved by the Payload Squad Lead prior to purchase	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. Section 9.1.3 includes a comprehensive packing checklist for the team to complete 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. Section 9.6.3.5 on the team's Launch Operating Procedures include detailed steps on setting the launch angle safely and within NAR guidelines 2. NDRT Mentor Dave Brunsting will be responsible for setting the launch vehicle to the proper angle as denoted on the launch procedures	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 3. Troubleshooting procedures, found in section 9.7 of the team's Launch Operating Procedures	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

9.10.3 Environmental Risks

Label	Hazard	Cause	Outcome	Probability	Severity	Before

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
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
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
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

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
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
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

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
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
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
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

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
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
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
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
VE.16	Particulate expulsion into environment	Improper construction practices	1. Delamination of material when using water jet 2. Dispersion of more particulate	4	2	8

VE.17	Launch window collision avoidance	1. Excessive cloud cover causing a lack of visibility for the team to identify other aircraft 2. Pilots of other aircraft failing to analyze NOTAMS broadcasts	Collision of team's launch vehicle with other aircraft	2	4	8
Recovery modules audio startles wildlife	Recovery modules produce continuous audio during and after launch	1	3	3	1. Nearby wildlife may become startled by the audio2. Nearby wildlife by be attracted to the launch vehicle and damage it	1
3	3					

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. This check is outlined in section 9.1.5 of the team's Launch Operating Procedures	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. This check is outlined in section 9.1.5 of the team's Launch Operating Procedures 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. This check is outlined in section 9.1.5 of the team's Launch Operating Procedures	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. This check is outlined in section 9.1.5 of the team's Launch Operating Procedures	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	1. 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. This check is outlined in section 9.1.5 of the team's Launch Operating Procedures 2. The Recovery Lead will use a cellular device featuring a GPS to track the launch vehicle	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. This check is outlined in section 9.1.5 and 9.6 of the team's Launch Operating Procedures 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. This check is outlined in section 9.1.3 of the team's Launch Operating Procedures 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. This check is outlined in section 9.1.3 of the team's Launch Operating Procedures 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. This check is outlined in section 9.1.3 of the team's Launch Operating Procedures	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. This check is outlined in section 9.1.3 of the team's Launch Operating Procedures	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. This check is outlined in section 9.1.5 of the team's Launch Operating Procedures	1	4	4

EV.13	Excessive moisture in contact with the potassium nitrate in black powder charges	Excessive moisture in the environment (humidity and/or rain)	1. The potassium nitrate dissolves and causes the drogue and/or main parachute to fail to deploy 2. Complete mission failure	2	4	8	1. The weather will be continually evaluated by the Safety Officer for the presence of moisture, either in high humidity or precipitation 2. Team Mentor Dave Brunsting will bring extra black powder charges and will assemble them in a dry environment	1. If the probability of precipitation is non-negligible, the launch will be postponed or canceled. This check is outlined in section 9.1.5 2. Black powder charges are available on the packing list in section 9.1.3 on the team's Launch Operating Procedures	1	4	4

9.10.4 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 4. The budget for the team's spending can be found in section 10.3	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	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 are available to all team members in the Safety Handbook, located in the team's Google Drive	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 well in advance 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	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

9.11 Incident Reporting

Safety Hazard Report Form

Personnel Hazard

Responsible Individual: NDRT Safety Officer

Date	Individual	Hazard(s)
12/11/2022	Tech editor/Vehicles and Recovery member	C.7 C.1

Description

On December 11th, 2022, during a team bonding event, a team member used the nose cone as a way to draw names out of a hat. The team member caught their hand on the inside of the nose cone and suffered a minor cut on their finger. The team was in the workshop at this time and quickly used the First-Aid kit to apply a bandage to the open wound.

Moving Forward

Moving forward, the safety team will continue to remind all members of proper workshop procedures, including a halt on horseplay and irresponsible use of the launch vehicle and/or other equipment.

Safety Hazard Report Form

Failure Mode

Responsible Individual: NDRT Safety Officer

Date	Individual	Hazard(s)
1/31/2023	Payload lead	C.8

Description

On January 31st, 2023, the payload squad was prototyping with a 12V power supply. The power supply contains two exposed leads that are not well-protected connected via alligator clips to the remainder of the system. As the squad was setting up the circuit, the squad remembered that the leads, because they were moving, could cause a short circuit. The payload lead was about to connect the plug to the overhead socket to finish setting up the circuit, but then remembered the shock hazard that was present and immediately stopped. No hazard occurred.

Moving Forward

Moving forward, the Safety team will continue to remind the team on the dangers of construction and fabrication during the design process. The Safety lead will direct team members to the workshop operating procedures, EIH staff, or Stinson-Remick staff for any fabrication questions. Members will be reminded of wearing proper PPE during construction, including long hair being tied back, wearing safety glasses, and not wearing baggy clothes.

Safety Hazard Report Form

Failure Mode

Responsible Individual: NDRT Safety Officer

Date	Individual	Hazard(s)
2/16/2023	Payload lead, Systems lead, Payload squad members	C.8

Description

On February 16th, 2023, the payload squad was performing a shake test on TROI. There were loose wires present on the top of the payload module that were not secured, and during the shake test, one of the wires came lose and cut a payload squad member on the ear. The cut was minor and first aid was administered.

Moving Forward

Moving forward, all design squads will ensure that all wires are secured when working on a system. This precaution can be done through taping wires down or using a PCB to minimize physical wire usage.

10 Project Plan

10.1 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	Attempted
LVT.2	Subscale Demonstration Flight	2.18., 2.18.1., 2.18.2.	Pass
LVT.3	System Battery Duration Test	2.6.	Pass
LVT.4	Vibration Test	LV.5	Pass
LVT.5	Fiberglass Static Bulkhead Loading Test	LV.6	Pass
LVT.6	Motor Mount Static Loading Test	LV.6	Attempted
LVT.7	Fin Can Drop Test	LV.6	Pass
RT.1	Launch Vehicle Demonstration Flight	3.1., 3.3., 3.10., 3.11., 3.12.2.	Pass
RT.2	Simulated Flight Test	3.1.1., 3.1.2.	Pass
RT.3	Ground Ejection Test	3.2.	Pass
RT.4	Electronics Shielding Test	3.1., 3.3., 3.10., 3.11., 3.12.2.	Pass
RT.5	Carbon Fiber Bulkhead Static Loading Test	R.2	Pass
RT.6	GPS Functionality Test	3.12., 3.12.2.	Pass
RT.7	E-Match and RF Interference Test	3.12.2., IN.2	Pass

Table 97: Testing Overview (continued)

Test ID	Title	Requirements Satisfied	Result
RT.8	Parachute Unfurling Test	2.3., 3.1., 3.1.1., 3.3.	Pass
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	Sensor Unit Test	4.2.3.3.	Pass
TROIT.3	Camera Unit Test	N/A	Pass
TROIT.4	Longitudinal Stepper Motor Test	N/A	Pass
TROIT.5	Telescoping Camera Arm Test	TROI.6	Pass
TROIT.6	Longitudinal Deployment Test	N/A	Pass
TROIT.7	RF Receiving Test	4.2.2., 4.2.2.1., 4.2.3., 4.2.3.1., 4.2.3.2.	Pass
TROIT.8	RF Command Processing Test	4.2.2., 4.2.2.1.	Pass
TROIT.9	Camera Stepper Motor Test	N/A	Pass
TROIT.10	Camera System Rotation Test	4.2.1., 4.2.1.1.	Pass
TROIT.11	Camera System Deployment Conditions Test	TROI.1, TROI.4, TROI.6	Omitted
TROIT.12	Camera Baseline Imaging Test	4.2.1.3., 4.2.1.4., TROI.3	Pass
TROIT.13	Camera RF Integration Test	4.2.1.4., 4.2.2., 4.2.2.1., 4.2.3., 4.2.3.1., 4.2.3.2.	Pass
TROIT.14	Payload State Identification Test	4.2.3.3.	Pass
TROIT.15	Payload Preliminary Integration Test	4.2.	Incomplete
ACST.1	Flap Mechanism Actuation Test	ACS.1	Pass
ACST.2	Drag Flap Dynamic Loading Test	ACS.2	Pass
ACST.3	Data Acquisition Test	ACS.3, ACS.4	Pass
ACST.4	State Transition Manager Test	ACS.5	Pass
ACST.5	PCB Electrical Design and Rules Check	N/A	Pass
ACST.6	PCB Electrical Continuity Test	N/A	Pass
ACST.7	Solder Joint Reliability Test	N/A	Pass
ACST.8	Sensor Unit Test	N/A	Pass
ACST.9	Standalone Servo Motor Unit Test	N/A	Pass
ACST.10	Data Filter Test	N/A	Pass
ACST.11	Apogee Prediction Algorithm Test	N/A	Incomplete
ACST.12	Control Algorithm Test	N/A	Incomplete
ACST.13	On-Ground Software Loop Test	N/A	Incomplete
ACST.14	Carbon Fiber Bulkhead Static Loading Test	N/A	Pass
INT.1	System Battery Duration Test	IN.1	Pass
INT.2	Integrated Electronics Shielding Test	IN.2	Pass
INT.3	Ground Ejection Test	IN.3	Pass

10.1.1 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	Attempted
RT.1	Recovery modules perform nominally	3.1., 3.3., 3.10., 3.11., 3.12.2.	Pass

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: Attempted. A Vehicle Demonstration Flight was attempted on 2/18. The recovery electronics successfully triggered in-flight separation and parachute deployment events, but the demonstration flight was not fully successful due to the shock cord snapping during descent. Results and analysis pertaining to a successful flight will be included in the FRR Addendum the team will submit.

Next Steps: The team has requested to submit an FRR Addendum.

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 assembled 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 Subscale Launch Analysis in CDR.

Next Steps: Fullscale design and construction can continue.

LVT.3, INT.1: System 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	All electronics remain fully operational after three hours have elapsed	2.6.	Pass
INT.1	All electronics remain fully operational after three hours have elapsed	IN.6	Pass

Materials and Equipment Needed: Fully assembled and integrated launch vehicle, fully charged batteries for each subsystem

Test Setup:

1. Verify the temperature of the testing environment is below 20 degrees Fahrenheit
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 unplugging or deactivating them

Analysis Procedure:

1. Check that all electronics remain powered by looking for flashing lights indicating their powered on status

Results: Pass. All on-board electronics were placed outside in a cold environment and remained functional after three hours elapsed.

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 test

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	Pass

Materials and Equipment Needed: Fully assembled fullscale launch vehicle
Test Setup:

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

Test Procedure:

1. Have multiple team members hold the launch vehicle vertically
2. Instruct the team members to shake the launch vehicle vigorously for one to three minutes

Analysis Procedure:

1. Disassemble the launch vehicle and inspect whether components have remained connected to their respective locations

Results: Pass. A vibration test was conducted as part of the Launch Operating Procedures for the 2/17 VDF attempt; no internal components became dislodged.

Next Steps: Test passes if no components become dislodged due to vibration. Test fails if components become dislodged; revisit method of connection if necessary. Repeat test before each launch vehicle demonstration flight

LVT.5: Fiberglass Bulkhead Static Loading Test

Objective: Verify fiberglass bulkheads in all 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	Bulkheads do not exhibit any signs of failure up to 1.5 times the maximum expected load	LV.6	Pass

Materials and Equipment Needed: Fiberglass coupler section, G10 fiberglass with the same dimensions and holes as the fixed bulkhead, G10 fiberglass body tube airframe interfacing blocks and screws, eyebolt, epoxy, load frame, safety glasses
Test Setup:

1. Epoxy fiberglass bulkhead onto a body tube, ensuring appropriate curing time
2. Attach eyebolt and airframe interface blocks to bulkheads, then attach bulkhead to the body tube with the use of screws

Test Procedure:

1. Place bulkhead and its respective test section into the load frame
2. Gradually increase the load applied to the bulkhead and test section until reaching 1.5 times the predicted force
3. Stop the load frame and remove the test materials

Analysis Procedure:

1. Visually inspect the bulkhead for signs of damage or fracture
2. Record the final load for the fiberglass bulkhead

Results: Pass. The fiberglass bulkhead did not exhibit signs of failure until it experienced a load of approximately 976 lbf, which is significantly above the 542 lbf required to meet a factor of safety of 1.5. Figure 120 shows the displacement graph for this test.

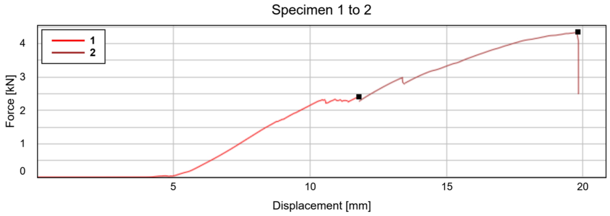


Figure 120: Fiberglass bulkhead displacement with respect to tensile load

Next Steps: Construction can proceed with the selected bulkhead material and size. For future instances where this test is conducted, consider shortening the length of the body tube test section.

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	Motor mount does not exhibit any signs of failure up to 1.5 times the maximum expected load	LV.6	Attempted

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 appear on the motor mount tube
2. Stop the load frame and remove the motor mount tube

Analysis Procedure:

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

Results: Attempted. The fiberglass material exhibited signs of failure at approximately 976 lbf, which is below the 1045.5 lbf requirement to reach a factor of safety of 1.5 but still above a factor of safety of 1.0, ensuring functionality during flight. However, it should be noted that the fiberglass bulkhead used in this test was missing a small amount of material, making it an imperfect circle that could not be fully epoxied to the body tube test section. Figure 121 displays this imperfection and the test setup. This caused a decrease in performance, so the true load that the fiberglass centering rings can withstand is higher. Thus, the team still believes the design is acceptable.

Figure 121: Fiberglass material imperfection

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

LVT.7: Fin Can Drop Test

Objective: Verify the fin can will not be damaged due to landing forces

Test ID	Success Criteria	Requirements Satisfied	Result
LVT.7	Fin can does not exhibit any signs of failure up to 1.5 times the maximum expected compressive load	LV.6	Pass

Materials and Equipment Needed: Fully integrated fullscale launch vehicle airframe, ladder, tape measure

Test Setup:

1. Use RockSim and OpenRocket to determine the maximum compression load on the Fin Can in flight
2. Use kinematic equations to solve for the height necessary to drop the Fin Can for it to experience 1.5 times the maximum expected in flight load
3. Find a test area with a surface similar to the launch field
4. Use the ladder to reach height commensurate with 1.5 times expected compressive load, measure for accuracy

Test Procedure:

1. Go to the test area similar to the launch field
2. Hold the Fin Can perpendicular to the ground from the ladder, having a second team member measure height
3. Drop the Fin Can perpendicular to the ground to simulate maximum compressive force, given height determined by the kinematic equations

Analysis Procedure:

1. Examine the Fin Can for any cracks visually - internally and externally
2. If an area is suspected to have broken or cracked, tap the area using a metal object (coin), and listen for any changes to the sound in comparison to the surrounding area
3. Push down on the suspected area to examine whether there is excess play

Results: Pass. Visual inspection of the fin can and epoxy joints verified that no cracks were present internally or externally after dropping from the calculated height (4 ft).


(a) Post-drop fin can section (b) Post-drop epoxy joint

Figure 122: Results of fin can drop test

Next Steps: N/A. Fullscale integration may continue with the current construction.

10.1.2 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 e-matches turn on at the desired altitudes	3.1.1., 3.1.2.	Pass

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 appropriate altimeter software (Featherweight vs. Stratologger) and input desired altitudes for separation event

Test Procedure:

1. Upload simulated altitude and flight data to altimeter
2. Repeat for additional altitudes as desired

Analysis Procedure:

1. Observe whether LED light turn on at desired altitudes

Results: Pass. All Featherweight and Stratologger altimeters indicated “ignition” at the desired altitudes for the drogue and main parachutes.

Next Steps: The altimeters need not be reprogrammed. For future instances of the test using Featherweight altimeters, the team should ensure to provide power to the altimeter before connecting it to the laptop software via USB cable. During the simulated flight, motor burnout should be triggered relatively early to ensure apogee is similar to the team’s target. For the Stratologger altimeters, the altimeter should be connected to the laptop via USB cable before being connected to a battery. The Stratologger software must be selected to data acquisition before initial setup finishes in order to continue with testing.

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	3.2.	Pass
INT.3	Black powder charge debris is not visible near the TROI camera system	IN.5	Pass

Materials and Equipment Needed: Fullscale launch vehicle, calculated and sized black powder charges, safety glasses, battery with ematch and wire leads, double-sided adhesive, recording device

Test Setup:

1. For each recovery module, load correctly sized black powder amount into each 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. Place double-sided adhesive around the inside of the payload body tube on the same side of the removable bulkhead that the payload will be located
4. Verify the payload is not integrated within the payload body tube
5. Clear any obstructions and place launch vehicle on the ground

Test Procedure:

1. Have a team member take a video of the ground ejection event
2. For each separation point/recovery module, ignite black powder by closing circuit on the battery
3. For each separation point, handle launch vehicle sections only after they have come to rest

Analysis Procedure:

1. Consult RSO and/or team mentor 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 adhesive and inside of body tube for signs of black powder debris

Results: Pass. NDRT team mentor Dave Brunsting determined the black powder charges were appropriately sized at each separation point due to adequate force of separation. Visual inspection of the payload body tube shown in Figure 123 verified no black powder debris was present in the area of the payload located behind the removable bulkhead.

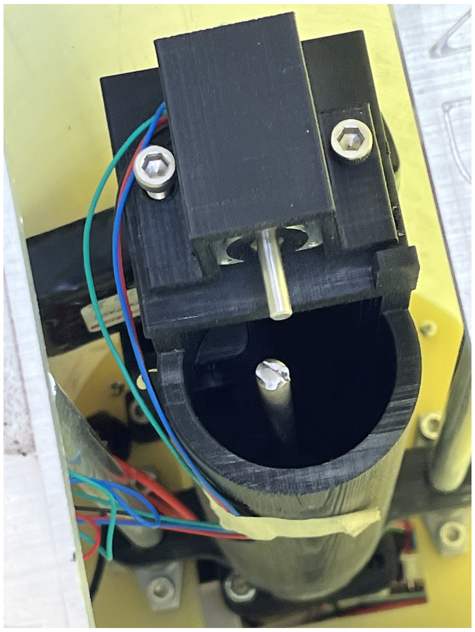


Figure 123: Post ground ejection test debris-free payload body tube

Next Steps: Black powder charge sizes may continue to be used for future launch attempts. The removable bulkhead does not need to be redesigned, as it successfully protects the payload from debris.

RT.4, INT.2: Electronics Shielding Test

Objective: Verify onboard electronics do not interfere with recovery electronics during flight

Test ID	Success Criteria	Requirements Satisfied	Result
RT.4	Recovery electronics do not output irrational data when integrated with the full launch vehicle system	3.1., 3.3., 3.10., 3.11., 3.12.2.	Pass
INT.2	Data from electronics are read and stored accurately	IN.2	Pass

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: Pass. No electronics from any system output physically inaccurate data after all were activated in close proximity to each other.

Next Steps: Repeat demonstration if any light indicators turned on after determining the cause of the failure.

RT.5, ACST.14: Carbon Fiber Bulkhead Static Loading Test

Objective: Verify carbon fiber bulkheads in all sections of the launch vehicle can withstand at minimum 1.5 times the predicted in-flight forces

Test ID	Success Criteria	Requirements Satisfied	Result
RT.5	Bulkheads do not exhibit any signs of failure up to 1.5 times the maximum expected load	R.2	Pass
ACST.14	Bulkheads do not exhibit any signs of failure up to 1.5 times the maximum expected load	N/A	Pass

Materials and Equipment Needed: Carbon fiber body tube section, carbon fiber bulkhead with same dimensions as PED and FED bulkheads (5.85 in. diameter), airframe interfacing blocks and screws, drill, 0.5 in. or greater drill bit, load frame, pin to secure body tube section within load frame, safety glasses

Test Setup:

1. Assemble the airframe interfacing blocks onto the recovery carbon fiber bulkheads
2. Attach airframe interface blocks to bulkheads, then attach bulkheads to the body tube with the use of screws
3. Drill holes with a minimum diameter of 0.5 in. on each side of the bottom side of the body tube test section

Test Procedure:

1. Place the bulkhead and its respective test section into the load frame
2. Secure the top of the body tube test section to the clam clamp interface in the load frame
3. Secure the bottom of the body tube test section to the base of the load frame using a pin
4. Gradually increase the load applied to the bulkhead and test section until reaching 1.5 times the predicted force
5. Stop the load frame and remove the test materials

Figure 124: Bulkhead static loading test setup

Analysis Procedure:

1. Visually inspect the bulkhead for signs of damage or fracture
2. Record the final load for each bulkhead and any data output by the load frame software

Results: Pass. The 5.85 in. bulkhead exhibited no signs of failure when loaded with forces up to 971 lbf, which is the approximate force required for the bulkhead to have a factor of safety of 1.5. Figure 125 displays the displacement with respect to loading. Because the 5.85 in. bulkhead experiences the highest amount of loading during flight and passed, the team concluded that other carbon fiber bulkheads will also be able to withstand their lower amounts of in-flight loading.

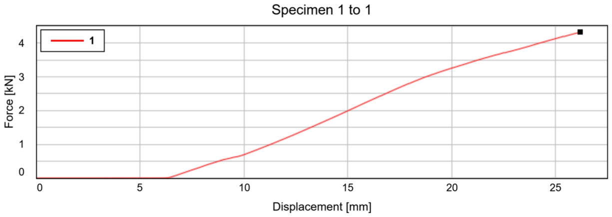


Figure 125: Carbon fiber bulkhead tension loading vs. displacement

Next Steps: Construction may continue with the planned bulkhead material and sizing. For future instances where this test may be conducted, the body tube test section should have a smaller height to make integration within the load frame easier. Different methods of attaching the test section to the load frame tension components may be explored.

RT.6: GPS Demonstration Test

Objective: Demonstrate GPS connectivity and accuracy at increased ranges

Test ID	Success Criteria	Requirements Satisfied	Result
RT.6	GPS maintains connection with its paired device and reports accurate location	3.12., 3.12.2.	Pass

Materials and Equipment Needed: Fully charged GPS, phone, online map tool with satellite coordinates

Test Setup:

1. Connect GPS and phone and verify the GPS is reporting the known original location

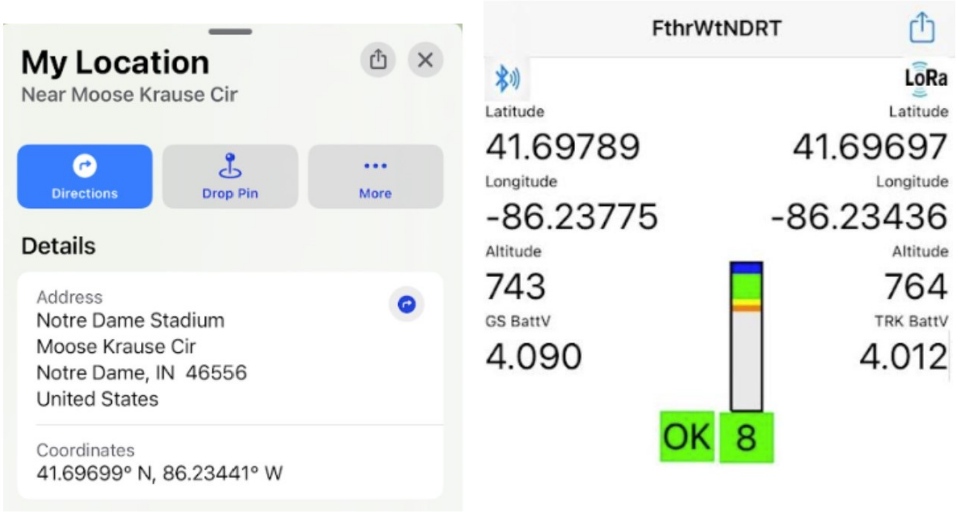
Test Procedure:

1. Bring the GPS to a predetermined location that is over 1000 ft away from the phone
2. Record the coordinates/location that the GPS outputs at the new location

Analysis Procedure:

1. Compare the GPS output to the known destination location

Results: Pass. The GPS was able to connect to a cellular device and transmit an accurate coordinate location at the known distance and location.



My Location
Near Moose Krause Cir

Details

Address
Notre Dame Stadium
Moose Krause Cir
Notre Dame, IN 46556
United States

Coordinates
41.69699° N, 86.23441° W

FthrWtNDRT

Latitude 41.69789
Longitude -86.23775
Altitude 743
GS BattV 4.090

Latitude 41.69697
Longitude -86.23436
Altitude 764
TRK BattV 4.012

(a) Coordinates of known location using phone (b) Coordinates of known location using GPS

Figure 126: Coordinate comparison between phone and GPS at a known location

Next Steps: N/A

RT.7: E-Match and RF Interference Test

Objective: Verify that radio transmissions sent or received by the TROI system do not activate e-match within the recovery system

Test ID	Success Criteria	Requirements Satisfied	Result
RT.7	E-matches are not inadvertently excited by radio transmissions within the TROI system	3.13.2., IN.2	Pass

Materials and Equipment Needed: Radio communication system capable of sending and receiving transmissions, unique radio frequency, e-match, breadboard, wire leads, 12 V battery

Test Setup:

1. Verify that the radio transmission system is operational and capable of sending and receiving transmissions on the selected frequency
2. Use the breadboard to construct a circuit with the e-match, wire leads, and the 12V battery
3. Place the e-match circuit and receiving component of the radio transmission system next to each other

Test Procedure:

1. Send a radio transmission to the receiving end of the radio communication system on the selected frequency
2. Observe the e-match circuit for signs of an ignition signal

Analysis Procedure:

1. If the e-match does not signal ignition, it is properly shielded from radio interference
2. If the e-match signals ignition, it is not properly shielded from radio interference and design plans for shielding must be adjusted

Results: Pass. E-matches did not show any signs of ignition when radio transmission was conducted. The test was conducted in two orientations; one with the wire leads of the e-match next to the top of the transmitting radio, and one with the wire leads next to the center of the antenna where the signal is strongest.

Next Steps:

RT.8: Parachute Unfurling Test

Objective: Verify the folding techniques for the main parachute enable nominal unfurling

Test ID	Success Criteria	Requirements Satisfied	Result
RT.	Parachute successfully unfurls from folding configuration	2.3., 3.1., 3.1.1., 3.3.	Pass

Materials and Equipment Needed: Main parachute, shock cord, deployment bag, quicklinks, fire-retardant blanket, masking tape

Test Setup:

1. Fold the main parachute using z-folds, securing lines with tape
2. Attach the shock cord, deployment bag, and fire-retardant blanket to the main parachute

Test Procedure:

1. Drop the main parachute from a suitably high distance
2. Observe whether the parachute unfolds

Analysis Procedure:

1. The test passes if the parachute visibly unfurls and expands during descent

Results: Pass. The main parachute nominally unfurled after being assembled following standard Launch Operating Procedures.

Next Steps: N/A

10.1.3 Payload Testing

TROIT.1: Payload Demonstration Test

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:

1. 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 effects match RAFCO

Results: Incomplete. As of FRR submission, the payload has not been flown in its final configuration. Results and analysis concerning the Payload Demonstration Flight will be included in the FRR Addendum submitted by the team.

Next Steps: If all components of success criteria are met, the demonstration passes.

TROIT.2, ACST.8: Sensor Unit Test

Objective: Verify all TROI and ACS sensors are calibrated accurately

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.2	TROI sensor output data is physically accurate	4.2.3.3.	Pass
ACST.8	ACS sensor output data is physically accurate	N/A	Pass

Materials and Equipment Needed:

- TROI accelerometer, IMU, wiring, computer, 3.7 V battery, sensor output code
- ACS accelerometer, two altimeters, IMU, breadboard, battery, laptop, Raspberry Pi, sensor output code

Test Setup:

1. Connect selected sensor to breadboard, Raspberry Pi (if ACS sensor), and battery
2. Connect Raspberry Pi to laptop wirelessly for ACS sensors

Test Procedure:

1. For each sensor, run sample code that prints all sensor outputs
2. Record output data for each sensor at rest and in motion
3. Repeat test for each individual sensor

Analysis Procedure:

1. Inspect each sensor output to verify it is physically accurate

Results: The ACS accelerometer, MPL3115A2 altimeters, and IMU all passed. The TROI accelerometer and IMU both passed. All sensors' output data that was physically accurate.

Next Steps: Sensors that passed may be integrated into electric schematics within their respective subsystems.

TROIT.3: Camera Unit Test

Objective: Verify the camera is able to capture images, including those with filters applied

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.3	Camera is able to capture images, including filtered images	N/A	Pass

Materials and Equipment Needed: TROI camera, computer
Test Setup:

1. Verify the TROI camera is fully charged

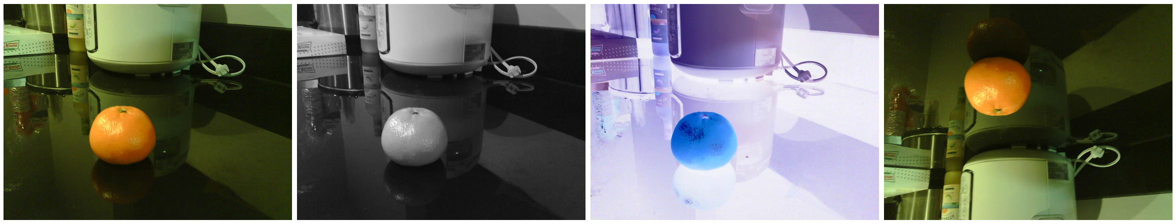
Test Procedure:

1. Take a non-filtered image of a neutral object or background
2. Repeat using the same neutral object or background for all additional filtering options

Analysis Procedure:

1. Visually inspect the quality of each image

Results: Pass. The camera is able to capture images, both filtered and unfiltered, of acceptable quality.



(a) Normal image (b) Grayscale image (c) Negative image (d) Flipped image

Figure 127: Various images captured by the TROI camera

Next Steps: The selected camera may be integrated with remaining components in the camera subsystem.

TROIT.4: Longitudinal Stepper Motor Test

Objective: Verify that the stepper motor is deploying after the launch vehicle lands

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.4	Longitudinal axis stepper motor responds to commands via ESP32 and deploys to the desired distance	N/A	Pass

Materials and Equipment Needed: Fully assembled mechanical payload, lead screw stepper motor, ESP32, lead screw stepper motor deployment code, 12 V battery
Test Setup:

1. Attach the lead screw stepper motor to the lead screw cover
2. Charge battery and integrate all electronics. Attach lead screw stepper motor to ESP32 board and driver

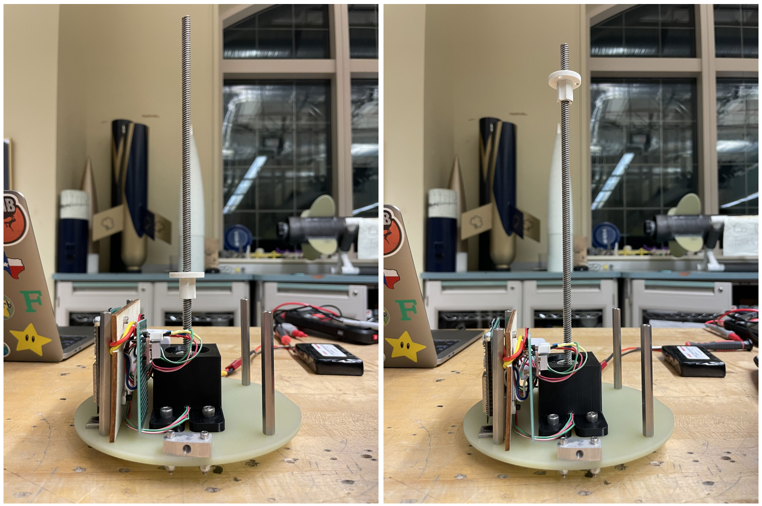
Test Procedure:

1. Turn on the system by connecting the battery
2. Run lead screw stepper motor code

Analysis Procedure:

1. Observe lead screw stepper motor actions after sending movement commands. Verify that the real motor movement deploys a non-negligible distance

Results: Pass. The longitudinal axis stepper motor successfully rotated the lead screw and caused the connected link to rotate (or move when the connected link was constrained from rotating).



(a) Before lead screw rotation (b) After lead screw rotation

Figure 128: Demonstration of lead screw rotation causing linear movement

Next Steps: Structural integration of TROI may continue.

TROIT.5: Telescoping Camera Arm Integration Test

Objective: Verify that the telescoping camera arm successfully extends to the deployed state from the retained state after detecting landing

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.5	Telescoping camera arm accurately deploys after detecting landing	4.2.3.3.	Pass

Materials and Equipment Needed: Telescoping camera arm, lead screw cover, camera stepper motor, ESP32-CAM, 12 V battery

Test Setup:

1. Attach the camera stepper motor to the lead screw cover
2. Attach the telescoping camera arm to the camera stepper motor

3. Lubricate the telescoping camera arm retention piece with solid lubricant
4. Charge battery and integrate all electronics. Attach camera stepper motor to ESP32 board and driver. Power camera stepper motor and upload stepper motor retention code to lock stepper motor

Test Procedure:

1. Place the telescoping camera arm in its deployed configuration
2. Disconnect the payload from power
3. Configure the telescoping camera arm to its retained position. Verify that the solid lubricant is present
4. Connect payload to power and verify that the motor provides back torque to resist motion when under power
5. Shake the system
6. Send command to deploy telescoping camera arm

Analysis Procedure:

1. Verify that the stepper motor provides back torque to resist motion when under power after step 1 of test procedure
2. Verify that the telescoping camera arm deploys and reaches its deployed state after step 6 of the test procedure
3. Verify that the telescoping camera arm can rotate 360° at the conclusion of the test

Results: Pass. The telescoping camera arm successfully deployed after landing was simulated. The camera remained attached to the telescoping camera arm. Figure 129 displays the result.

Figure 129: Fully extended telescoping camera arm

Next Steps:

TROIT.6: Longitudinal Deployment Test

Objective: Verify the lead screw stepper motor deploys the system to the desired distance

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.6	Telescoping camera arm accurately deploys and passes a shake test	N/A	Pass

Materials and Equipment Needed: Fully assembled mechanical payload, lead screw stepper motor, lead screw stepper motor deployment code, 12 V battery, ESP32, measuring device

Test Setup:

1. Attach the lead screw stepper motor to the lead screw cover
2. Charge battery and integrate all electronics. Attach lead screw stepper motor to ESP32 board and driver

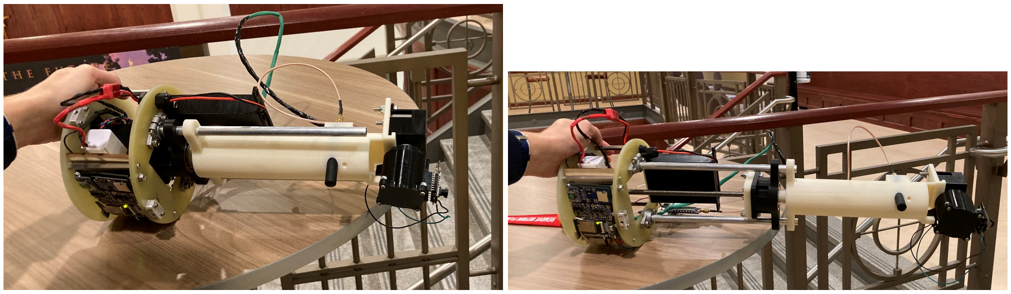
Test Procedure:

1. Turn on the system by connecting the battery
2. Run lead screw stepper motor code

Analysis Procedure:

1. Observe lead screw stepper motor actions after sending movement commands
2. Measure deployment of TROI after movement is completed and compare it to the commanded length

Results: Pass. The longitudinal axis stepper motor successfully rotated the lead screw and caused the connected link to move the expected deployed distance. Figure shows TROI before and after longitudinal deployment.



(a) Before longitudinal deployment (b) After longitudinal deployment

Figure 130: Demonstration of full system longitudinal deployment

Next Steps: Integration of TROI may continue.

TROIT.7: RF Receiving Test

Objective: Verify the TROI RF subsystem is capable of receiving radio communications sent by HAMM operator in the NASA format

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.7	Sample, non-noise radio communication sent by HAMM operator is received by payload	4.2.2., 4.2.2.1., 4.2.3., 4.2.3.1., 4.2.3.2	Pass

Materials and Equipment Needed: DRA818V, AUX Cable, Microphone Breadboard Connector, USB-C Audio Connector, Baofeng Radio, Easy Digi VOX, LiPo 3.7 V Battery, Audacity, 1200 Baud AFSK wav file

Test Setup:

1. Connect the TROI RF subsystem to Computer 1, which records on Audacity
2. Connect Computer 2 to a Baofeng Radio via the Easy Digi connector
3. Verify the LiPo 3.7V battery is fully charged
4. Initialize the DRA818V with the following Serial commands via the TX and RX pins of an Arduino: AT+DMOSETGROUP=1,144.5000,144.5000,0000,0,0000 and AT+DMOSETVOLUME=4

Test Procedure:

1. Use Computer 2 to transmit a 1200 Baud AFSK wav file by pressing the push to talk (PTT) button while the wav file is playing on the computer

2. Use Computer 1 to record the received audio on Audacity to verify the reception of the DRA818V
3. Export the recorded audio to a wav file to be compared with the original wav file. Demodulate the recorded audio afterwards

Analysis Procedure:

1. The test passes if the receiving computer successfully records non-noise audio on Audacity from a distance greater than or equal to 2,500 ft (maximum drift radius in NASA Req. 3.10.).

Results: Pass. The receiving computer successfully recorded non-noise audio on Audacity at a distance of 0.5 mi (2,640 ft) away from the sending computer.

Next Steps: The RF subsystem will be tested to see if it is capable of processing RF transmissions and translating them into readable commands for the camera subsystem. If the RF command processing test passes, the subsystem can be further integrated with TROI for camera RF integration testing to verify the RF subsystem is capable of processing and sending commands to the camera per RAFCO.

TROIT.8: RF Command Processing Test

Objective: Verify the TROI RF subsystem converts radio communications to information readable by the TROI camera subsystem

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.8	RF subsystem correctly and accurately converts information for the camera system	4.2.2., 4.2.2.1.	Pass

Materials and Equipment Needed: DRA818V, AUX Cable, Microphone Breadboard Connector, USB-C Audio Connector, Baofeng Radio, Easy Digi VOX, LiPo 3.7 V Battery, Audacity, TNC

Test Setup:

1. Create an APRS packet with proper call sign and payload commands
2. Connect Baofeng radio to audio port on computer
3. Connect serial part of Arduino Nano to computer using putty
4. Power both the radio receiver and Arduino
5. Set volume on computer to maximum level

Test Procedure:

1. Move the radio and computer 0.5 mi from the TNC to mimic the maximum drift radius
2. Play the APRS packet and press push to talk on the radio at the same time

Analysis Procedure:

1. Verify the TX LED on the Arduino is flashing, which signals demodulation

Results: Pass. The system correctly demodulated RAFCO into a form processable by the camera subsystem.

Next Steps: Although RAFCO was demodulated successfully, most other components of the APRS packet were broken up due to the team using TNC 1 rather than TNC 2, which is the more modern packet format. This does not impact payload performance with respect to NASA's mission, but the team is working to rectify this.

TROIT.9: Camera Stepper Motor Test

Objective: Confirm that the axis stepper motor can work in tandem with commands sent by the ESP32

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.9	Camera axis stepper motor responds to commands via ESP32	N/A	Pass

Materials and Equipment Needed: Fully assembled payload, ESP32, NEMA stepper motor, camera stepper motor deployment code, 12 V battery

Test Setup:

1. Attach the camera stepper motor to the lead screw cover
2. Charge battery and integrate all electronics
3. Attach camera stepper motor to ESP32 board and driver

Test Procedure:

1. Turn on the system by connecting the battery
2. Run camera stepper motor code

Analysis Procedure:

1. Observe camera stepper motor actions after sending movement commands. Verify real motor movement matches expected motor movement

Results: Pass. The camera axis stepper motor responds and actuates according to in-house stepper motor code.

Next Steps: If the test passes, TROI code can be further developed and physical integration may continue.

TROIT.10: Camera System Rotation Test

Objective: Verify camera system is able to rotate 360º about the NASA-defined z-axis (NASA Req. 4.2.1.1.)

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.10	Camera system is capable of rotating 360 degrees around the defined z-axis	4.2.1., 4.2.1.1.	Pass

Materials and Equipment Needed: ESP32-CAM, ESP32 Main, battery, telescoping camera arm, camera axis stepper motor, camera

Test Setup:

1. Charge battery and position telescoping camera arm to fully deployed state
2. Connect electronics

Test Procedure:

1. Activate camera axis stepper motor and electronics
2. Allow camera assembly to rotate 360° both clockwise and counterclockwise. Document its performance

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 direction

Results: Pass. The camera is capable of rotating 360 ° according to in-house code commands.

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.11: Camera System Deployment Conditions 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.11	Camera system deploys after the launch vehicle lands at various angles	TROI.1, TROI.4, TROI.6	Omitted

Materials and Equipment Needed: See the Payload Equipment section in the Launch Operating Procedures
Test Setup:

1. Remove the nose cone and integrate the TROI into the payload body tube
2. Charge battery
3. 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 -15°, +15°, +30°, and +45° 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 in. above the payload body tube

Results: Omitted. The payload design is such that body tube landing angles will not influence deployment of the camera system.

Next Steps: N/A

TROIT.12: 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.12	Camera system captures and stores images of nominal quality	4.2.1.3., 4.2.1.4., TROI.3	Pass

Materials and Equipment Needed: TROI's camera, control camera, camera stand, and a secondary device (computer)
Test Setup:

1. Place TROI's camera so that it faces a landscape, optimally with variations and many colors

2. Set up a second camera (control camera), in close proximity to TROI's camera, that captures clear images and has time stamps

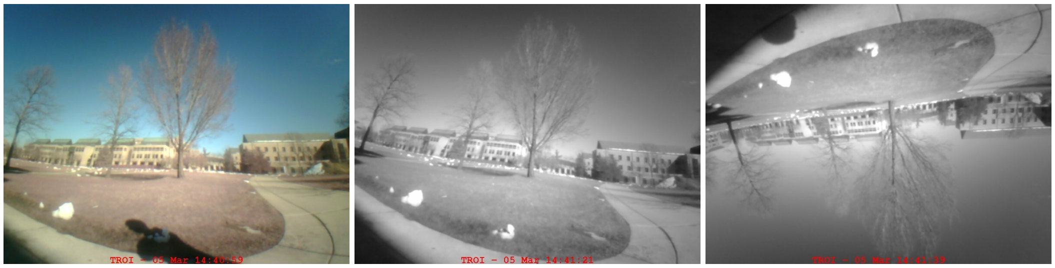
Test Procedure:

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
3. Compare images for differences in color and discoloration
4. Compare images for differences in quality (blurriness, completeness of image, exposure)
5. Compare timestamps
6. Record in a spreadsheet whether or not TROI's images are satisfactory or unsatisfactory in comparison to the control images
7. Compare consecutive timestamps on TROI's images to ensure they reach the time requirement and mark whether their time differences are satisfactory or unsatisfactory

Results: Pass. The camera successfully captured images within 30 seconds of each other. The images are of acceptable quality and apply special effects. Figure displays sample images.



(a) C3: Normal image (b) D4: Grayscale effect (c) F6: Flipped effect

Figure 131: Time-stamped camera image examples

Next Steps: The camera image quality is acceptable, but can continue to be improved.

TROIT.13: 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.13	TROI RF subsystem receives RAFCO and accurately transmits commands to the camera subsystem	4.2.2., 4.2.2.1., 4.2.3., 4.2.3.1., 4.2.3.2	Pass

Materials and Equipment Needed: ESP32-CAM, ESP32 Main, RF ground station, battery
Test Setup:

1. Charge battery and assemble TROI electronics
2. Connect the imaging code to the RF code such that the deployment subsystem is not used and the TROI remains rigid throughout the test
3. 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: Pass. The RF subsystem received and demodulated simulated RAFCO, then transmitted it to the camera system. The camera system accurately responded to the desired commands and captured acceptable images with special effects applied when necessary.

Next Steps:

TROIT.14: 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.14	The accelerometer successfully identifies state as in motion or stationary for a prototype test.	4.2.3.3.	Pass

Materials and Equipment Needed: Accelerometer, IMU, ESP32 Main, battery
Test Setup:

1. Fix all materials to a singular, transportable object
2. Charge battery and ensure ESP32 microcontroller has the correct code to record accelerometer values

Test Procedure:

1. Activate accelerometer and ESP32 Main electronics
2. Start the code and timing device simultaneously
3. Hold the payload still for five seconds
4. Shake the payload slowly for five seconds
5. Shake the payload quickly for five seconds
6. Reduce speed and force of shaking for five seconds
7. Hold the payload still for five seconds

Analysis Procedure:

1. Read data off of SD card
2. Evaluate time stamps and output of launch/landing status to see if code time stamps align with real-time actions

Results: Pass. The time-stamped sensor output aligned with real-time movement of the payload system. The sensors accurately determined and reported the known launch state.

Next Steps: If success criteria is met, relevant code can be scaled up for the full scale launches.

TROIT.15: Payload Preliminary Integration Test

Objective: Verify that the fully integrated TROI operates as expected during and after launch

Test ID	Success Criteria	Requirements Satisfied	Result
TROIT.15	Subsystems integrate nominally and correctly follow deployment/post-deployment operating sequences	N/A	Incomplete

Materials and Equipment Needed: Fully assembled mechanical payload, accelerometer, IMU, ESP32 Main, 12 V battery, fully integrated payload code

Test Setup:

1. Mount electronics to TROI tiered bulkheads
2. Charge battery and ensure ESP32 microcontroller has the correct code to record accelerometer and IMU readings
3. Integrate TROI with launch vehicle

Test Procedure:

1. Start the code
2. Launch the launch vehicle following standard launch procedures
3. Launch vehicle lands
4. Record time of launch vehicle landing
5. Recover TROI
6. Read data off of SD card

Analysis Procedure:

1. Analyze the time stamps on the payload SD card readings
2. Ensure that the landing stage as denoted by the SD card readings matches with the recorded time by the team

Results: Incomplete. As of FRR submission, the payload has not been flown in its final configuration. This test will be conducted using data from the Payload Demonstration Flight. The analysis will be included in the FRR Addendum that the team will submit.

Next Steps: Test passes if sensor output for indication of landing matches visual verification of landing. If the sensors do not register landing at the real landing time, review code for errors.

10.1.4 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 degrees	ACS.1	Pass

Materials and Equipment Needed: Fully assembled ACS, motor command capabilities, protractor
Test Setup:

1. Connect ACS servo motor to servo controller board
2. Connect servo controller board to PCB with Raspberry Pi 4
3. Connect 3.7 V LiPo battery to the Raspberry Pi
4. Connect 7.4 V LiPo battery to the 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: Pass. This test was passed as different servo angles ranging from 16° to 60° were used and resulted in accurate motor movements. The range from 16° to 60° corresponds to a flap angle range from 0° to 45° as intended. However, the relationship between motor angle and flap angle is non-linear due to the nature of the mechanism itself. As per initial observations, the relationship between the two angles appears to be sinusoidal. This will have to be accounted for when developing the proportional control algorithm.

(a) Drag flap retention (b) Drag flap extension

Figure 132: Drag flap actuation stages

Next Steps: The Proportional Control Algorithm Test (ACST.12) and On-Ground Software Loop Test (ACST.13) should be performed to prove that the motor is capable of actuating at the correct time in flight and in accordance with a proportional control law.

ACST.2: Drag Flap Dynamic Loading 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	Pass

Materials and Equipment Needed: Fully assembled ACS, PCB, motor connected to servo controller board, weights, adhesive, laptop, protractor

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 (0 to 30 degrees)
2. After actuation cycle is complete, remove weights from drag flaps

Analysis Procedure:

1. Verify there are no signs of fracture or mechanical failure on the drag flaps and flap lever arms
2. Verify the flaps maintain their commanded angle

Results: Pass. When a force greater than 25 lb was applied on each flap, the servo motor was still able to actuate the flaps successfully and overcome the applied force. No signs of fatigue or failure were observed.

Next Steps: N/A

ACST.3: Data Acquisition Test

Objective: Verify the ACS software is capable of logging and sampling data quickly and accurately

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.3	ACS software can collect data at sample rates of at least 10 Hz	ACST.3, ACST.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: Development of ACS software may continue.

ACST.4: State Transition Manager Test

Objective: Verify the ACS sensor suite is capable of identifying the launch vehicle state

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.4	The system transitions to the correct state based on the set parameters for launch and apogee acceleration and altitude. No exceptions are raised in any of the tested states	ACS.5	Pass

Materials and Equipment Needed: Raspberry Pi, 3.7 V battery, power boost (to get to 5 V), laptop, multimeter
Test Setup:

1. Connect all electronics
2. Use the multimeter to verify the battery voltage reads within 3.2 V - 4.2 V

Test Procedure:

1. Set the legacy data flag to True in the code
2. Run the code with subscale apogee target, acceleration and altitude threshold values

Analysis Procedure:

1. Look at the output data file and check if all states have been triggered correctly according to the coded threshold values for acceleration, altitude, and velocity

Results: This test used data from the 12/04/2022 subscale flight as simulated input to the state transition manager function. The function correctly used accelerometer z-axis data to calculate vertical acceleration and altimeter altitude to identify LAUNCHED/BURNOUT/OVERSHOOT/APOGEE states.

Next Steps: Perform the On-Ground Software Loop test (ACST.13) to check for commanded servo actuation according to a proportional control law.

ACST.5: PCB Electrical Design and Rules Check

Objective: Verify that the PCB design is electrically consistent and complies with manufacturer design requirements

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.5	Fusion determines the board and schematic are electrically consistent	N/A	Pass

Materials and Equipment Needed: Laptop with Fusion360 capabilities, PCB .sch and .brd files
Test Setup:

1. Verify the electrical schematic and PCB layout are fully completed

Test Procedure:

1. Select the ERC button under the "Validate" section of the the .sch file
2. Select the DRC button under the "Rules DRC/ERC" section of the .brd file

Analysis Procedure:

1. Verify that the ERC output includes "board and schematic are consistent"
2. Verify that the DRC output is "DRC: No errors"

Results: Pass. Fusion determined that the board and schematic were consistent, and no errors were raised.

Next Steps: Once physical PCB is obtained, conduct the PCB Electrical Continuity Test.

ACST.6: PCB Electrical Continuity Test

Objective: Verify the manufactured PCB is functional

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.6	The system passes the continuity test with each trace on the PCB connecting the correct pair of pins on both components	N/A	Pass

Materials and Equipment Needed: PCB, multimeter

Test Setup:

1. Place the PCB on a table
2. Set the multimeter to continuity mode

Test Procedure:

1. Touch all pairs of PCB pads with the multimeter leads

Analysis Procedure:

1. Listen for a beep for each PCB pad pair. If beeps are heard, the test passes

Results: Pass. A beep was heard for each PCB pad pair.

Next Steps: Proceed to construction of electrical wiring systems on the PCB.

ACST.7: Solder Joint Reliability Test

Objective: Verify solder joints do not break and are reliable

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.7	Solder joints remain intact and none of the wires come loose. No cold solder joints or poor solder joints are found during visual inspection	N/A	Pass

Materials and Equipment Needed: Fully assembled PCB with all sensors, microprocessor, power boost, servo controller board, and buzzer attached

Test Setup:

1. Solder all components to the PCB

Test Procedure:

1. Inspect all solder joints for signs of wear or poor soldering
2. Pull each individual solder joint with moderate force

Analysis Procedure:

1. Inspect solder joints for signs of wear or disconnect

Results: Pass. All solder joints were deemed reliable and showed no signs of disconnect.

Next Steps: N/A

ACST.9: Standalone Servo Motor Test

Objective: Verify the servo motor can actuate along its full range (0 to 180 deg)

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.9	The servo motor actuates from 0 to 180 degrees within 1 second at no load and is precise to within 3 degrees of the commanded servo angle	N/A	Pass

Materials and Equipment Needed: Servo motor, PWM servo controller board, Raspberry pi, laptop, 3.7V battery, 7.4V battery, breadboard, protractor, timing device

Test Setup:

1. Connect servo motor, PWM servo controller, and both batteries to the breadboard
2. Connect the Raspberry Pi to the laptop wirelessly

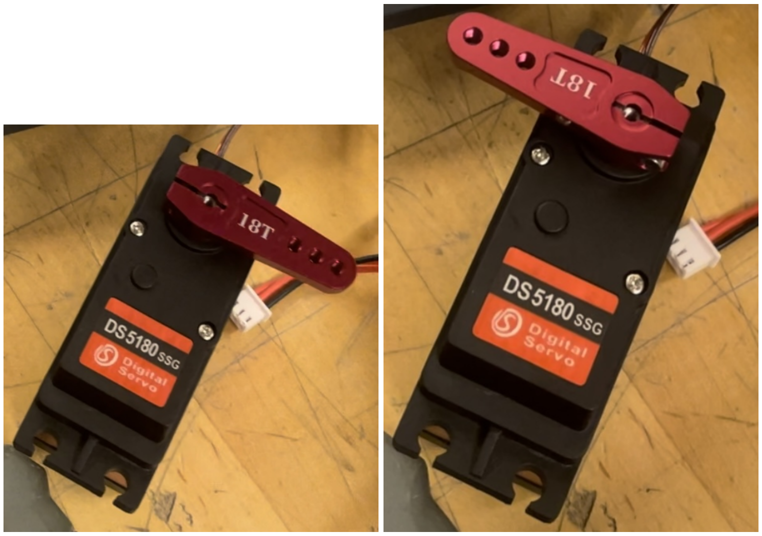
Test Procedure:

1. Run sample code that commands the servo motor to actuate from 0 to 180 degrees, making sure to record the time needed to actuate from 0 to 180 degrees

Analysis Procedure:

1. Use protractor to verify that the real actuation angle is within three degrees of the commanded actuation angle
2. Inspect the time taken to actuate along the full range of motion. The test passes if this value is under one second

Results: Pass. The servo motor accurately actuated according to the Raspberry Pi's commands, relayed through the PWM servo controller board.



(a) Servo motor minimum actuation (b) Servo motor maximum actuation

Figure 133: Demonstration of servo motor actuation across full range

Next Steps: Perform the Flap Mechanism Actuation Test (ACST.1) after ACS is fully assembled.

ACST.10: Data Filter Test

Objective: Verify the Kalman filter smooths data and reduces noise sufficiently. Verify the velocity output aligns with OpenRocket and MATLAB predictions

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.10	Filtered data is smooth but remains accurate. Only erroneous spikes are diminished while true data is not significantly affected	N/A	Pass

Materials and Equipment Needed: Raspberry Pi, laptop, 3.7V battery

Test Setup:

1. Connect Raspberry Pi to power source and laptop

Test Procedure:

1. Run the ACS code with sample data

Analysis Procedure:

1. Input both raw data and Kalman filter data to MATLAB in matrix form with time
2. Compare the graphs, looking for smoothness, noise reduction, and accuracy
3. Verify large spikes do not imapct filtered data significantly
4. Verify velocity output is similar to OpenRocket and MATLAB predictions

Results: Pass. The Kalman filter successfully reduced noise and maintained accuracy of the input data. The velocity output was similar to OpenRocket and MATLAB predictions

Next Steps: N/A

ACST.11: Apogee Prediction Algorithm Test

Objective: Verify the apogee prediction algorithm output is consistent with the real apogee

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.11	The predicted apogee is comparable to the real apogee	N/A	Incomplete

Materials and Equipment Needed: Fullscale launch vehicle, fully integrated ACS
Test Setup:

1. Follow the Launch Operating Procedures for the Vehicle Demonstration Flight

Test Procedure:

1. Follow the Launch Operating Procedures for the Vehicle Demonstration Flight

Analysis Procedure:

1. Verify that the predicted apogees decrease when the flaps are extended

Results: Incomplete. Test will be conducted as soon as possible.

Next Steps:

ACST.12: Proportional Control Algorithm Test

Objective: Verify that the commanded servo angle is proportional to the difference between the predicted and target apogees

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.12	The proportional control algorithm functions nominally with respect to measured apogee values	N/A	Incomplete

Materials and Equipment Needed: Fullscale launch vehicle, fully assembled ACS
Test Setup:

1. Follow the Launch Operating Procedures for the Payload Demonstration Flight

Test Procedure:

1. Follow the Launch Operating Procedures for the Payload Demonstration Flight

Analysis Procedure:

1. Check the data to compare the predicted apogee and servo motor angles are proportional to each other
2. Review the video footage of flight to verify drag flaps actuated during flight

Results: Incomplete. Test will be conducted after data for the next Vehicle Demonstration Flight attempt is processed.

Next Steps:

ACST.13: On-Ground Software Loop Test

Objective: Verify all ACS software and electrical components function nominally

Test ID	Success Criteria	Requirements Satisfied	Result
ACST.13	No errors or exceptions are raised during the duration of the test	N/A	Incomplete

Materials and Equipment Needed: Fully assembled ACS, laptop
Test Setup:

1. Place assembled ACS in stable position

Test Procedure:

1. Run ACS code with legacy data
2. Run ACS code with real-time data

Analysis Procedure:

1. For both legacy and real data, examine the outputs to verify no errors were raised and visually verify the mechanism actuated nominally

Results: Incomplete. Test will be conducted as soon as possible.

Next Steps: N/A

10.2 Requirements Compliance

10.2.1 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 ...	Complete	I	The team has engaged 1121 participants in Educational Direct Engagement STEM activities across 21 events as of FRR submission. See the STEM Engagement Activity Report.	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

10.2.2 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 …	Complete	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. The measured apogee for the 2/18 demonstration flight range from 4757.9 to 4997.2 ft.	5.1.1, 8.5.1.2
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.	Complete	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.	No components of the launch vehicle sustained significant damage after the 2/18 flight.	LVT.1, 8.6
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.	Complete	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.	The vehicle was fully prepared for flight within 2 hours of the flight waiver opening on the 2/18 demonstration flight.	N/A.
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 . . .	Complete	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 launch vehicle and payload remained charged and in launch-ready configuration for over two hours at the 2/18 demonstration flight.	LVT.3
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.	8.6
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.	8.6
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 . . .	Complete	I	Inspection will verify that the RSO is the only personnel approving any and all motor changes.	The motor was not changed after CDR.	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.	Complete	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. The Demonstration Flight section of FRR describes the flight on 2/18, which used a different launch vehicle from the subscale vehicle.	3.5.3, 8

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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, LVT.2
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.	In Progress	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. The team flew a Vehicle Demonstrat Flight attempt on 2/18, and will fly again on 3/10.	N/A
2.19.1.	Vehicle Demonstration Flight—All teams will successfully launch and recover their full-scale rocket prior to FRR in its . . .	In Progress	D	The team will demonstrate and provide the relevant proof of a successful full-scale launch in FRR.	The team will conduct additional Vehicle Demonstration Flights to verify currently unmet requirements.	N/A
2.19.1.1.	The vehicle and recovery system will have functioned as designed.	In Progress	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.	The vehicle functioned as designed, but the recovery system was unable to function as designed due to Rocketman failing to ship the team's desired shock cords in a timely fashion prior to launch.	8
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 . . .	Complete	I	Inspection will verify that all full-scale Vehicle Demonstration Flight requirements are met.	The payload was flown during the 2/18 demonstration flight and will be on upcoming Vehicle Demonstration Flights.	N/A
2.19.1.3.1.	If the payload is not flown, mass simulators will be used to simulate the payload mass.	Complete	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.	The payload was flown during the 2/18 demonstration flight and will be on upcoming Vehicle Demonstration Flights.	N/A

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
2.19.1.3.2.	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.	Complete	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.	The payload was flown during the 2/18 demonstration flight and will be on upcoming Vehicle Demonstration Flights.	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 . . .	Complete	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.	ACS was active during the 2/18 demonstration flight and will be active for subsequent flights.	LVT.1
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 . . .	Complete	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.	The team flew the designated motor on the 2/18 launch and will fly it on subsequent flights.	8.1
2.19.1.6.	The vehicle shall be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted . . .	Complete	D	Inspection of FRR will verify the team used a specified ballasted weight during the full-scale demonstration flight.	The vehicle was flown in its fully ballasted configuration on the 2/18 demonstration flight and will continue to be flown as such.	8.1
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).	In Progress	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.	The team has not completed a successful full-scale demonstration flight as of submission, but will not modify components after completing one.	N/A
2.19.1.8.	Proof of a successful flight shall be supplied in the FRR report.	In Progress	I	Inspection of FRR will verify that the team provided proof of a successful flight.	The team has included information on the 2/18 demonstration flight in this submission and will include proof of a successful flight in the FRR Addendum.	8
2.19.1.8.1.	Altimeter flight profile data output with accompanying altitude and . . .	In Progress	I	Inspection of FRR will verify the team supplied the required flight data from altimeters.	The team has included information on the 2/18 demonstration flight in this submission and will include proof of a successful flight in the FRR Addendum	8
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 . . .	In Progress	I	Inspection of FRR will verify the team included quality pictures in the report.	The team has included information on the 2/18 demonstration flight in this submission and will include proof of a successful flight in the FRR Addendum	8
2.19.1.9.	Vehicle Demonstration flights shall be completed by the FRR submission deadline. No exceptions will be made . . .	In Progress	I, D	Inspection of FRR will verify that the team completed it before the deadline.	The team will submit information for a successful Vehicle Demonstration Flight in FRR Addendum.	LVT.1
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 . . .	In Progress	I	Inspection of FRR will verify that the team launched a successful full-scale demonstration flight. Inspection of the launch vehicle at FRR will verify that it is the same vehicle flown in the full-scale demonstration flight.	The 2/18 flight attempt included the payload, which was not flown in its final configuration. Subsequent flights will verify unmet Payload Flight Demonstration requirements.	8

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	In Progress	D	The full-scale demonstration flight will demonstrate the payload device is fully retained for the entirety 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.	The payload flown in the 2/18 demonstration flight was retained until the intended point of deployment. Additional requirements will be verified by subsequent Payload Demonstration Flights.	LVT.1, TROIT.1
2.19.2.2.	The payload flown shall be the final, active version.	In Progress	I	Inspection of the payload will verify that the payload is not modified during flight.	The final, active payload is nearing completion and will be flown in subsequent Payload Demonstration Flights.	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.	Complete	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.	The payload was not flown in its final, active form on the 2/18 launch. FRR Addendum will be completed by the required deadline.	N/A
2.19.2.4.	Payload Demonstration Flights shall be completed by the FRR Addendum deadline. NO EXTENSIONS WILL BE GRANTED.	In Progress	I	Inspection will verify that the team is aware of the additional responsibilities and actions that come with submitting an FRR Addendum.	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 . . .	Complete	I	Inspection of FRR will verify if the team needs to complete an FRR Addendum.	FRR Addendum will be completed by the required deadline.	N/A
2.20.1.	Teams required to complete a Vehicle Demonstration Re-Flight and . . .	Complete	I	If necessary, inspection of the FRR Addendum will verify that it was completed by the deadline.	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 . . .	Complete	I	Inspection of FRR will verify if the team completed a successful full-scale demonstration flight.	The team understands the consequences of not completing a successful Payload Demonstration Flight.	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 . . .	Complete	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.	If the team does not complete a successful payload demonstration by submission of the FRR Addemdum, the team will petition for a launch to 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 . . .	Complete	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 was verified at the 2/18 launch.	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.	Complete	I	Inspection of the launch vehicle will verify that any and all lithium polymer batteries are sufficiently labeled and protected.	All lithium polymer batteries were sufficiently labeled and protected at team flight demonstrations.	N/A
2.23.	Vehicle Prohibitions	Complete	I	Inspection will verify that all Vehicle Prohibitions requirements are met.	Vehicle Prohibitions will be addressed during design of the launch vehicle. All requiremenmts will be verified using appropriate methods.	N/A

Table 99: NASA Launch Vehicle Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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
2.23.6	The launch vehicle will not exceed Mach 1 at any point during flight.	Complete	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. The maximum recorded velocity on the 2/18 flight was 647.3 fps.	5.1.2, 8.5.1.3LVT.1
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).	Complete	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. The 2/18 demonstration flight used 0 oz of ballast.	3.4.2, 8.1
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

10.2.3 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
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.	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.	Complete	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. The vibration test and 2/18 fullscale flight verified no components came into physical contact due to strength of connections.	4.5.1, 4.5.2, 6.4, LVT.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.	Complete	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 demonstrated fiberglass components display acceptable load-bearing abilities.	3.3.5, 5.3, LVT.5

Table 100: NDRT Launch Vehicle Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	I,D	Reusability will be verified by demonstrating launch vehicle flight and recovery does not significantly damage launch vehicle components.	No launch vehicle internal or external components exhibited signs of damage after the 2/18 fullscale flight.	LVT.1, 8.6

10.2.4 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 . . .	Complete	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.	During the 2/18 demonstration flight, FED will triggered the apogee deployment event of the drogue parachute, and the PED initiated the main parachute deployment event at an altitude of 584 feet.	4.2, 8.3RT.1
3.1.1.	The main parachute shall be deployed no lower than 500 feet.	Complete	D	The deployment of the main parachute above 500 feet will be verified at the full-scale demonstration flight.	The PED initiated the main parachute deployment process at an altitude of 584 feet during the 2/18 demonstration flight	4.2, 8.3, RT.1
3.1.2.	The apogee event may contain a delay of no more than 2 seconds.	Complete	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. The apogee event contained a delay of 0.52 seconds for the 2/18 demonstration flight.	4.3.1, 8.5.1.4, RT.1
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.	Complete	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 was supervised by team mentor Dave Brunsting, who deemed forces of separation appropriate.	RT.3
3.3.	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing. Teams whose heaviest . . .	Complete	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.	The maximum predicted kinetic energy for any section was 65 ft-lbf. The maximum kinetic energy for any independent section was the fin can at 71.97 ft-lbf for the 2/18 demonstration flight.	5.2.1, 8.5.2.1RT.1
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).	Complete	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, RT.1
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, …	Complete	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 descent time was 64.22 s for the 2/18 demonstration flight.	5.2.2, 8.5.1.2RT.1
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.	Complete	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. The GPS correctly transmitted the launch vehicle location on the 2/18 fullscale flight.	4.6.2, RT.6
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.	Complete	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. The GPS Functionality Test verified GPS location reporting accuracy at sufficient distances.	RT.6, RT.1
3.13.	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	Complete	T	RF isolation testing will verify that recovery system electronic devices will not be adversely affected by additional on-flight devices.	Recovery system electronics' output data from the 2/18 demonstration flight were highly similar to simulation results, demonstrating they were not adversely affected. No electronics output illogical values when activated in proxmity to each other.	8, RT.4

Table 101: NASA Recovery Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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
3.13.3.	The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves . . .	Complete	T	Magnetic wave isolation tests will be conducted to verify that recovery system electronics are shielded from inadvertent excitation.	No electronics from any system output physically inaccurate data after all were activated in close proximity to each other.	RT.4
3.13.4.	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery . . .	Complete	T	Electronics interference tests will be conducted to verify that the recovery system electronics are shielded from remaining causes of inadvertent excitation.	No electronics from any system output physically inaccurate data after all were activated in close proximity to each other.	RT.4

10.2.5 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.	Complete	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. The recovery bulkheads exhibited no signs of failure at 971 lbf, the required loading for a 1.5 factor of safety.	4.5.1, 5.3, RT.5

10.2.6 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 team has submitted documentation for the second, non-scoring payload. A successful Payload Demonstration Flight will be flown before FRR Addendum.	6.1, TROIT.1
4.2.	Radio Frequency Command (RAFCO) Mission Requirements	In Progress	T	Testing will verify that payload subsystems integrate nominally and enable RAFCO requirements to be met.	The team will verify all RAFCO Mission Requirements through appropriate verification methods and plans.	6.1.1, TROIT.15
4.2.1.	Launch Vehicle shall contain an automated camera system capable of swiveling 360° to take images of the entire surrounding area of the launch vehicle.	Complete	D, T	Testing of the payload system will verify that the camera system is automated and capable of swiveling 360° to take images. This function will also be verified through the full-scale demonstration flight.	The telescoping camera arm is capable of rotating 360° around the NASA-defined z axis.	6.5.1, 6.5.2, TROIT.10
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 . . .	Complete	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 has defined the correct z axis.	6.6.1.4, TROIT.10
4.2.1.2.	The camera shall have a FOV of at least 100° and a maximum FOV of 180°	Complete	I	Inspection will verify that the camera lens has a FOV within the acceptable range.	A 140° 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 and associated in-house code were integrated into the ESP32-CAM camera subsystem to enable time stamps. Time stamps will be included in PLAR.	6.6.1, TROIT.12
4.2.1.4.	The camera system shall execute the string of transmitted commands quickly, with a maximum of 30 seconds between photos taken.	Complete	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 has negligible latency, as demonstrated in the Camera Baseline Imaging Test.	6.7.2, TROIT.12, TROIT.13
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, TROIT.7, TROIT.8, TROIT.13
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, TROIT.7, TROIT.8, TROIT.13

Table 103: NASA Payload Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
4.2.3.	The NASA Student Launch Management Panel shall transmit the RAFCO using APRS.	Complete	D, T	Radio transmission testing using HAM radio will verify that the RF subsystem operates successfully using APRS.	The RF receiving test using HAM radio and RF subsystem verified the RF subsystem is able to receive commands on the given frequency.	6.6.3, TROIT.7, TROIT.13
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 …	Complete	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. The RF receiving test verifies the RF subsystem is able to receive commands on the given frequency.	6.6.3, TROIT.7, TROIT.13
4.2.3.2.	The NASA Management Team shall transmit the RAFCO every 2 minutes.	Complete	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. The RF receiving test verifies the RF subsystem is able to receive commands on the given frequency.	6.6.3, TROIT.7, TROIT.13
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.	Complete	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 accelerometer correctly identifies landing state to prompt RF system activation.	6.6.1, 6.7.5, TROIT.14, TROIT.1
4.2.4.	The payload shall not be jettisoned.	Complete	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. The vehicle demonstration flight attempt on 2/18 verified the payload did not jettison at any time.	6.4, TROIT.1
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.	9
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

Table 103: NASA Payload Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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

10.2.7 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, TROIT.11
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.	Complete	T	The payload body tube will be placed in various landing angles to simulate camera system deployment.	The TROI deployment mechanism performance is not dependent on landing angle of the launch vehicle.	6.5.1, TROIT.11

Table 104: NDRT Payload Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	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. The Telescoping Camera Arm test verified this capability.	6.5, TROIT.5

10.2.8 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.	Complete	A, T	Testing will verify the ACS is capable of actuating flaps upon command. 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. ACS code succesfully commands actuation of the drag flaps across their entire range of motion.	7.2, 7.4, ACST.1
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.	Complete	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.	ACS carbon fiber bulkheads did not display any signs of failure through 971 lbf, which was the value for a 1.5 factor of safety.	7.2.7, 7.2.8, ACST.2
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 ensure timely data collection and drag flap adjustments in-flight.	7.4.1, 7.4.2, ACST.3

Table 105: NDRT Non-Scoring Payload (ACS) Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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.	Complete	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.	The ACS utilizes a microprocessor and control software to process and record data points collected by the sensor suite in a csv format.	7.5, ACST.3
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.	Complete	T	Legacy flight data will verify the ACS's functionality, including its ability to identify the current flight stage using appropriate flight parameters.	The ACS utilizes a sensor suite consisting of a 3-axis accelerometer, an IMU, and two altimeters to measure all relevant flight parameters. Legacy flight data from the 12/4 subscale flight was input to the state transition manager function, which correctly identified burnout, overshoot, and apogee states.	7.4, ACST.4
ACS.6	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

10.2.9 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.	9.1
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.	9
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.	9
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.	9
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.	9

Table 106: NASA Safety Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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 and ensure that all team members are certified to operate the machinery used during construction.	9
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.	9.2, 9.3, 9.4, 9.5
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.	9
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.	9.1
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.	9.1
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.	9.1
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.	9.2
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.	9
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.	9
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.	9

Table 106: NASA Safety Requirements (continued)

Req. ID	Description	Status	Verification Method	Verification Plan	Verification Description	Location
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.	9, 9.10
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.	9.7
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.	9

10.2.10 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 NASA Req. 2.6. This accounts for systems that function mid- or post-flight. The batteries must also function across all flight conditions.	Complete	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 passed. The 2/18 demonstration flight reaffirms battery duration.	INT.1
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.	Complete	I, T	The team is utilizing carbon fiber for many launch vehicle components due to its RF-shielding capabilities. The team will conduct an electronics shielding test to verify that shielding methods are functional.	No electronics from any system output physically inaccurate data after all were activated in close proximity to each other.	3.4.1, 4.5.1, INT.2
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

Table 107: NDRT Integration Requirements (continued)

Req. ID	Description	Justification	Status	Verification Method	Verification Plan	Verification Description	Location
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..	Complete	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 can verify that designs are compliant with the mass budget.	All systems and respective components 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.	Complete	T	TROI is protected from black powder charge detonation by a removable wall and Al ring. The effectiveness of these components will be tested during the Ground Ejection Test.	No signs of black powder debris were found near the TROI system after charge ejection.	6.8.1, INT.3
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.	Complete	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.	Inspection of adhesive joints after the 2/18 fullscale launch verified all bonds held through in-flight events.	3.5.1.5, LVT.1

10.3 Budgeting and Funding Summary

Table 108 breaks down team funding sources that are received or expected before the end of the NASA Student Launch competition cycle. After carry-over from the previous year, donations from corporate sponsors make up the largest portion of team funds. As reported in CDR, the Michiana Rocketry Association's annual donation of $200.00 is expected before travel to Huntsville. Plus, a prediction of $900.00 revenue from New Team Merchandise Sales expected in March is included and based off of merchandise sale success in years prior. Since CDR, contributions from alumni and United Technologies Corporation added a combined $10,200.00 to the team's total funds. It is important to note that the team's total funds will increase beyond that reported in Table 108 due to donations expected during Notre Dame's Day of Fundraising on April 25. Though these donations are expected, they are not included here due to their variability from year to year.

Table 109 gives an overview of the team's allocations by category and spending within each category. Due to inflation of material costs beyond predictions at PDR, the launch vehicle budget has exceeded its original allotment. However, the total for the launch vehicle and all subsystems is within the original budget. With full-scale vehicle procurements complete, only purchases related to competition travel are expected for the remainder of the academic year. Remaining funds are expected to be sufficient for the team's travel and completion of the competition. In the event that purchases exceed the allocated project budget, Table 108 demonstrates that the team has ample funds to serve as a large safety net for this year as well as future projects.

Tables 110 through 115 provide detailed line item budgets for each squad and category. Aside from ongoing supply chain struggles with Rocketman Parachutes as described in Section 8.3], all materials were sourced by and received from trustworthy vendors. Similar to CDR, items in the team's possession – delivered, picked up, or 3D printed – have a green status field; items 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	
United Technologies Corp. Donation	$10,000.00	
Blue Origin Donation	$2,000.00	
EE Senior Design	$500.00	
Old Team Merchandise Sales	$500.00	
Alumni Donation	$200.00	
Northrop Grumman Donation	$100.00	
New Team Merchandise Sales	$900.00	Predicted
Michiana Rocketry Donation	$200.00	Expected
Total	**$47,205.00**	

Table 109: NDRT 2022-23 Budget Summary

Category	Allocation	Actual & Budgeted Spending	Margin
Launch Vehicle	$4,200.00	$5,164.31	122.96%
Recovery System	$1,500.00	$1,349.50	89.97%
Apogee Control System	$1,200.00	$880.98	73.42%
360° Rotating Optical Imager	$1,700.00	$1,131.93	65.58%
Vehicle Subtotal	***$8,600.00***	***$8,526.72***	***99.15%***
Safety	$200.00	$47.01	23.51%
Educational Outreach	$200.00	$47.16	23.58%
Huntsville Travel	$11,000.00	$11,000.00	100.00%
Miscellaneous	$1,000.00	$936.57	93.66%
Total	**$21,000.00**	**$20,240.60**	**96.38%**
Total Available	$47,205.00	$47,205.00	
Remaining Funds	$26,205.00	$26,964.40	

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					$4,563.62	
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	Delivered
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
G10 FR4 3/16 Inch Sheet (6x48in)	Composite Warehouse	1	$68.00	$15.45	$83.45	Delivered
J-B Weld 8267 SteelStik Steel Reinforced Epoxy Putty Stick, 2 oz.	Amazon	1	$6.54	$7.99	$122.20	Delivered
West System 105A Epoxy Resin Bundle with Hardener		1	$86.60			
West System 406-2 Colloidal Silica, 1.7 oz.		1	$21.07			
TOTAL					**$5,164.31**	
Budget Allocation					**$4,200.00**	
Remaining					**-$964.31**	

Table 111: TROI Payload Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
Electronics					$478.80	
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
Lithium Polymer Battery Pack w/ PCB, 11.1V, 3000 mAh	Tenergy	1	$53.99	$14.26	$68.25	Delivered
Gravity: I2C Triple Axis Accelerometer	DFRobot	1	$4.90	$21.00	$25.90	Delivered
Variety Pack of Capacitors and Resistors	Digi-Key	1	$11.49	$8.52	$20.01	Delivered
Arduino Nano	Arduino	1	$24.90	$10.74	$35.64	Delivered
Custom PCB for Main Electronics Integration, 3 Pack	OSH Park	1	$62.50	$15.00	$77.50	Ordered
Assortment of LEDs, Capacitors, Resistors	Digi-Key	1	$28.96	$19.02	$47.98	Ordered
Adafruit DS3231 Precision RTC Breakout	Adafruit	1	$17.50	$13.15	$32.55	Delivered
CR1220 3V Lithium Coin Cell Battery (12mm Diameter)		2	$0.95			
Lesnow Solder Wick Braid, 10' Long	Amazon	1	$7.99	$6.47	$88.88	Delivered
4P Dupont Line Pins, Female-Female Cable Connector		1	$7.99			
Treedix OV2640 Camera Module, 140° Wide Angle CMOS 2MP		1	$9.99			
A4988 Stepstick Stepper Motor Driver Module, 10 Pack		1	$13.99			
Chanzon 2N700 TO-92 Sic Mosfet MOS Transistor, 100 Pcs		1	$7.99			
DSD TECH Serial Pass-through Module w/ Button for Arduino		1	$9.99			
DSD TECH Wireless Bluetooth Module for UNO R3 Nano		1	$8.49			
Onkuey T-Plug Connectors for RC LiPo Battery (10 pairs)		1	$5.99			
Bingfu Ham Radio Antenna, 2 Pack		1	$9.99			
Hardware					$653.13	
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, 1060 Al		2	$20.42			
Female 4-40 Threaded Hex Standoff		4	$4.59			
Stainless Steel 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
12" Clear Plastic Storage Box/Tool Box	Amazon	1	$21.99	$2.13	$32.61	Delivered
6063 Aluminum Tube (10mm OD x 8mm ID x 250 mm L), 2 Pcs		1	$8.49			
Steel Hex Drive Flat Head Screw, M8 x 1.25mm Thread x 18mm Long, 50 Pack	McMaster-Carr	1	$14.11	$32.56	$110.91	Delivered
18-8 Stainless Steel Screw, 10-32 Thread x 7/8" Long, 100 Pack		1	$20.81			
Compression Spring, 0.6" OD x 3.5" Long		1	$8.41			
TN R12-2RS Ball Bearing Sealed for 3/4" Shaft Diameter		1	$10.73			
TN R12 Ball Bearing Open for 3/4" Shaft Diameter		1	$8.53			
Alloy Steel Acme Lead Screw, 1/4"-16 Thread Size, 12" Long		1	$15.76			
				TOTAL	**$1,131.93**	
				Budget Allocation	**$1,700.00**	
				Remaining	**$568.07**	

Table 112: Recovery Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
Electronics					$69.44	
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				
WAGO 221 Lever-Nuts Wire Connector Assortment Pack, 75 Pcs	Amazon	1	$38.95	$4.55	$71.26	
1S 2-Pin Male-Female Battery Plug Wire, 10 Pack		1	$8.99			

22AWG Copper Wire w/ Silicone Insulation, 7m Long, 6 Pack		1	$16.95			Delivered
Hardware & Laundry					$1,280.06	
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				
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
SkyAngle CERT 3 XXL Parachute	Wildman Rocketry	1	$239.00	$17.54	$256.54	Delivered
Deployment Bag, 5.5" & 6" Diameter x 20" Long	Fruity Chutes Inc.	1	$62.68	$16.01	$78.69	Delivered
Fruity Chute Classic Elliptical Parachute, 24" Diameter	Madcow Rocketry	1	$64.00	$12.55	$76.55	Delivered
Molybdenum Disulfide Lubricant, 2 oz.	Amazon	1	$12.99	$9.87	$57.66	Delivered
Nylon Shear Pins, 4-40 Thread x 3/4" Long, 40 Pack		1	$7.98			
Non-Hardening Molding Clay, 5 lb		1	$16.56			
Valencia Pipe PVC Sch. 40 Pipe, 3/4" OD x 24" Long	Home Depot	1	$2.79	$7.96	$121.62	Delivered
Everbilt 3/8 in. Stainless Steel Quick Link		3	$13.47			
Everbilt 3/16 in. Stainless Steel Quick Link		7	$6.98			
Everbilt 3/8 in. Zinc-Plated Quick Link		4	$5.40			
Tubular Nylon Webbing (4400 lb), 1.25" thickness, 10' length	Rocketman Parachutes	1	$26.50	$0.00	$271.00	Delivered
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			
12" Square Nomex Blanket		1	$21.50			
Deployment Bag, 6" Diameter x 5' Long		1	$16.00			
Kevlar Shock Cord, 0.19" thickness, 5' length		1	$20.00			Ordered
Kevlar Shock Cord, 0.19" thickness, 25' length		1	$45.00			
3/4" Panel-Mount key Switch	McMaster-Carr	6	$25.59	$26.30	$421.30	Delivered
Key for 3/4" 2 Panel-Mount Key Switch		2	$6.01			
Carbon Steel Connecting Rod, 10-32 Thread x 4" Long		1	$16.66			
Steel Socket Head Screw, 10-32 Thread x 9/16" Long		1	$10.84			
18-8 Stainless Steel Hex-Drive Screw, 10-32 Thread x 1/2" Long		1	$11.29			
Aluminum Connecting Rod, 10-32 Thread x 6" Long		2	$11.93			
Steel Nylon-Insert Locknut, 7/16"-14 Thread, 100 Pack		1	$17.50			
316 Stainless Steel Washer for 7/16" Screw, 25 Pack		1	$8.83			
Multipurpose 6061 Aluminum, 12" W x 12" L x 1/4" T		1	$35.61			
Steel Eyebolt with Shoulder, 1/4"-20 Thread x 1" Long		1	$3.37			
Steel Socket Head Screw, 8-32 Thread x 11/16" Long, 10 Pack		3	$39.99			
Aluminum Female Threaded Hex Standoff		9	$14.76			
Steel Socket Head Screw, 10-32 Thread x 9/16" Long, 50 Pack		1	$14.01			
Steel Button Head Hex Drive Screw, 8-32 Thread x 1-3/4" Long, 25 Pack		1	$9.02			
Steel Button Head Hex Drive Screw, 8-32 Thread x 5/8" Long, 50 Pack		1	$8.67			
Steel Heat-Set Inserts, 6-32 Thread x 0.286" Long, 10 Pack		1	$7.75			
Steel Socket Head Screw, 4-40 Thread x 5/8" Long, 100 Pack		1	$7.28			
				TOTAL	**$1,349.50**	
				Budget Allocation	**$1,500.00**	
				Remaining	**$150.50**	

Table 113: ACS Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
BNO055 IMU	Adafruit	1	$29.95	$20.34	$102.44	Delivered
ADXL343 Accelerometer		2	$5.95			
MPL3115A2 Altimeter		2	$9.95			
PWM Servo Driver		1	$14.95			
Piezo Buzzer		1	$1.50			
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	
PowerBoost 1000 Basic		1	$14.59			
Ovonic 7.4V LiPo Battery		1	$17.39			

ZOSKAY 80 kg Digital Servo Motor		1	$49.99			Delivered
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			
4816 Adafruit BMP390 Altimeter	Adafruit	2	$10.95	$12.22	$34.12	Delivered
Double Pull Pin Switch Kit	Lab Rat Rocketry	1	$14.95	$5.95	$20.90	Delivered
Custom PCB for Main Electronics Integration, 3 Pack	OSH Park	1	$90.15	$7.35	$97.50	Delivered
ANNIMOS 80KG 1/5 Scale Motor Servo	Amazon	2	$48.99	$6.23	$95.20	Delivered
Crazepony 7.4V 3000 mAh 2S LiPo Battery		1	$24.99			
3.7V 5000 mAh 115659 LiPo Battery Pack		1	$14.99			
Wear-Resistant Black Nylon Sheet, 12" W x 12" L x 3/4" T	McMaster-Carr	1	$90.33	$35.21	$349.62	Delivered
Multipurpose 6061 Aluminum, 4" W x 6" L x 1/2" L		1	$19.29			
Steel Shoulder Screw, 4-40 Thread x 3/4" Long		8	$3.33			
Brass Narrow Hex Nut, 4-40 Thread x 3/16" Wide, 100 Pack		1	$3.21			
Steel Socket Head Screw, 4-40 Thread x 1/2" Long, 100 Pack		1	$6.38			
Flanged Socket Head Screw, 10-32 Thread x 5/8" Long		10	$2.83			
Nylon Sheet, 12" W x 12" L x 1/4" T		1	$44.49			
Steel Threaded Rod, 1/4"-20 Thread x 12" Long		4	$2.31			
Steel Hex Nut, 1/4"-20 Thread, 50 Pack		1	$7.57			
HDPE Sheet, 12" W x 12" L x 1/8" T		1	$6.42			
Steel Hex Nut, 7/16"-14 Thread, 50 Pack		1	$11.19			
Steel Socket Head Screw, 6-32 Thread x 3/8" Long, 50 Pack		1	$3.84			
Steel Socket Head Screw, 5-40 Thread x 3/8" Long, 100 Pack		1	$7.38			
Steel Threaded Rod, 1/4"-20 Thread x 12" Long		2	$2.31			
Steel Shoulder Screw, 4-40 Thread x 3/4" Long		8	$3.33			
Steel Narrow Hex Nut, 4-40 Thread, 100 Pack		1	$3.86			
Ultra-Grip T-Handle Hex Key, 3/32" Size		1	$3.31			
				TOTAL	**$880.98**	
				Budget Allocation	**$1,200.00**	
				Remaining	**$319.02**	

Table 114: Safety, Educational Outreach, Miscellaneous Expenses

Item	Vendor	Qty	Cost/Unit	Fees	Total Cost	Status
Safety					$47.01	
N95 NIOSH Certified Respiratory Masks, 20 Pack	Amazon	1	$16.99	$3.08	$47.01	Delivered
Med PRIDE NitriPride Nitryl Gloves, 100 Pack		1	$9.99			
KN95 Face Masks, 50 Pack		1	$16.95			
Educational Outreach					$47.16	
Silver Metallic Paper Sheets, 60 Pack	Amazon	1	$17.09	$1.20	$18.29	Delivered
Silver Metallic Paper Sheets, 60 Pack	Amazon	1	$18.99	$1.33	$20.32	Delivered
Jumbo Smoothie Straws, 8.5" Long, 100 Pack	Amazon	1	$7.99	$0.56	$8.55	Delivered
Miscellaneous & Shared Resources					$936.57	
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
Team Bagel Breakfast (Vehicle Demonstration Flight Attempt)	Einstein's Bagels	1	$77.98	$5.46	$83.44	Delivered
Nose Cone Retrieval Service	Affordable Tree Care	1	$231.75	$0.00	$231.75	Delivered
4000 lb Nylon Tubular Webbing, 1" x 30' Long - EMERGENCY ONLY	Amazon	1	$21.95	$2.59	$39.53	Delivered
7000 lb Tubular Nylon Webbing, 1" x 6' Long - EMERGENCY ONLY		1	$14.99			
Launch Vehicle Paint Job	TBD	1	$300.00	$0.00	$300.00	Budgeted
				COMBINED TOTAL	**$1,030.74**	
				COMBINED Budget Allocation	**$1,400.00**	
				COMBINED Remaining	**$369.26**	

Table 115: Competition Travel Expenses

Item	Total Cost	Status	Description
Team Lodging	$3,291.84	Ordered	Team Airbnb (4 nights)
Van Rental	$1,450.00		5 rented vans @ $58.00/day (5 days)
Team Mentor Lodging	$600.00	Budgeted	Hotel for $150/night (4 nights)
Trip Gas	$1,200.00		5 vans, 23 MPG @ $3.50/gal (1500 mi)
Food Per Diem	$4,200.00		$30/person/day for 28 people (5 days)
Other Food & Misc.	$258.16		Remaining funds
TOTAL	**$11,000.00**		
Budget Allocation	**$11,000.00**		
Remaining	**$0.00**		

A MATLAB Hand Calculations

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 `InputMass.m` and `InputParachutes.m` functions are used by the `fullvehicledescentcalc.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.

InputMass.m

```
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
% Last updated 2/24/2023
%% Unit Conversions
oz2slug = 0.00194256; % Conversion

%% Weight Inputs
% Total Masses (no laundry or prop)
M(1) = 63.507; % Nosecone Mass (oz)
M(2) = 189.208; % Payload Tube Mass (oz)
M(3) = 158.582; % Recovery Tube Mass (oz)
M(4) = 195.320; % 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 = 106; % oz, includes everything for main on vdf
M_mainshock = 0;
% droguechute_only = 2.1;
% droguechute_harnessql = 28.9; % Harness, blanket, 2 QLs and Swivel
M_droguechute = 26.2;% oz, includes everything for drogue on vdf
M_drogueshock = 0;% oz
M_noseshock = 18.6; % oz, Wall and Cords
```

```
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
```

InputParachutes.m

```
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
% Last updated 2/24/2023

%% Tumbling Drag Calcs
include_tumb = 1; % Yes 1, No 0;
CdA_tumb = 1;
if include_tumb == 1
    d_vehicle = 6.16/12; %  Diameter of vehicle, ft
    l_vehicle = 130.5/12; % 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*0.57; % 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*0.0; % 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*0.9; % Adjustment for known performance
CdA_drogue = CdA_drog_chute + CdA_tumb;
end
```

fullvehicledescentcalc.m

```
%% 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_postvdf1();
[CdA_main, CdA_drogue, CdA_main_chute] = Input_Parachutes_postvdf1();

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 = 5270; % 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 - Overwritten with Used Settings
h_main_charge1 = 608; % ft
h_main_charge2 = 560; % ft
h_main_charge3 = 512; % ft
h_ned_charge3 = 0; % ft
```

```
h_ned_charge2 = 900; % ft
h_ned_charge1 = 733; % ft
%% Main Deployment Calcultions
if dep_bag == 1
    t_dep_bag = 2.5; % 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'])
```