University of Notre Dame
2020-2021

Notre Dame Rocketry Team
Critical Design Review

NASA Student Launch 2021

Planetary Landing System and Apogee Control System

Submitted January 4, 2021

365 Fitzpatrick Hall of Engineering
Notre Dame, IN 46556

Contents

1 Summary of CDR Report

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NAR/TRA Section:	NAR: 85879 L3/TRA: 12369 L3
Launch Location:	18946 Avery Rd, Three Oaks, MI 49128
Launch Dates:	February 13, 2021 & February 20, 2021
Total Hours Logged:	1426 hours

1.1 Launch Vehicle Summary

Table 1: Summary of launch vehicle parameters

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

Table 2: Summary of Recovery System

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

1.2 Payload Summary

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

2 Changes Made Since PDR

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

Table 3: Summary of changes made since PDR

Section	Change	Justification
Changes Made to Vehicle Criteria		
3.3.2	Overall weight	Refinement of designs and addition of ballast
3.4.3	Camera shroud added to the outside of the payload tube	To obtain footage of ACS drag tab deployment and recovery events
3.4.5	Fin height Changed from 5.959 in. to 6.200 in.	To increase stability
3.4.8	Payload tube bulkhead thickness changed from 0.125 in. to 0.187 in.	To ensure a factor of safety > 2.0
Changes Made to Recovery Subsystem		
3.8.5	Drogue parachute changed	Accounting for additional mass
3.8.6.1	Speed cuts and polycarbonate sheet removed	Unnecessary to meet system weight allotment
3.8.6.1, 3.8.6.2	Switch covers added	Prevent vortex formation in cavities
3.8.6.2	Exhaust blocking ring added	Further protection for CRAS-S avionics from ejection gasses and debris
3.8.7.1	PCB removed	Reduce system cost and simplify electrical connections
Changes Made to Payload Criteria		
6.7	New requirement set to reorient at a maximum slope of 30 degrees	Ensure PLS functionality on a wider variety of landing terrains

Table 3: Summary of changes made since PDR

Section	Change	Justification
4.4.3, 4.5	Gyroscope and spring loaded legs replaced by a threaded rod and servo system	Allows for active landing gear and orientation system
4.4.3, 4.5	Landing design changed from 4 cylindrical legs to 3 flat plate carbon fiber legs	Facilitates machining and integration of the legs into the system
4.3	Gyroscope bulkhead replaced with a fiberglass solid bulkhead which will serve as the platform for the cameras and data transmission electronics	Gyroscope unnecessary given change from passive to active orientation system
Changes Made to Project Plan		
6.8.2	PLS ballast design constructed concurrently with PLS active design	Ensures the team is able to meet the projected vehicle demonstration flight date of February 13th.
6.8.1	Budget Increase	Additional funds received from apparel sales

3 Design and Verification of Launch Vehicle

3.1 Mission Statement

The mission of the launch vehicle is to safely and reliably deliver the Planetary Landing System (PLS) to an altitude of 5,300 ft. above ground level (AGL), deploy recovery systems upon descent, jettison the PLS at an altitude between 1,000 ft. and 500 ft. AGL, and return safely to ground level such that it can perform a subsequent successful launch on the same day (NASA Req. 2.4). Furthermore, the launch vehicle will maintain stability throughout ascent, and land with all components structurally intact, within a radius of 2,500 ft. of the launch pad and with a kinetic energy no greater than 75 lb-ft (NASA Req. 3.10, NASA Req. 3.3).

3.2 Mission Success Criteria

A successful vehicle design must meet all requirements, as fully outlined in Section 6.2. These criteria are categorized into NASA requirements and team-derived functional, design, and environmental requirements deemed necessary for a successful mission. The critical vehicle design criteria for ensuring a safe and successful flight are the following, which are explained in further detail below:

1. The vehicle must maintain stability throughout flight (NASA Req. 2.14, NDRT Req. VD.7).
2. The vehicle must remain structurally intact throughout flight.
3. The vehicle must be designed to carry the PLS to the target apogee altitude of 5,300 ± 30 ft. in a range of wind speeds and launch rail angles (NASA Req. 2.1, NASA Req. 1.12, NDRT Req. VF.1).
4. All recovery separations must occur, and all parachutes must deploy fully upon descent (NASA Req. 3.1).
5. The PLS experimental payload must jettison from the launch vehicle at an altitude between 500 ft. and 1000 ft. AGL (NASA Req. 4.3.1).
6. All vehicle components must land within a radius of 2,500 ft. around the launch rail, at a kinetic energy at or below 75 ft-lbs., without harming or endangering spectators (NASA Req. 3.10, NASA Req. 3.3).

Stability is an essential component of a safe and successful flight. A suitable static stability margin range was deemed to be 2.0 - 3.0 calibers throughout flight, from launch rail exit to apogee. The lower bound of 2.0 calibers will ensure that the vehicle is able to correct its trajectory in the presence of perturbing forces and moments (NASA Req. 2.14), while the upper bound is set to prevent excessive weather cocking from altering the flight angle and significantly lowering the apogee altitude (NDRT Req. VD.7).

Another primary criterion for a safe and successful flight is the assurance that all structural components are able to withstand the expected loads induced during flight. In order to demonstrate that this requirement is satisfied, the primary launch vehicle components are each subject to stress analysis and impact testing, and must demonstrate a safety factor of at least 1.5 (NDRT Req. VF.3).

Given that the vehicle is required to launch in a range of rail cant angles from 5 - 10 degrees, and in winds from 0 - 20 mph, the final design will inevitably yield a sizable range of predicted apogee altitudes. To ensure that the target apogee altitude is met within a reasonable error margin of 30 ft., the launch vehicle will utilize an apogee control system (ACS). The launch vehicle is designed to overshoot the target apogee altitude in all but the worst-case launch scenario, so that the ACS may be relied on to intervene, controlling the projected apogee altitude and yielding a small margin of error.

The mission success criteria pertaining to each subsystem (Recovery, ACS, PLS) are outlined further at the beginning of their respective sections.

3.3 Launch Vehicle Design Overview

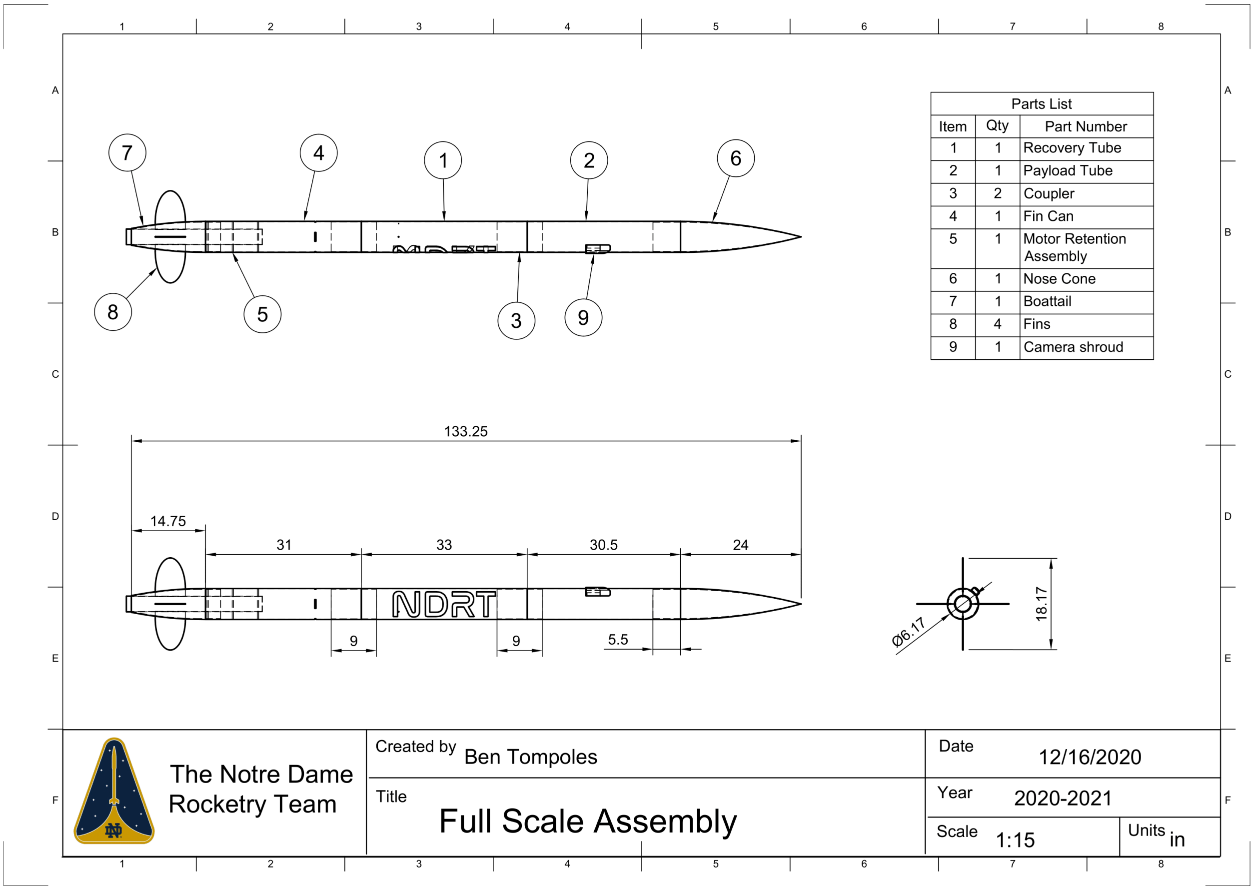
The mission success criteria outlined above constitute the primary design drivers of the launch vehicle, with the ultimate objective of optimizing performance criteria. Specifically, the vehicle was designed to provide the payload and mission systems with a low-drag, high-strength structure capable of safely and reliably carrying them to the target apogee altitude of 5,300 ft and returning back to ground level, in compliance with all NASA and NDRT team-derived requirements outlined in Section 6.2. The launch vehicle consists of four independent sections, with a single outer diameter of 6.17 in. spanning from the nose cone shoulder to the boattail shoulder. This design was chosen over alternatives to provide sufficient and isolated space for the payload, recovery, and ACS subsystems. The use of three separation points ensures that each deployment event (drogue parachute, main parachute, and PLS jettison) is associated with an independent separation point. This mitigates any added complications that may arise if multiple deployment events were to utilize a single separation point. Additionally, the use of a single-diameter design eliminates the unnecessary added drag, weight, and construction complexity associated with a variable-diameter design. A rendered CAD model of the launch vehicle is shown in Figure 1.

Figure 1: CAD model of the 2020-2021 launch vehicle design

Two design parameters have been fixed to prevent an excess of variability in the design process. Namely, the primary body tube size was set to an inner diameter of 6.0 in. to provide the subsystems with a known amount of design space (NDRT Req. VD.6). The specific choice of 6.0 in. was based on its widespread commercial availability and its historical success in previous competition seasons. Similarly, the motor was fixed to the Cesaroni L-1395 Blue Streak motor. The team owns three of these motors due to launch cancellations in the 2019-2020 season, and the motor has proven to be reliable in previous vehicle demonstration flights. Fixing these two decisions at the outset of the design process provided a starting point for many of the decisions analyzed in the sections that follow.

3.3.1 Vehicle Dimensions

A CAD drawing of the final launch vehicle design, complete with component labels and overall dimensions, is provided in Figure 2.



Parts List		
Item	Qty	Part Number
1	1	Recovery Tube
2	1	Payload Tube
3	2	Coupler
4	1	Fin Can
5	1	Motor Retention Assembly
6	1	Nose Cone
7	1	Boattail
8	4	Fins
9	1	Camera shroud

The Notre Dame Rocketry Team
Created by Ben Tompoles
Date 12/16/2020
Title Full Scale Assembly
Year 2020-2021
Scale 1:15
Units in

Figure 2: CAD drawing of the launch vehicle design with component labels and overall dimensions

The dimensions of the launch vehicle airframe were chosen to provide sufficient space for each of the integrated subsystems, while achieving a low-drag, low-weight, high-strength structure. The airframe shape was designed to provide a single diameter throughout the body tube sections for ease of subsystem design and integration, with a nose cone at the forward end and a boattail at the aft end designed to reduce drag in subsonic flight. A summary of airframe components and materials is provided in Table 4.

Table 4: Summary of launch vehicle component materials

Component	Material
Nose cone	G10 Fiberglass
Body tubes	Kevlar and Fiberglass-Filament
Boattail	G10 Fiberglass
Couplers	G12 Fiberglass
Motor mount tube	Phenolic
Centering rings	G10 Fiberglass
Payload bulkhead	G10 Fiberglass
Camera shroud	PLA

The three points of separation on the launch vehicle are at the nose cone and payload tube interface, the payload tube and recovery tube interface, and the recovery tube and fin can interface. Each of these separation points is associated with black powder charge energetics located within the recovery CRAS-M and CRAS-S subsystems. The locations of the separation points and energetics are shown in the OpenRocket diagram in Figure 3, and the numerical locations as measured from the nose cone tip are shown in Table 5.

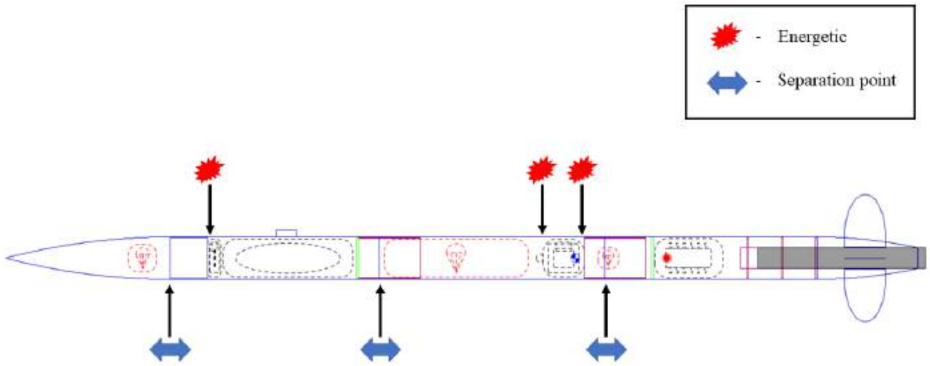


Figure 3: OpenRocket diagram showing locations of energetics and separation points

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

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

3.3.2 Mass Statement

Table 6 shows the basic and allowable masses of the entire launch vehicle and its subsystems, while Table 7 shows the component-level mass estimate of the empty airframe.

Table 6: Overall Mass Statement

Component/Subsystem	Basic Mass Estimate (oz.)	Allowable Mass (oz.)
Payload	67.6	80
ACS	70.5	80
Main Recovery System	154.8	160
Nose Recovery System	24.0	25
Motor	151.3	152
Airframe	303	303
Total	**771.2**	**800**

Table 7: Launch Vehicle Mass Statement

Component/Subsystem	Basic Mass Estimate (oz.)
Nose Cone	28.2
Payload Fairing	53
Payload Section Bulkhead	7.5
Payload Section Coupler	18.5
Camera Shroud	1.7
Recovery Tube	57.3
Recovery Tube Coupler	18.5
Fin Can Body Tube	53.9
Motor Mount	7.9
Centering Rings (x3)	17.0
Fins (x4)	17.4
Boattail	22.1
Total	**303.0**

3.3.3 Motor Selection

The motor chosen to provide the thrust for this year's mission is the L1395-P Blue Streak Rocket Motor produced by Cesaroni Technology Inc. The selection of this motor was primarily motivated by the fact that NDRT is currently in possession of three L1395-P models, unused due to the 2019-2020 competition cancellation, yielding a cost-saving opportunity of at least $879.00. Additionally, the selection of this motor at the outset of the season simplified the design process by fixing one parameter, narrowing the candidate options for other parameters. The L1395-P has been used by NDRT in previous seasons, and its success in various demonstration flights ensures confidence in the reliability of its performance. The motor specifications are provided in Table 8, and a plot of the motor thrust curve simulated in Rocksim is provided in Figure 4.

Table 8: Cesaroni L1395-P Blue Streak Motor Specifications

Feature	Value
Diameter (in.)	2.95
Length (in.)	24.45
Loaded Weight (oz)	151.31
Propellant Weight (oz)	82.77
Burnout Weight (oz)	64.68
Impulse (lb-s)	1101.46
Average Thrust (lb)	314.03
Maximum Thrust (lb)	400.48
Burn time (s)	3.51
Cost (USD)	292.99

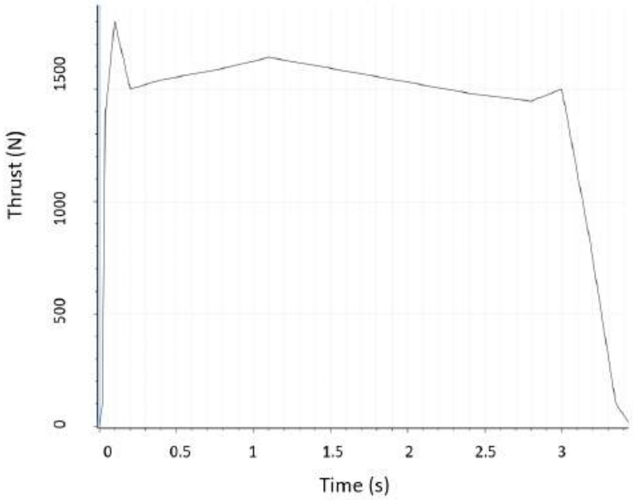


Figure 4: Thrust curve for the Cesaroni L1395-P motor simulated using Rocksim

3.3.4 Target Apogee

The target apogee altitude was set to 5,300 ft AGL at the PDR milestone (NASA Req. 2.1, NASA Req. 2.2). The wide range of apogee altitudes predicted under different wind and launch rail cant angles, outlined in Section 3.9.1, necessitates the use of the ACS to provide assurance that the launch vehicle is able to reach the target apogee altitude within a small margin of ± 30 ft. To ensure that the ACS will actively intervene to lower the altitude in all possible flights, the target apogee altitude of 5,300 ft was chosen because it lies at the bottom of the range of apogee predictions.

3.4 Vehicle Structural Components

Each of the launch vehicle structural components was selected through a trade study. The structural integrity of each component was analyzed using FEA, as outlined in the following sections, to ensure that they will withstand the predicted loads in flight with a safety factor of no less than 1.5 (NDRT Req. VF.1-NDRT Req.VF.3). The analysis of the launch vehicle components in the following sections demonstrates that the designs are complete and ready to manufacture.

3.4.1 Nose Cone

The nose cone selected for this year's launch vehicle is the FNC-6.0 made of G10 fiberglass by Public Missiles LTD. The only design requirement for the nose cone was that it must have an outer shoulder diameter of 6 in. to interface with the body tubes. The primary design drivers in selecting the nose cone were weight and drag minimization. Secondary drivers were cost minimization and internal volume maximization for the purpose of providing additional space for the payload recovery system. The FNC-6.0 was chosen because it had an optimal balance of these requirements. A summary of the characteristics of the chosen nose cone is provided in Table 9, and a CAD drawing with its dimensions is shown in Figure 5.

Table 9: Characteristics of the selected nosecone

Characteristic	FNC-6.0 Nose cone
Exposed length (in.)	24.0
Shoulder length (in.)	5.00
Shape parameter	Ogive
Weight (oz)	28.0

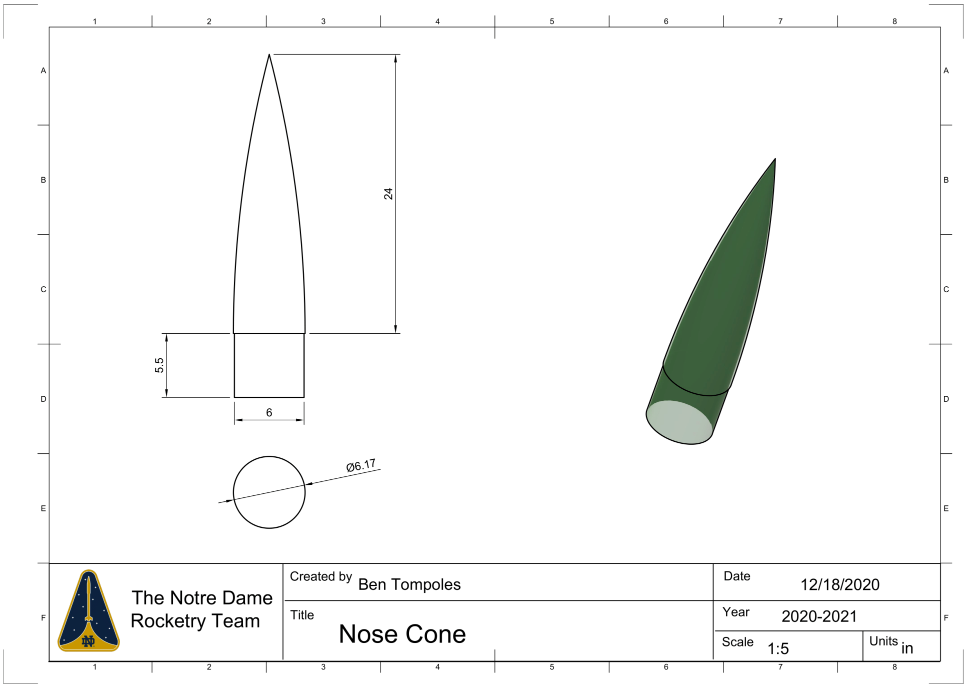


Figure 5: CAD drawing of the nose cone with dimensions

To ensure that the PLS is able to jettison from the forward end of the payload tube without interference, the nose cone will separate from the rest of the vehicle and be recovered under its own parachute. To verify that the FNC-6.0 is strong enough to withstand landing before a full-scale launch is attempted, the nose cone impact test outlined in section 6.1.2 will be performed before a full-scale flight is attempted.

3.4.2 Payload Tube

The purpose of the payload tube is to integrate the PLS experimental payload and the Recovery CRAS-S subsystem in a configuration that can interface with and separate from the nose cone and the recovery tube. The nose cone shoulder is able to slide into the payload tube, and a coupler is epoxied 3 in. within the aft end of the payload tube for insertion into the recovery tube. Additionally, a Fiberglass bulkhead is required at the forward end of the coupler for the attachment of the main parachute shock chord. Because the inner diameter of the body tubes was fixed to 6.0 in., the payload tube design was fully defined by choosing a material and a length.

The main criterion for choosing a material for the payload tube were high specific strength and RF transparency, to ensure that GPS signals are able to pass through for recovery. Weight was not of high concern: given reasonable upper and lower bounds, the thrust curve for the chosen motor was capable of achieving the desired apogee in all flight simulations. The material chosen to best meet these design goals was the Kevlar and Filament-Fiberglass Hybrid Airframe fabricated by Giant Leap Rocketry. This material choice provides strength and weight properties similar to G10 Fiberglass at a lower cost. The payload tube will be cut from a length of 48.0 in. (provided by the manufacturer) to 30.5 in. This length was chosen to provide sufficient space for the integration of all components, while eliminating unnecessary skin friction drag. Considering the shoulder length of the nose cone and the coupler, the payload tube provides a functional length of 22.5 in. for the PLS and CRAS-S integrated systems.

The coupler chosen for attachment to the payload tube was the G12 FW Fiberglass Coupler produced by Apogee Components. This choice was based on the coupler material availability, while keeping the material strength and weight consistent. The coupler will be cut to a length of 9.0 in. Of this length, 3 in. will be epoxied into the payload tube, leaving 6 in. of length exposed for insertion into the recovery tube (NASA Req. 2.5.1). Finally, a camera shroud will be epoxied to the outer diameter of the payload tube, as outlined in Section 3.4.3. A summary of the important characteristics of the chosen payload tube assembly is provided in Table 10, and a CAD drawing of the full payload tube assembly is shown in Figure 6.

Table 10: Characteristics of the selected payload tube assembly

Characteristic	Value
Length (in.)	30.5
Inner diameter (in.)	6.00
Outer diameter (in.)	6.17
Weight (oz)	53.0
Material	Kevlar and Filament-Fiberglass
Compressive strength (psi)	65,000
Coupler length (in.)	9.00
Coupler exposed length (in.)	6.00
Coupler inner diameter (in.)	5.79
Coupler outer diameter (in.)	6.00
Coupler weight (oz)	18.5
Coupler material	G12 Fiberglass

To verify that the chosen payload tube design is suitable to withstand the expected loads in flight, FEA was performed using ANSYS Structural to model the most critical loading scenario. The maximum load predicted to impact the payload tube occurs at maximum motor thrust, during which it experiences a compressive axial load of 400.5 lbf. To model this scenario, a fixed support was applied at the forward edge, and a compressive force of 400.5 lbf was applied at the aft edge, as shown in Figure 7.

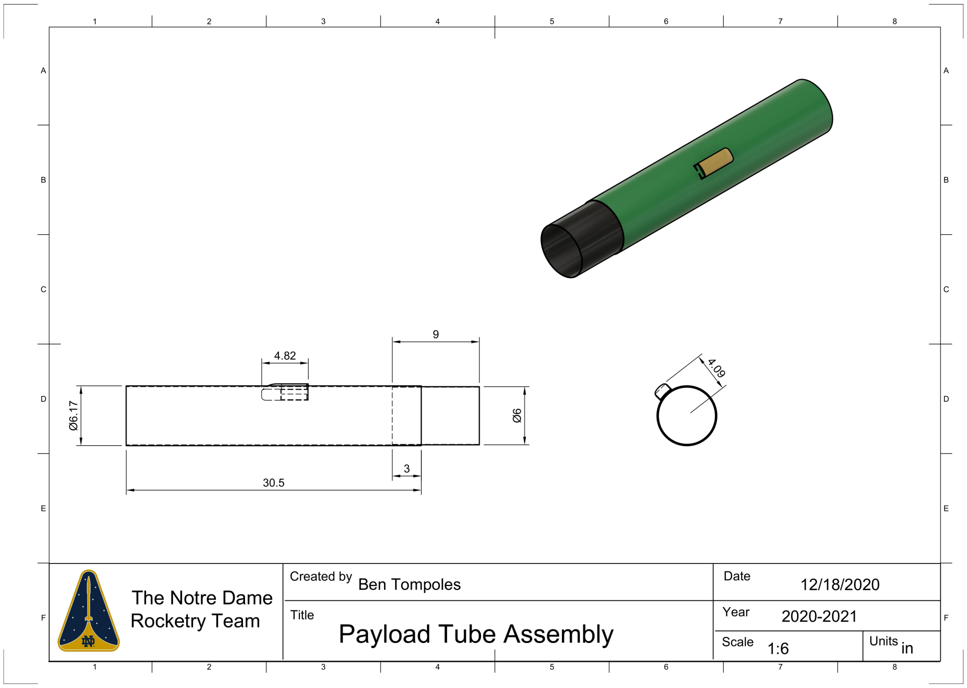
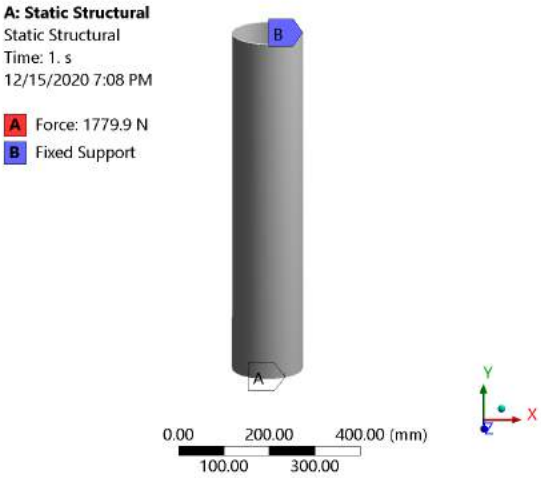


Figure 6: CAD drawing of the payload tube assembly with dimensions



A: Static Structural
Static Structural
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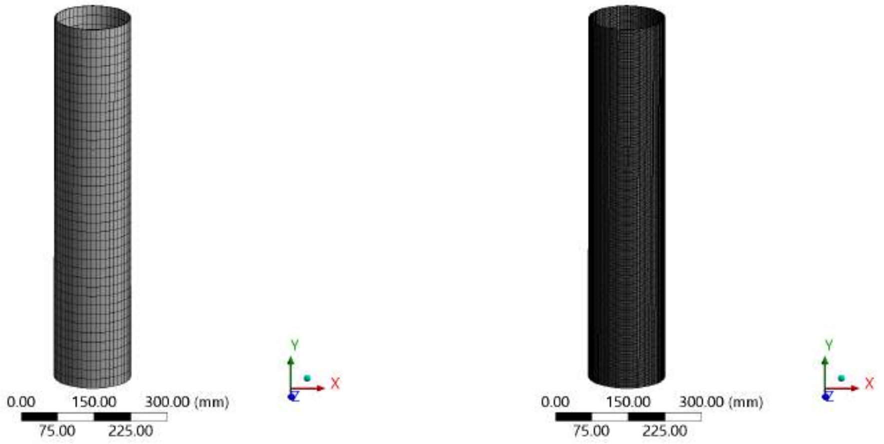
🟥 A Force: 1779.9 N
🟦 B Fixed Support

Figure 7: FEA setup of payload tube loading scenario

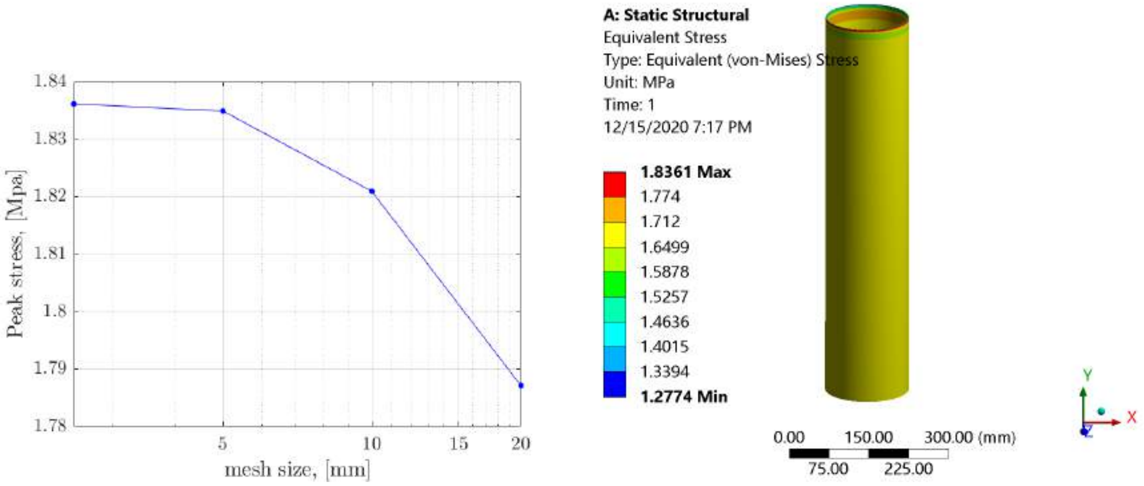
Brick mesh elements were used for this analysis. To ensure the accuracy of the FEA results, the mesh element size was refined until convergence was observed using a refinement factor of 2. The coarsest element size used was 20 mm and the finest was 2.5 mm. A comparison of these mesh sizes is shown in Figure 8.



(a) Coarse mesh (20 mm) (b) Fine mesh (2.5 mm)

Figure 8: Visual comparison of the coarsest and finest meshes used to ensure convergence

The FEA was performed to solve for the von-Mises stress, for comparison to the material compression strength of 65,000 psi. The results of the analysis are shown in Figure 9, along with the graphical verification that the mesh refinement was sufficient for a fully converged solution.



(a) Graphical convergence of the solution (b) von-Mises stress solution at finest mesh

Figure 9: FEA solution for the payload tube

The solution showed a maximum stress of 266.3 psi, which implies a factor of safety of 244.0 for the payload tube during maximum loading. This demonstrates that the material choice of Kevlar and Fiberglass-filament is sufficient to withstand the expected loads in flight to an extremely redundant degree. While a lighter material could therefore be used in its place, no changes were made because a significant change in weight would yield a significant, undesirable change in the projected apogee altitude.

3.4.3 Camera Shroud

The camera shroud was designed to integrate the Mobius2 Actioncam onto the launch vehicle during flights to record high quality video footage of the various stages of the launch. The shroud will be epoxied to the 6.17 in. outer diameter of the payload tube, with the open end of the shroud facing in the aft direction. This placement gives the camera visibility of the ACS drag tabs to verify that they successfully deploy during ascent, as well as the recovery main and drogue parachute deployment events. The camera will slide into the shroud through the opening, and be held in position by a retaining wall that will slide into the gaps on either side of the shroud. This retaining wall is open in the center to provide a viewport for the camera lens. The end of the shroud that faces upwards is rounded to reduce air resistance caused by its protrusion from the side of the payload tube. To ensure that the addition of the camera shroud does not cause excess aerodynamic instability or flow separation (NASA Req. 2.14), CFD was performed and analyzed in Section 3.9.3. The camera shroud will be 3D printed from PLA using a Makerbot printer. A drawing of the camera shroud design is shown in Figure 10.

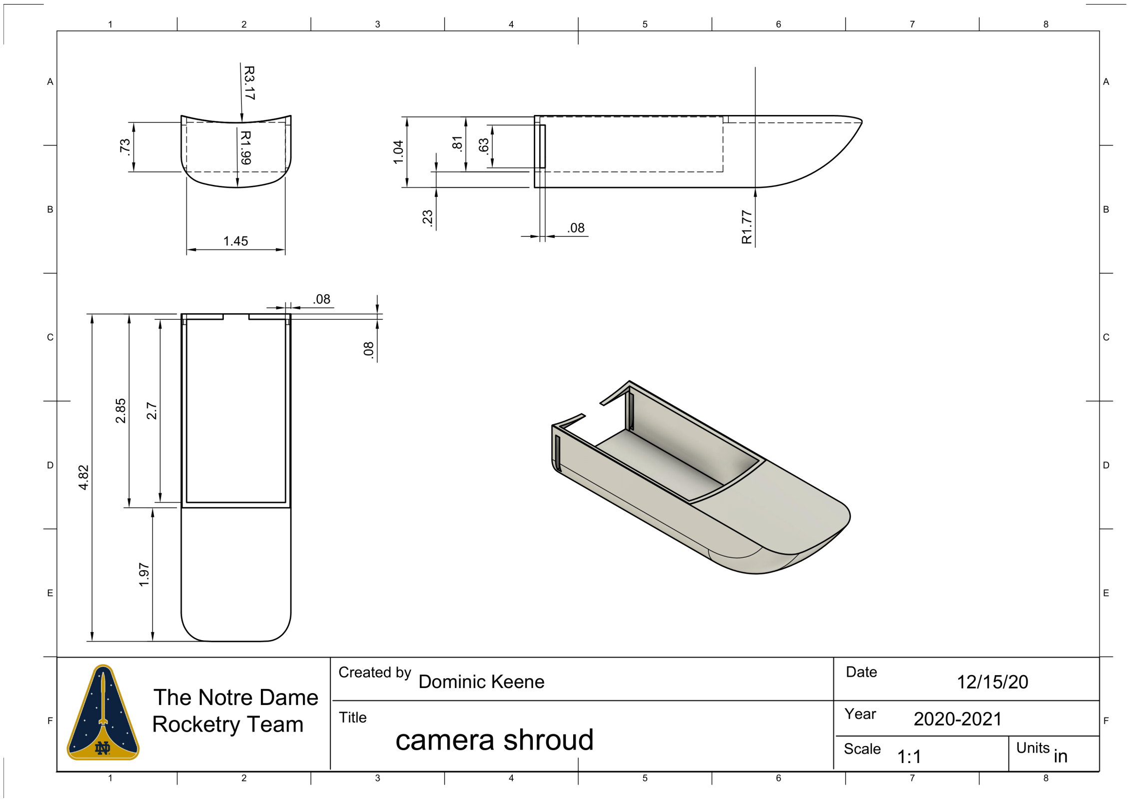


Figure 10: CAD drawing of the camera shroud design with dimensions

The Mobius2 Actioncam is capable of shooting 1080p video at 60 frames per second with a super wide angle field of view of 130°, with all footage saved onto a removable microSD memory card. The camera weighs approximately 1.587 oz, and has outer dimensions of approximately 2.52 in. (L) by 1.40 in. (W) by 0.709 in. (H).

3.4.4 Recovery Tube

The recovery tube design was based on the same design considerations outlined in 3.4.2. The purpose of the recovery tube is to integrate the CRAS-M recovery subsystem and the recovery main and drogue parachutes in a configuration that can interface with and separate from the payload tube and the fin can. This will be accomplished using two couplers on either side of the recovery bay, one of which will be epoxied 3 in. into the aft end of the payload tube. The second coupler, used to interface with the fin can, will be epoxied into the recovery tube and slotted into the fin can. The same materials of Kevlar and Filament-Fiberglass for the recovery tube and G12 Fiberglass for the coupler will be used for the recovery tube assembly. The recovery tube will be cut to a length of 33.0 in. from the manufacturer length of 48.0 in. to provide sufficient space for the CRAS-M subsystem and all parachutes. Considering the space between the payload tube bulkhead and the forward ACS bulkhead, the main recovery hardware is provided a functional length of 42.0 in. for the CRAS-M and packed parachutes. A summary of the important characteristics of the chosen recovery tube assembly is provided in Table 11, and a CAD drawing of the full payload tube assembly is shown in Figure 11.

Table 11: Characteristics of the selected recovery tube assembly

Characteristic	Payload tube assembly
Length (in.)	33.0
Inner diameter (in.)	6.00
Outer diameter (in.)	6.17
Weight (oz)	57.3
Material	Kevlar and Filament-Fiberglass
Compressive strength (psi)	65,000
Coupler length (in.)	9.00
Coupler exposed length (in.)	6.00
Coupler inner diameter (in.)	5.79
Coupler outer diameter (in.)	6.00
Coupler weight (oz)	18.5
Coupler material	G12 Fiberglass

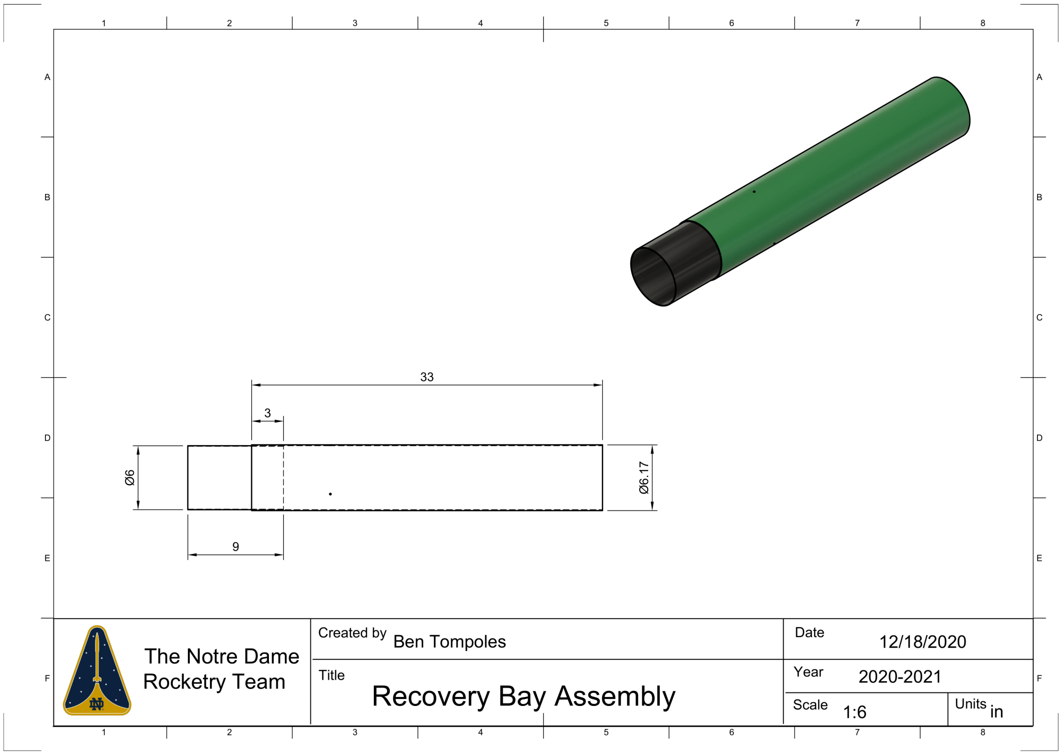
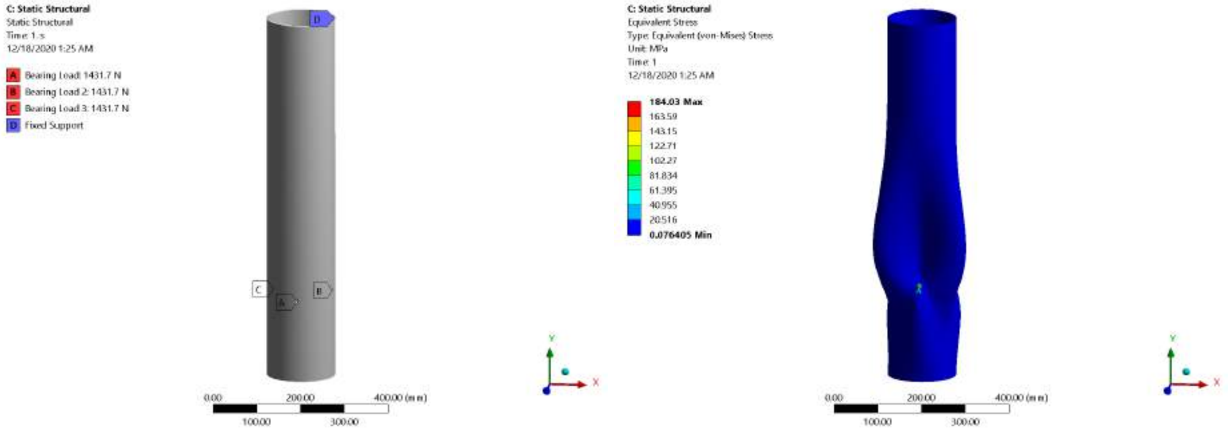


Figure 11: CAD drawing of the recovery tube assembly with dimensions

FEA was conducted to verify that the recovery tube will be able to withstand the worst-case predicted loads in flight. In particular, the most critical loading applied to the recovery tube occurs at the deployment of the main parachute, which is predicted to create an upward acceleration of 36 g's in the conservative worst-case scenario in which the parachute instantaneously opens. During deployment, the shock chord pulls on the recovery eyebolt, which transfers the load through the forward CRAS-M bulkhead, which is secured by three #12 bolts to the recovery tube. Therefore, the load is transferred to the recovery tube in the form of a bearing load on the clearance holes.

From the acceleration prediction, the bearing load on each hole is expected to be 321.9 lbf. For the FEA model setup, these loads were applied and the forward and aft faces of the tube were given fixed supports to conduct a static structural analysis. Next, the same mesh refinement process described in section 3.4.2 was used to ensure that the results converged. The analysis yielded a maximum stress of 26,687 psi. Given a compressive strength of 65,000 psi, this demonstrates a factor of safety of 2.435 for the recovery bay under the worst-case loading prediction during main parachute deployment. The results of this analysis can be seen in Figure 12.



(a) Payload tube loading setup modelling main parachute deployment

(b) von-Mises stress solution with exaggerated deformation

Figure 12: FEA results for the recovery bay

3.4.5 Fin Can

The purpose of the fin can is to integrate the ACS subsystem and the forward half of the motor retention system, in a configuration that can interface with and separate from the recovery tube. The fin can, like the other airframe tube components, will be made of kevlar and filament-fiberglass supplied by Giant Leap Rocketry, chosen because of its high specific strength and RF transparency. This body tube will be purchased so that the vehicle is ready to manufacture, with the slight modification of machining slot holes in the tube. These slots will be machined in order to integrate the ACS subsystem, leaving room for the tabs to deploy radially from the vehicle through the tube. The length of the body tube will be cut to 31.0 in. to fit the ACS and the centering rings for the motor mount in the vehicle forward of the boattail. A summary of the important characteristics of the fin can design is provided in Table 12, and an engineering drawing of the fin can is shown in Figure 13.

Table 12: Characteristics of the selected fin can design

Characteristic	Payload tube assembly
Length (in.)	31.0
Inner diameter (in.)	6.00
Outer diameter (in.)	6.17
Weight (oz)	53.9
Material	Kevlar and Filament-Fiberglass
Compressive strength (psi)	65,000

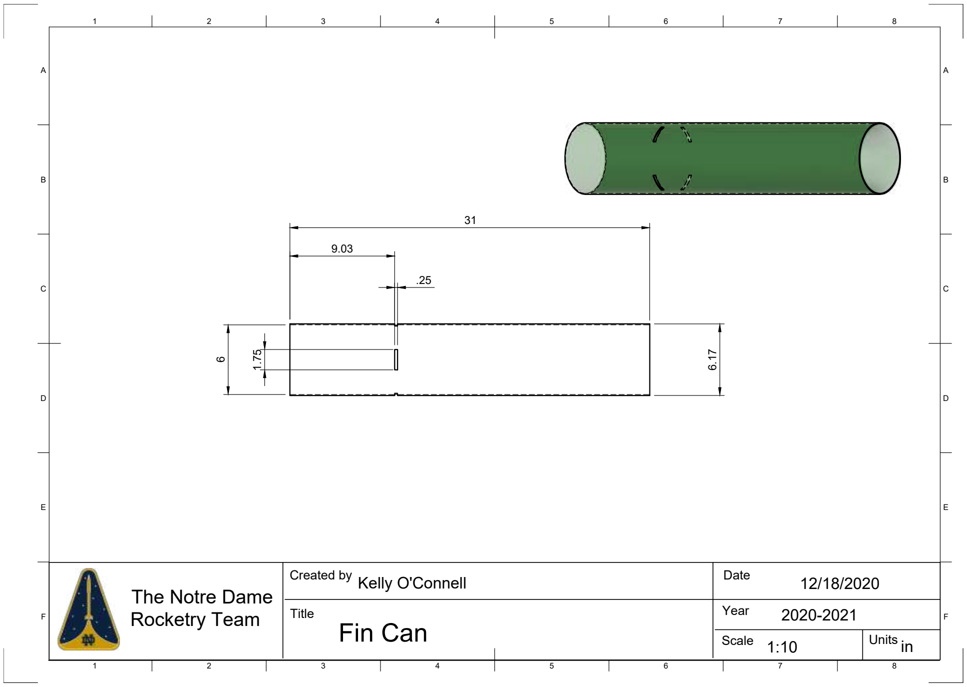
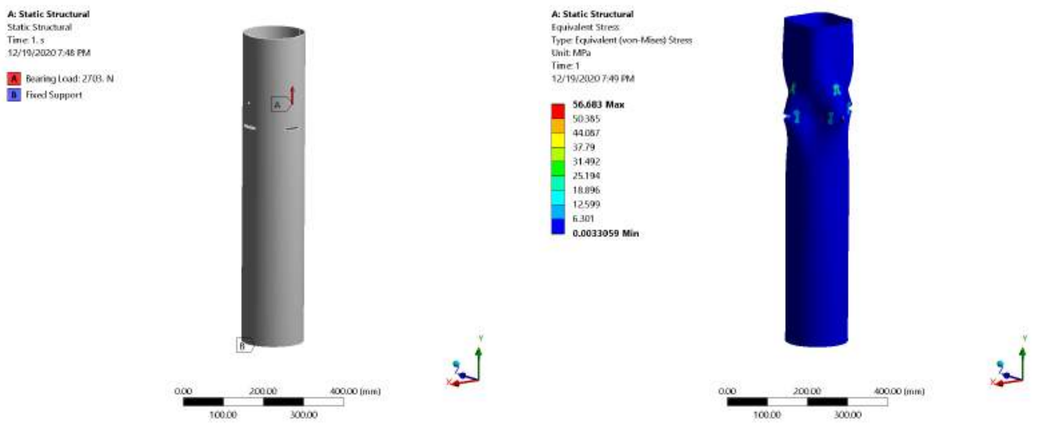


Figure 13: CAD drawing of the fin can with dimensions

The worst loading applied to the fin can occurs at main parachute deployment, which is predicted to create an upward acceleration of 36 g's in the conservative worst-case scenario, in which the parachute is instantaneously opened. During deployment, the load is transferred to the fin can in the form of a bearing load on the clearance holes. FEA was conducted using the mesh refinement method outlined in Section 3.4.2 to ensure convergence. The setup involved a bearing load of 607.7 lbf to model the upwards acceleration, and a fixed support at the lower surface of the fin can. The analysis yielded a peak von-Mises stress of 8221 psi, resulting in a factor of safety of 7.90. The FEA setup and solution are shown in Figure 14.



(a) Fin can loading

(b) von-Mises stress solution

Figure 14: FEA results for the fin can

3.4.6 Boattail

At the aft end of the launch vehicle, a boattail will be epoxied to the fin can so that the motor mount tube is integrated within both components. The boattail is instrumental in decreasing the pressure drag acting on the launch vehicle during flight. Of all those available, the boattail that best matched the vehicle dimensions was the BTL-6.0.3.0 made of G10 fiberglass and produced by Public Missiles Ltd. Due to its Ogive profile, it allows a seamless transition from the 6.17 in. outer diameter of the launch vehicle's body to the 3.00 in. diameter of the motor. By providing a smaller diameter at the aft end, the low pressure wake area is decreased, therefore decreasing pressure drag.

The fins will interface with the motor mount tube through slots cut into the body of the boattail at 90° angles. Considering the fin dimensions, each fin slot will be 6.0 in. by 0.125 in. A CAD drawing of the selected boattail is shown with dimensions in Figure 15.

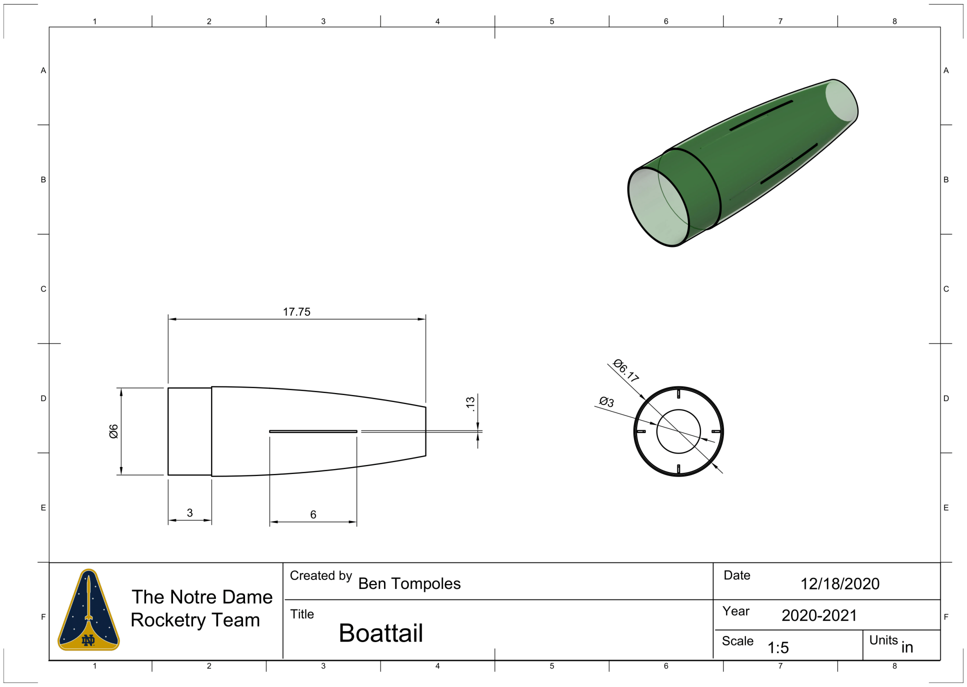


Figure 15: CAD drawing of the boattail with dimensions

3.4.7 Fins

Fins are a crucial component to mission success because they help to stabilize the launch vehicle throughout flight. The team has done research to determine the optimal fin shape and material for the launch vehicle design. From the research done in PDR, it was determined that elliptical fins made out of G10 Fiberglass are both the right planform and material for the launch vehicle design. The simulated flight data demonstrated that an elliptical shaped fin had the lowest drag force out of the planform shapes considered, which was expected because elliptical fins produce the minimum induced drag. Similarly, fiberglass outperformed the other candidate materials in terms of yield strength and weight.

The fin dimensions were chosen to ensure a static stability margin between 2.0 and 3.0 calibers through an entire flight (NASA Req. 2.14, NDRT Req. VD.7). Each fin has a root chord length of 6.0 inches, a height of 6.20 inches, and a thickness of 0.125 inches. Furthermore, an airfoil shape will be approximated for the fin cross section by rounding the leading edge and chamfering the trailing edge with sandpaper, to further reduce the drag for subsonic flight. At the intersection of the fins and the fin slots in the boattail, fillets made out of epoxy will be applied, providing additional strength to the fin assembly and reducing interference drag. The fillet radius is estimated to be 0.25 inches. A summary of important parameters in the fin design is provided in Table 13, and a CAD drawing of the fin design is shown in Figure 16.

Table 13: Fin Properties

Characteristic	Fins
Shape	Elliptical
Material	G10 Fiberglass
Cross-section	Airfoil
Number of Fins	4
Root Chord (in.)	6.00
Height (in.)	6.20
Thickness (in.)	0.125
Span (in.)	18.2
Total weight (oz)	17.4

G10 Fiberglass was chosen as the fin material primarily because of its high strength. In order to ensure the material will be durable enough to sustain landing, a fin impact test will be performed before a flight is attempted. The impact test can be found in Section 6.1.1.

An understanding of the fin flutter speed is crucial for mitigating the possibility of fin damage during flight (Risk VS.5). When the flight speed reaches the fin flutter speed, the possibility for damage to the fins becomes a genuine concern. The fin flutter speed can be calculated from the fin flutter boundary equation as follows in expressions 1 through 6, with variables defined in Table 14.

$$v_f = a\sqrt{\frac{\frac{G}{1.337AR^3P(\lambda+1)}}{2(AR+2)\left(\frac{t}{c_r}\right)^3}} \tag{1}$$

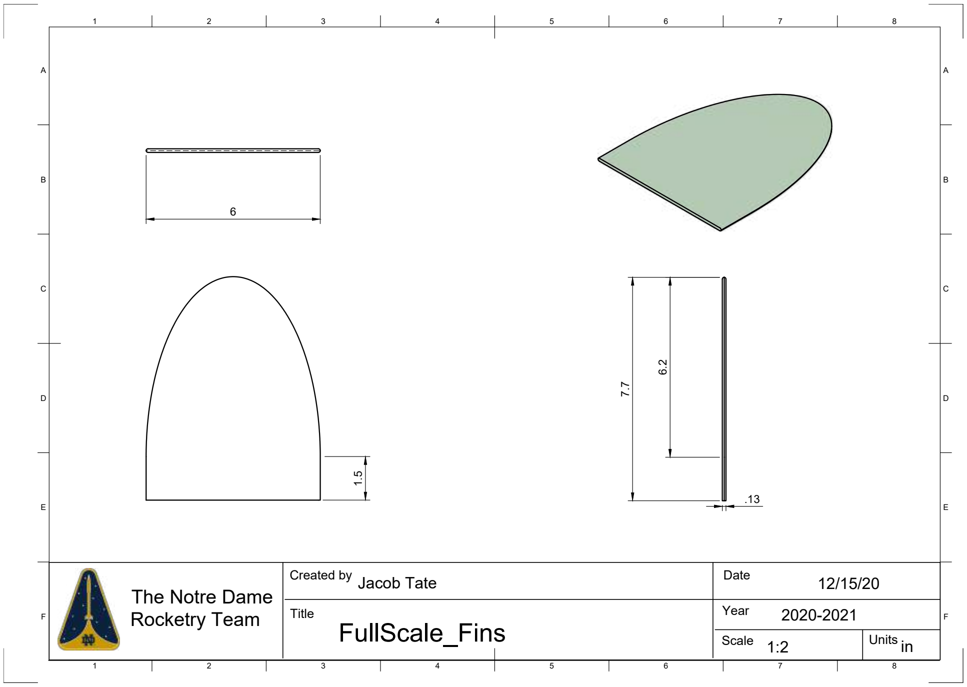


Figure 16: CAD drawing of the fins with dimensions

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

$$\lambda = \frac{c_t}{c_r} \tag{3}$$

$$a = \sqrt{(1.4)(1716.59)(T+460)} \tag{4}$$

$$T(^{\circ}F) = 59 - 0.00356h \tag{5}$$

$$P(\text{lbs}/\text{ft}^2) = 2116(\frac{T+459.7}{518.6})^{5.256} \tag{6}$$

A MATLAB program was written to calculate the value of the fin flutter speed throughout flight using the fin flutter boundary equation. This program was written to account for the small changes to temperature and pressure based on the change in height. The program determined that the smallest fin flutter speed is 9749.24 ft/sec. Throughout the flight, the launch vehicle's velocity never exceeds the fin flutter speed, with a safety factor of 15.6. As a result, the vibrations of the fins pose a negligible threat to the structure.

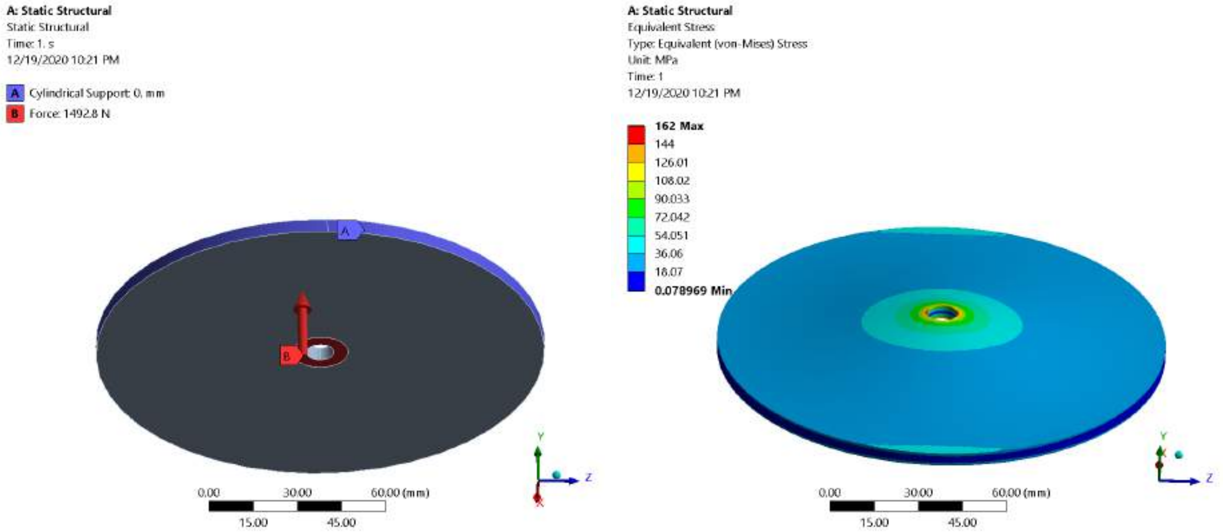
3.4.8 Payload Tube Bulkhead

A bulkhead will be used to separate the payload tube and recovery tube, epoxied at the edge of the coupler in the payload tube. This bulkhead serves the purpose of maintaining pressure isolation in the recovery tube during black powder charge ejection, and taking the

Table 14: Fin flutter boundary equation variables

Name	Variable	Value	Units
Flutter speed	v_f	-	ft/s
Speed of sound	a	-	ft/s
Shear modulus	G	442,365	psi
Aspect ratio	AR	1.42	-
Pressure	P	-	lbs/ft^2
Thickness	t	0.125	in.
Root chord	c_r	6.0	in.
Planform area	S	58.43	in^2
Tip chord	c_t	0.0	in.
Semi-span	b	9.1	in.
Taper ratio	λ	0.0	-
Temperature	T	-	°F
Height	h	-	ft

shock chord load from the main parachute during deployment. Maintaining pressure isolation is necessary to protect systems from the black powder charges while ensuring the correct pressure chamber volume. The payload tube bulkhead will have a 3/8 in. clearance hole for a recovery eyebolt, which the main parachute shock chord will attach to. The chosen bulkhead material of G10 Fiberglass has a flexural strength of 60,000 psi. The bulkhead will have a diameter of 6.0 in. and a thickness of .187 in., which was increased from the original thickness of 0.125 in. after initial FEA results showed a safety margin below 2.0. The FEA performed to verify the structural integrity of this bulkhead was modelled based on the conservative worst-case loading scenario during main parachute deployment, during which the payload tube is predicted to experience an acceleration of 36 g's. A fixed cylindrical support was applied around the bulkhead edge where it will be epoxied to the inner payload tube surface, and a force of 335.6 lbf was applied to the area of a washer which will transfer the load from the recovery eyebolt during main parachute deployment. To ensure the validity of the results, the mesh refinement method outlined in Section 3.4.2 was used to check for convergence. The results of the FEA yielded a maximum von-Mises stress of 23,496 psi, demonstrating a factor of safety of 2.55 for the payload tube bulkhead. The FEA setup and results are shown in Figure 17.



(a) Payload bulkhead loading modelling main parachute deployment

(b) von-Mises stress solution with exaggerated deformation

Figure 17: FEA results for the payload bulkhead

Other bulkheads in the launch vehicle are structural components of either the PLS, CRAS-M, CRAS-S, or ACS, and are analyzed for structural integrity in their respective sections.

3.4.9 Motor Retention

The motor retention system comprises of the motor mount tube, centering rings, and the retainer. Together, these aid to align the thrust force vector to the center line of the launch vehicle to prevent instability during ascent. In order to provide this stability, the motor is housed inside of the motor mount tube, which is then epoxied to the airframe via G10 Fiberglass centering rings using J-B Weld epoxy. The choice of J-B Weld is motivated by its heat-resistant and high strength properties, ideal for motor applications. After insertion, the motor is secured within the motor mount tube via a motor retainer. The chosen motor retainer is the Aero Pack 75mm Retainer, which is specially designed for 75mm motors like the Cesaroni L1395-P. With J-B Weld epoxy, the threaded base of the retainer is secured to the aft end of the motor mount tube, and a retainer cap is screwed on to secure the motor inside the motor retention system. A photo of the chosen motor retainer is provided in Figure 18.

Figure 18: Aero Pack 75mm motor retainer

Due to the variable inner diameter of the boattail, the centering rings are all attached at the forward portion of the motor mount that will be inside of the fin can, each at 5 in. intervals. Due to its low price with still a relatively high yield strength, phenolic fiberglass was chosen as the material for the motor mount tube. The chosen motor mount tube is a 3 in. inner diameter, 30 in. long tube, which will be cut to 27.0 in. to save internal space for ACS. Three centering rings of equal diameter and 0.125 in of thickness will be utilized. A table summarizing the characteristics of the motor retention assembly is shown in Table 15, and a CAD drawing with dimensions is provided in Figure 19.

Table 15: Motor retention assembly characteristics

Characteristic	Motor retention assembly
Motor mount tube material	Phenolic
Motor mount tube length (in.)	27.0
Motor mount tube inner diameter (in.)	3.00
Motor mount tube outer diameter (in.)	3.11
Motor mount tube weight (oz)	8.97
Number of centering rings	3
Centering ring material	G10 Fiberglass
Centering ring inner diameter (in.)	3.11
Centering ring outer diameter (in.)	6.00
Centering ring thickness (in.)	0.125
Centering ring weight (oz)	2.83
Motor retainer material	Aluminum
Motor retainer weight (oz)	5.651

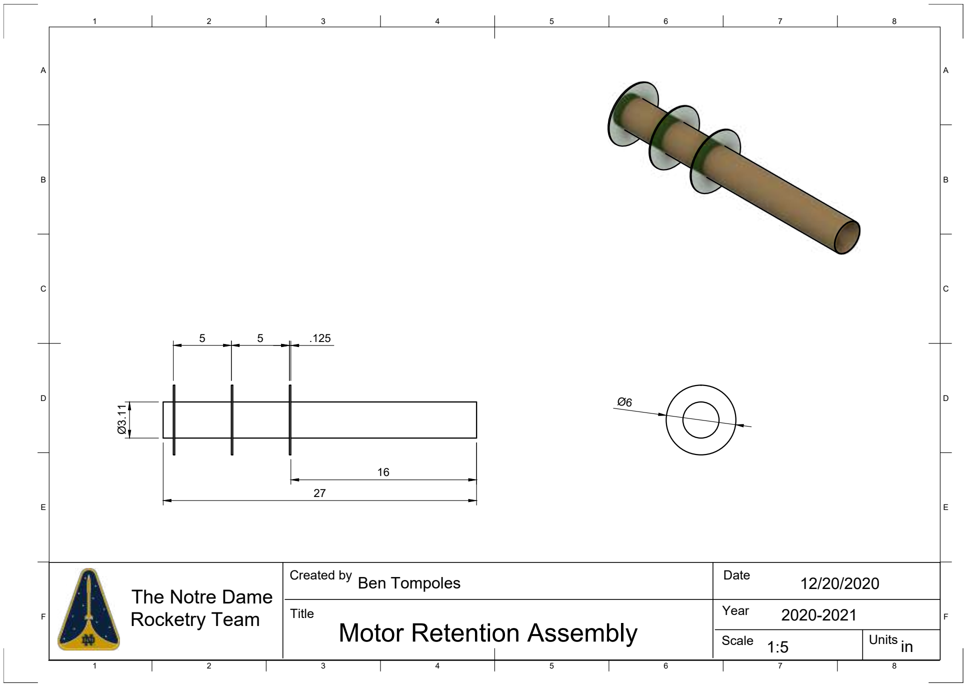


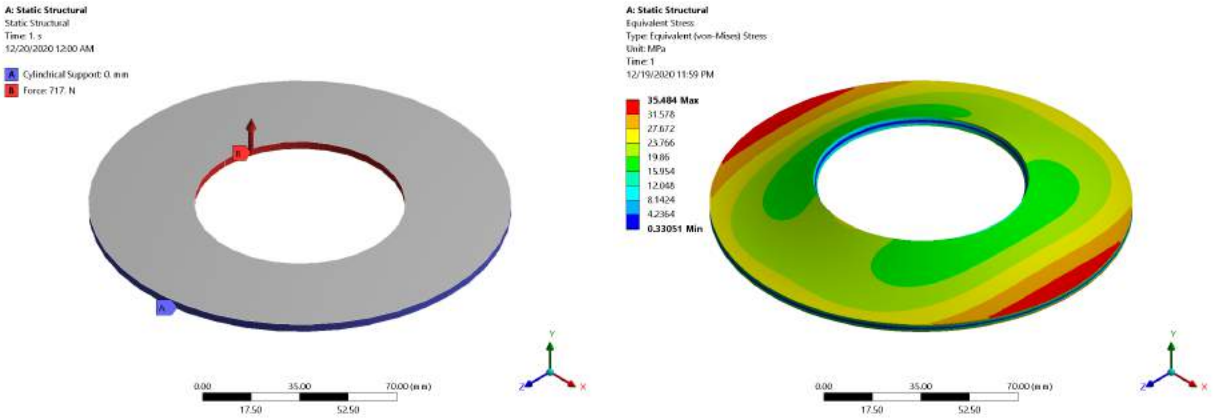
Figure 19: CAD drawing of the motor retention assembly with dimensions

To verify the structural integrity of the centering rings, FEA was used to model their critical loading scenario, the peak motor thrust. For the analysis, it was assumed that each centering ring takes an equal load from the motor thrust, from which a free body diagram yielded a load of 161.2 lbf. This force was applied in shear at the inner diameter of the centering ring, while a fixed cylindrical support was applied to the outer diameter to model the epoxy attachment to the inner surface of the fin can. To ensure the validity of the results, the mesh refinement method outlined in Section 3.4.2 was used to check for convergence. The FEA yielded a maximum von-Mises stress of 5,147 psi, which corresponds with a factor of safety of 11.66 for the G10 Fiberglass centering ring in bending. The results of the FEA are shown in Figure 20.

It should be noted that the results show asymmetry in the stress distribution, even though the load was applied symmetrically to a circular geometry. The asymmetry is due to the fact that G10 Fiberglass is an anisotropic material, so the stress will not distribute evenly in all directions.

3.5 Structural Analysis Summary

The verification of all primary structural components in the vehicle design was obtained through FEA in the preceding component sections. A summary of the component materials and factors of safety is provided in Table 16.



(a) Centering ring loading modelling peak motor thrust (b) von-Mises stress solution with exaggerated deformation

Figure 20: FEA results for the centering ring

Table 16: FEA results for vehicle primary structures

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

For the nose cone and the fins, the critical loading condition of concern occurs at landing rather than during flight, which requires impact loading analysis rather than the static FEA used for the other components. For this reason, drop tests will be performed to assess the ability of these components to withstand the impact loads at landing, before a full-scale flight is attempted. These drop tests are described in further detail in Tests TV.3 and TV.4.

3.6 Subscale Flight Results

Three subscale flights were conducted on November 13, 2020 at the Three Oaks, MI launch site, each employing 3D-printed ACS drag tabs at full, half, and no deployment variations. The primary goal of these launches was to verify the performance characteristics of the launch vehicle design, and to test the effectiveness of the ACS drag tabs in lowering the apogee of the launch vehicle. Additionally, the subscale launches were used to:

- Predict a launch vehicle drag coefficient when ACS tabs are not deployed

- Predict ACS drag tab drag coefficients according to their extended lengths
- Verify simulated flight trajectory and apogee predictions
- Ensure a safe and stable flight with a scale model of the launch vehicle

3.6.1 Scaling Factor and Dimensions

The subscale vehicle was designed to perform accurate test flights that would reflect how the full scale vehicle will perform. The team decided to build a 42.3% scale model of the launch vehicle, based on the availability of commercially made components that would fit this scale. The subscale vehicle includes all of the major airframe components of the full-scale vehicle: the nose cone, body tubes, boattail, fins, and couplers. For gathering useful test flight data, the dimensions of most of the parts were almost exactly 42.3% in order to reproduce the drag coefficient the full scale vehicle will experience. In order to keep the ratio consistent, the team decided to 3D print the nose cone and laser cut the fins because exact dimensions needed were not available commercially. The full-scale fin height was changed after the subscale launch vehicle was constructed, so there is a small error in its scaling. For drag similarity, ogive shape parameters were used for both the nose cone and the boattail. The component which strayed the furthest from the chosen scale was the boattail, but the difference was deemed small enough that the results would not be noticably affected, especially because pressure drag is less important in the incompressible speed regime. The exact dimensions of the subscale components along with their comparisons to the full-scale dimensions, and the error from the 42.3% scaling factor, can be found in Table 17 below.

Table 17: Subscale launch vehicle dimensions and scaling error

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

A CAD drawing of the subscale vehicle with dimensions can be seen in Figure 21, and a picture of the fully constructed subscale vehicle is shown in Figure 22.

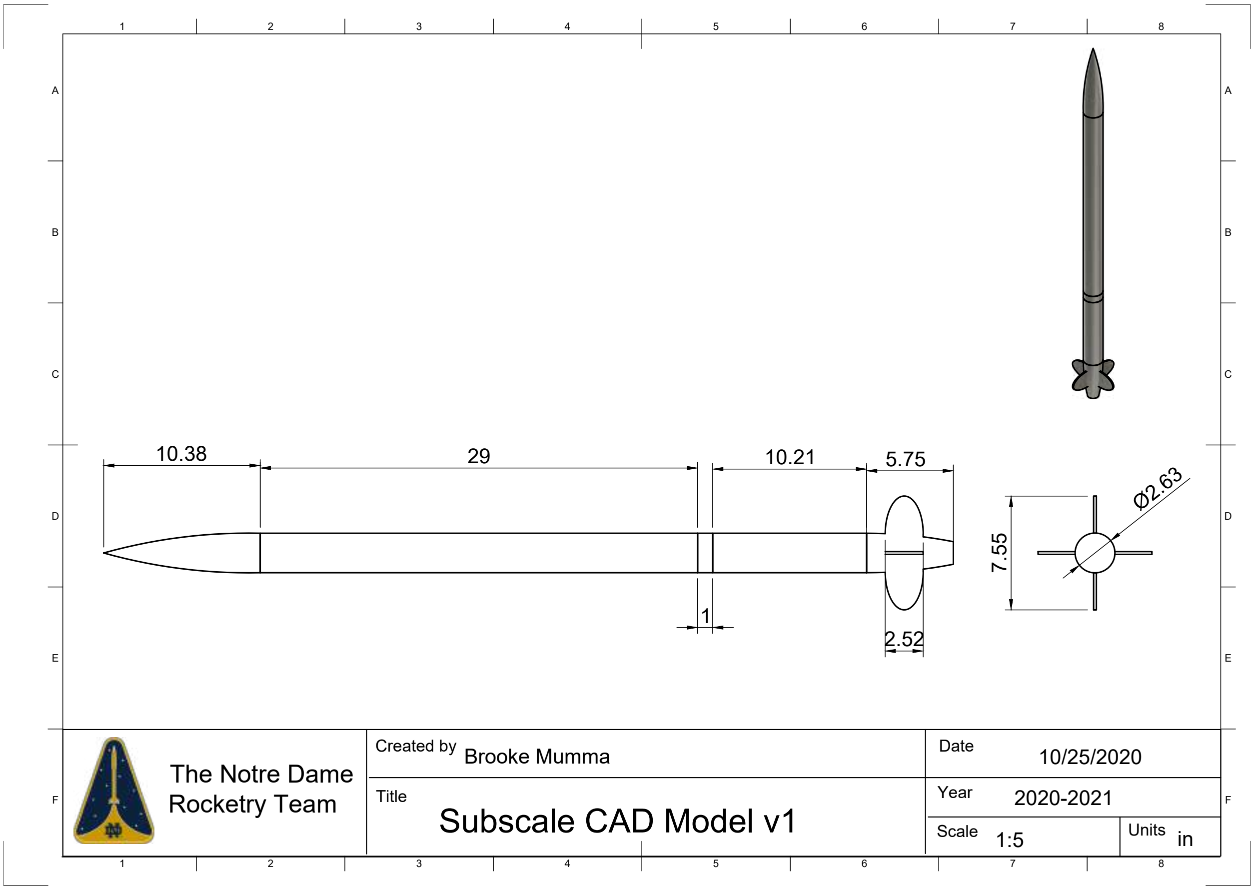


Figure 21: CAD drawing of the subscale launch vehicle with dimensions

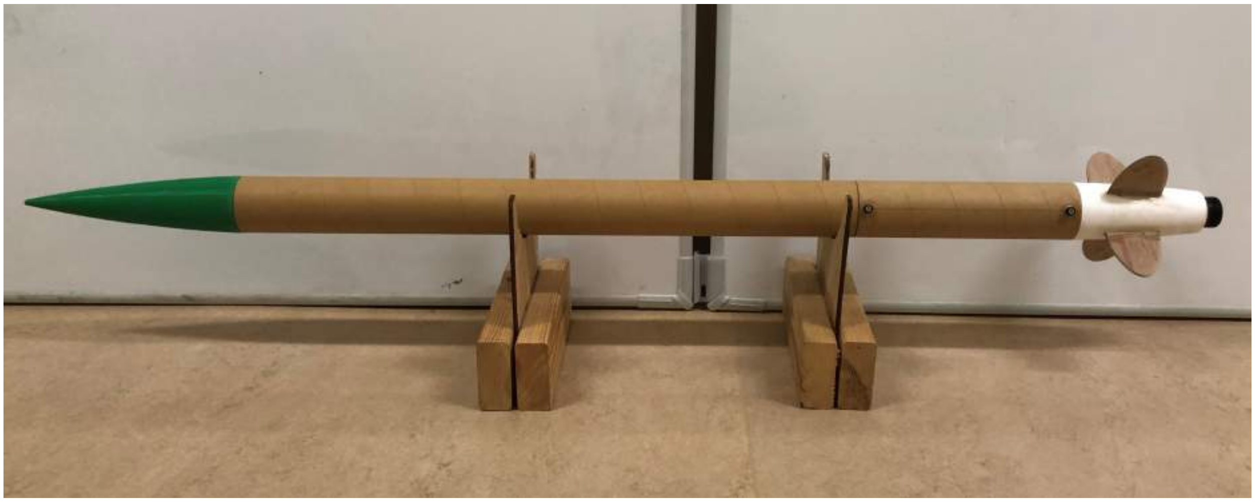


Figure 22: Image of the fully constructed subscale launch vehicle

3.6.2 Launch Day Conditions

The weather conditions and launch rail information for the three subscale launches that took place on November 13, 2020 at the Three Oaks, MI launch site are provided in Table 18.

Table 18: Subscale launch day conditions

Condition	Value
Wind speed (mph)	12
Temperature (°F)	36
Humidity	72%
Launch rail angle	10°
Flight 1 launch rail length (ft)	6.0
Flight 2 and 3 launch rail length (ft)	8.0

It is worth noting that the first flight, with the no-tabs configuration, was launched from a shorter launch rail compared to the second and third flights. After observing slight weather cocking upon rail departure in the first flight, the launch vehicle was moved to a longer rail for the next two flights to ensure that a fast enough off-rail velocity was reached to attain stability. Unfortunately, this change of launch rail length appears to have affected the trajectory results for the second and third flights, as seen in the following analysis.

A flight simulation was performed using the weather conditions shown in Table 18 with an OpenRocket model of the subscale launch vehicle, which yielded an apogee altitude of 1092 ft. This simulated trajectory is compared to the actual flight data in the next section.

3.6.3 Subscale Launch Analysis

The predicted apogee for the launch vehicle was 1092 ft without the ACS tabs extended. This prediction was obtained using simulations in OpenRocket and equivalent launch day conditions to those during the subscale launch. The apogee results from the subscale test launches are shown in Table 19. A plot of the subscale ascent data for each of the three launches, with the OpenRocket simulated flight included for comparison, is shown in Figure 23.

Table 19: Subscale test flight apogee results

ACS configuration	Apogee altitude (ft)
No drag tabs	1060
Half tabs	1124
Full tabs	957

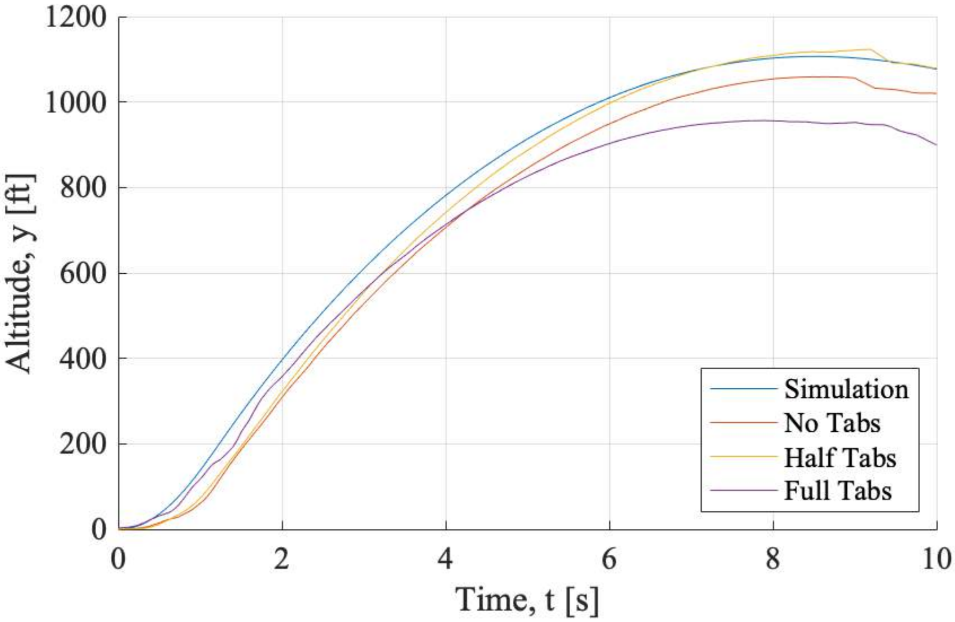


Figure 23: Plot of subscale test flight ascent data with OpenRocket simulated flight

From the apogee results and the flight data plots, it is apparent that the ACS drag tabs are able to decrease the launch vehicle apogee in their full extension configuration. The apogee result of the configuration with no drag tabs was impacted by early weather cocking that occurred at the launch rail exit, and the results of the following two flights yielded higher apogee altitudes because a longer launch rail was used to ensure that the rail exit speed was high enough to yield stability. Based on the similarity between the simulated flight and the half tabs configuration, the ACS drag tabs at half extension do not strongly impact the apogee altitude. This is most likely due to the failure of the tabs to extend past the boundary layer in this configuration.

Additionally, the discrete subscale altitude data was used to estimate the velocity throughout flight using the forward difference method, and the same was done for acceleration, to approximate the derivatives as follows:

$$v = \frac{dy}{dt} \approx \frac{y_{i+1} - y_i}{\Delta t} \tag{7}$$

$$a = \frac{dv}{dt} \approx \frac{v_{i+1} - v_i}{\Delta t} \tag{8}$$

Using this method, plots of the velocity and acceleration of the subscale launch vehicle throughout flight were generated as shown in Figure 24, along with the simulated plots.

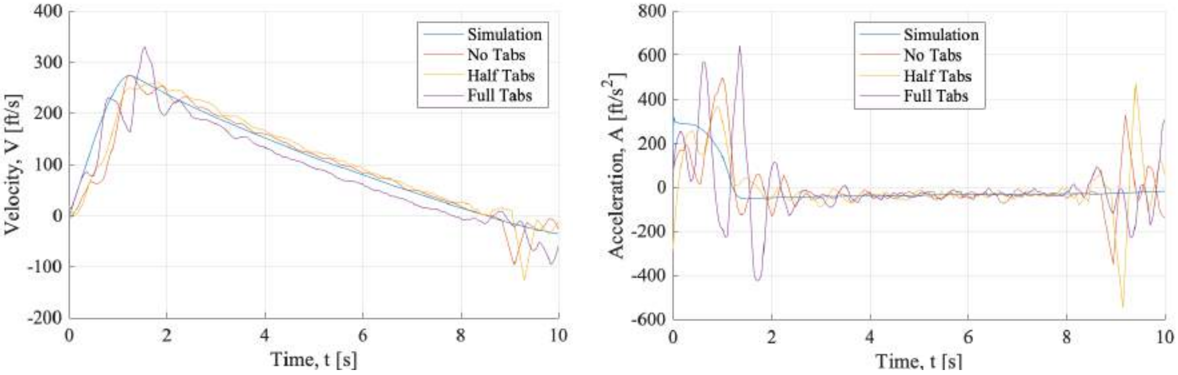


Figure 24: Subscale velocity and acceleration plots along with simulated values

The velocity data further supports the hypothesis that the half extension configuration did not strongly impact the flight, and that the difference in altitude seen in the no-tabs flight was due to the initial weather cocking. This is because the no tabs and half tabs flights yielded very similar velocities throughout ascent, whereas the full tabs configuration yielded a noticeably lower velocity on ascent.

Finally, the subscale launch data was used to estimate the drag coefficient on the launch vehicle. To do so, the equation of motion shown in Eqn. 9 was simplified to Eqn. 10 by only considering the portion of flight after burnout, thereby eliminating the thrust component. Then, the drag force prediction at each point in flight was applied to Eqn. 11 to obtain an estimate of the drag coefficient, C_d.

$$ma = F_t + F_d + mg \tag{9}$$

$$F_d = ma - mg \tag{10}$$

$$F_d = \frac{1}{2}\rho C_d V^2 A \tag{11}$$

Different ranges of velocities yielded different drag coefficient estimates. Averages were used to smooth out the noise in the data, and the estimates for different ranges are provided in Table 20.

Table 20: Subscale drag coefficient estimates for different velocity ranges

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

Clearly, the smaller velocity ranges tended to yield more accurate drag coefficient estimates, especially for portions with minimal noise. The last value of 0.3078 agrees well with the OpenRocket simulated C_d of approximately 0.3 throughout flight.

3.6.4 Implications for Full Scale

The subscale test launches successfully demonstrated the effectiveness of ACS drag tabs to lower the apogee of the launch vehicle. There were no launch vehicle design changes made after analyzing the results of the subscale launches. The apogee was approximately equal to what the simulation predicted, giving the team higher confidence in the simulation results from OpenRocket models. Because of the similarity between the launch data and the simulated flights, the drag coefficient did not need to be updated. Also, the sensors used in the subscale launch collected sufficient data and are viable choices for use in the full scale vehicle.

3.7 Apogee Control System

3.7.1 Mission Statement

The purpose of the Apogee Control System (ACS) is to guide the launch vehicle to the target apogee of 5300 ft and increase apogee consistency in each launch by introducing a controlled variable drag force during flight. The ACS acts as a closed-loop control system located on board the launch vehicle. During flight, the ACS gathers data on the acceleration and altitude of the rocket, and uses that data to engage four drag surfaces, called drag tabs, to the appropriate extension and retraction. These drag tabs will be used from burnout to apogee, and their movements will be dictated by a PID control law. Following apogee, the drag tabs will be retracted for a final time.

3.7.2 Mission Success Criteria

In order to be considered successful, the ACS will ensure that the launch vehicle reaches the target apogee of 5300 ft, while not compromising the safety or stability of flight. In doing so, it must fulfill the following success criteria:

1. On-board sensor data shall indicate that the reaches an apogee of 5300 ± 30 ft. (NDRT Req. VF.1).
2. The drag tabs shall extend aft of the burnout center of mass (NDRT Req. AD.5).
3. The drag tabs shall ensure that no destabilizing moments are generated by extending at the same time and rate.
4. Drag tabs shall not deploy until after burnout has occurred, and shall fully retract once apogee has occurred, remaining dormant for the remainder of the flight.
5. The system shall not experience any structural failures in its components.

3.7.3 System Level Design Overview

In order to meet the design specifications laid out in the mission success criteria, a set of control surfaces will be deployed from the fin can at the center of pressure of the launch vehicle. These surfaces (drag tabs) will be actuated by a servo motor connected to aluminum linkages, which will convert the motor's torque to linear extension of the tabs. At full actuation, the tabs are expected to extend approximately 1.88 in. from the body of the launch vehicle, producing a variable drag force to gradually decelerate the vehicle to the projected apogee of 5300 ft.

In order to control drag tab deployment, the altitude, velocity, and acceleration of the launch vehicle will be monitered by various sensors, including an inertial measurement unit (IMU), accelerometer, and altimeter. The data from these sensors will be filtered using a Kalman filter, and the filtered data will be fed into a microcontroller, which will use a PID control loop to control drag tab actuation.

3.7.4 Mechanical Design

3.7.4.1 Fabrication

The ACS system consists of multiple cylindrical decks that hold the individual components that make up the system. These decks are connected together by four threaded rods that run through all four decks, and the decks are supported by bolts attached to the rods. The top deck is a bulkhead made of aluminum that holds a threaded eye bolt that is attached with a bolt. Below the top deck is a high density polyethylene (HDPE) deck that contains the PCB, microcontroller, and the sensors which will be mounted with screws. Under the deck that houses the electronics is the mechanism for deploying the drag tabs, which converts the rotational motion of the servo motor to linear motion through a drive shaft, central hub, linkages, and a slotted deck to guide the tabs outwards. The mechanism fully retracted and extended can be seen below in Figure 25.

(a) Retracted Drag Tabs (b) Extended Drag Tabs

Figure 25: Drag Tab Motion

The drive shaft connects directly to the motor and transfers the rotational movement of the motor to the central hub through five protruding spokes. The central hub connects to the linkages using nuts and bolts, and the linkages connect to the drag tabs using press fitted inserts and bolts. Detailed drawings of the components that make up the deployment mechanism can be seen in Figures 26-30. Originally, all five of these driving mechanism components were going to be made using HDPE. A FEA of the drag tabs, however, revealed that drag tabs made out of HDPE did not have a high enough factor of safety. Thus, both the drag tabs and the slotted deck will be made out of Nylon 6/6, which has a higher yield strength than HDPE.

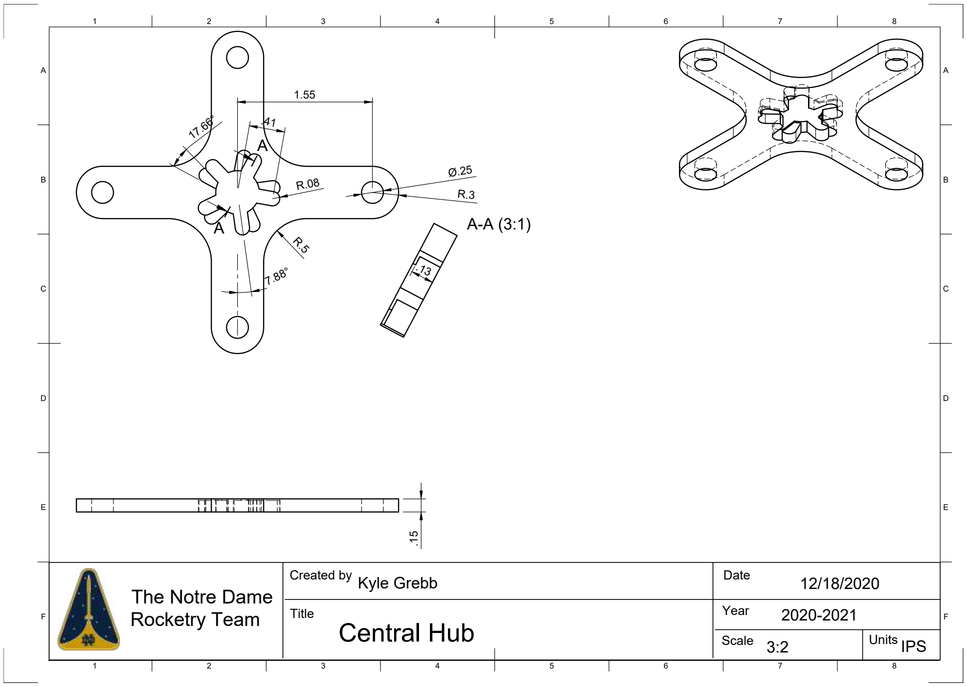


Figure 26: Central Hub Drawing

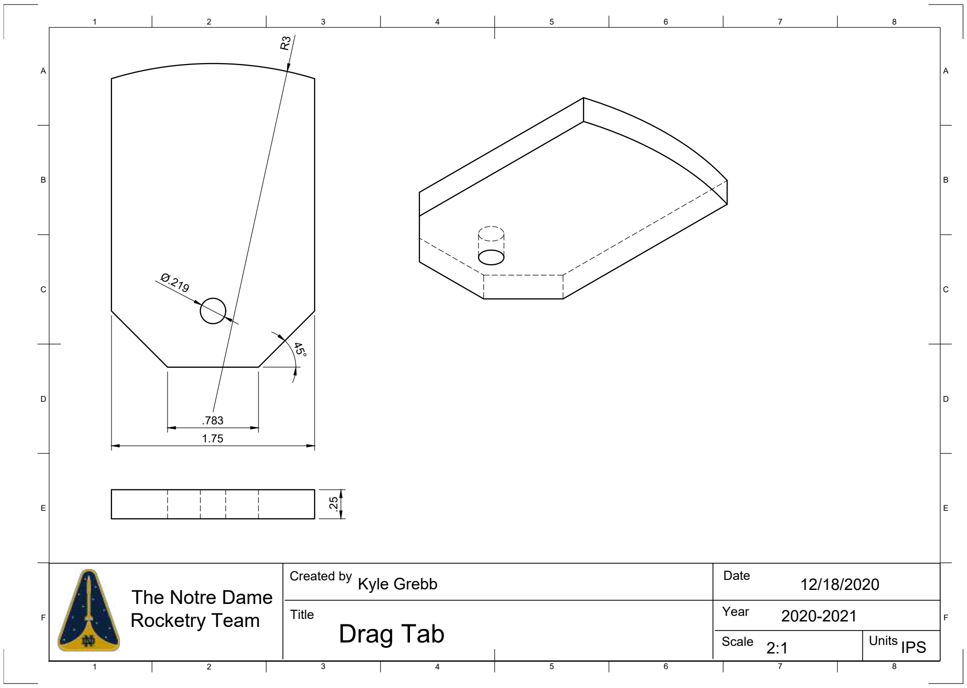


Figure 27: Drag Tab Drawing

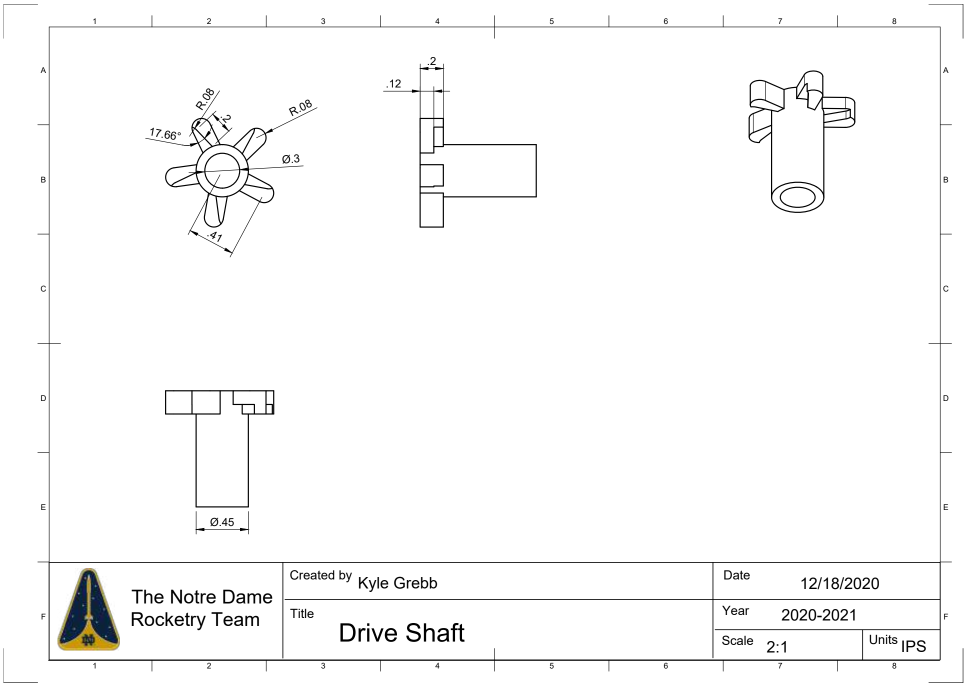


Figure 28: Drive Shaft Drawing

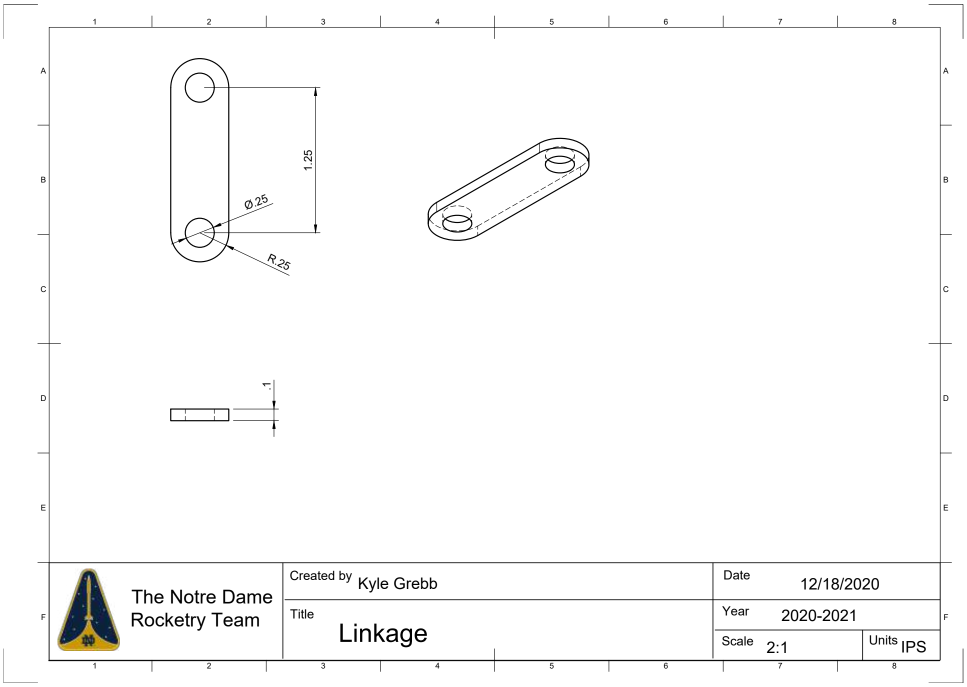


Figure 29: Linkage Drawing

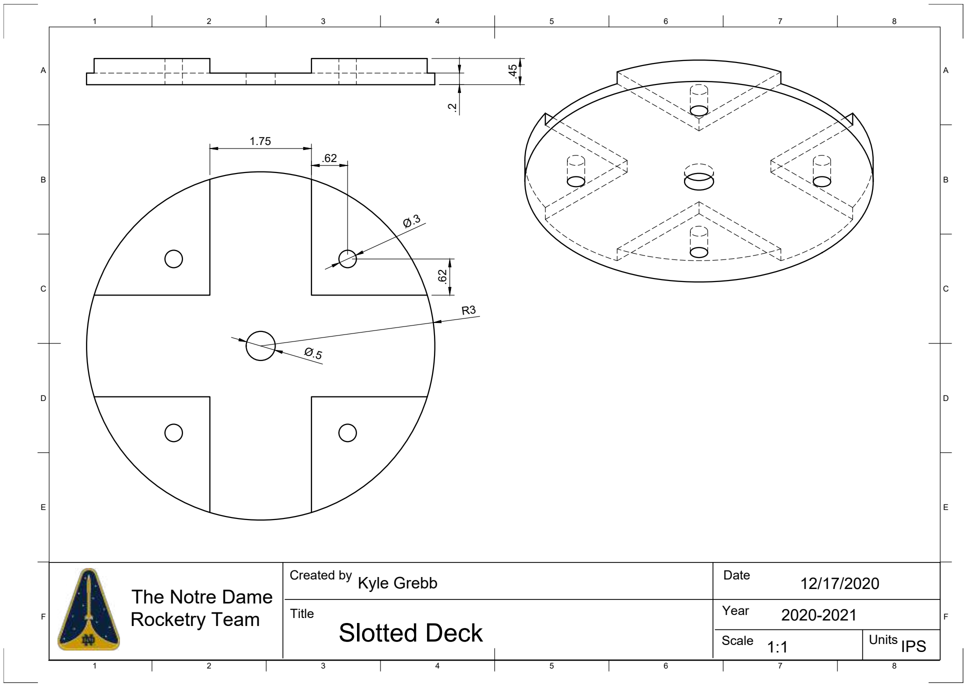


Figure 30: Slotted Deck Drawing

The next deck below the mechanism is also made of HDPE and supports the servo motor, which is attached to the deck with screws. Below the motor is the bottom deck which is made out of oak wood and has a twist to lock interface on its side to allow for easy removal from the rocket body. This deck will support a HDPE wall that is mounted with screws that the battery and other electronics will be mounted to.

To fabricate the ACS system, some components will be purchased while others will be created in house. The electrical components, the four threaded rods that hold the system together, the nuts, washers, bolts, screws, and the press fitted inserts will all be purchased. All of the other system components, such as the drag tabs and the various decks in the system, will be fabricated from various materials. The top bulkhead will be made from aluminum to provide extra strength, the two decks, tabs, and tab actuation mechanism will be made of high density polyethylene to reduce weight, and the bottom twist to lock mechanism will be made out of oak wood. To create these components, rectangular pieces of stock of each component's respective material will be placed on a CNC Techno Mill with a $\frac{1}{8}$” end mill available through the Notre Dame Student Fabrication Lab. The CNC Mill will be used to subtract material to create the desired geometry with a high degree of accuracy. Using a CNC Mill ensures that the parts will smoothly interface with each other so that there is no unwanted vibration of the system during flight, and that the rotational movement of the motor will produce precise movement of the drag tabs.

3.7.4.2 Finite Element Analysis

In order to confirm the structural integrity of the drag tabs during flight, a static FEA analysis was conducted on the CAD model of one drag tab using ANSYS Structural. The boundary conditions applied to the model reflect the conditions experienced by a drag tab when it is under the most stress during flight. This typically occurs when the tabs are fully deployed during burnout, which is the moment the velocity of the vehicle is the highest. The maximum drag force during flight was estimated to be 16.67 lbf. The drag tab model had a cylindrical support on the interior of the pin hole. The analysis settings were set to measure von-Mises stress and total deformation. The maximum stress predicted was 9731.7 psi and the maximum deformation predicted was 0.0268 mm. These values were confirmed by running the model with various mesh sizes that demonstrate that the values converged to the final values. The final results are shown in Figure 31.

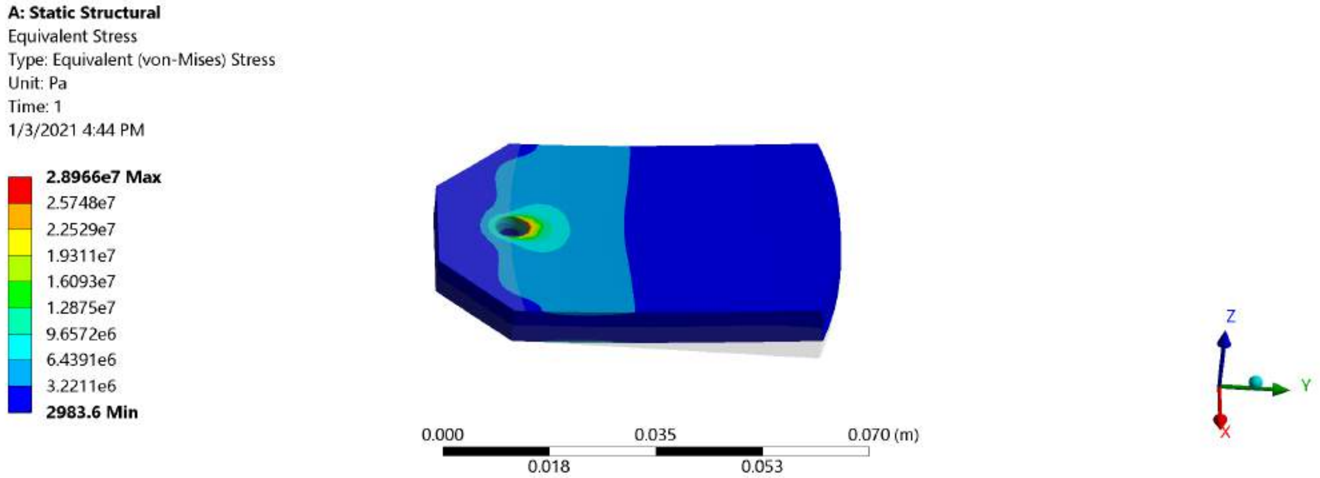


Figure 31: Drag Tab FEA von-Mises Stress

A similar analysis was conducted on the upper bulkhead of the apogee control system. This bulkhead was subject to force from the recovery load. The maximum recovery load was predicted to be 607.8 lbf. To simulate a worst case scenario, 150 % of this force was used in the model. The force used was 911.7 lbf. This force was applied to the center of the model and the supports were applied at all of the bolt holes on the model. Like the previous analysis, von-Mises stress and total deformation were measured. The maximum stress predicted was 1489 psi and the maximum deformation predicted was 0.002 mm. The resulting factor of safety was 26.86. Again, these values were confirmed by running the model with various mesh sizes that demonstrate that the values converged to the final values. The final results are shown in Figure 32.

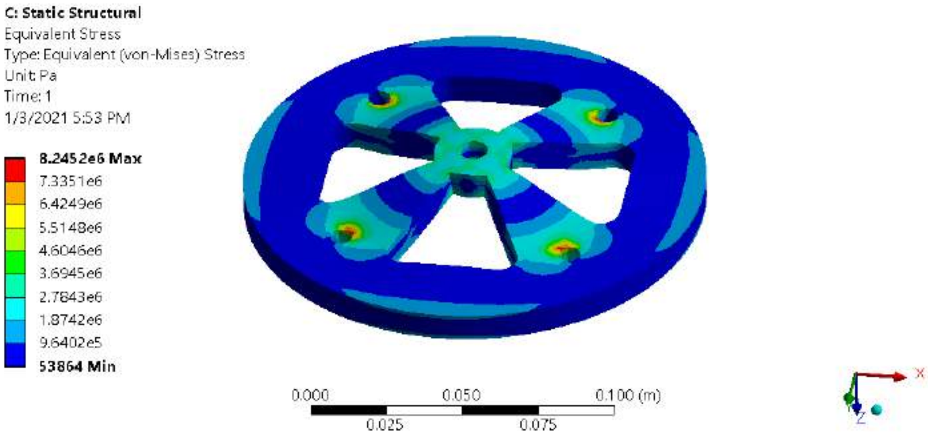


Figure 32: ACS Bulkhead FEA von-Mises Stress

3.7.4.3 System Integration

The system will be integrated into the fin can of the launch vehicle such that the drag tabs extend from the vehicle's center of pressure, and will consist of a series of HDPE decks slotted onto threaded rods. The rods will be secured into a wooden bulkhead at the aft end of the system, and an aluminum bulkhead at the fore end. The aluminum bulkhead will be carrying the majority of the force from the deployment of the recovery system, distributing that weight from an eyebolt in its center to the body tube of the vehicle. A model of the integrated system is shown in Figure 33.

In order to allow the tabs to extend outward from the body of the launch vehicle, slotted holes will be cut into the fin can body tube at 90 degree angles from each other, offset 45 degrees from the fins. To ensure that the control surfaces do not interfere with the body tube, they must be able to easily and securely align with the slotted holes. This will be accomplished using a twist-to-lock mechanism consisting of a ring adaptor and the base bulkhead of the ACS. The ACS bulkhead will be machined to include slots which will interface with protrusions on the inner surface of the ring adaptor, allowing for the system to be slotted in and given a 90 degree twist, locking it in place for alignment purposes. Following alignment, four screws will secure the top aluminum bulkhead, stabilizing the system and distributing the load of parachute from the eyebolt attached to the top bulkhead to the body of the fin can. A model of the twist-to-lock system is shown in Figures 34-35.

Figure 33: Integrated System

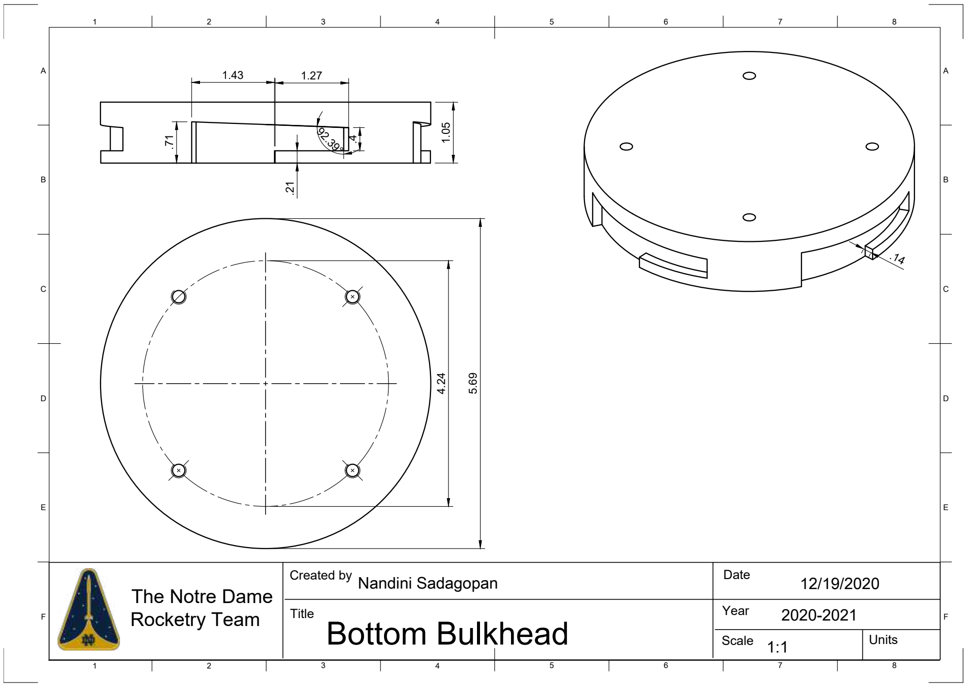


Figure 34: Bottom Bulkhead

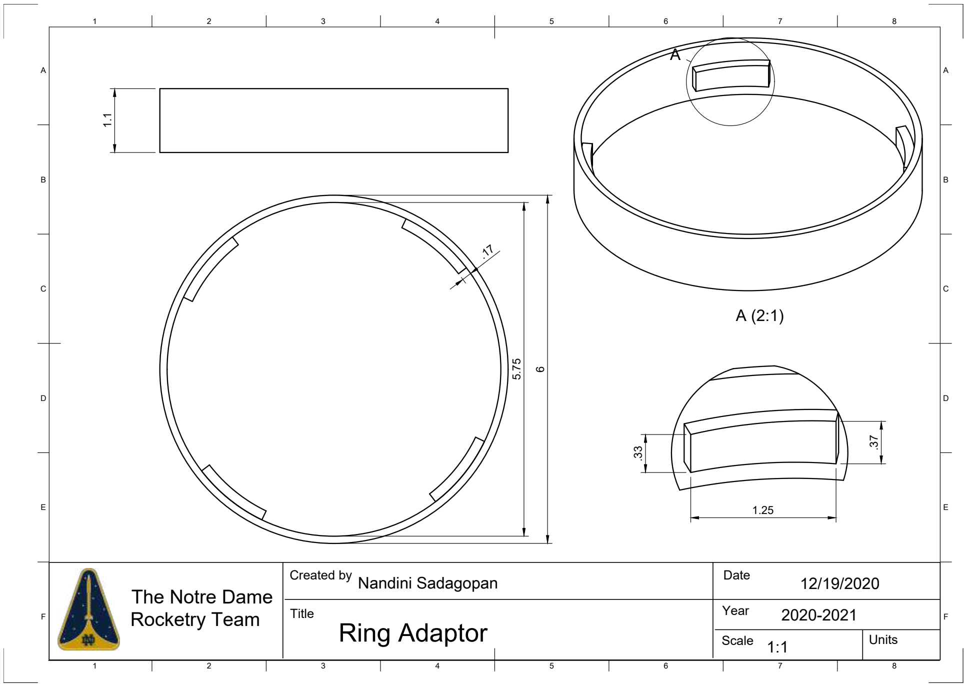


Figure 35: Ring Adaptor

3.7.5 Mass Statement

Table 21: ACS Mass Statement

Component/Subsystem	Basic Mass (oz.)	Predicted Mass (oz.)
Aluminum Bulkhead	12.09	12.57
Batteries	4.05	4.25
Drag Tabs	2.76	2.87
Electronics Bulkhead	2.43	2.72
Electronic Components	0.61	0.63
Eye Bolt	0.95	0.99
Linkage	0.45	0.47
Nuts	18.56	21.90
Servo Assembly	5.10	5.49
Shell with Grooves	5.32	5.53
Shoulder Screws	0.93	0.97
Threaded Rods	5.21	5.42
Twist Lock Mechanism	12.53	13.78
Total	**70.98**	**77.58**

As Table 21 shows, the total predicted mass of the ACS is 77.07 oz, which is less than the system allowable weight of 80oz (NDRT Req. AD.1).

3.7.6 Electrical Design

3.7.6.1 Sensors

The ACS will utilize the ADXL345 accelerometer to monitor the motion of the rocket with respect to the three coordinate axes (NDRT Req. AF.1). This information can then be used in a Kalman filter to create an estimate of the current velocity and altitude of the rocket. This data is essential for the PID control system to accurately adjust the drag force to ensure that the target apogee is reached. The technical specifications of the sensor can be seen in Table 22.

Table 22: ADXL345 Accelerometer Technical Specifications

Specification	Value
Sample Rate (Hz)	3.2k
Acceleration range (g)	2 - 16
Sensitivity (LSB/g)	32
Supply voltage range (V)	2.0 - 3.6
Weight (oz)	0.0448
Dimensions (mm)	24 x 19 x 2

The ADXL345 was selected for several reasons. It utilizes the I2C interface, which allows it to communicate with the Raspberry Pi. Additionally, it can detect up to 16 g's of acceleration, which is more than the maximum acceleration the rocket experiences during its ascent. Lastly, the sampling rate and sensitivity are sufficient for the accuracy needed for the PID control system to reach the target apogee.

In order to obtain a redundant acceleration measurement, as well as determine the orientation of the rocket, the ACS will utilize the MPU9250/6500 inertial measurement unit (IMU). This IMU contains an accelerometer, gyroscope, and magnetometer to provide motion and orientation data. This motion data can be utilized by the PID control algorithm to reach the target apogee. Table 23 contains the technical specifications of the MPU9250/6500.

The MPU9250/6500 was selected as the IMU for the ACS because of its high sampling rates and sensitivities for each sensor. However, since the IMU will be in 9-axis mode, the sampling rates will need to be lowered to not overload the microcontroller. Additionally, the IMU supports the I2C communication protocol, which allows it to easily interface with the Raspberry Pi. The ACS will utilize the MPL3115A2 barometer to measure the altitude of the

Table 23: MPU9250/6500 IMU Technical Specifications

Specification	Value
Accelerometer Range (g)	16
Accelerometer Sensitivity (LSB/g)	16,384
Accelerometer Max Sampling Rate(Hz)	32,000
Gyroscope Range (deg/s)	2000
Gyroscope Sensitivity (LSB/deg/sec)	131
Gyroscope Max Sampling Rate (Hz)	8000
Magnetometer Range (μT)	4800
Magnetometer Sensitivity (μT/LSB)	0.6
Magnetometer Max Sampling Rate (Hz)	1,000.00
Supply voltage range (V)	3.0 - 5.5
Weight (g)	2.72
Dimensions (mm)	25.5 x 15.4 x 3

launch vehicle from air pressure measurements (NDRT Req. AF.1). Altitude data is essential for the PID control algorithm, and can also be used to create an estimate for the velocity of the rocket. Table 24 contains the technical specifications of the MPL3115A2.

Table 24: MPL3115A2 Technical Specifications

Specification	Value
Sample Rate (Hz)	100
Accuracy (m)	0.3
Supply voltage range (V)	3.0 - 5.5
Weight (g)	1.2
Dimensions (mm)	18 x 9 x 2

The MPL3115A2 was selected as the barometer for the ACS due to its high sensitivity. Additionally, its sampleng rate of 100 Hz is sufficiently fast for this application. Lastly, this sensor utilizes the I2C communciation protocol, which makes it easy to interface with the Raspberry Pi.

3.7.6.2 Servo Motor

The ACS will use the Hitec D980TW servo motor in order to actuate the drag tabs. This servo was chosen because it has a relatively low current consumption and weight, while still maintaining a high enough torque capability to drive the actuation of the apogee control system. The Hitec D980TW servo also features an internal feedback resistor and a narrow deadband width of 2 microseconds, ensuring a high rotational precision. The specifications of the Hitech D980TW servo can be seen in Table 25.

Table 25: D980TW Servo Motor Technical Specifications

Specification	Value
Weight (oz)	2.76
Rotation speed (sec/60°)	.17
Torque (oz-in)	611.00
Cost ($)	170
Maximum rotation angle (°)	120
Operating current draw (A)	0.5
Operating voltage range (V)	4.8 - 7.4
Deadband Width (μs)	2

The programmability of the D980TW motor will enable the team to adjust the servo's movement to better suit the actuation of the ACS. The range of movement of the servo arm will need to be decreased to around 90° to ensure more precise movements. This will be accomplished through the DPC-11 servo programmer, allowing the team to interface a PC directly with the motor. The D980TW servo will be controlled by the Raspberry Pi Zero W microcontroller. The Raspberry Pi Zero W will output a PWM signal to the motor which will alter the angular position of the servo arm. This angular movement will deploy or withdraw the drag tabs to control the apogee of the launch vehicle. The circuit used to wire the D980TW servo with the lithium polymer battery power source is shown in Figure 36.

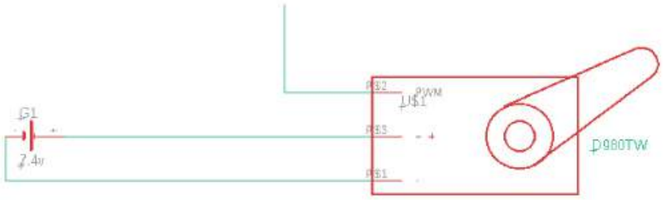


Figure 36: Servo Motor Wiring Diagram

3.7.6.3 Microcontroller

The ACS will utilize a Raspberry Pi Zero W microcontroller to integrates each of the system's sensors and actuators. The Raspberry Pi is capable of providing the computing power necessary for processing the sensor data and running the control algorithms. Additionally, its small form factor is optimal for the size of the rocket. Lastly, it supports the I2C protocol for interfacing with sensors, and can output a PWM signal to control the servo motor. Table 26 shows the technical specifications of the Raspberry Pi Zero W.

Table 26: Raspberry Pi Zero W Technical Specifications

Specification	Value
System Clock (GHz)	1
RAM (MB)	512
Number of pins	40
Micro USB Supply Voltage (V)	5

3.7.6.4 Batteries

The team has chosen a 2000 mAh 3.7 V Turnigy LiPo battery to power the Raspberry Pi, and a 1300mAh 7.4 V Zippy LiPo battery to power the servo motor. These batteries were chosen to allow for the system to remain powered in an idle state for at least two hours (NDRT Req. AE.2). The chosen servo motor has an idle current draw of 30 mA, with a maximum stalled current draw of 6200 mA. The Zippy battery has a capacity which will allow the servo to idle for at least 24 hours, which will provide redundancy in case the battery is not fully charged during rocket assembly. Likewise, the Raspberry Pi Zero draws an average of 100 mA, which means that the Turnigy battery will be able to power it for approximately 20 hours, which is well beyond the expected idle time of the system.

The Raspberry Pi Zero requires an input voltage of 5 Volts. In order to provide this from the 3.7 V Turnigy battery, a power booster must be used. In order to ensure that the Raspberry Pi receives a constant 5 V power, the team will utilize the Adafruit PowerBoost 500, which has been successfully utilized in previous years for this purpose.

3.7.6.5 Printed Circuit Board

The ACS will utilize a printed circuit board (PCB) to connect the three sensors to the Raspberry Pi Zero W in a compact and secure manner. The PCB was designed using Autodesk Eagle. Figure 37 shows a wiring diagram for the system, Figure 38 shows a schematic for the PCB, and Figure 39 shows a CAD model of the PCB.

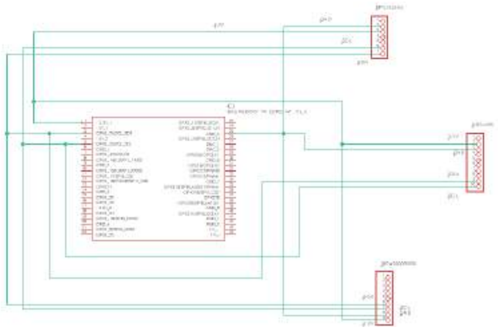


Figure 37: Printed Circuit Board Wiring Diagram

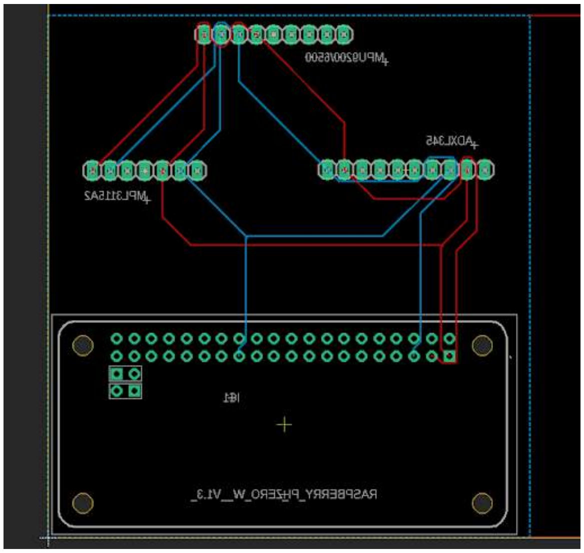


Figure 38: Printed Circuit Board Layout

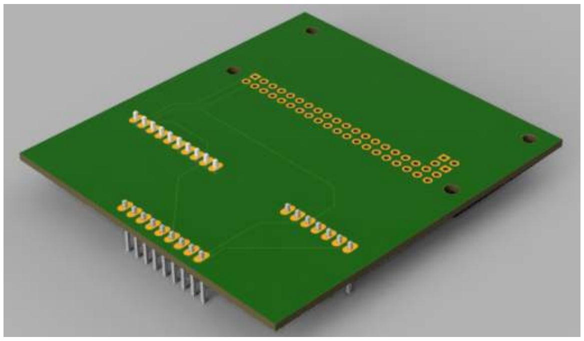


Figure 39: Printed Circuit Board CAD Model

3.7.6.6 Electrical Component Integration

All electrical components of the Apogee Control System will be secured to the HDPE decks and walls to ensure they will withstand forces and vibrations experienced during the launch vehicle's flight. The PCB design includes mounting holes to secure the Raspberry Pi microcontroller, altimeter, accelerometer, and IMU. The D980TW servo motor also has mounting holes and hardware which will be used to secure it to threaded holes in the bulkhead. The batteries used to power both the microcontroller and the servo motor will be secured in 3D printed battery mounts, epoxied to the HDPE. This will ensure that all electrical components are stable and will not become dislodged during flight.

3.7.7 Control Structure

The ACS control code will first activate when the system is initially powered on. An attached piezo buzzer will give auditory confirmation that the system is on and acquiring data. The system will write logging data to the SD card which acts as the memory for the Raspberry Pi, so detailed logs of the flight data and filtered outputs will be available for analysis after flight. Sensor data will be continuously passed through the Kalman filter, which will continue to search for liftoff, which will be indicated by either a spike in acceleration or a spike in altitude. Once in this stage, the system will use filtered data to determine when burnout has occurred. Once burnout is detected, a proportional-integral-derivative(PID) control algorithm will be used to determine the optimal drag tab extension length. The system will work as a closed-loop controller in order to continuously calculate the optimal drag tab extension and communicate this information with the servo motor. This process will finish when sensor data indicates that apogee has been reached, at which point the system will retract and remain dormant for the rest of flight. A flow chart of the ACS control structure can be seen in Figure 40.

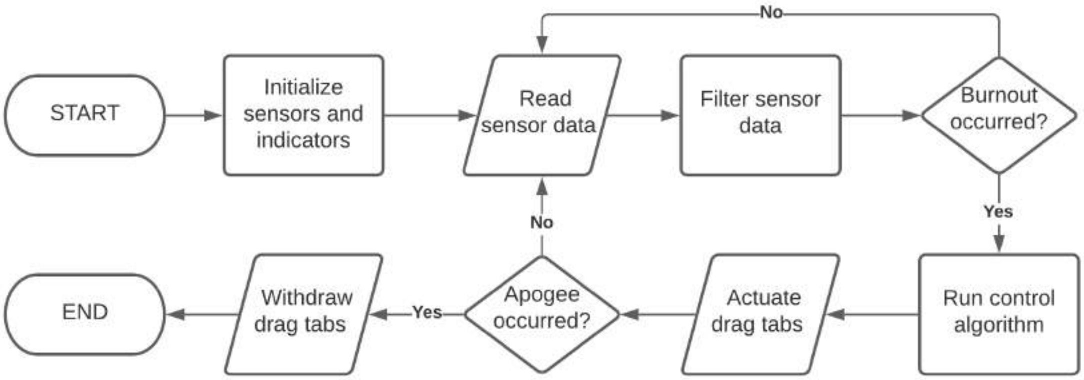


Figure 40: ACS Control Flow Diagram

3.7.7.1 Data Filtering

The ACS receives data in various forms about the state of the launch vehicle from several different sensors, all of which is useful for accurately determining the state of the rocket. The goal of the data filtering stage is to combine this sensor data with an estimate of the current state of the rocket to filter out noise and iteratively come to a new, more accurate estimate of the current state of the launch vehicle. The team has considered several data filtering algorithms, including the Gauss-Newton and Double-Exponent Smoothing filters, but ultimately decided to utilize a Kalman filter due to its relative accuracy, efficiency, and general ease of implementation.

One advantage the Kalman filter has over some other models is that it is “memoryless”. That is, the next state of the model (which in our case consists of the vertical position, acceleration, and velocity), is dependent only on the current state and current sensor data. This allows the model to make accurate predictions about the future state of the rocket while storing only the minimal amount of information.

Each iteration of the Kalman filter occurs in two stages: first, the filter uses a prediction stage to model the filter’s expectations of how the rocket will move. Second, the filter uses a step to update the filter and correct the extrapolation made in the prediction steps. The prediction step starts with the vector $\hat{x}_{k(-)} = \langle y, v_y, a_y \rangle$, which contains the current estimate of the state of the rocket. We use a matrix Φ_k to translate from an estimate of the current state $\hat{x}_k$ to an estimate of the next state, $\hat{x}_{k+1}$. This matrix is derived from basic kinematics equations, and is defined in Eq. 12.

$$\Phi_k = \begin{pmatrix} 1 & \Delta & \frac{1}{2}\Delta^2 \\ 0 & 1 & \Delta \\ 0 & 0 & 1 \end{pmatrix} \tag{12}$$

Here, Δ represents the change in time between this time sample and the previous time sample. This definition can then be combined with the definition of $\hat{x}_k$ to get the relation seen in Eq. 13.

$$\hat{x}_{k(-)} = \Phi_{k-1}\hat{x}_{k-1(+)} \tag{13}$$

The quantity $\hat{x}_{k(-)}$ represents the model’s estimate of the current state of the rocket obtained exclusively from the previous state. This can then be combined with the vector z, which contains the current sensor readings. We can use the matrix H to convert from vectors $\hat{x}$ in the “state” space to vectors z in the “sensor” space. We will use this conversion, along with the Kalman gain K, to create a more refined estimate of the rocket state using Eq. 14.

$$\hat{x}_{k(+)} = \hat{x}_{k(-)} + K_k(z_k - H_k\hat{x}_{k(-)}) \tag{14}$$

This quantity can then be outputted to the rest of the system, which will use it to inform the PID control algorithm and determine the current stage of flight the launch vehicle is in. However, some further analysis is still required to prepare the model for the next iteration. To do this, we introduce a couple extra matrices into the formulation. The matrices Q_k and R_k store the state and measurement covariances respectively, and are hyperparameters which need to be experimentally calibrated. Lastly, we introduce a matrix P_k, which gives an estimate of the current covariance of our $\hat{x}_k$. In order to update the Kalman gain matrix, the Eq. 16 - 17 are used.

$$
\begin{aligned}
P_{k(-)} &= \Phi_{k-1} P_{k-1(+)} \Phi_{k-1}^T + Q_{k-1} && (15) \\
P_{k(+)} &= [I - K_k H_k] P_{k(-)} && (16) \\
K_k &= P_{k(+)} H_k^T [H_k P_{k(+)} H_k^T + R_k]^{-1} && (17)
\end{aligned}
$$

In the definition of Eq. 5 above, I refers to the identity matrix. This filter relies on a basic, linear kinamatic model which assumes no drag. However, it is still effective at removing noise from the sensor data and performing a fusion of data from many disparate sensors. The team will consider several further optimizations on this approach, including the utilization of rotation data to correct for the tilt in the launch vehicle, although this model still provides a solid foundation for data filtering. Figure 41 shows the result from running a Kalman filter on the full-tab subscale test flight.

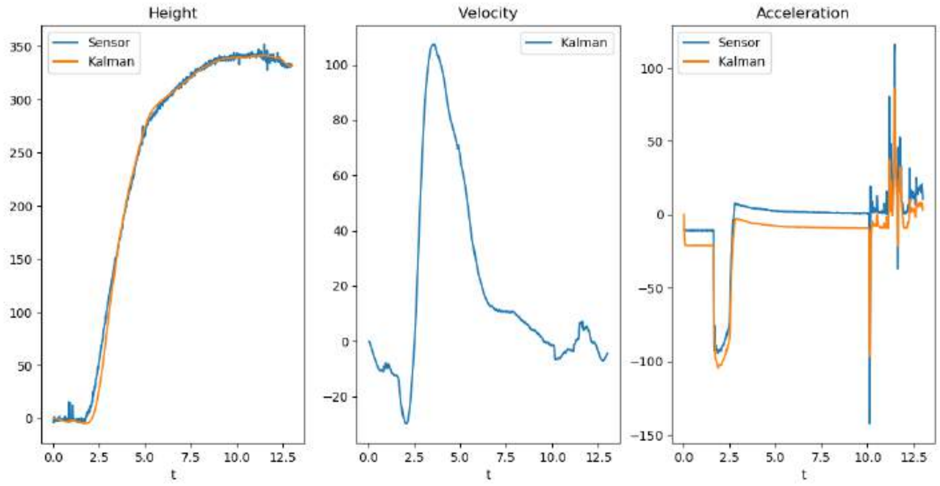


Figure 41: Kalman Filtered Subscale Data

As Figure 41 demonstrates, the Kalman filter is useful for smoothing out the otherwise noisy data, as well as giving a reasonable approximation for the velocity of the rocket.

3.7.7.2 Automatic Control Algorithm

After burnout has been detected, actuation of the drag tabs will be actively controlled with a PID algorithm until apogee is detected. The servo motor will function as the actuator, as its angle will adjust the extension of the tabs as previously described. The algorithm will incorporate model predictive features; from the current state of the rocket, a fourth order Runge-Kutta integration will be performed to predict the final apogee of the rocket. This predicted value will be compared to the target apogee of 5300 ft, and the tabs will be extended according to the PID control law given in Equation 18.

$$\Phi(s) = K_P E(s) + K_D s E(s) + K_I \frac{E(s)}{s} \tag{18}$$

Here, $E(s)$ is the error in the frequency domain, Φ is the angle of servo rotation, and K_P, K_D, and K_I are the proportional, derivative, and integral gains respectively. The integral of the error will be computed using a trapezoidal method of numerical integration, and the derivative of the error will be calculated using a first order backward finite difference method. The algorithm includes an error threshold such that the servo does not try to extend the tabs further than they are able. Because the drag varies so significantly between burnout and apogee, gain scheduling will be employed. Sets of gains will be selected for three regimes based on the airspeed of the rocket, which will allow finer adjustment and help prevent undershooting. In order to select the gains for each airspeed regime and test the effectiveness of the tabs, the flights will be simulated using a Matlab script based on OpenRocket modeling that will generate adaptive flight data.

3.7.8 Subscale Flight

The team completed a successful subscale launch on November 13th, 2020. This subscale test simulated the ACS by including three different 3D-printed rings constructed out of ABS plastic. These rings were 40 % scale models of the drag tabs at no extension, half extension, and full extension. Three launches were conducted, and a different tab ring was used for each. The half-extension and full-extension drag tab rings can be seen in Figure 42.

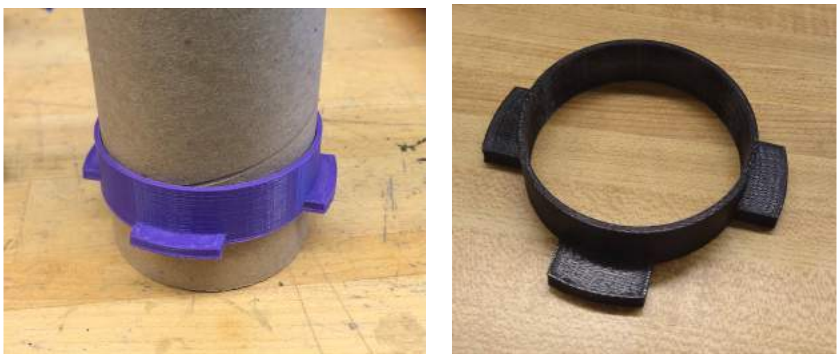


Figure 42: ACS Subscale Drag Tabs

3.7.8.1 Launch Analysis

In order to determine the efficacy of the drag tabs, as well as to prototype the sensor array, the team included a sensor sled inside the subscale launch vehicle. This sensor sled included an ADXL345 accelerometer, MPL3115A2 altimeter, and MPU9250/6500 IMU, as well as a Raspberry Pi Zero W microcontroller, which was powered by a 3.7 V battery attached to an Adafruit Powerboost 500. The assembled sensor array can be seen in Figure 43.

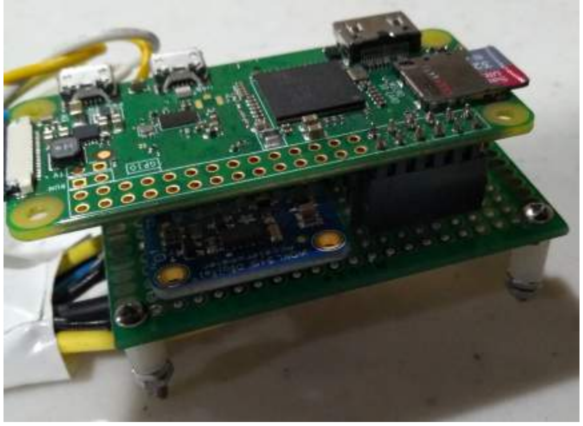


Figure 43: ACS Subscale Sensor Array

The team collected altitude data from the altimeter, acceleration data from the two accelerometers, and full gyroscope and magnetometer data from the IMU. The measured apogees from each flight are summarized in Table 27.

Table 27: ACS Detected Apogees

Flight	Full Tab	Half Tab	No Tab
Average Apogee (m)	291.5	340.9	323.9
Maximum Apogee (m)	301.3	351.8	341.4

Here, the average apogees were obtained by locating the index of the maximum altitude and averaging the altitudes of the preceding and following 10 indices. As this table demonstrates, the rocket generally reached a lower maximum altitude when drag tabs were present. The notable outlier to this trend is the half-tab flight. However, this discrepancy can be largely accounted for by differences in wind speed at the time of launch. Overall, the drag tabs were effective in adjusting the target apogee that the rocket approaches without compromising the stability of the rocket.

3.7.8.2 Implications for Full Scale

The results of the subscale launch have two main implications for the full scale ACS. Through this test flight, the team has managed to demonstrate that the sensor array functions properly, both in terms of the sensors themselves and the code used to read from them. The team was able to recover the sensor array and extract meaningful results from the collected data. Additionally, the team was able to demonstrate, at least to within a margin of error, that the ACS mechanism is able to apply a drag force to the rocket which is capable of decreasing its apogee. Going forward, the team will be able to utilize the data gathered from the subscale test flight to further refine its data collection and filtering process.

3.8 Launch Vehicle Recovery Subsystem

3.8.1 Mission Statement and Success Criteria

The launch vehicle recovery system will reliably return all vehicle components to the ground, specifically by fulfilling the following success criteria:

1. Each section of the vehicle will have a maximum kinetic energy of 75 ft-lb at landing (NASA Req 3.3).

2. Each section of the vehicle will land within 2500 ft of the launch pad (NASA Req 3.10).

3. Each section of the vehicle will descend from the vehicle's apogee in less than 90 seconds (NASA Req 3.11).

4. The recovery system will collect the official altitude readings from battery-powered altimeters, which will serve as proof of flight (NASA Req 3.4, NASA Req 2.3)

5. The recovery system will contain electronic tracking devices in each untethered section to transmit the vehicle's position during flight (NASA Req 3.12).

3.8.2 Recovery Subsystem Design Overview

The recovery system will reliably reduce the kinetic energy of each section of the launch vehicle by deploying parachutes at different altitudes (NASA Req 3.1). The launch vehicle will first be slowed by a drogue parachute, deployed by black powder charges at apogee, and then by the main parachute, which will also be deployed by black powder charges at 575 ft AGL (NASA Req 3.1.1). At 525 ft AGL, the nose cone will separate from the payload bay and deploy a small chute, allowing the payload to jettison. Figure 44 shows the general flight path of the launch vehicle.

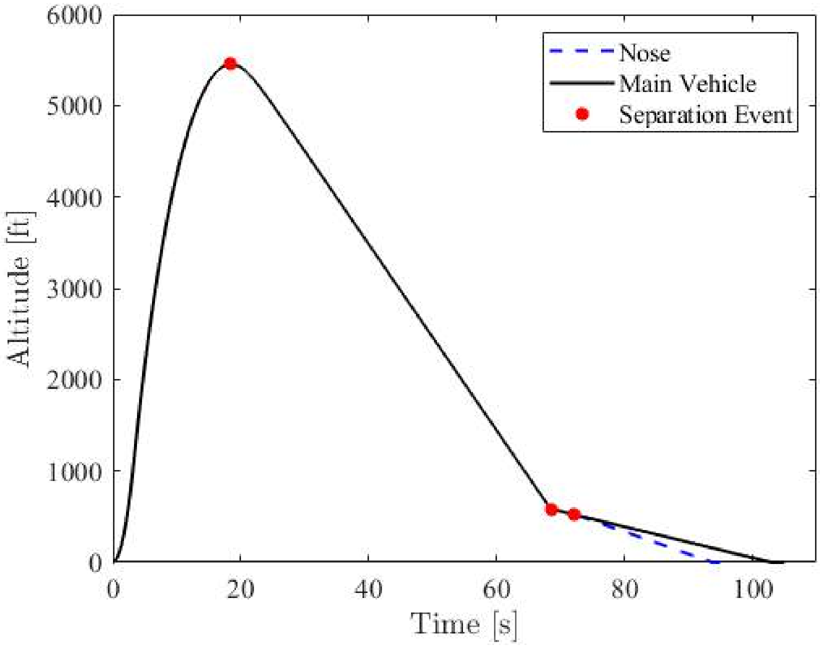


Figure 44: General Vehicle Flight Path

All parachutes will be protected from the ejection charges with deployment bags or fire-retardant blankets (NDRT Req. RF.2), and they will be connected to the recovery bulkheads via shock cords, quicklinks, and eyebolts. The main and drogue parachutes will be deployed by the same altimeters, located in the Compact Removable Avionics System-Main, or the CRAS-M. As the nose cone will descend untethered, it will have its own independent avionics system, the Compact Removable Avionics System-Secondary, or the CRAS-S. The black powder charges will be contained in PVC charge wells located on each of the CRAS-M and CRAS-S bulkheads. Both the CRAS-M and the CRAS-S will contain independently redundant electronics (NASA Req 3.4), and these recovery electronics will be entirely separate from any payload circuitry (NASA Req 3.8).

3.8.3 Mass Statement

Table 28 contains the mass estimate for the CRAS-M, and Table 29 contains the mass estimate for the CRAS-S.

Table 28: CRAS-M Mass Estimate

Component	Basic Mass (oz)	Predicted Mass (oz)
Parachute System	65.00	70.95
Bulkheads	25.65	26.77
Attachment Hardware	22.01	22.56
Ballast	22.00	22.00
Electronics	6.57	6.80
Other Hardware	3.59	3.79
Charge Wells	3.59	3.79
Avionics Mounting	3.06	3.19
Shielding	1.32	1.40
Altimeters	1.08	1.10
Energetics	1.07	1.23
Epoxy and Clay	0.70	0.85
Total	**154.79**	**163.64**

Table 29: CRAS-S Mass Estimate

Component	Basic Mass (oz)	Predicted Mass (oz)
Electronics	6.11	6.33
Parachute System	5.20	5.32
Bulkheads	4.22	4.54
Attachment Hardware	2.46	2.55
Charge Wells	1.58	1.67
Shielding	1.51	1.60
Other Hardware	1.28	1.35
Altimeters	0.83	0.85
Electronics Mounting	0.53	0.56
Epoxy and Clay	0.20	0.24
Energetics	0.07	0.08
Total	**24.00**	**25.11**

As shown in Tables 28 and 29, both the CRAS-M and the CRAS-S are designed within the mass allowances set by NDRT Reqs. RD.1 and RD.4.

3.8.4 Deployment Method

Black powder ejection charges were chosen to deploy the parachutes because of their low weight, low cost, and simplicity relative to other systems considered, such as compressed CO_2 or mechanical systems, satisfying NASA Req 3.1.3 that motor ejection will not be used as a form of deployment. The drogue parachute deployment will be controlled by three independent altimeters each with their own black powder charges. The primary ejection charge will be ignited at apogee, the secondary charge will be ignited one second after apogee, and the tertiary charge will be ignited two seconds after apogee (NASA Req 3.1.2). The same deployment sequencing will be employed for the main deployment at 575 ft AGL and will be controlled from the same altimeters. The nose recovery will be controlled by two independent altimeters each with their own black powder charge. The primary charge will be ignited at 525 ft AGL and the secondary charge will be ignited one second later. Removable shear pins will be used to secure the main, drogue, and nose parachute compartments (NASA Req 3.9). The complete calculations for sizing the black powder charges are shown in Appendix A and the values for each charge are shown in Table 30.

Table 30: Black Powder Allocations

Event	Charge	Predicted Mass (g)
Drogue	Primary	0.7
	Secondary	1.2
	Tertiary	1.2
Main	Primary	4.2
	Secondary	4.7
	Tertiary	4.7
Nose	Primary	1.9
	Secondary	2.4

These values will be confirmed during ground testing (NASA Req 3.2), and the procedure for this test is outlined in Test TR.3.

3.8.5 Parachute System Design

3.8.5.1 First Stage

A two ft diameter, parabolic parachute with a C_d of 0.97 will be deployed at apogee as a drogue parachute. This parachute was chosen over the two ft elliptical parachute with a C_d

equal to 1.5 discussed in the preliminary design report because its drag coefficient and effective area lowered the decent time and drift radius to under 90 seconds and 2500 ft, respectively (NASA Req 3.10; NASA Req 3.11), without causing an acceleration in excess of 46 g at main deployment (NDRT Req. RE.1). Table 31 shows the parameters of the chosen drogue parachute.

Table 31: Drogue Parachute Parameters

Parameter	Value
Diameter (ft)	2
C_d	0.97
Shape	Parabolic
Brand	Rocketman
Packing Volume (in^3)	7.96
Mass (oz)	1.5
Canopy Material	1.1 oz Ripstop Nylon
Shroud Lines	250 lb Nylon
No. Shroud Lines	4

The terminal speed of descent, V_T, under the drogue chute was calculated using the following equation:

$$V_T = \sqrt{\frac{mg}{\frac{\pi}{8}\rho C_d D^2}} = 110\,\text{ft/s} \tag{19}$$

where m is the total vehicle mass, g is the acceleration due to gravity, ρ is the density of air, C_d is the parachute's drag coefficient, and D is the parachute's diameter. The maximum loads expected under the drogue are due to the accelerations of main and drogue deployment. The calculation for the acceleration due to main deployment, shown in Section 3.8.5.2, was found to be 36 g. The calculation for the maximum acceleration due to drogue deployment, expected if the primary and secondary black powder charges are insufficient and deployment occurs two seconds after apogee, is shown in Equation 21.

$$V_2 = V_{apo} + gt = 64.4\,\text{ft/s} \tag{20}$$

$$a_d = \frac{\frac{\pi}{8}\rho C_d D^2 V_2^2}{mg} = 0.34\,\text{g} \tag{21}$$

where V_2 is the vehicle speed two seconds after apogee, V_{apo} is the speed at apogee, t is the time after apogee, and a is the maximum expected acceleration due to drogue deployment. This is a worst-case acceleration calculation, using the assumption that the parachute opens instantaneously and that the primary and secondary charges fail to separate the airframe sections. The resultant forces on the parachute system from the two events are calculated in Equations 22 and 23.

$$F_{\text{drogue}} = ma_d = 15.0\,\text{lbf} \tag{22}$$

$$F_{\text{main}} = ma_m = 1588\,\text{lbf} \tag{23}$$

The parachute and attachment hardware setup for drogue deployment is shown in Figure 45 and will be discussed in the following paragraphs.

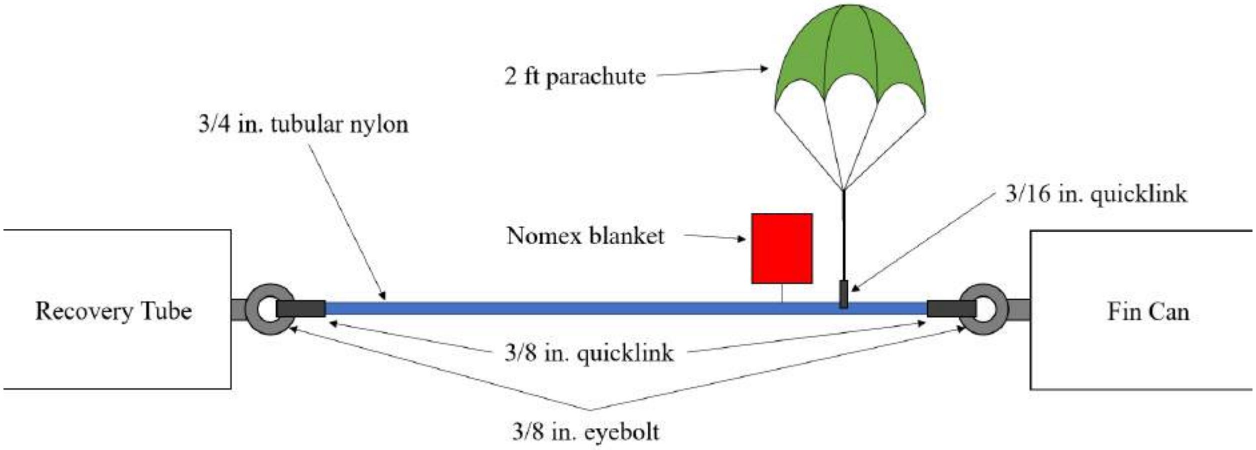


Figure 45: Drogue Parachute Setup

The drogue parachute will be attached to the launch vehicle by means of a recovery harness which also acts as a shock cord. The specifications of this recovery harness are shown in Table 32.

Table 32: Drogue Recovery Harness Parameters

Parameter	Value
Width (in)	3/4
Length (ft)	35
Material	Tubular Nylon
Brand	OneBadHawk
Breaking Strength (lbs)	2300

The shock cord for the first stage of recovery takes the full load of both the drogue and main deployment, meaning it has a FOS of 1.5 (NDRT Req RF.7). The shock cord is connected to the airframe via 3/8 in. stainless steel quicklinks and 3/8 in. forged stainless steel eyebolts, which each take a portion of the opening load proportionate to the mass of the sections underneath them. The eyebolts and quicklinks on the drogue cord only carry the fin can, which sets the force as:

$$F_{\text{fin can}} = m_{\text{fin can}} a_m = 608\,\text{lbf} \tag{24}$$

where m_{fincan} and a_m are, respectively, the mass and acceleration of the fin can at main parachute deployment. The 3/8 in. quicklinks can withstand a maximum shock load of 6000 lbs, which translates to a FOS of 9.87, and the 3/8 in. eyebolt can withstand a maximum shock load of 3100 lbs for a FOS of 5.11 (NDRT Req RF.7). The drogue parachute will be attached to the recovery harness using a 3/16 in. quick link, which can withstand a maximum static load 875 lbs. This is far greater than the maximum expected load that the drogue parachute and quicklink will experience. To protect the drogue parachute and recovery harness from the effects of the black powder ejection mechanism, a nomex fire-retardant blanket will be wrapped around the parachute and harness. This protection mechanism was chosen due to its low weight, simplicity, and efficacy.

3.8.5.2 Second Stage

A 12 ft diameter, parabolic parachute with a C_d of 0.97 will be deployed at 575 ft. AGL as the main parachute. This parachute will be stowed in a deployment bag and guided open by a two ft elliptical pilot chute with a C_d equal to 1.5. Table 33 shows the parameters of the chosen Main parachute, and Table 34 shows the parameters of the pilot chute.

Table 33: Main Parachute Parameters

Parameter	Value
Diameter (ft)	12
C_d	0.97
Shape	Parabolic
Brand	Rocketman
Packing Volume (in^3)	138.23
Mass (oz)	17
Canopy Material	1.1 oz Ripstop Nylon
Shroud Lines	Nylon
No. Shroud Lines	4

Table 34: Pilot Parachute Parameters

Parameter	Value
Diameter (ft)	2
C_d	1.5
Shape	Elliptical
Brand	Fruity Chutes
Packing Volume (in^3)	12.2
Mass (oz)	2.2
Canopy Material	1.1 oz Ripstop Nylon
Shroud Lines	220 lb Nylon
No. Gores	8

The terminal speed of descent, V_T, under the main chute was calculated using the following equation:

$$V_{T1} = \sqrt{\frac{m_{575} g}{\frac{\pi}{8}\rho C_d D^2}} = 18.4\,\mathrm{ft/s} \tag{25}$$

$$V_{T2} = \sqrt{\frac{m_{525} g}{\frac{\pi}{8}\rho C_d D^2}} = 16.6\,\mathrm{ft/s} \tag{26}$$

where m_{575} is the total vehicle mass at an altitude of 575 ft AGL and m_{525} is the total vehicle mass at 525 ft AGL after payload and nose jettison. The maximum load expected under the main chute is due to the acceleration of main deployment, and the calculation is shown in Equation 27.

$$a_m = \frac{\frac{\pi}{8}\rho C_d D^2 V_{T1}^2}{m_{575} g} = 36\,\mathrm{g} \tag{27}$$

As in Section 3.8.5.1, this is a worst-case acceleration calculation, assuming that the parachute opens instantaneously. The resultant force on the shock cord from the main separation event was calculated Equation 23 to be 1588 lbf. The parachute setup and attachment hardware for drogue deployment is shown in Figure 46.

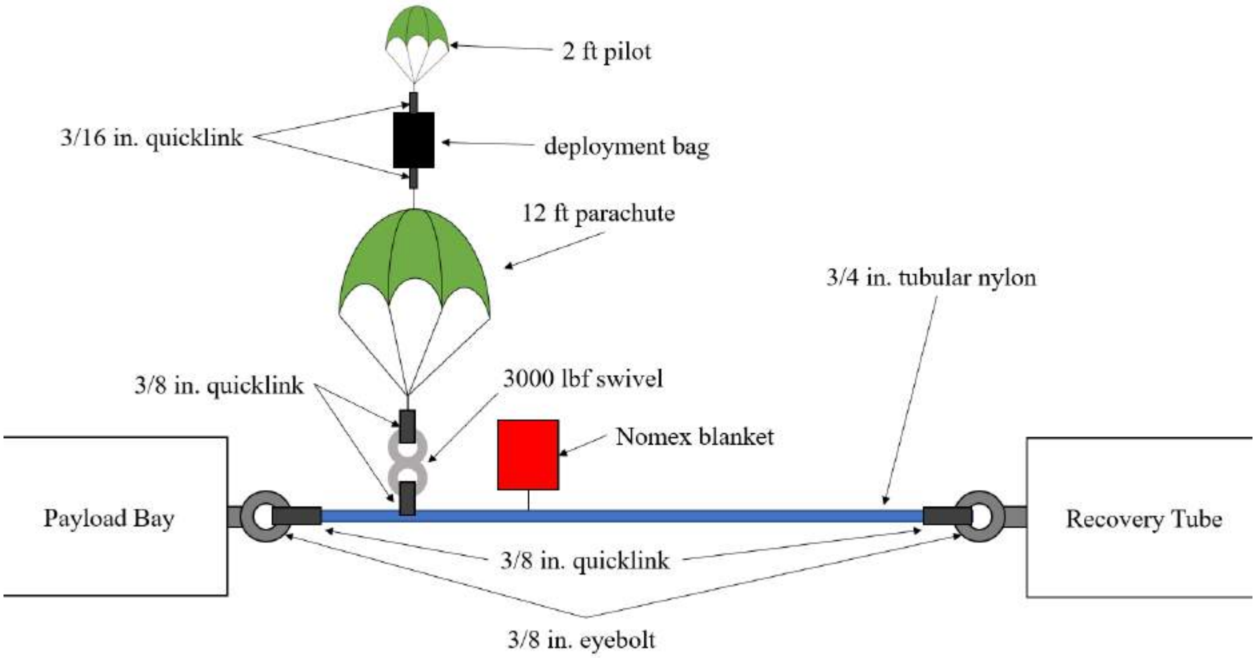


Figure 46: Main Parachute Setup

The main parachute will be attached to the launch vehicle by means of a recovery harness which also acts as a shock cord. The specifications of this recovery harness are shown in Table 35.

Table 35: Main Recovery Harness Parameters

Parameter	Value
Width (in)	3/4
Length (ft)	35
Material	Tubular Nylon
Brand	OneBadHawk
Breaking Strength (lbs)	2300

This shock cord takes the full load of main deployment, meaning it has a FOS of 1.5 (NDRT Req RF.7). The shock cord is connected to the parachute with two 3/8 in. stainless steel quicklinks and a 3000 lb swivel. The quicklinks can withstand a maximum shock load of 6000 lbs for a FOS of 3.78, and the swivel has a FOS of 1.89. The shock cord is attached to the airframe on either end via 3/8 in. stainless steel quicklinks and 3/8 in. forged stainless steel eyebolts, which each take a portion of the opening load proportionate to the mass of the sections underneath them:

$$F_{\text{paybay}} = (m_{\text{paybay}} + m_{\text{nose}})a_m = 460\,\text{lbf} \tag{28}$$

$$F_{\text{recovery}} = (m_{\text{recvovery}} + m_{\text{fin can}})a_m = 966\,\text{lbf} \tag{29}$$

The payload quicklink can withstand a maximum shock load of 6000 lbs, which translates to a FOS of 13.04, and the payload eyebolt can withstand a maximum shock load of 3100 lbs for a FOS of 6.74. The recovery quicklink can withstand a maximum shock load of 6000 lbs, which translates to a FOS of 6.21, and the 3/8 in. eyebolt can withstand a maximum shock load of 3100 lbs for a FOS of 3.21. The pilot parachute and deployment bag will be attached to the main chute using 3/16 in. quicklinks, which can withstand a maximum static load 875 lbs. This is far greater than the maximum expected load that the pilot chute and deployment bag will experience. The deployment bag and a Nomex fire-retardant blanket will be used to protect the main parachute and recovery harness against debris and gases from the black powder ejection.

3.8.5.3 Payload Jettison

A two ft diameter, elliptical parachute with a C_d of 1.5 will be deployed at 525 ft AGL as the main parachute for nose recovery. This parachute was chosen because its drag coefficient and effective area lowered the decent time and drift radius of the nose to under 90 seconds and 2500 ft, respectively (NASA Req 3.10; NASA Req 3.11). Table 36 shows the parameters of the chosen drogue parachute. The terminal speed of descent, V_T, under the nose chute was calculated using the following equation:

Table 36: Nose Parachute Parameters

Parameter	Value
Diameter (ft)	2
C_d	1.5
Shape	Elliptical
Brand	Fruity Chutes
Packing Volume (in^3)	12.2
Mass (oz)	2.2
Canopy Material	1.1 oz Ripstop Nylon
Shroud Lines	220 lb Nylon
No. Gores	8

$$V_T = \sqrt{\frac{mg}{\frac{\pi}{8}\rho C_d D^2}} = 24.4\,\text{ft/s} \tag{30}$$

where m is the mass of the nose system, g is the acceleration due to gravity, ρ is the density of air, C_d is the parachute's drag coefficient, and D is the parachute's diameter. The maximum loads expected under the nose chute are due to the accelerations of nose deployment:

$$a_n = \frac{\frac{\pi}{8}\rho C_d D^2 V_{T2}^2}{m_{nose} g} = 0.46\,\text{g} \tag{31}$$

where V_2 is the vehicle speed two seconds after apogee, V_{apo} is the speed at apogee, t is the time after apogee, and a_n is the maximum expected acceleration due to drogue deployment. This is a worst-case acceleration calculation, using the assumption that the parachute opens instantaneously and that the primary and secondary charges fail to separate the airframe sections. The resultant forces on the parachute system from the events was calculated:

$$F_{\text{nose}} = m_{\text{nose}} a_n = 1.54\,\text{lbf} \tag{32}$$

The parachute and attachment hardware setup for nose jettison is shown in Figure 47 and will be discussed in the following paragraphs.

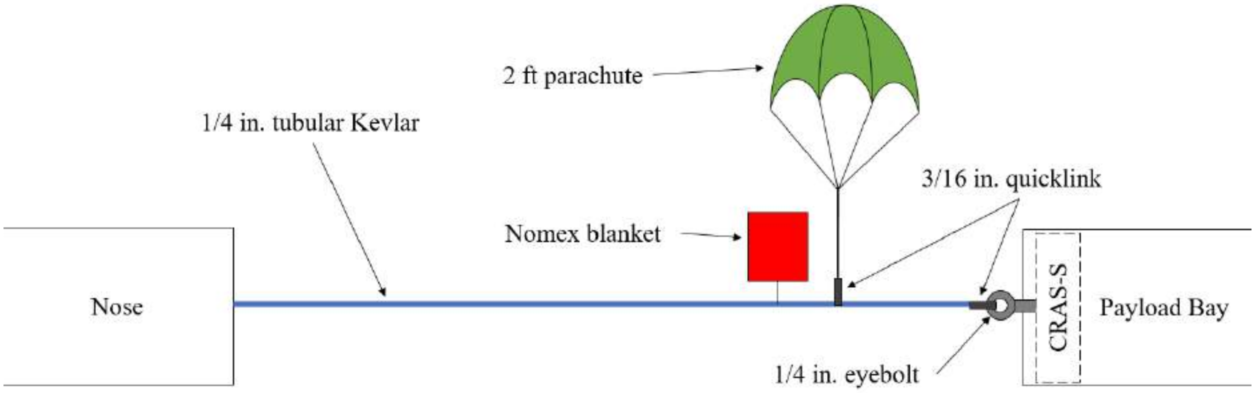


Figure 47: Nose Parachute Setup

The drogue parachute will be attached to the launch vehicle by means of a recovery harness which also acts as a shock cord. The specifications of this recovery harness are shown in Table 37.

Table 37: Nose Recovery Harness Parameters

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

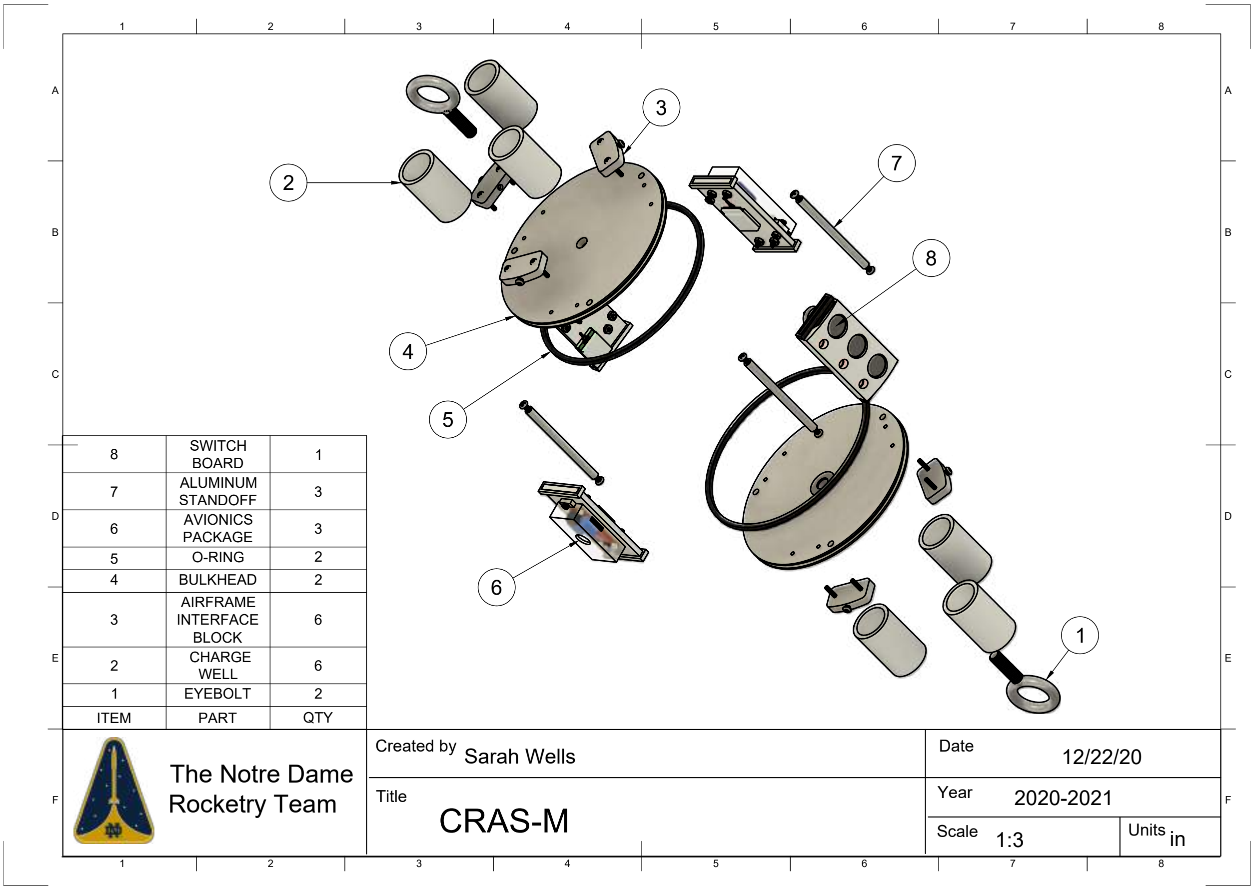
Using the breaking strength in Table 37, the shock cord has a FOS of 779.2 (NDRT Req RF.7). The airframe is connected to the shock cord on one ends with a 3/16 in. stainless steel quicklink, as is the parachute. This quicklink is attached to a 1/4 in. forged stainless steel eyebolt with a max load of 650 lbs for a FOS of 471. The quicklink itself can withstand a maximum static load of 875 lbs. This is far greater than the maximum expected load that the drogue parachute and quicklink will experience. The other end of the shock cord will be epoxied into the nosecone. The parachute and recovery harness will be wrapped in a nomex fire-retardant blanket as protection from the debris and gases emitted from the black powder ejection mechanism. The fire retardant blanket was chosen as a protection mechanism due to its simplicity, low weight, and efficacy.

3.8.6 Component Level Design

3.8.6.1 CRAS-M

The CRAS-M, shown in Figure 48, controls the deployment of the drogue and main parachutes and is located in the recovery bay. It consists of two aluminum bulkheads which enclose three avionics packages and a switchboard containing three key-lock switches for the altimeters, all connected by minimally load bearing aluminum standoffs. The bulkheads distribute the force from the parachutes upon deployment to the airframe and secure the system within the launch vehicle. Fiberglass, wood, and polycarbonate were considered as material for the bulkheads but aluminum was ultimately chosen through a trade study due to its high strength to weight ratio and ease of machining. Each bulkhead will house three PVC pipe charge wells for the black powder ejection charges and a 3/8 in. eyebolt to secure the recovery harness, as was discussed in Sections 3.8.5.1 and 3.8.5.2. Both of these eyebolts have FOS greater than 2 (RF.7).

Since the bulkhead, dimensions shown in Figure 49, transmits the majority of the recovery load to the airframe, Finite Element Analysis was performed on the bulkhead using ANSYS Structural. Figure 50 shows the simulated loading on the bulkhead and the resultant Von Mises

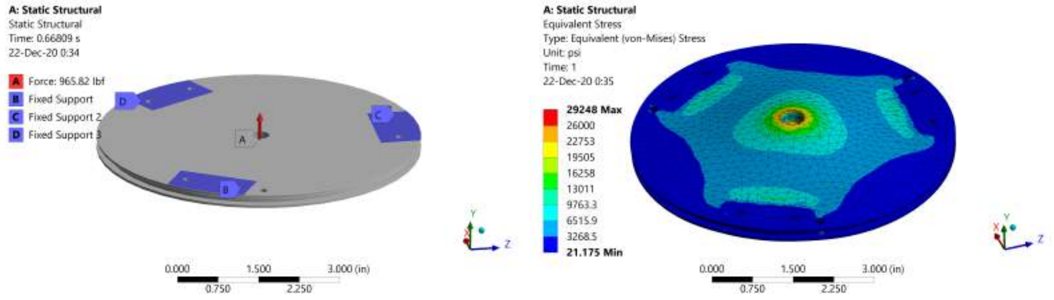


ITEM	PART	QTY
8	SWITCH BOARD	1
7	ALUMINUM STANDOFF	3
6	AVIONICS PACKAGE	3
5	O-RING	2
4	BULKHEAD	2
3	AIRFRAME INTERFACE BLOCK	6
2	CHARGE WELL	6
1	EYEBOLT	2

Created by Sarah Wells
Title CRAS-M
Date 12/22/20
Year 2020-2021
Scale 1:3
Units in

Figure 48: CRAS-M Exploded View

stress. The recovery loading was simulated by fixing the area that contacts the airframe interface blocks, dimensions shown in Figure 51, and applying an axial force of 966 lbf, which was calculated in Section 3.8.5.2 on the area that contacts the eyebolt washer. Using the finest possible mesh, the resultant peak stress on the bulkhead was 29,350 psi. The ultimate tensile strength of Aluminum 6061 T6 is 45,000 psi, giving the bulkhead a FOS of 1.54.



(a) Simulated Forces (b) Results

Figure 50: CRAS-M Bulkhead FEA

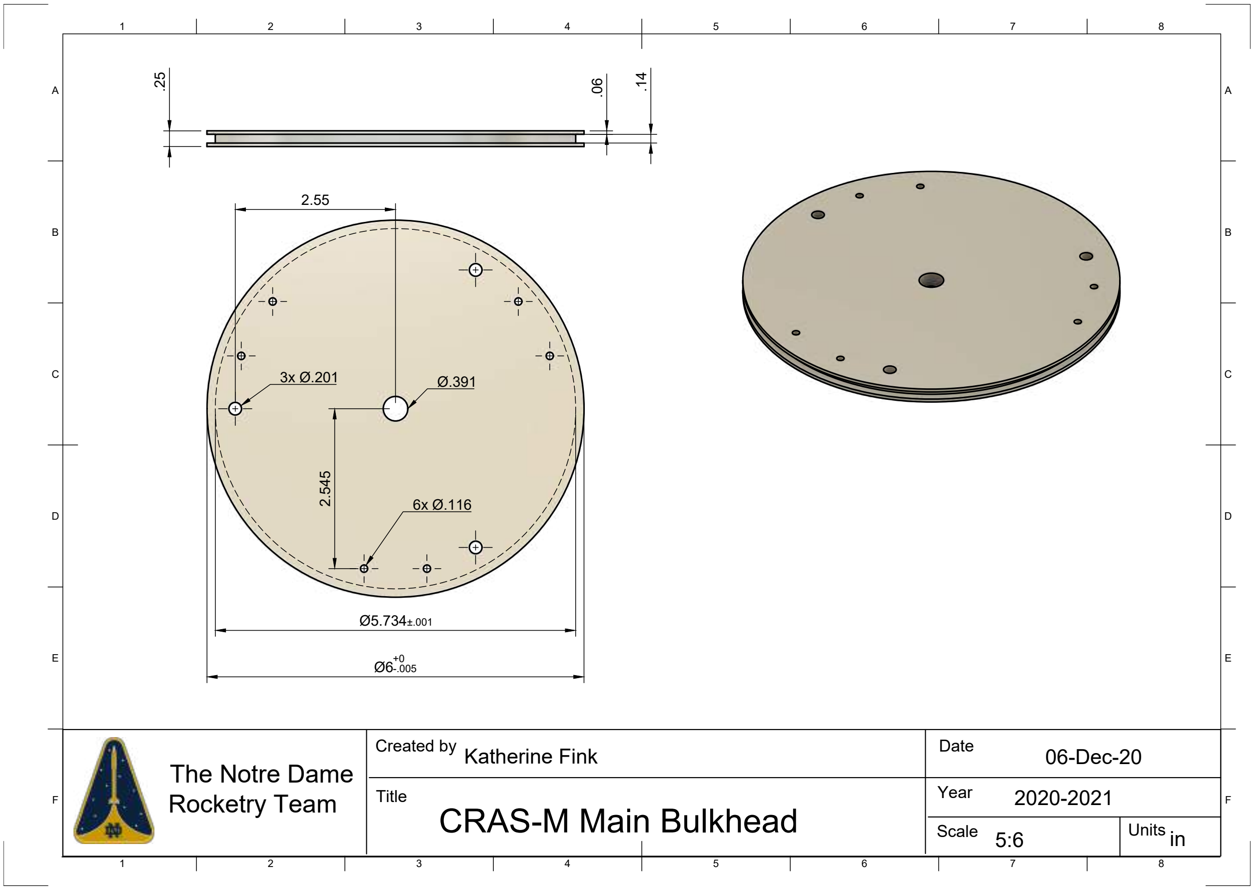


Figure 49: CRAS-M Bulkhead Drawing

The bulkhead will also be sealed tightly to the airframe with the use of an O-ring to ensure that the integrated avionics packages will not be impacted by the black powder ejection charges. The O-ring was chosen due to its reliability and reusability. The CRAS-M bulkheads will be secured directly into the airframe through airframe interfacing mounting blocks. This pathway will be the main load bearing path of the CRAS-M and the interior will experience minimal force. The bulkheads will be secured to the airframe with 3 Alloy Steel screws with a 12-24 thread and a length of 3/8 in. on each bulkhead to ensure that the pathway is able to safely withstand the maximum level of possible load. The FOS for the screw was calculated:

$$FOS = \frac{\tau_{max}\frac{\pi}{4}D^2}{\frac{1}{n}F_{main}} = 4.54 \tag{33}$$

where τ_{max} is the max shear strength of the screw, 68400 psi, D is the screw's minor diameter, n is the number of screws used, and F_{main} is the force from main deployment. Although the entire CRAS-M will contain six, load-bearing screws in total, the inner avionics packages and aluminum standoffs are minimally load bearing. Thus, using a worst case analysis, only three screws were considered when calculating the factor of safety for each screw evaluated.

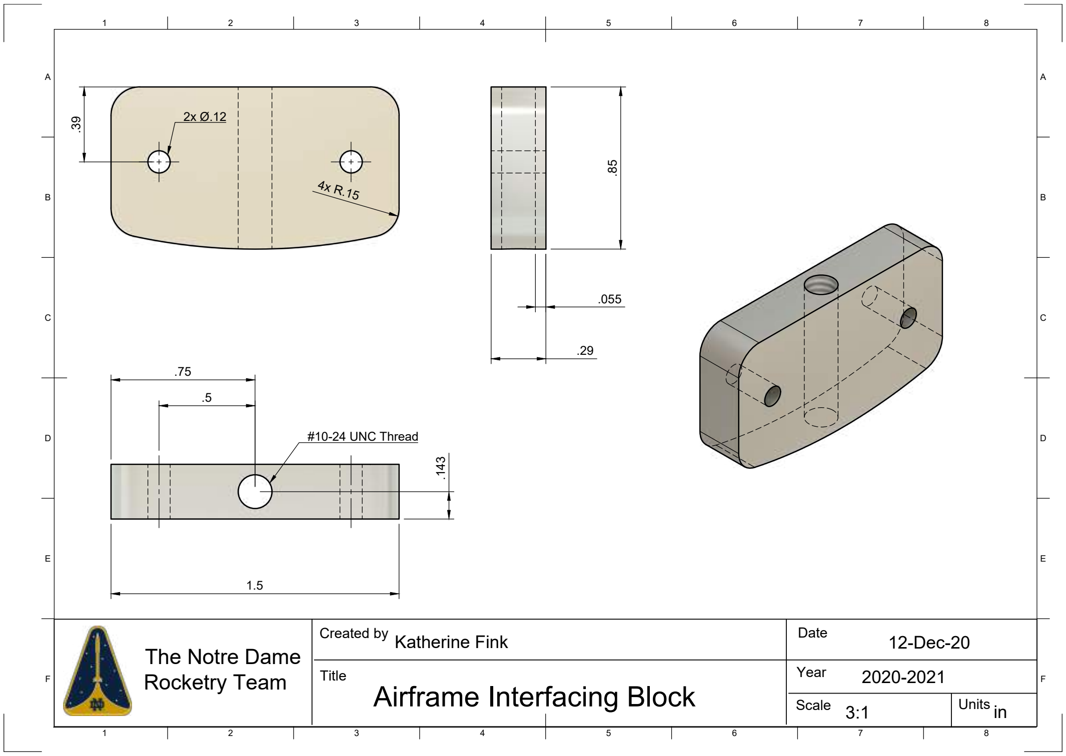
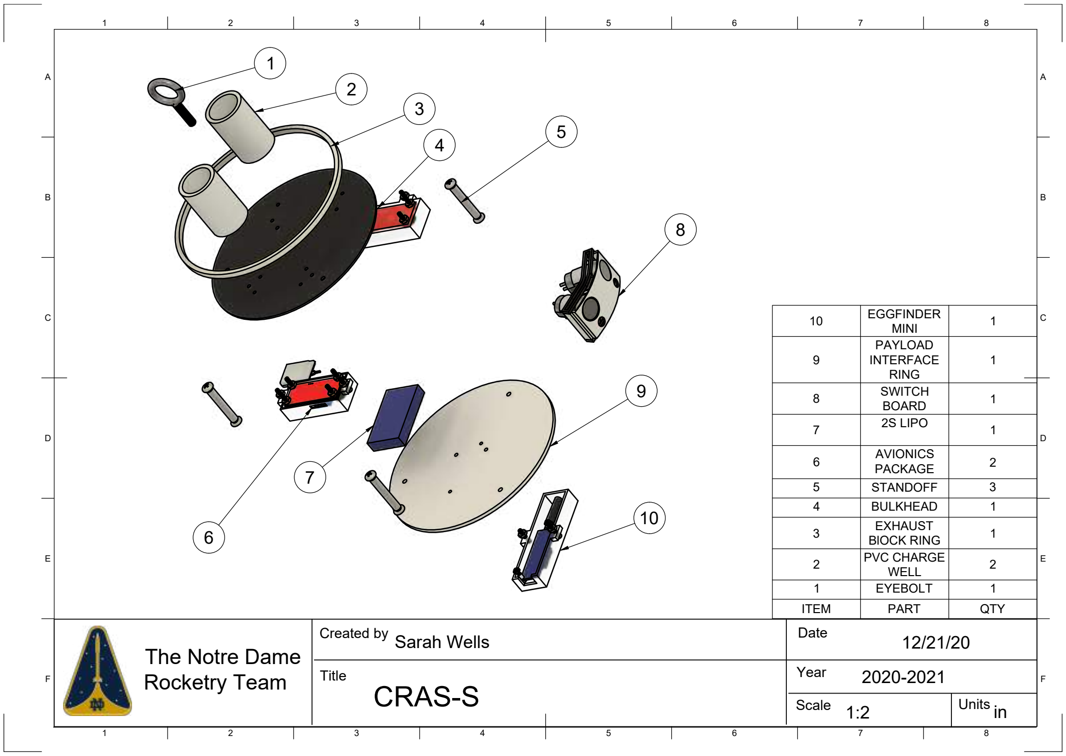


Figure 51: Airframe Interfacing Blocks Drawing

3.8.6.2 CRAS-S

The CRAS-S, shown in Figure 52, controls the deployment of the nose cone parachute and is located in the payload bay. It consists of a thin fiberglass bulkhead and a Tecamid payload interface ring which enclose two integrated avionics packages and a switchboard containing two keyed rotary switches and LED lights which signal the position of the switches for both integrated avionics packages.

The CRAS-S bulkheads are fixed using three steel standoffs which will be placed over the legs of the Planetary Landing System to evenly transmit the load. Additionally, an Eggfinder Mini GPS transmitter will be attached to the outer side of the payload interface ring with its 2S Lipo battery on the interior side of the ring (NDRT Req PF.12). The main bulkhead will transfer the force from the nose cone parachute to the steel standoffs as it deploys and positions the secondary recovery system within the vehicle. Fiberglass, wood, and polycarbonate were considered as material for the bulkhead but aluminum was ultimately chosen through a trade study due to its high strength to weight ratio and ease of machining. The dimensions of the bulkhead are shown in Figure 53. The bulkhead houses two PVC charge wells which contain the black powder ejection charges and a ¼ in. forged eye bolt to secure the recovery harness. The bulkhead will be 1/16 in. thick to ensure the strength of the recovery system while minimizing the weight of the CRAS-S.



ITEM	PART	QTY
10	EGGFINDER MINI	1
9	PAYLOAD INTERFACE RING	1
8	SWITCH BOARD	1
7	2S LIPO	1
6	AVIONICS PACKAGE	2
5	STANDOFF	3
4	BULKHEAD	1
3	EXHAUST BIOCK RING	1
2	PVC CHARGE WELL	2
1	EYEBOLT	1

Figure 52: CRAS-S Exploded View

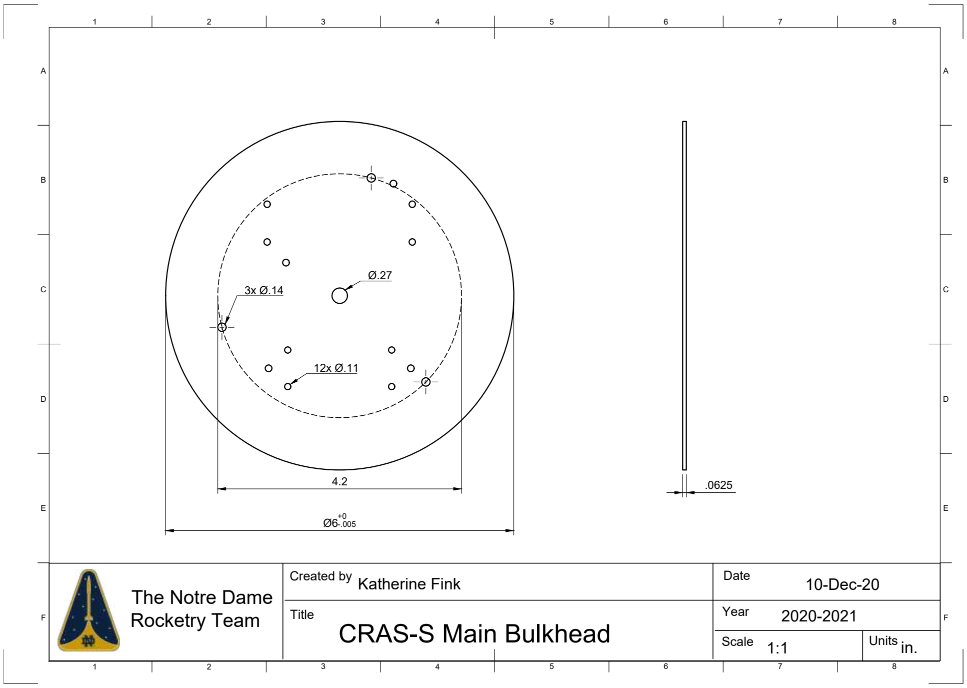


Figure 53: CRAS-S Bulkhead Drawing

Debris and gases from the blackpowder ejection charge mechanism could potentially impact the integrated avionics packages by seeping between the edges of the bulkhead and the airframe. As the CRAS-S will not be bolted directly into the airframe, traditional sealing mechanisms such as an O-ring or clay could not be considered to eliminate this problem. Instead, the CRAS-S will rely on holding to tight tolerances to seal it from the ejection gasses. Since the bulkhead is only 1/16 in. thick, an HDPE exhaust blocking ring will be used to increase the area against the airframe and reducing the amount of gas that moves past the barrier. The dimensions of the exhaust blocking ring are shown in Figure 54.

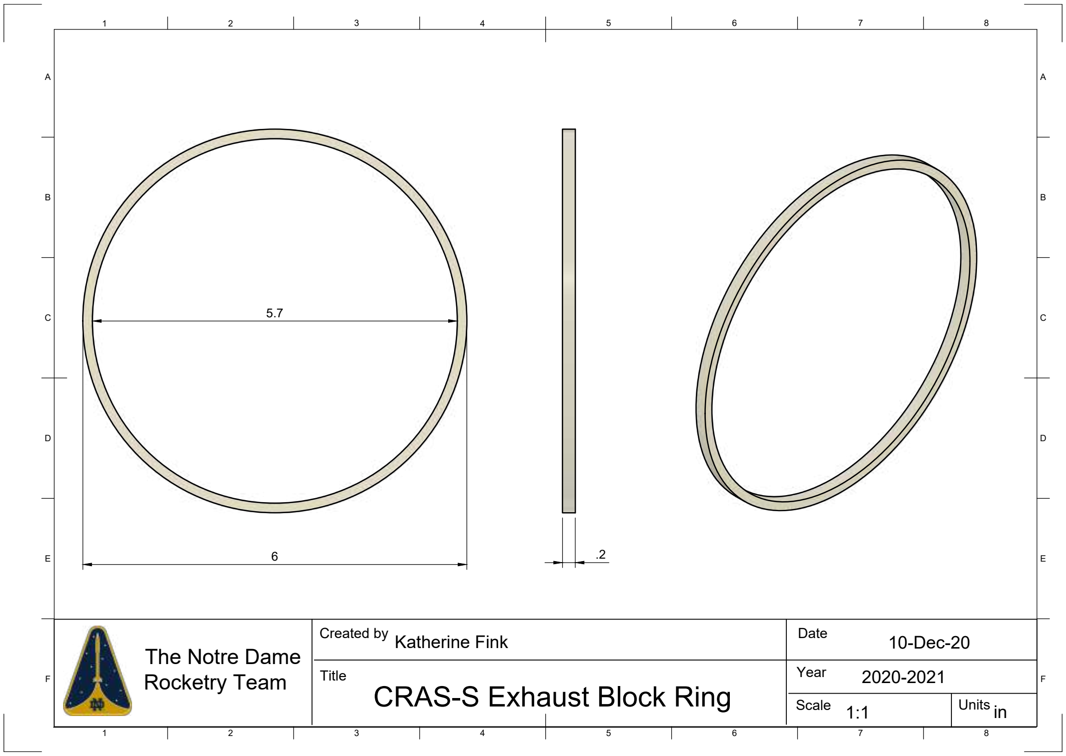


Figure 54: Exhaust Blocking Ring Drawing

The CRAS-S will interface with the payload on the bottom bulkhead, also called the payload interfacing bulkhead, shown in Figure 55.

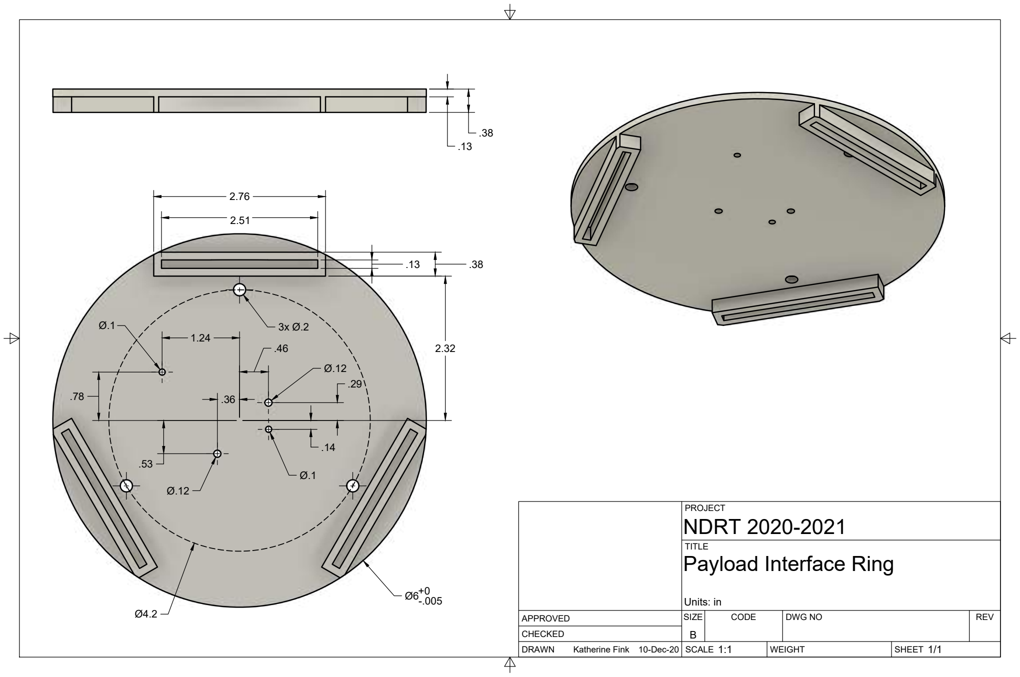


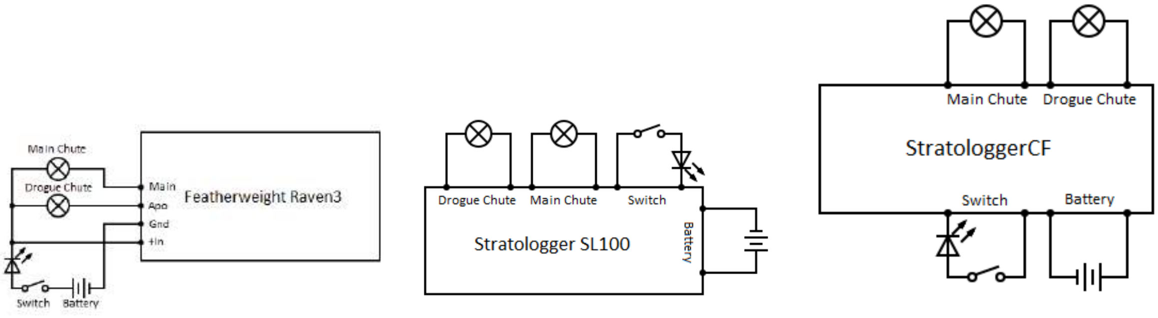
Figure 55: Payload Interfacing Bulkhead Drawing

The bulkhead and the portion that interfaces with the payload legs will be machined from one sheet of Tecamid in order to increase its structural integrity.

3.8.7 Electronics

3.8.7.1 Altimeters

In order to independent control 3 ejection charges for main and drogue deployment and 2 ejection charges for nose deployment, 5 separate altimeters were needed (NASA Req 3.4). As discussed in PDR, a Featherweight Raven3 and two Perfectflite Stratologger SL100s were used because of their high reliability and low cost. For the last two altimeters, two Perfectflite StratologgeCFs were chosen over a range of commercial altimeters due to their low price and compatibility with the system. Electrical schematics for each of the altimeters are shown in Figure 56.



(a) Raven3 (b) SL100 (c) SLCF

Figure 56: Altimeter Electrical Schematics

The altimeter circuits using the Stratologgers will be constructed using direct electrical connections instead of a PCB, which was chosen in trad studies completed for PDR. This change was made to reduce the cost of the recovery system, as well as to streamline its electrical connections. The logic of the recovery system is shown in Figure 57.

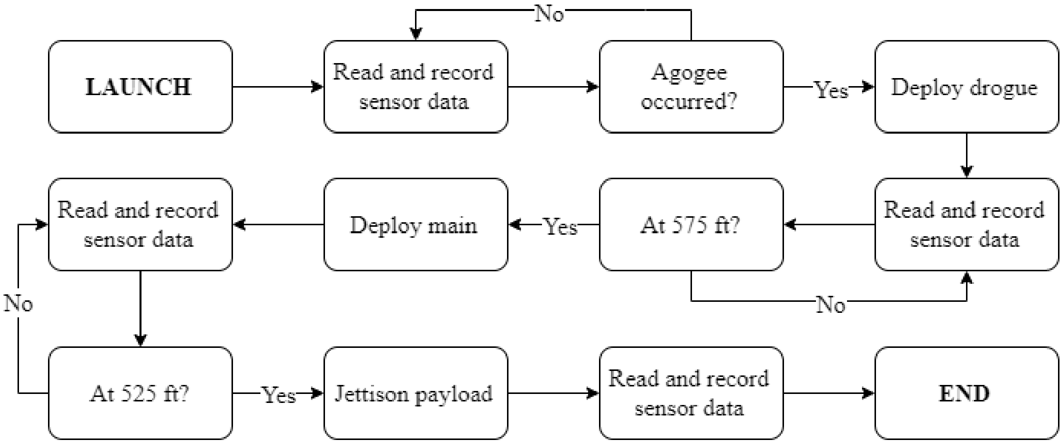


Figure 57: Altimeter Logic

The parameters of each of the chose altimeters are shown in Table 38.

Each of the altimeters will be shielded from any devices that my adversely affect it, such as the on-board transmitters (NASA Req 3.13; NASA Req 3.13.2; NASA Req 3.13.3; NASA Req 3.13.4). This will be achieved both by placing the altimeters in physically separate compartments from any RF or magnetic wave producing device and by mounting the altimeters inside shielding boxes (NASA Req 3.13.1), which are constructed from 3D printed PLA and lined with copper tape covered in masking tape to prevent any short circuiting.

3.8.7.2 GPS Tracking

Table 38: Recovery Altimeter Parameters

Parameter	SL100	SLCF	Raven3
Dimension (in.)	2.75 x 0.9 x 0.5	2 x 0.84 x 0.5	1.8 x 0.8 x 0.5
Power (V)	4-16	4-16	3.8-16
Max Output Current (A)	10	5	9
Max Capacity (mAh)	–	–	170
Mass (oz)	0.45	0.38	0.23
Current Draw (mA)	1.5	1.5	<5

The recovery system will include two Eggfinder Mini GPS Transmitters (NASA Req 3.12). One Eggfinder will be installed in the CRAS-M to track the location of the main vehicle, and the other Eggfinder will be installed in the CRAS-S to track the location of the nose cone after deployment (NASA Req 3.12.1). Both of these Eggfinders will be fully functional on launch day (NASA Red 3.12.2). The Eggfinder Mini was chosen due to its compact design, cost effectiveness relative to other GPS transmitters, and reliability, which the Eggfinder has proven multiple times in the team's previous launch vehicles. The Eggfinder Mini Transmitters can communicate with Eggfinder receivers using a combination of a programmable radio frequency in the 902-928 MHz range and a transmitter ID. One of the transmitters will be set to 915 MHz and the other will be set to 902 MHz. To protect the Eggfinders in flight, protective shields will be 3D printed and affixed over the transmitters. Figure 58 shows the dimensions of this shield.

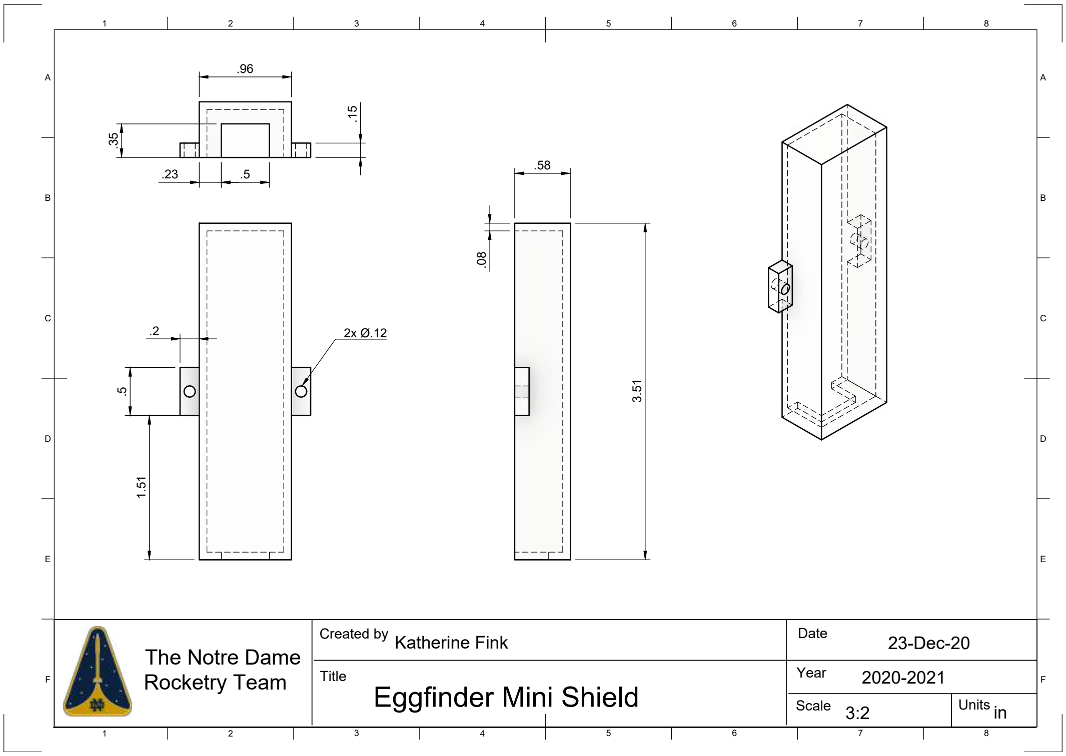


Figure 58: Eggfinder Mini Shield Drawing

3.8.7.3 Batteries

Each of the three altimeters in the CRAS-M and each of the two altimeters in the CRAS-S will be powered by a 1S LiPo battery, and each of the Eggfinder Mini GPS Transmitters will be powered by a 2S LiPo battery (NASA Req 3.5). The specifications of the batteries are shown in Table 39.

Table 39: Battery Specifications

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

These batteries were chosen because they met the specifications of each of the electrical components while remaining light, small, and inexpensive. In order to determine the battery life, the current consumption of the altimeters and GPS transmitters was needed and is shown in Table 40.

Table 40: Recovery Electronic Components Current Consumption

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

Given the specifications in Tables 39 and 40, Equations 34 through 36 are used as follows,

$$c = 0.85C, \tag{34}$$

$$A_{\text{avg}} = \frac{A_w w}{3600000}, \tag{35}$$

$$D = \frac{c}{24A_{\text{avg}}}, \tag{36}$$

where C is the capacity rating of the battery in milliamp hours (mAh), c is the derated capacity of the battery in milliamp hours (mAh) due to estimated self-discharge, A_w is the current consumption of the device when awake, A_{avg} is the average current consumption of the device over one hour (3,600,000 milliseconds) in milliamps, and D is the battery life expressed in days assuming the batteries are on for the duration of their battery life. These equations can be used to prove that the selected 1S LiPo battery and 2S LiPo battery will reliably power the recovery electronics before and throughout flight. The results of Equations 34 through 36 are given in Table 41.

Table 41: Battery Life Estimations

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

These values will be confirmed in an Altimeter Battery Life Test, described in Test TR.2.

3.8.7.4 Switches

Each altimeter will be armed from the launchpad by a keyed rotary switch located on the outside of the vehicle's airframe (NASA Req 3.6). Keyed rotary switches were chosen over other switch options for both the CRAS-M and CRAS-S through a trade study, which took into consideration their cost, ease of access, and rigidity and clarity of state. The placement of the switches on the same side of the launch vehicle's exterior will expedite the altimeter arming process on launch day (NDRT Req RD.6, NDRT Req RD.7), and the addition of LED indicators next to each switch enhances their clarity of state. Furthermore, the key mechanism is simple, low profile, and is expected to remain unaffected by in-flight forces (NASA Req 3.7).

3.9 Mission Performance Predictions

3.9.1 Flight Ascent Simulations

Detailed models of the launch vehicle design were generated in both OpenRocket and RockSim, and flight simulations were run to observe performance in the range of allowable wind conditions and launch rail cant angles. Each simulation was run five times, and the averages of the results were recorded. Table 42, Table 43, and Table 44 compare off rail velocity (ft/s), apogee (ft), and max velocity (ft/s) of the launch vehicle for varying wind speeds (0 - 20 mph in increments of 5 mph) using OpenRocket and RockSim simulations. Table 42 has a launch angle of 5°, Table 43 has a launch angle of 7°, and Table 44 has a launch angle of 10°.

Table 42: OpenRocket and RockSim Simulation Critical Values for Launch Angle of 5°

	OpenRocket			RockSim		
Average Wind Speed (mph)	Off Rail Velocity (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Off Rail Velocity (ft/s)	Apogee (ft)	Max Velocity (ft/s)
0	68.5	5706	619	68.4	5686	619
5	68.5	5664	619	68.4	5663	619
10	68.5	5613	618	68.4	5628	619
15	68.5	5560	617	68.4	5599	619
20	68.5	5519	616	68.4	5563	619

Table 43: OpenRocket and RockSim Simulation Critical Values for Launch Angle of 7°

	OpenRocket			RockSim		
Average Wind Speed (mph)	Off Rail Velocity (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Off Rail Velocity (ft/s)	Apogee (ft)	Max Velocity (ft/s)
0	68.5	5651	619	68.6	5626	620
5	68.5	5595	619	68.6	5587	620
10	68.5	5534	619	68.6	5549	620
15	68.5	5477	618	68.6	5514	619
20	68.5	5461	617	68.6	5472	619

Table 44: OpenRocket and RockSim Simulation Critical Values for Launch Angle of 10°

	OpenRocket			RockSim		
Average Wind Speed (mph)	Off Rail Velocity (ft/s)	Apogee (ft)	Max Velocity (ft/s)	Off Rail Velocity (ft/s)	Apogee (ft)	Max Velocity (ft/s)
0	68.6	5534	620	68.9	5502	621
5	68.6	5448	620	68.9	5450	621
10	68.6	5382	620	68.9	5411	621
15	68.6	5322	619	68.9	5349	621
20	68.6	5286	618	68.9	5310	620

The similarity between the results from both simulation platforms provides confidence that the launch vehicle models are well-suited to provide accurate flight predictions. The large range of apogee predictions, from 5,706 ft to 5,286 ft, demonstrates that the ACS is necessary in order to achieve the target apogee altitude of 5,300 ft. All flights, with the exception of the worst-case scenario, overshoot the target apogee so that the ACS is ensured to intervene and bring the launch vehicle to the desired altitude using a PID control algorithm. The single flight simulation that dropped below the target apogee predicted an apogee altitude of 5,286 ft, which is still within the allowable range of ±30 ft, so it was deemed acceptable. A plot showing the representative range of flight trajectories from the OpenRocket predictions is provided in Figure 59.

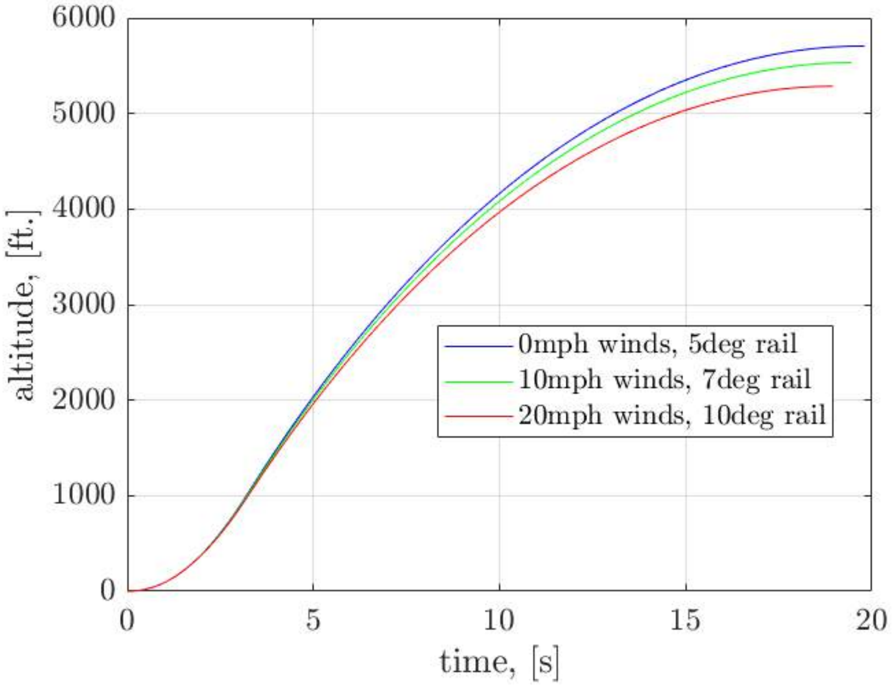


Figure 59: Simulated flight ascent trajectories using OpenRocket

3.9.2 Stability

The static stability of the launch vehicle at the rail exit was simulated in OpenRocket, and was found to be 2.33 when launched vertically, with an off-rail velocity of 68.2 ft/s. The static stability based on the center of pressure (CP) and center of gravity (CG) locations as simulated in OpenRocket was 2.17 calibers (NASA Req. 2.14, NDRT Req VD.7) . This value was calculated using a CP 96.5 in. aft of the tip of the nose cone, a CG 83.1 in. aft of the nose cone, and the outer diameter of the vehicle: 6.17 in., calculated using the Equation

$$\text{Stability} = \frac{CP - CG}{d_{\text{outer}}} \tag{37}$$

Within OpenRocket, the CP was simulated using the Barrowman stability equations. The CG was also simulated in OpenRocket by averaging all component weights and CG locations. The CP and CG are shown on the vehicle in Figure 60, where the red dot is CP and the blue dot is CG, and a summary of stability information for the launch vehicle design is provided in Table 45.

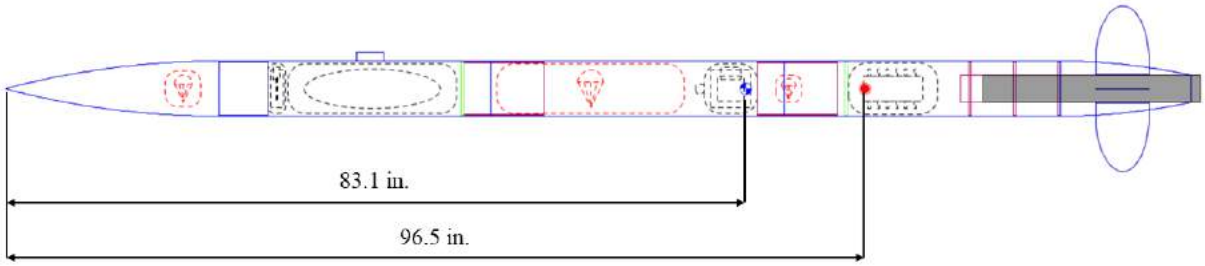


Figure 60: CG and CP locations measured from the nose cone tip on an OpenRocket model of the launch vehicle

Table 45: Summary of launch vehicle stability information

CG Location (in.)	CP Location (in.)	Static stability margin (cal.)	Simulated off-rail stability margin (cal.)	Off-rail velocity (ft/s)
83.1	96.5	2.17	2.33	68.2

3.9.3 CFD

CFD analysis was utilized to further verify the aerodynamic performance predictions of the launch vehicle design. Specifically, CFD was used to verify that the addition of the camera shroud will not significantly impact the aerodynamic stability in flight (NASA Req 2.15) , and to obtain estimates for the drag coefficient that occurs under different drag tab configurations and Mach numbers.

First, three different CAD models of the launch vehicle were generated representing no deployment, half deployment, and full deployment of the drag tabs. Next, meshes were generated from each of these CAD models using Pointwise v18.2. Far field pressure boundary conditions were used for each of the simulations and a rectangular prism mesh volume was created to encase the launch vehicle. The boundaries of the mesh were placed at 20 vehicle body lengths fore and aft of the launch vehicle in the flow direction, and 10 vehicle body lengths in the other four directions. An image of the mesh near the launch vehicle as generated in Pointwise is provided in Figure 61. The cells are colored based on skewness equiangle.

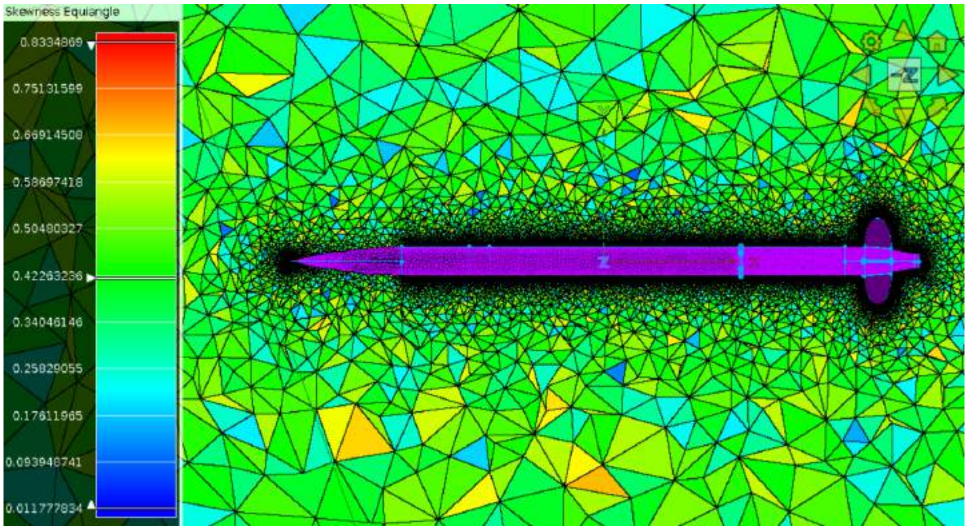


Figure 61: Cross section of volume mesh surrounding the launch vehicle

Next, ANSYS Fluent was used to run the CFD simulations on the mesh. The setup conditions were applied as follows:

- Pressure-based, steady solver with energy equation
- k-Omega SST viscosity model
- Ideal-gas assumption applied for compressibility of air
- Boundary conditions set to far-field pressure for the outer "walls" with an axial Mach number of 0.56 applied
- Launch vehicle boundary condition set to no-slip wall
- SIMPLE scheme solution with second-order upwind spatial discretizations for all equations
- Convergence defined by residuals below 10^{-3} for the continuity equation

First, the results of a simulation performed on the model with no ACS drag tabs, with axial flow moving at Mach 0.56, was used to verify that the camera shroud has minimal aerodynamic impact on the stability of the launch vehicle. This Mach number was chosen because it represents the burnout velocity in flight, at which point the flow separation off the camera shroud is expected to be the most severe. An image of the result of the simulation is shown in Figure 62.

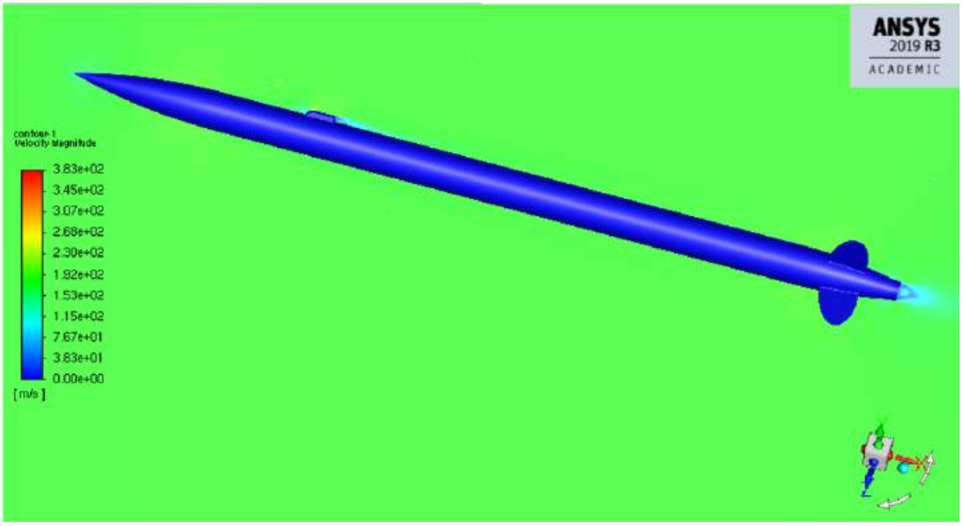


Figure 62: CFD result showing axial flow velocity for the Mach 0.56 condition

Based on the simulation results the impact of the flow separation due to the camera shroud is limited. The flow reattaches well before interacting with drag tabs and fins, indicating that disturbance to the flow is limited and minimal.

Next, the drag coefficient of the launch vehicle was taken from the results for each of the drag tab extensions in axial flow at Mach 0.56. A summary of those results is shown in Table 46.

Table 46: Drag coefficients from CFD results for different ACS drag tab extensions

ACS drag tab configuration	Drag coefficient
No tabs	0.2451
Half tabs	0.3940
Full tabs	0.6784

The drag coefficient values in the table for a Mach number of 0.56 can be extrapolated to estimate drag coefficients at different Mach numbers using Prandtl-Glauert mapping according to the following expression.

$$C_d = \frac{1}{\left(1 - M^2\right)^{1/2}} C_{d_0} \tag{38}$$

Where C_d is the drag coefficient, M is the Mach number, and C_{d_0} is the incompressible drag coefficient. Although Prandtl-Glauert mapping is for 2D flow, it is still a good approximation for this physical model because the flow is axisymmetric and the impact from the camera shroud is negligible by the time the flow reaches the drag tabs. Extrapolating the C_d values shown in

Table 46 using Eqn. 38, the C_d can be plotted for different Mach numbers as shown in Figure 63. This range of C_d values for different drag tab extensions will be implemented in the ACS software to more accurately predict the drag force that the tabs will produce.

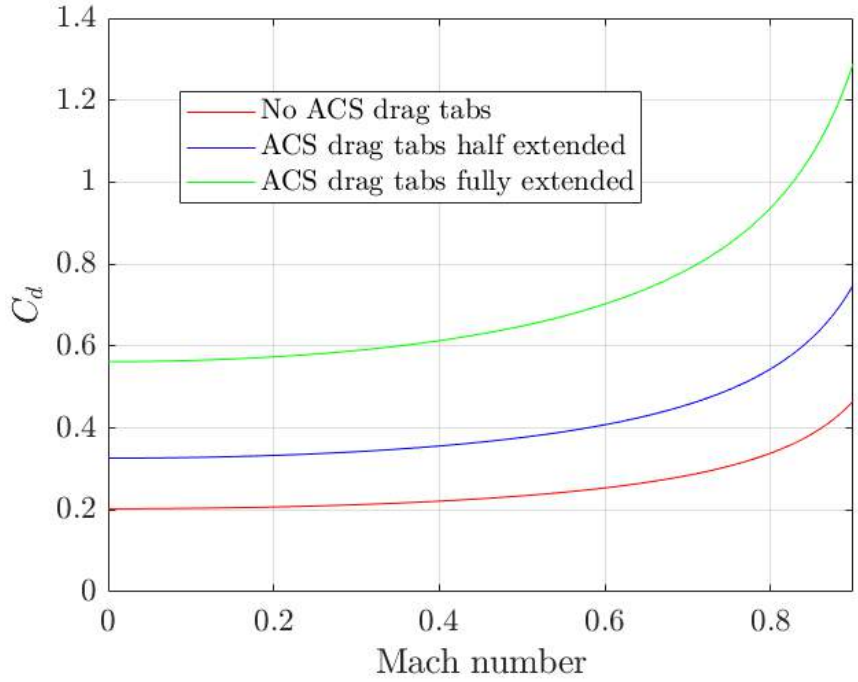


Figure 63: Launch vehicle drag coefficients at different ACS drag tab configurations and Mach numbers

3.9.4 Descent and Kinetic Energy

3.9.4.1 Launch Vehicle

The vehicle will descend in 4 sections, three of which (the payload bay, recovery tube, and fin can) will descend under the main parachute, while the nosecone will descend separately under its own parachute. All of the sections will descend under the drogue parachute for the first portion of descent. The properties of these parachutes can be found in Table 47. Further discussion of the parachute selection can be found in Section 3.8.5.

Table 47: Selected Parachute Parameters

Parameter	Drogue	Main	Nose
C_d	0.97	0.97	1.5
Diameter (ft)	2	12	2
Descent Speed (ft/s)	110.38	16.57	24.40
Shape	parabolic	parabolic	elliptical
Brand	Rocketman	Rocketman	Fruity Chutes

The descent velocities of the vehicle sections were calculated using three independent methods:

1. Hand calculations: using the drag equation to determine terminal velocity under each parachute and then calculate the resultant kinetic energy and descent time
2. OpenRocket simulation: using the provided terminal velocities to determine landing kinetic energy and the provided descent time
3. In-house MATLAB flight simulator: integrating the governing differential equations of vehicle motion to determine terminal velocities (used to calculate kinetic energy) and descent time

The calculated kinetic energies of each section using the three methods are summarized in Table 48. Each of these terminal kinetic energies is under 75 ft-lb, satisfying NASA Req 3.3 .

Table 48: Terminal Kinetic Energy of Vehicle Sections in ft-lb

Section	Hand Calcs	OpenRocket	MATLAB
Fin Can	73.98	61.88	73.98
Recovery Tube	47.4	52.14	47.4
Payload Bay	22.2	19.27	22.2
Jettisoned Nose	24.39	17.09	27.74

The calculated descent times for both untethered sections are summarized in Table 49. Each of these descent times is under 90 s, satisfying NASA Req 3.11.

Table 49: Descent Time of Vehicle Sections in s

Section	Hand Calcs	OpenRocket	MATLAB
Main Launch Vehicle	80.83	76.21	80.18
Jettisoned Nose	71.10	72.43	73.07

The differences in values between the three methods are minor and can be accounted for in examining the calculation process employed by each of the three. The hand calculations did not account for any initial rail cant in determining horizontal velocity and relied on an input apogee, for which the highest expected apogee from Section 3.9.1 was used to ensure that even the maximum descent time would be under 90 s. While the OpenRocket accurately calculated its own apogee and accounted for rail cant as well as the launch vehicle's rotation as it ascends, the software was limited in its evaluation of jettisoned components. To enable payload and nose jettison, the nose had to be modeled as a motor-less sustainer set to stage at 65 s after launch, about where the vehicle descends to 525 ft AGL. This may have introduced error into the calculation of the vehicle's descent speed. The in-house MATLAB flight simulator was written to address these issues in the OpenRocket simulation. The simulation calculates a vehicle apogee, taking wind speed and rail cant into account, and can more accurately model the payload and nose jettison. The simulator's ability to predict apogee was used as a benchmark to asses its overall accuracy, and it was calibrated against the OpenRocket and RockSim models used in Section 3.9.1. A convergence study was performed on the simulation as well, in order to prove that the time-step it used was satisfactory. However, the MATLAB simulator uses a simplified differential equation, integrated using the Euler Method, and a few simplifying assumptions to account for the lift on the vehicle as it ascends which causes it to turn into the wind. The MATLAB simulator also assumes that the parachutes open near instantaneously, which may minorly impact the descent time of the vehicle. The hand calculations and the MATLAB flight simulator provided very similar values. This, coupled with the software limitations in modeling the payload and nose jettison in OpenRocket, led to a high level of confidence in the accuracy of the MATLAB simulation and hand calculations for the mission performance predictions.

3.9.4.2 Planetary Landing System

The PLS is predicted to jettison from the launch vehicle at an altitude of 525 ft, descend at a approximate velocity of 17.5 ft/s, and have a maximum drift of 830 ft. These values are achieved through the use of the Fruity Chute, Spectra 36 inch selected parachute. The parameters of this parachute are found below 50.

Table 50: PLS Parachute Parameters

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

Table 51 shows the different calculation preformed to corroborate these values and ensure they were below the required limit.

Table 51: Descent and Kinetic Energy Value Calculations

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

Calculations were preformed using the PLS body and recovery system basic mass estimate of 52 oz and including a 15% MGA which yielded a predicted mass of 65 oz. As seen in the table, all values are well under the maximum allowed values.

3.9.5 Drift

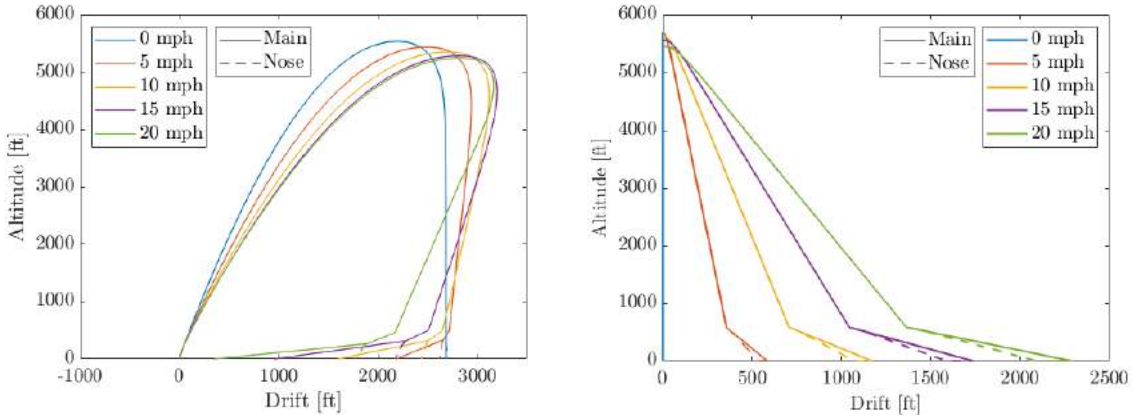
3.9.5.1 Launch Vehicle

The drift radius was calculated assuming the launch vehicle reached apogee directly above the launchpad. As discussed in Section 3.9.4.1, three independent methods were used to determine this measurement: hand calculations, an in-house MATLAB script, and OpenRocket. Table 52 shows the drift calculations for the two simulations at varying wind speeds. As discussed in Section 3.9.4.1, the various simulations each have their benefits and drawbacks that contribute to the difference between their values. The hand calculations and the MATLAB simlation both yielded very similar values, with small differences due to how the

Table 52: Drift Radius of Vehicle Sections in ft

	Hand Calcs		OpenRocket		MATLAB	
Wind (mph)	Main Body	Nose Cone	Main Body	Nose Cone	Main Body	Nose Cone
0	0	0	286	286	1	1
5	595	521	164	83	586.3	537.2
10	1190	1043	475	418	1172	1072
15	1784	1564	945	941	1738	1590
20	2397	2085	1638	1561	2290	2094

MATLAB simulator accounts for rail cant and the vehicles horizontal velocity. The OpenRocket produced much different results, mainly due to the addition of weather cocking to the simulation and the software limitations of the software in regards to jettisoning the payload and nose. This difference can be visualized in Figure 64.



(a) OpenRocket Drift Simulation

(b) MATLAB Drfit Simulation

Figure 64: Difference in Drift Simulations

Regardless, for all simulations, the vehicle maintained the 2500 ft drift radius as required by NASA Requirement 3.10.

3.9.5.2 Planetary Landing System

The drift radius was calculated by multiplying the descent time by the wind speed, assuming the apogee is directly above the launchpad. The maximum value was found using a maximum wind speed of 20 mph. The maximum calculated drift of 830 ft is well within the launch field, thus there is room for uncertainty in the apogee location and parachute deployment and acceleration time while still fulfilling the max drift requirement. Figure 65, created in MATLAB, shows the simulated drift for varying wind speeds, assuming a constant wind speed during descent.

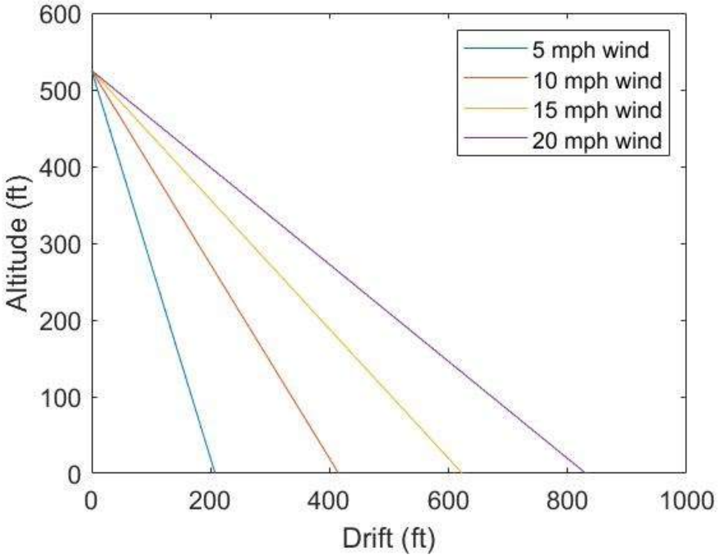


Figure 65: Drift radii of the PLS for varying wind speeds

Additionally, hand calculations were performed to ensure that the drift radius of the PLS did not exceed the allowed 25000 ft required by NASA Req. 3.10. Table 53 shows these calculations bellow.

Table 53: Drift Radius of PLS Sections in ft

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

4 Planetary Landing System

4.1 Mission Statement

The Planetary Landing System (PLS) is the Notre Dame Rocketry Team's experimental payload for the 2021 NASA Student Launch Competition. The team will independently design, build, and test a system that can be deployed from a launch vehicle and land on the surface of a planet. The mission shall be successful if the apparatus is safely retained during launch, deployed 500-1000 feet from the ground during descent, land upright or autonomously reorient after landing, capture a 360 degree image, and transmit the image to a host computer. All of this must be completed without causing damage to the launch vehicle, surroundings, or spectators. In order to integrate with the launch vehicle, the PLS has size restraints of 21 inches in length, 6 inches in diameter, and 80 oz in weight (NDRT Req PD.1, NDRT Req PD.2).

4.2 Mission Success Criteria

The PLS is subdivided into 6 subsystems: retention, recovery, landing, orientation correction, imaging, and data transmission. Each subsystem has a specific corresponding mission to achieve to be considered successful. These missions are listed in Table 54 below.

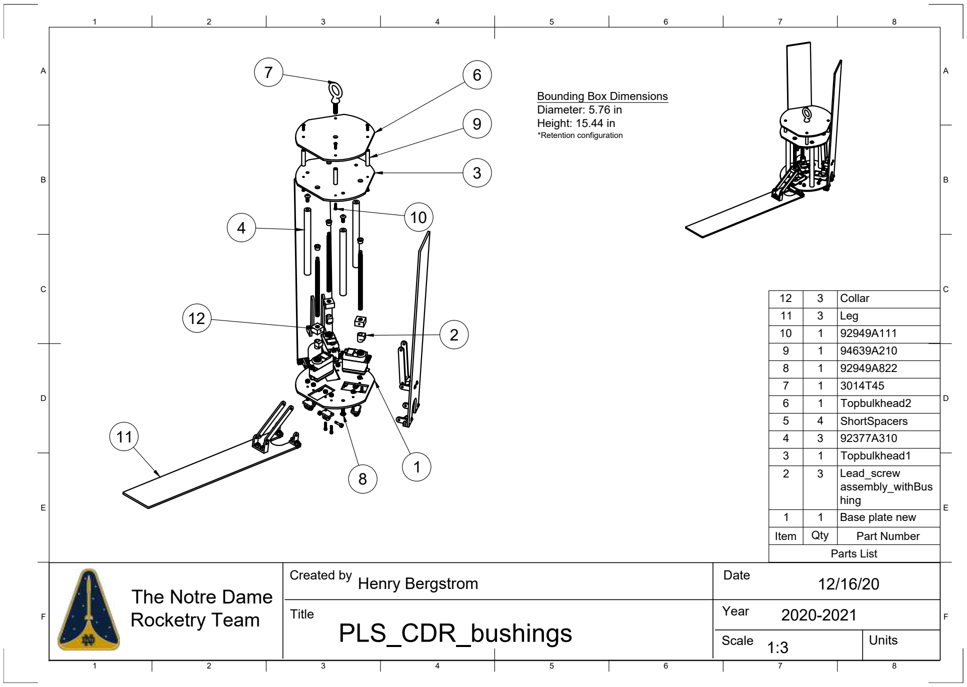
Table 54: PLS subsystem missions

Subsystem	Success Criteria
Retention	Securely retains payload in the launch vehicle from launch to jettison event, at which point it deploys the PLS at an altitude between 500 ft and 1000 ft above ground level (NASA Req 2.18.2.1, NASA Req 4.3.1).
Recovery	Deploys at an altitude of 525 feet above ground level after the payload jettisons from the launch vehicle and will slow down the payload's velocity to a maximum of 20 ft/s with a minimum descent time of 25 seconds (NASA Req 4.3.1).
Landing Gear	Protects all internal components of the planetary landing system from an impact force of approximately 123 pounds per foot and allows the orientation correction system to accomplish vertical orientation post landing (NASA Req 4.3.2).
Orientation Correction	Autonomously, vertically orients imaging and data transmission system at or after landing within a tolerance of ± 5 degrees (NASA Req 4.3.2, NASA Req 4.3.3). Houses an IMU to store payload orientation information at landing and after orientation correction.
Imaging	Capture a 360 degree image after the planetary lander system has vertically oriented. System is activated through a host computer (NASA Req 4.3.4).
Data Transmission	Wirelessly transmits the captured image and GPS location to the host computer within a 2 km radius (NASA Req 4.3.4).

4.3 System Level Design Overview

The structure of the PLS is provided by a cylindrical body composed of 3 fiberglass bulkheads connected by nylon and polypropylene spacers. These will provide a platform to secure all necessary electronics for orientation correction, imaging, and data transmission purposes. Three flat carbon fiber legs are attached to the bottom bulkhead through machined aluminum hinges; a support arm attaches to each leg and provides a connection to a threaded rod which will be used to control each leg's position for correction of the PLS's orientation after landing. An eyebolt connects to the top bulkhead to attach to the payload recovery system. The system is retained during flight by a 2 tier bulkhead and centering ring system that restrains axial movement and provides support to the legs without translating any force to the servo motors. Additionally, 3 wooden dowels fixed to the retention system penetrate the bottom bulkhead to restrain the PLS from rotational movement during flight. The retention system is capable of holding 10 ounces of ballast.

The system is designed to a total length of 19 inches, and 70 oz. Additionally an exploded view of the PLS body is found in Figure 66 and a rendered view of the vehicle in the deployed configuration is found in figure 67.



Item	Qty	Part Number
12	3	Collar
11	3	Leg
10	1	92949A111
9	1	94639A210
8	1	92949A822
7	1	3014T45
6	1	Topbulkhead2
5	4	ShortSpacers
4	3	92377A310
3	1	Topbulkhead1
2	3	Lead_screw assembly_withBushing
1	1	Base plate new

Parts List

The Notre Dame Rocketry Team

Created by Henry Bergstrom

Date 12/16/20

Title PLS_CDR_bushings

Year 2020-2021

Scale 1:3

Units

Figure 66: Exploded View of PLS Body

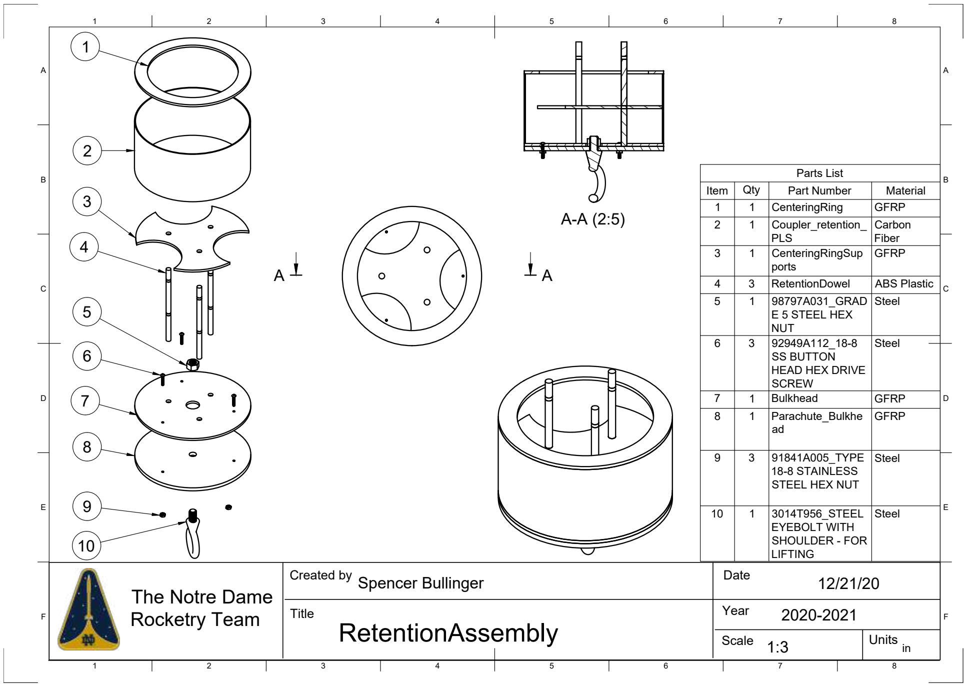
Figure 67: PLS Body Render in Deployed Configuration

4.4 Component Level Design

In the subsections below, each component of the PLS is described in detail. The design, material selection, machining procedure, assembly, and testing plans are outlined to ensure the corresponding mission requirements as outlined in Section 4.2 and team requirements are fulfilled. The six subsections are in order of the mission sequence: retention of the PLS, recovery, landing, orientation correction, imaging, and finally wireless transmission.

4.4.1 Retention

The PLS retention subsystem will limit rotation and translation of the PLS during flight, prevent the PLS servos from experiencing any load, and act as a carrier for ballast. Additionally, the retention system must allow for safe deployment of the PLS. The system consists of a bulkhead connected to a coupler tube. Three internal dowels, running parallel to the length of the system, will be attached to this bulkhead and connected to the coupler tube through a support bulkhead. Additionally, a centering ring will be attached to the top of the coupler tube. The system is shown in Fig. 68.



Parts List			
Item	Qty	Part Number	Material
1	1	CenteringRing	GFRP
2	1	Coupler_retention_PLS	Carbon Fiber
3	1	CenteringRingSupports	GFRP
4	3	RetentionDowel	ABS Plastic
5	1	98797A031_GRADE 5 STEEL HEX NUT	Steel
6	3	92949A112_18-8 SS BUTTON HEAD HEX DRIVE SCREW	Steel
7	1	Bulkhead	GFRP
8	1	Parachute_Bulkhead	GFRP
9	3	91841A005_TYPE 18-8 STAINLESS STEEL HEX NUT	Steel
10	1	3014T956_STEEL EYEBOLT WITH SHOULDER - FOR LIFTING	Steel

Figure 68: PLS Retention System

The three dowels interface with holes in the bottom bulkhead of the PLS to limit any rotation during flight. These dowels are supported by a support bulkhead to reduce the moment experienced during flight. A centering ring, located at the top of the coupler tube, interfaces with the bottom of the PLS legs. The centering ring is designed to absorb the 260 lbs nose cone ejection force from the PLS legs. This load is thereby prevented from being transmitted to the servos and damaging them. The GPS transmitter, an Eggfinder Mini powered by a 2S Lipo battery, is secured to the support bulkhead attached halfway between the bottom bulkhead and the top centering ring. The large availability of open space within the system allows for the necessary ballast needed to reach the system's allotted 80oz mass. The CRAS-S bulkhead interfaces with the PLS legs in the top of the payload bay, constraining the PLS in the longitudinal direction. The bulkhead is retained during flight using shear pins and the nosecone shoulder to prevent axial movement of the CRAS-S.

The retention system is integrated into the vehicle payload tube by three screws within the bottom bulkhead. These screws constrain the retention system relative to an additional stationary bulkhead epoxied in the payload bay. This design allows for the removal of the retention system for modification as needed. The testing plans for the retention system include a shake test and flip test. The shake test will ensure that none of the system's components come lose or get damaged during flight and that the PLS body is properly retained; the flip test will ensure that the axial retention of the PLS is successful by simulating the vehicle's descent orientation. Both tests are desccribed in more detail in Test TP.8. The retention system will be made of a variety of materials, as shown in Figure 68. The bottom bulkhead, centering ring, and support ring will all be machined from 1/8 inch fiberglass.

The dowels will be constructed of wood. Figure 69 shows the FEA performed on the dowels, which were simulated using ABS plastic as an approximation for wood. The dowels were shown to have a FOS of 1.5. The ballast will consist of sand bags secured to the bottom bulkhead. All components of this system are connected with epoxy.

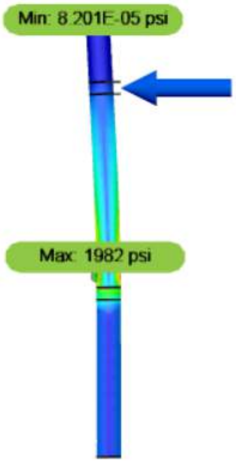


Figure 69: Main Deployment Load on Retention Dowel

4.4.2 Deployment & Recovery

The PLS will deploy from the payload bay through the pull of the parachute bag during the nose cone ejection from the launch vehicle, at an altitude of 525 ft. The black powder charge from CRAS-S separates the nose cone from the payload bay, allowing it and CRAS-S to deploy from the payload bay. The CRAS-S is attached to the parachute bag, whose deployment thus initiates the removal of the PLS.

The recovery subsystem consists of a parachute, deployed from a parachute bag and secured to the main PLS body using an 3/16 inch eyebolt, quick-link, and ¼ inch kevlar shock cord of 9 inch length. A diagram of this system, showing the different stages of deployment, is shown in Figure 70.

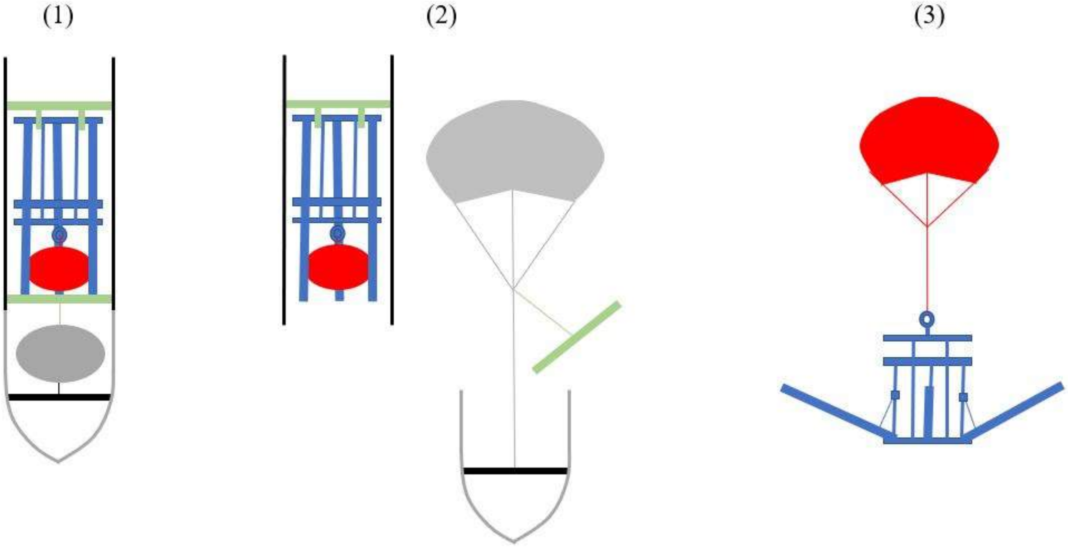


Figure 70: Schematic of PLS Recovery Stages

The parachute was chosen based on the descent requirements of the PLS, and the parachute bag was determined based on the parachute packing volume. The PLS needs to deploy between 500 and 1000 ft (Req. 4.3.1), descend and land at a maximum velocity of 20 ft/s (RF.2), and stay within 2500 ft of the launchpad to remain within the external borders of the launch field (RF.3) with wind speeds of up to 20 mph. In order to fulfill these requirements, the parachute size was determined using Equation 39:

$$F_d = \frac{1}{2}\rho C_d V^2 A \tag{39}$$

Where F_d is the drag force, ρ is the density of air, C_d is the drag coefficient of the parachute as given by the manufacturer, and A is the area of the parachute. The maximum velocity is found by setting the drag force equal to the weight of the PLS. In order to account for any uncertainty, the calculated descent velocity should have a safety factor of at least 1.2 to remain well below the maximum allowable impact velocity during landing. The initial descent time calculation was made using the assumption that the parachute will be instantaneously deployed and the PLS will instantaneously reach its descent velocity. Thus, the time to fall was calculated using a constant descent velocity to yield a maximum descent time. It can then be estimated that the actual descent time will be 95% of this value in order to account for the time it takes for the parachute to deploy and the PLS to accelerate.

The parameters of the selected parachute and the calculated values are stated in Table 55, based on the intended deployment height of 525 ft and the 60 oz PLS mass body estimate.

Table 55: PLS Parachute Parameters

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

The drift radius was calculated by multiplying the descent time by the wind speed, assuming the apogee is directly above the launchpad. The maximum value was found using a maximum wind speed of 20 mph. The maximum calculated drift of 830 ft is well within the launch field, thus there is room for uncertainty in the apogee location and parachute deployment and acceleration time while still fulfilling the max drift requirement. Figure 71, created in MATLAB, shows the simulated drift for varying wind speeds, assuming a constant wind speed during descent.

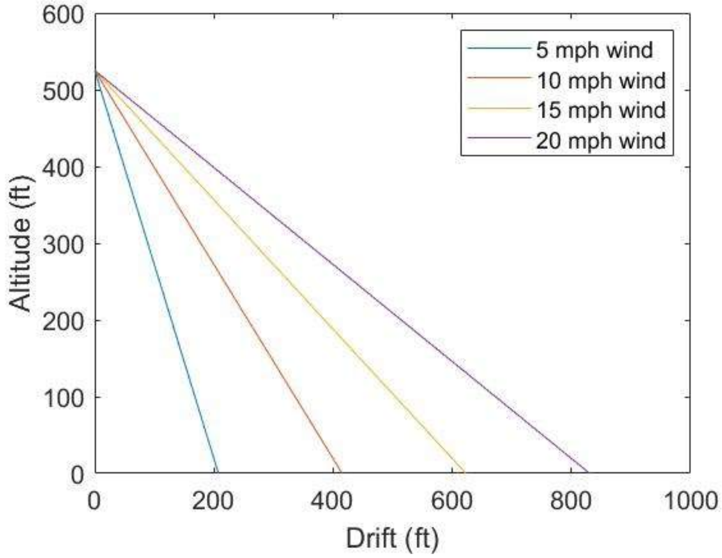


Figure 71: Drift radii of the PLS for varying wind speeds

In order to test the recovery subsystem design to ensure it will perform as expected an ejection test will be preformed. The test will consist of simulating the nosecone deployment, the payload bay will be flipped with the CRAS-S removed to ensure that the PLS is able to vacate the payload bay, the time required for the PLS to vacate will be recorded.

4.4.3 Landing

In order to ensure a controlled landing, the PLS is equipped with 3 carbon fiber legs which are responsible for spreading out the force of impact by landing across a wide area and are also used to orient the PLS. These landing legs are initially folded into a vertical position parallel to the PLS body to allow for the compact storage of the system within the launch vehicle's payload bay. Once the system is jettisoned from the vehicle, the legs are deployed during the descent via the lead screw mechanisms to form 90° angles with the main body of the PLS. Each leg has a surface area of 36 square inches, which provides ample contact area for the PLS with the ground to maintain stability and disperse the impact force upon landing. Each leg's angle can be individually adjusted after landing to stabilize the orientation of the PLS. Figure 72 shows the CAD drawings for the PLS and landing leg system in the stowed and deployed position.

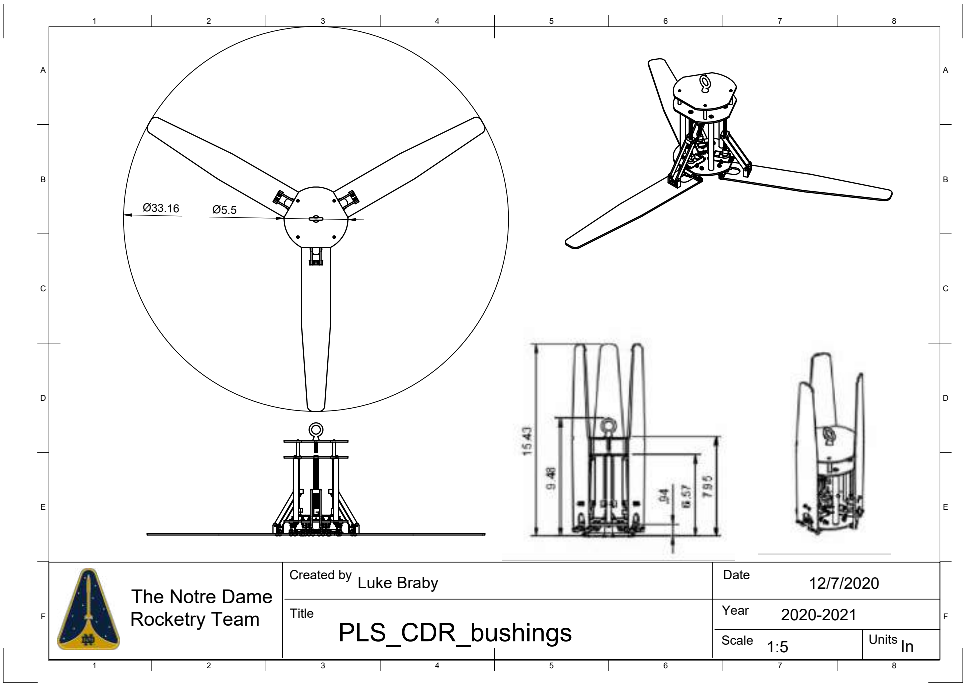


Figure 72: PLS body and landing gear overview

These legs will be milled and made of carbon fiber. Instructions for utilizing the CNC machine can be found in Safety Operating Procedure 2.2.8. Carbon fiber was selected for the landing legs due to its high strength to weight ratio. Aluminum hinges will also be milled to create the attachment points between the legs and the PLS body bulkhead. This bulkhead will be the base of the PLS system and will also be manufactured using a CNC machine. Fiberglass was selected for its rigidity, low weight, ease of milling, and lack of interference with the electrical components that it houses. These selections and mechanisms are designed to ensure safety and usability. Beyond FEA, extensive testing will be performed on the PLS to ensure each of its functions integrate well into the whole design and perform fluidly.

The lead screw mechanism is a critical component for the functionality of the PLS. Separate lead screws will be used to actuate each leg; this control provides the capability of system orientation on three separate axes. The rotation of a lead screw displaces a leadscrew nut up or down the leadscrew. This leadscrew nut is connected through a pin joint to a support arm, which is connected through another pin joint to the landing leg. These components will be bolted together using shoulder bolts to allow for free rotation of the necessary pin joints. The rotation of the servo motor is translated through this series of linkages to the rotation of each landing leg.

To actuate the lead screws, a continuous servo motor will be used due to the accurate positional data of the motor shaft compared to a standard DC gear motor. The servo motor's positional data provides the information to determine the location of the leadscrew nut, and determines the angle of the landing leg relative to the PLS main body. Each servo motor will actuate a 1/4“-12 lead screw with a 4:1 speed ratio. This high speed ratio gives the leadscrew nut a high lead of 0.333” per turn. The servo motor that was selected to actuate the lead screw was a 2000 Series Dual Mode Servo from Servo City. The critical parameters of the selected servo motor are seen in Table 56.

Table 56: PLS Servo Motor Parameters

Parameter	Value
Brand	2000 Series Dual Mode
No-Load Speed (7.4 V)	290 RPM
Stall Torque (7.4 V)	75 oz-in

Accurately detecting the jettison event is critical to avoid premature or delayed leg deployment. Premature leg deployment might cause the legs to contact the payload bay, preventing deployment and exerting unexpected force on the servo motor and threaded rod system. On the other hand, delayed leg activation greater than 18 seconds would not allow the legs to fully deploy prior to land and would compromise the landing stability of the system. To detect ejection of the payload, a jumper pin connected to a Raspberry Pi will be used. The jumper pin will be connected via a string fastened to the interior of the payload bay. When the PLS deploys from the payload bay, the string will become taut and will pull the jumper pin from the digital pins on the Raspberry Pi. For redundancy purposes, there will be two jumper pins used for the PLS for redundancy of the system to guarantee the prevention of premature deployment and deployment failure. This redundancy mitigates failure mode PI.8. Figure 73 shoes a basic diagram for how this system will operate.

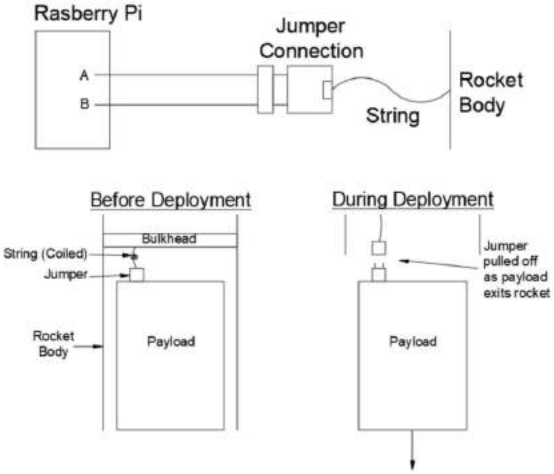


Figure 73: PLS Deployment Detection Pin System

Upon jettisoning from the launch vehicle, the PLS landing legs will all open to an initial angle of 90 degrees from the main body. This will allow the PLS to safely land and allow for more efficient orientation correction. This correction will be done by changing the leg angle upon landing. In order for the legs to reach this position before landing, the servo motor must have sufficient driving torque at the required speed. The equations to determine the torque required to raise the load of square threads is seen in Equations 40-41

$$\tau = \frac{Fd_m}{2}\left(\frac{l+\pi f d_m}{\pi d_m - fl}\right) \tag{40}$$

$$F = \frac{1}{2}\rho v_p^2 C_D A \tag{41}$$

F is the force on the lead screw, which is taken in Equation 41 as the drag force on the landing leg. The cross section is approximated as a rectangular cross section perpendicular to the flow, as this will result in a conservative estimate of the drag force. The coefficient of drag was taken to be approximately 1.50. The coefficient of friction, f, was given a conservative value of 0.4 between the carbon steel lead screw and the polyethylene nut. If unforeseen factors influence the motion of the lead screw and increase the friction, lubrication can be applied to reduce the coefficient of friction. d_m is the mean diameter of the lead screw, and l is the lead, which are 0.25 inches and 0.333 in. per revolution respectively. ρ is the density of air which was assumed to be standard day conditions, v_p was taken to be the max payload descent velocity of 17.6 ft/s, and A

is the cross-sectional area of the landing leg, which was found to be 36 in.^{2}. The required torque to raise the load was 0.05 oz-in., which is significantly below the stall torque of the servomotor. Due to the torque speed curve of servomotors being relatively flat, and the operating torque being sufficiently far from the stall torque, the operating speed can be assumed to be the no-load speed. To determine if this speed is sufficient to open the legs 90 degrees before landing, Equation 42 was used to determine the distance travelled on the lead screw.

$$\Delta Y = N * l * t \tag{42}$$

N is the rotational speed of the lead screw; the speed ratio between the motor shaft and lead screw is 1:1. The rotational speed was taken to be half the no load speed of 290 rpm, to introduce a conservative safety factor of 2. l is the lead of the lead screw, and t is the descent time of PLS, which is 28 seconds. Even with half the no load speed, the servomotor is still able to translate the lead screw nut a max distance of 150 in. in the descent time, which is more than needed to open the landing legs to the required 90 degrees. To determine if the servomotors could control the legs upon the PLS landing, a similar analysis was performed using Equation 42. This analysis assumed two legs held the full weight of the PLS equally. Figure **??** shows the force balance used to determine the force on the support arm, which is the load on the lead screw. Using this position of the legs, the required operating torque would be 0.145 oz-in, which is still significantly below the stall torque.

To the most strenuous environmental conditions the PLS landing legs experience is the initial impact of landing. The impact velocity of the PLS is 17.6 fps. The estimated time it takes for this to occur is estimated to be 0.2 seconds; this is a short impact time to ensure a conservative approximation of the force exerted on the system. Using the Impulse-Momentum Theorem with these parameters, the system experiences a total force of 123 lbf. Like in the previous analysis, the most extreme case is taken to be that two legs experience the entire force. In the 90 degree deployment position, the main structural components that take this load are the main leg hinges. Structural analysis performed on these components are assumed to be an envelope analysis of the other load bearing aluminum hinges on the PLS. Since these hinges are close to the center line of the PLS body, the hinges are assumed to take the load equally. Figure 74 shows the FEA performed on these components.

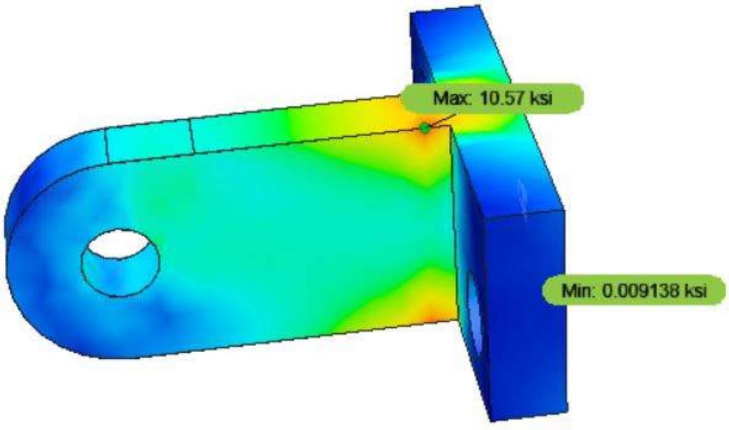


Figure 74: Impact Load on Aluminum Hinge. FOS = 3.3

The main leg hinge experiences a max stress of 10.57 ksi. The hinge will be manufactured from 6061 T6 Aluminum, which has a yield strength of 35 ksi. This provides an acceptable safety factor of 3.3. These hinges will attach the main body of the PLS system to the carbon fiber legs, each of which will have CNC-milled holes for bolts to join the section.

4.5 Orientation Correction

The orientation correction system is tasked with autonomously orienting the PLS upon landing to within five degrees of vertical (NASA Req 4.3.3). To accomplish this, the orientation system will independently control its three landing legs using servos and lead screws. The servos being used are 2000 Series Dual Mode Servo, running on continuous rotation mode. In order to safely calculate power requirements for the servo battery, the team assumed all three servos drawing stall current for the duration of operation. This calculation is shown in Equation 43.

$$E = t_{max} * I_{max} * N_{servos} \tag{43}$$

Here, E is the capacity rating needed for the servo battery, in mAh, t_{max} is the maximum duration of operation, in hours, I_{max} is the stall current of the servo motors, in mA, and N_{servos} is the number of servos in operation. T_{max} is taken to be five minutes, or 0.083 hours,I_{max} is equal to 3000 mA, and N_{servos} is equal to three. Based on this equation, the servo battery must have a capacity rating of at least 750 mAh. With a factor of safety of 1.5, 1,125 mAh is the target for battery capacity.

The servos will be controlled by an Arduino Nano board. The system will first receive a landing detection serial input from the PLS Raspberry Pi. Once this signal is received, the arduino will use angular position data from a IMU and loop through a proportional control algorithm to level the lander. The algorithm used to level the body of the lander will use the three legs to orient upon two primary axes of rotation.

The X and Y axes of rotation correspond with the primary axes of the PLS sensor. Upon landing, the three legs of the lander will all be perpendicular to the payload body. In order to orient the lander on the X axis of rotation, either leg 1 or legs 2 and 3 simultaneously will lower until the sensor measures an angle within five degrees of vertical with margin for error. Once X orientation is complete, the system will move on to orientation on the Y axis of rotation. Only legs 2 and 3 will be used for Y orientation. Based on the direction of tilt on the Y axis, one leg will raise while the other lowers. Once both axes have been corrected, the system will verify once again that both angle measurements are within the desired range. If not, it will loop through the algorithm again to make more corrections.

Accounting for the fact that tuning one axis of rotation will probably affect the other in some small capacity, the ranges of acceptable angles while the algorithm is being performed will be set smaller than the range given by NASA Req 4.3.3. Then, when the angles are being verified, the NASA range of plus/minus five degrees will be used. Once orientation correction is complete, a confirmation will be sent from the Arduino to the Raspberry Pi via serial communication.

Given the uncertainty of the landing position of the PLS, it is important to account for several factors, namely, the slope and roughness of the terrain. The starting position for the PLS will have the legs at perpendicular angles to the main body of the PLS and parallel to the ground, as it should land. Within the two independent variables, slope and terrain, there are 2 and 3 choices respectively. There is high, medium, and low slope (ranging from 0-30 degree inclines), and rough and smooth terrain. Each combination of slope and terrain will be tested to ensure the orientation correction system will be able to function properly. Additional testing will include landing detection, to ensure the system can detect landing before activating the reorientation system.

4.5.1 Imaging

This payload will need to take a 360-degree image of the landscape after landing (NASA Req 4.3.4). To achieve this, the team will be utilizing four Raspberry Pi cameras with wide-angle lenses. The cameras will be offset 90 degrees from one another. With a horizontal field of view of approximately 120 degrees, the cameras will be able to capture a 360 degree image fracture into four pictures that will be stitched together after they are transmitted to the team. The camera is shown in Figure 75, while the lens is shown in Figure 76. This setup will provide enough image data to construct the required panoramic image.

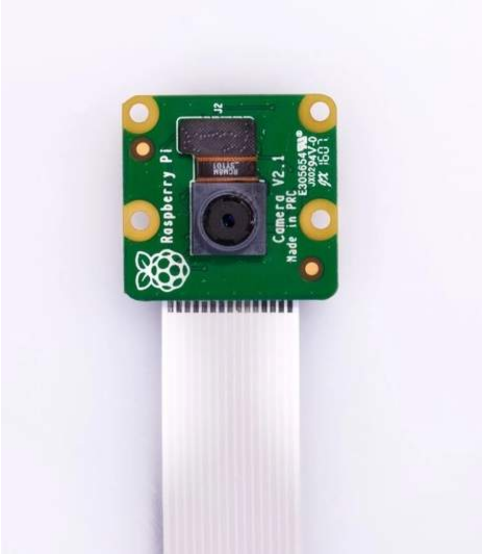


Figure 75: Raspberry Pi Camera


Figure 76: Wide Angle Lens

The Raspberry Pi only has one input port for a camera, so the team will need to utilize an additional device in order to connect 4 cameras. These cameras will be connected utilizing a ArduCam Multi Camera Module. This module is shown in Figure 77. This will allow the team to take a picture on each individual camera. The images taken are stored in a .jpg file format, which will allow for easy manipulation and processing later on.

Figure 77: ArduCam Multi Camera Module

After the images are taken, they will be stitched together utilizing a Python OpenCV algorithm. This will generate the desired 360-degree image file, which will be sent through the data transmission subsystem. Because the Raspberry Pi utilizes the Linux kernel and has a file system, the four initial images and the final panoramic image will be able to be stored in flash memory for easy accessibility. This system will be powered by a 3.7 V battery connected to a 5 V boost converter, which will permit this payload subsystem to be powered for at least 2 hours on the launch pad (NASA Req 2.7, NDRT Req RF.7, NDRT Req RE.3).

4.5.2 Wireless Transmission

The last subsystem of the PLS is the wireless data transmission of the image data to a host computer at the landing site (NASA Req 4.3.4). In order to complete this task, the team will be utilizing two Raspberry Pis and a radio bonnet. One Raspberry Pi will reside in the PLS, while another Raspberry Pi will be located at the launch site. The Raspberry Pi in the PLS will act as a transmitter, while the Raspberry Pi at the launch site will act as a receiver. A schematic of the subsystem is shown in Figure 78 below.

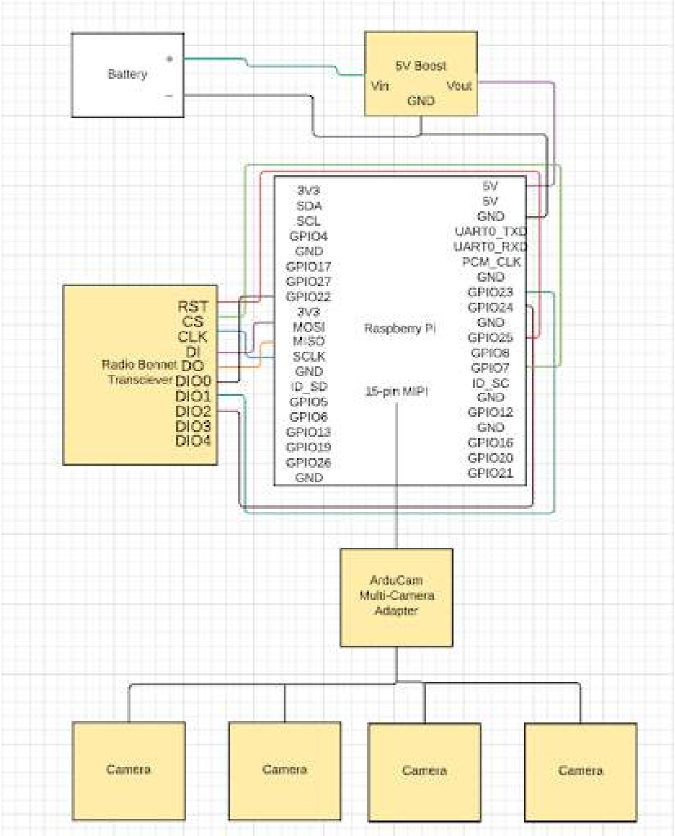


Figure 78: Schematic of Data Transmission and Imaging Subsystems

This system will be powered by a 3.7 V battery connected to a 5 V boost converter, allowing this payload subsystem to be powered for at least 2 hours on the launch pad (NASA Req 2.7, NDRT Req RF.7, NDRT Req RE.3).

The transmission itself will be handled by a pre-packaged radio transceiver developed by Adafruit and the LoRa Radio Bonnet RFM96W. This device will allow the team to very easily transmit and receive data using a pre-packaged Adafruit API. The data will be transmitted using the LoRa scheme over a 433 MHz carrier wave, which can carry a signal over 2 km. This distance varies with antenna schemes, so the team will need to test to determine the distance at which the transceivers lose sight of one another. The distance of 2 km was measured by Adafruit using an omnidirectional antenna, so the switch to a dipole antenna should increase the range of transmission. This device also allows for handshaking and confirmation signals, to ensure that the data packets were received properly and mitigate data loss.

The image will need to be split into smaller packets in order to be transmitted over the system, which will be done using OpenCV. Furthermore, this device will allow for easy debugging on an LCD, and includes push-buttons. Each of these devices will be connected to a dipole antenna, which was chosen due to the consistent orientation of the subsystem.

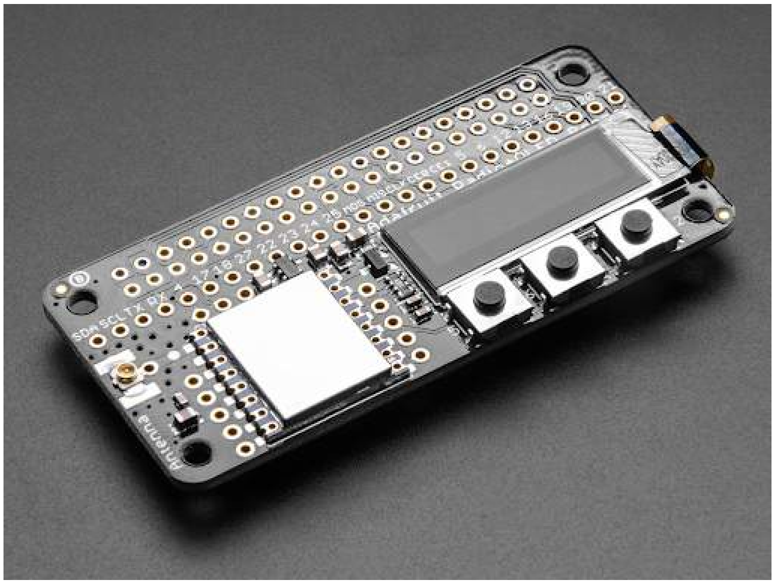


Figure 79: Adafruit LoRa Radio Bonnet RFM96W

This system will be compact enough to fit directly on top of the Raspberry Pi, and the antenna will be oriented directly upward in the payload.

4.6 Comprehensive Mass Statement

The overall mass of the PLS is currently 77.7 oz, which has a mass growth allowance of 15%. The mass is subject to change, so the amount of ballast needed to bring the PLS up to its allotted mass of 80 oz will vary. The ballast will be located in the retention system (see Section 4.4.1), which has been designed to allow for this fluctuation. The mass breakdown for each PLS subsystem is shown in Table 57, where the mass estimate is the total of each subsystems' components, and the predicted mass includes the mass growth allowance.

Table 57: PLS Mass Breakdown

Subsystem	Mass Estimate (oz)	Predicted Mass (oz)
Body	16.15	18.57
Legs	31.61	36.35
Electronics	4.03	4.63
Recovery	4.56	5.25
Retention	11.21	12.89
Total	67.55	77.69

4.7 Vehicle Integration

The PLS is integrated within the payload tube through a retention system that is screwed into the bottom payload tube bulkhead. The retention system features three dowels that interface with holes on the bottom bulkhead of the PLS to limit any rotational motion during flight. The legs of the PLS rest on the centering ring of the retention system. CRAS-S is located on the upper bulkhead of the payload tube, and it constrains the motion of the PLS on its longitudinal axis. A figure of the integrated system is shown below in Figure 80.

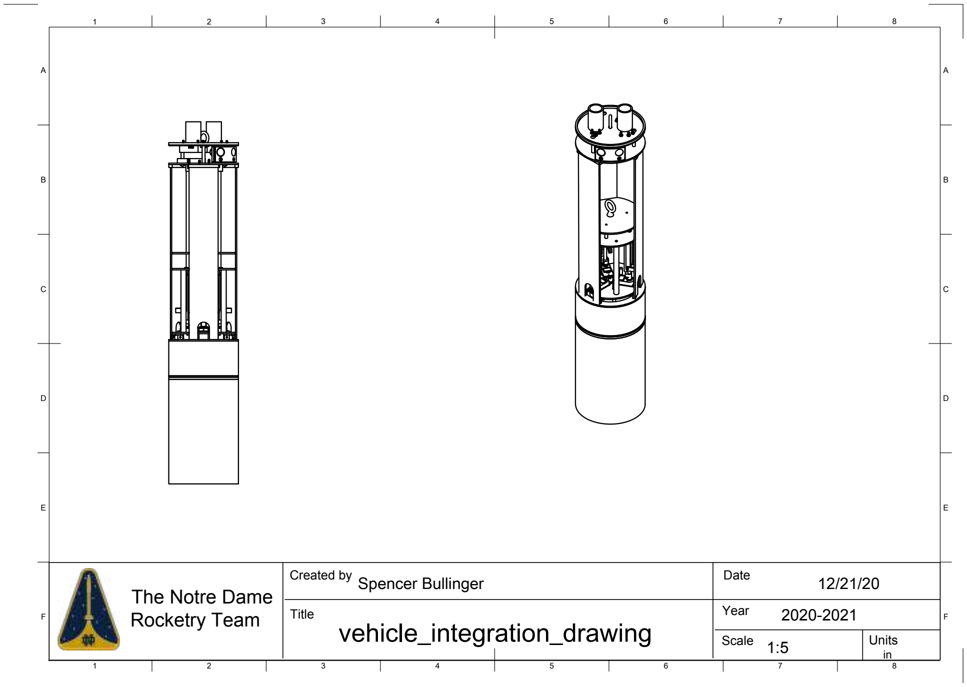


Figure 80: PLS Vehicle Integration

To integrate the PLS into the vehicle, the retention system first slides into the payload bay and is secured to the main parachute bulkhead with three screws. Next, the PLS is activated and its jumper pins are attached. The PLS then slides into the payload bay and interfaces with the retention system. The dowels of the retention system will fit within the bottom bulkhead of the PLS while its legs will rest on the top of the system. Lastly, CRAS-S slides into the payload bay over the PLS. Additionally, CRAS-S is designed with a special contour on its bulkhead to keep the PLS legs from radially shifting.

The PLS remains in its integrated configuration within the launch vehicle until deployment. Upon deployment, CRAS-S separates the nose cone from the payload tube. The PLS no longer is constrained along its longitudinal axis, allowing it to slide out from the payload tube and the retention system. As the PLS exists the payload tube, it will sever its jumper cables, beginning the process of its leg deployment. A flight simulation test will be performed in order to assess the retention capabilities of the integrated vehicle. In addition, the deployment mechanism will be evaluated on its reliability and time of deployment.

5 Safety

5.1 Launch Concerns and Operations Procedures

5.1.1 Packing List

Standard Launch Procedure
Vehicle Demonstration Checklist
Pre-Departure Packing List

Required Personnel

NAR/TRA Level 2 Certified Launch Manager (LM): Dave Brunsting
Safety Officer (SO): Jacob Shapiro
Project Manager (PM): Brooke Mumma
Chief Engineer (CE): Joseph Sutton
Vehicles Lead (VL): Benjamin Tompoles
ACS Lead (AL): Patrick Faley
Recovery Lead (RL): Katherine Fink
PLS Lead (PL): Estefania Castillo Villarreal
If absolutely necessary, a qualified team member may assume the duties of a design lead given approval by the Safety Officer and applicable Design Lead.

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

Personal Protective Equipment PM: ____________ SO: ____________

- ☐ Box of nitrile gloves
- ☐ Pair of cut resistant gloves
- ☐ First aid kit
- ☐ Fire resistant battery bags
- ☐ Dusk masks
- ☐ Safety glasses
- ☐ Pair of heat resistant gloves
- ☐ Leather gloves

Tools PM: ____________ SO: ____________

☐ 1 hand drill, fully charged
☐ Drill bit case with standard range of bits
☐ Standard wrenches
☐ Standard Alan wrenches
☐ Screwdriver set
☐ Scissors
☐ Hot glue gun
☐ Soldering iron
☐ Digital multimeter
☐ Exacto knives
☐ Metal files
☐ Wire cutters
☐ Wire strippers
☐ Bluntnose pliers
☐ Needlenose pliers
☐ Dial caliper
☐ Tape measure
☐ Protractor

General Equipment

PM: ______________ SO: ______________

☐ Electrical tape
☐ Duct tape
☐ Masking tape
☐ 2 folding tables
☐ Scale
☐ Tarp
☐ Garbage bags
☐ Wooden vehicle support stands (2)
☐ Rocketpoxy A and B Parts
☐ JB Weld
☐ Lead solder
☐ Pens/pencils
☐ Assorted screws, bolts, and nuts
☐ Sandpaper
☐ Epoxy applicators
☐ Extra wire spool

Vehicle Equipment

VL: ______________ SO: ______________

☐ Nose cone
☐ Payload tube assembly
☐ Recovery tube assembly
☐ Motor tube and boattail assembly
☐ Shear pins
☐ Motor casing
☐ Motor retention cap
☐ Camera
☐ Camera shroud screws

ACS Equipment

AL: ______________ SO: ______________

☐ Assembled ACS structure
☐ ACS electronics toolbox
☐ Fire-proof battery case
☐ Fully charged Turnigy 2000 mAh batteries (2)
☐ Turnigy 2000 mAh battery charger
☐ 6-32 nylon screws
☐ 10-32 nylon screws
☐ 6-32 nylon lock nuts
☐ 10-32 nylon lock nuts
☐ Fully charged laptop
☐ Extra ballast mass

Recovery Equipment

RL: ______________ SO: ______________

☐ Assembled CRAS-M structure
☐ Assembled CRAS-S structure
☐ Power switch keys (2)
☐ Featherweight Raven3 altimeter (1)
☐ Stratologger SL100 altimeters (2)
☐ Stratologger CF altimeters (2)
☐ Fully Charged 170 mAh

batteries (6)
- ☐ 170 mAh battery charger
- ☐ Assembled altimeter perfboards
- ☐ Box of E-matches
- ☐ 1/4 in eyebolts (2)
- ☐ 3/8 in eyebolts (2)
- ☐ 3/8 in quick links (4)
- ☐ 3/16 in quick links (5)
- ☐ 35 ft long 3/4 in diameter tubular nylon harness
- ☐ 25 ft long 1/4 in diameter tubular kevlar harness
- ☐ 12 ft parabolic Rocketman main parachute
- ☐ 2 ft parabolic Rocketman drogue parachute
- ☐ 2 ft parabolic Rocketman nose cone parachute
- ☐ Main Parachute Deployment Bag
- ☐ 24 in Nomex blankets (2)
- ☐ Talcum powder
- ☐ O-rings (2)
- ☐ Exhaust blocking ring
- ☐ Sealing clay
- ☐ Fully charged laptop with Featherweight Interface Program and Perfectflite DataCap installed
- ☐ Data cable for Raven altimeters
- ☐ Data cable for Stratologger altimeter

PLS EQUIPMENT

PL: ____________ SO: ____________

- ☐ Assembled PLS vehicle
- ☐ Full charged lithium polymer batteries (2)
- ☐ Battery charger
- ☐ Jumper cables (3)
- ☐ Leg retention pins (3)
- ☐ 4 ft elliptical Fruity Chutes PLS parachute
- ☐ 1/4 in diameter tubular kevlar harness
- ☐ 3/16 in quick link
- ☐ Fully charged laptop
- ☐ Extra ballast mass

LAUNCH MANAGER-HANDLED EQUIPMENT

LM: ____________ SO: ____________

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

- ☐ Cesaroni L1395 Blue Streak Rocket Motor (3)
- ☐ 120 g black powder
- ☐ Fire-retardant cellulose wadding

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

Safety Officer: ______________________________ Date: ____________

5.1.2 Recovery Preparation

STANDARD LAUNCH PROCEDURE
VEHICLE DEMONSTRATION CHECKLIST
RECOVERY PREPARATION

Required Personnel: Recovery Lead, Safety Officer, Launch Manager

Required PPE: Leather gloves, Nitrile gloves, Safety glasses

INSPECTION

RL: ______________ SO: ______________

⚠**Failure to complete the following steps could result in the following failure modes: R.1, R.2, R.3, R.4, R.5, R.6, R.7, R.8, R.9, R.10, R.11, R.12, R.13, VS.3, VS.9, or an unidentified failure mode and thus a failed launch.**

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

PRE-FLIGHT CHECKLIST

RL: ______________ SO: ______________

⚠**Failure to complete the following steps could result in the following failure modes: R.1, R.2, R.3, R.4, R.5, R.6, R.7, R.8, R.9, R.10, R.11, R.12, R.1, VS.3, VS.9, or an unidentified failure mode and thus a failed launch.**

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

- ☐ Main Parachute Folding RL: ______________
  - ☐ Raise the parachute in the air, making sure all 4 shroud lines are straight and that the loop is on the top of the parachute.
  - ☐ Shake the parachute lightly to untangle the cords if needed.
  - ☐ Attach a quicklink to the open loop at the end of the shroud lines. Hold this quicklink to keep parachute from flying away.
  - ☐ Line all of the shroud lines up such that they are the same length. Use masking tape to group the shroud lines at this position to make folding easier. **Tape must be removed prior to launch or failure modes R.5 will occur!**
  - ☐ Lay the parachute out on the ground, and make sure every connection/quick link are securely tight to the parachute.
  - ☐ After the shroud lines are straight again, pull the parachute flat, and then fold it in half, this will make all 4 lines go into one nice orderly group.
  - ☐ Fold both sides into the middle tightly. Adjust how much the sides go in, to fit the

diameter of the vehicle.

- ☐ Fold the parachute in half the opposite direction. The parachute should be roughly a rectangule in shape.

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

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

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

- ☐ Slide the parachute into the deployment bag, and then fold the flap over the bag.
- ☐ Make sure the loop on the deployment bag is secure on the shroud line.
- ☐ Main parachute is now ready to be installed into the vehicle.

☐ Pilot Parachute Folding RL: ______________

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

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

- ☐ Loosely roll the parachute in the nomex blanket, and then fold the blanket so that it fits in the vehicle body.

  - ☐ Make sure the loop on the nomex blanket is secure on the shroud cord.
  - ☐ Pilot parachute is now ready to be installed into the vehicle.
- ☐ Nose Cone Parachute Folding RL: ____________
  - ☐ Raise the parachute in the air, making sure all 8 shroud lines are straight and that the loop is on the top of the parachute.
  - ☐ Shake the parachute lightly to untangle the cords if needed.
  - ☐ Attach a quicklink to the open loop at the end of the shroud lines. Hold this quicklink to keep parachute from flying away.
  - ☐ Line all of the shroud lines up such that they are the same length. Use masking tape to group the shroud lines at this position to make folding easier. **Tape must be removed prior to launch or failure modes R.7 will occur!**
  - ☐ Lay the parachute out on the ground, and make sure every connection/quick link are securely tight to the parachute.
  - ☐ Fold over the gores on both sides towards the center. You want to organize the parachute until it is about 15% of the diameter of the parachute size.
  - ☐ Z-fold the parachute into thirds.
  - ☐ Pull the fabric on the underside of the parachute around the edge and onto the top. You want the fabric on the underside to be smooth with no folds.
  - ☐ Form a crease down the center of the folded parachute.
  - ☐ Bring the shroud line bundle up the crease to about 1/3 of the distance from the end. **Do not bring the shroud lines to the very end.**
  - ☐ Now start to wrap the shroud lines around the parachute. Ensure the back of the parachute is smooth with the material all pulled around into the crease.
  - ☐ Stop wrapping when you reach the end of the parachute.
  - ☐ Attach quicklink to nose cone recovery harness quicklink.

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

  - ☐ Loosely roll the parachute in the nomex blanket, and then fold the blanket so that it fits in the nose cone.
  - ☐ Make sure the loop on the nomex blanket is secure on the shroud cord.
  - ☐ Pilot parachute is now ready to be installed into the nose cone.
- ☐ Drogue Parachute Folding RL: ____________
  - ☐ Raise the parachute in the air, making sure all 4 shroud lines are straight and that the loop is on the top of the parachute.
  - ☐ Shake the parachute lightly to untangle the cords if needed.
  - ☐ Attach a quicklink to the open loop at the end of the shroud lines. Hold this quicklink to keep parachute from flying away.
  - ☐ Line all of the shroud lines up such that they are the same length. Use masking tape to

group the shroud lines at this position to make folding easier. **Tape must be removed prior to launch or failure modes R.6 will occur!**

- ☐ Lay the parachute out on the ground, and make sure every connection/quick link are securely tight to the parachute.
- ☐ After the shroud lines are straight again, pull the parachute flat, and then fold it in half, this will make all 4 lines go into one nice orderly group.
- ☐ Fold both sides into the middle tightly. Adjust how much the sides go in, to fit the diameter of the vehicle.
- ☐ Fold the parachute in half the opposite direction. The parachute should be roughly a rectangular in shape.

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

- ☐ Zig-zag shroud lines carefully on the middle of parachute. **Tangled shroud lines could result in failure mode R.6**
- ☐ Fold the parachute in thirds such that the sides cover up the shroud lines twice.
- ☐ Attach quicklink to drogue recovery harness quicklink.

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

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

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

⚠**Electronics must remain OFF until immediately prior to launch.**

☐ Integrated Avionics Package Setup RL: ______________

☐ CRAS-M Pre-Flight Assembly RL: ______________

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

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

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

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

☐ CRAS-S Assembly RL: ______________

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

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

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

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

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

- ☐ Black powder separation charges LM: ______
  - ☐ Create eight ejection charges using e-matches and black powder. Ensure that the e-match loose wires are shunted together to prevent accidental ignition of the black powder. The sizes of the charges are in the next steps.
    - ☐ CRAS-M main charge 1: 8.5 g
    - ☐ CRAS-M main charge 2: 8.5 g
    - ☐ CRAS-M main charge 3: 8.5 g
    - ☐ CRAS-M drogue charge 1: 2.0 g
    - ☐ CRAS-M drogue charge 2: 2.5 g
    - ☐ CRAS-M drogue charge 3: 2.5 g
    - ☐ CRAS-S charge 1: 3.0 g
    - ☐ CRAS-S charge 2: 3.5 g

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

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

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

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

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

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

Safety Officer: ______ Date: ______

5.1.3 Planetary Landing System Preparation

Standard Launch Procedure
Vehicle Demonstration Checklist
Planetary Landing System Preparation

Required Personnel: PLS Lead, Safety Officer, Launch Manager

Required PPE: Leather gloves, Nitrile gloves, Safety glasses

Inspection

PL: _______________ SO: _______________

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

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

Pre-Flight Checklist

PL: _______________ SO: _______________

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

- ☐ PLS Parachute Folding RL: _______________
  - ☐ Raise the parachute in the air, making sure all 8 shroud lines are straight and that the loop is on the top of the parachute.
  - ☐ Shake the parachute lightly to untangle the cords if needed.
  - ☐ Attach a quicklink to the open loop at the end of the shroud lines. Hold this quicklink to keep parachute from flying away.
  - ☐ Line all of the shroud lines up such that they are the same length. Use masking tape to group the shroud lines at this position to make folding easier. **Tape must be removed prior to launch or failure modes R.6 will occur!**
  - ☐ Lay the parachute out on the ground, and make sure every connection/quick link are securely tight to the parachute.
  - ☐ Fold over the gores on both sides towards the center. You want to organize the parachute until it is about 15% of the diameter of the parachute size.
  - ☐ Z-fold the parachute into thirds.
  - ☐ Pull the fabric on the underside of the parachute around the edge and onto the top. You want the fabric on the underside to be smooth with no folds.
  - ☐ Form a crease down the center of the folded parachute.
  - ☐ Bring the shroud line bundle up the crease to about 1/3 of the distance from the end.

  Do not bring the shroud lines to the very end.
  - ☐ Now start to wrap the shroud lines around the parachute. Ensure the back of the parachute is smooth with the material all pulled around into the crease.
  - ☐ Stop wrapping when you reach the end of the parachute.

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

  - ☐ Slide the parachute into the deployment bag, and then fold the flap over the bag.
  - ☐ Make sure the loop on the deployment bag is secure on the shroud line.
  - ☐ PLS parachute is now ready to be installed into the vehicle with the PLS.

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

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

- ☐ PLS Pre-Flight Assembly PL: ______________

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

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

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

- ☐ Use multimeter to ensure batteries are fully charged.
  - ☐ Insert fully charged battery into battery slot.
  - ☐ Plug battery into the power port on the electronics bay.
  - ☐ Inspect PLS once more before integration.
- ☐ See "Vehicle Preparation" to finish PLS integration

TROUBLESHOOTING

RL: ______________ SO: ______________

- ☐ The Raven altimeter performs a continuity check before flight to ensure that all ejection charges are properly connected. Should the altimeter fail this check on the launch pad, the altimeters may need to be removed and examined.

⚠**Ensure that the battery box switches are in the "off" position. Failure to turn off the altimeters could result in unintentional black powder ignition.**

- ☐ Take the rocket off of the launch pad and back to the preparation table.
- ☐ Remove the shear pins from the rocket and separate the sections.
- ☐ Remove the parachute, Nomex protector and shock cords from the rocket.
- ☐ Separate the fin can and recovery tube
- ☐ Unbolt the CRAS-M from the aft recovery bulkhead.
- ☐ Slide the CRAS-M out of the rocket.

⚠**Recheck to ensure that the battery box switches are in the "off" position. Failure to do so could result in unintentional black powder ignition.**

- ☐ Disconnect the black powder charges from the lever nut wire connections.

- ☐ Unbolt and remove the CRAS-M upper bulkhead and filler.
- ☐ Remove the CRAS-M core and examine the altimeter wire connections for defects. If none are detected, plug the Raven altimeters into a computer for diagnostics. Consult the user's manual for more information.

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

Safety Officer: ______________________________ Date: __________

5.1.4 Apogee Control System Preparation

STANDARD LAUNCH PROCEDURE
VEHICLE DEMONSTRATION CHECKLIST
APOGEE CONTROL SYSTEM PREPARATION

Required Personnel: ACS Lead, Safety Officer, Launch Manager

Required PPE: Leather gloves, Nitrile gloves, Safety glasses

INSPECTION

AL: __________ SO: __________

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

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

PRE-FLIGHT CHECKLIST

AL: __________ SO: __________

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

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

- ☐ Test batteries with a multimeter to ensure each battery is fully charged.
- ☐ Install the battery in the appropriate battery slot.
- ☐ Ensure the SD card is inserted in the Raspberry Pi prior to powering the system
- ☐ Connect the battery's molex connector to the circuit board and flip the power switch to

the ON position.

- ☐ Confirm that the power-LED has illuminated.
- ☐ Inspect the status LEDs for the sensors and SD card to ensure the Raspberry Pi controller is properly receiving sensor data and writing to the SD card
- ☐ Turn ON the arming switch. Ensure the arming LED turns on. **Ensure the launched state phase LED is OFF**
- ☐ Check that the drag tabs are flush with the support plates
- ☐ Complete ACS Integration in "Vehicle Preparation"

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

Safety Officer: ______________________________ Date: __________

5.1.5 Launch Vehicle Preparation

STANDARD LAUNCH PROCEDURE
VEHICLE DEMONSTRATION CHECKLIST
LAUNCH VEHICLE PREPARATION

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

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

TRANSPORTATION VL: __________ SO: __________

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

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

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

INSPECTION VL: __________ SO: __________

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

- ☐ Confirm weather is suitable for launch with RSO and LCO. If launch is postponed or cancelled, pack up equipment and return to team workshop.

- ☐ Inspect nose cone, payload tube, recovery tube, fin can and boattail assemblies for deformations or cracks to ensure there is no damage
- ☐ Light tug on eyebolts or extruded components to check adhesive strength at each connection to make sure they are strong
- ☐ Visually inspect fins for any cracks or deformations

PRE-FLIGHT CHECKLIST

VL: ____________ SO: ____________

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

- ☐ **Complete Recovery Preparation** RL: ______
- ☐ **CRAS-M Integration** RL: ______
  - ☐ Ensure both main and drogue parachute shock cords are securely attached to the CRAS-M eyebolts with quick links. **Make certain the main parachute is fore of the CRAS-M and the drogue parachute is aft of the CRAS-M!**
  - ☐ Insert CRAS-M into recovery tube
  - ☐ Secure CRAS-M using 6 screws and holes cut out of recovery tube. **One end of each shock cord should still be loose**
  - ☐ Place several handfuls of cellulose recovery wadding on each side of the CRAS-M.
  - ☐ Lightly coat the outside of all parachutes with talcum powder.

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

  - ☐ Insert folded main parachute in fore section of recovery tube. Ensure that the parachute is not packed so tightly that is cannot be pulled out. Ensure shock cord is loose and available to attach to payload tube.
  - ☐ Insert folded parachute in fore section of recovery tube. Ensure that the parachute is not packed so tightly that is cannot be pulled out. Ensure shock cord is loose and available to attach to payload tube.
  - ☐ Ensure that the eye bolt in the payload tube is secure.
  - ☐ Attach main parachute shock cord to the payload bay eyebolt with a quicklink.
- ☐ **Complete ACS Preparation** AL: ______
- ☐ **ACS Integration** AL: ______
  - ☐ Attach loose end of drogue parachute shock cord nearest to the ACS top bulkhead eyebolt before inserting ACS into fin can
  - ☐ Insert ACS into fin can and secure using the built-in ACS twist-to-lock mechanism
  - ☐ Inspect all 4 drag tab cutouts in the fin can to ensure that the tabs are visible and have clearance to extend

  - ☐ Inspect through the barometric vent holes to ensure that the LEDs are still lit and indicating the system is not in the launched state
  - ☐ If the LEDs indicate a premature launched state, the ACS system must be removed and ACS Preparation must be repeated until satisfactory
  - ☐ Make a final inspection of the system's installation by reviewing drag tab clearances, LEDs, and twist-to-lock security. Revisit ACS Preparation if needed.
- ☐ Secure fin can to recovery tube using 4 shear pins and the provided holes.
- ☐ **At this point, independent sections of vehicle remaining should be: nose cone, motor, and assembly of payload tube, recovery tube, and fin can. One end of the main parachute shock cord should also be loose.**
- ☐ **Complete PLS Preparation** PL: ________
- ☐ **PLS Integration** PL: ________
  - ☐ Ensure PLS jumper cable and pin are attached to PLS retention assembly.
  - ☐ Power ON PLS vehicle
  - ☐ Connect PLS transmitter with team ground station.
  - ☐ Insert PLS retention assembly into payload tube. Secure using 3 screws and holes in the payload tube.
  - ☐ Ensure PLS parachute is attached to the PLS eyebolt with a quick link and shock cord.
  - ☐ Insert jumper cable pin into PLS pin slot BEFORE inserting into vehicle.
  - ☐ Slide PLS into payload tube, placing the end with servo motors in first.
  - ☐ Align bulkhead with 3 retention pins and gently slide until PLS meets payload tube barrier bulkhead.
  - ☐ Ensure PLS parachute is sitting gently between the PLS legs and is not stuck on any components.
- ☐ **CRAS-S Integration** RL: ________
  - ☐ Ensure nose cone parachute shock cord is securely attached to the CRAS-S eyebolt with a quick link.
  - ☐ Attach other end of nose cone parachute shock cord to nose cone eye bolt with a quicklink.

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

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

  - ☐ Position payload tube vertically such that PLS opening is facing upward. **Two members must hols payload tube to maintain stability and prevent dropping.**
  - ☐ Place CRAS-S flat on the PLS legs such that the nose cone parachute is free and the payload tube is sealed.

  - ☐ One member hold nose cone parachute in the nose cone while another member positions nose cone shock cord on top of CRAS-S to prevent tangling.
  - ☐ Seal nose cone on to payload bay with the designed friction fit.
  - ☐ Rotate nose cone and payload tube assembly to be horizontal.

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

- ☐ Secure nose cone to payload bay using 4 shear pins and the provided holes.
  - ☐ Attach loose end of main parachute shock cord to PLS retention bulkhead eyebolt using a quicklink.
- ☐ Slide recovery and payload tubes together.
- ☐ **Flight Camera Integration** VL: ________
  - ☐ Insert the MicroSD card into the back of the camera
  - ☐ Press power button and wait for steady yellow light from camera
  - ☐ Press the recording button (camera icon) and wait for a flashing yellow light.
  - ☐ Insert the camera into the camera shroud so that the lens is facing downward
  - ☐ On the edge closest to the lens, place three small washers and loosely fit a lock nut onto the tie rod
  - ☐ On the edge further from the lens, place the medium washer and then two small washers and loosely fit the lock nut on the tie rod
  - ☐ If the camera does not fit, or has too much space to move, repeat previous three steps
  - ☐ If a proper fit is achieved, tighten the lock nuts with crescent wrench

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

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

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

- ☐ Center of gravity and stability check VL: ________

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

  - ☐ Perform center of gravity (CG) test to ensure the center of gravity matches the simulated CG by placing the fully assembled vehicle on a thin wooden stand so that it is cantilevered on both sides. Make slight adjustments to the vehicle position until it perfectly balances.
  - ☐ Mark the measured CG and simulated CG on the vehicle
  - ☐ Mark the simulated center of pressure (Cp) on the vehicle
  - ☐ Ensure calculated stability corresponds to predicted value

  - ☐ Re-open vehicle and ballast as necessary to maintain a stability margin of >2 calipers or within 10% of predicted margin (whichever is greater)
- ☐ Slide recovery and payload tubes together if opened.
- ☐ Secure the recovery tube to the payload bay with 4 shear pins

TROUBLESHOOTING

SO: ______________

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

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

⚠ **If believed to be damaged, battery should not be used AT ALL. While the team is still at the launch site, the battery should be housed in a fire proof battery case. The battery should then be disposed of according to University Standards upon return.**

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

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

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

Safety Officer: ________________________________ Date: ______________

5.1.6 Motor Preparation

STANDARD LAUNCH PROCEDURE
VEHICLE DEMONSTRATION CHECKLIST
MOTOR PREPARATION

Required Personnel: Safety Officer, Launch Manager

Required PPE: Nitrile gloves, Safety glasses

INSPECTION

LM: ______________ SO: ______________

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

VE.11, VE.13, VFM.1, VFM.3, VFM.4, VFM.5, VS.1, VS.2, VS.3, VS.5, VS.7, VS.8, or an unidentified failure mode and thus a mission failure

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

PRE-FLIGHT CHECKLIST
LM: ____________ SO: ____________

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

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

- ☐ **Motor Preparation** LM: ______
  - ☐ Insert the propellant into the casing, ensuring that the two spacers precede the propellant
  - ☐ Screw on the rear closure
  - ☐ Insert the motor into the motor mount, ensuring proper motor direction
  - ☐ Attach the motor retainer ring
  - ☐ Check motor for a secure fit

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

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

Safety Officer: ______________________________ Date: ____________

5.1.7 Launch Setup

STANDARD LAUNCH PROCEDURE
VEHICLE DEMONSTRATION CHECKLIST
LAUNCH SETUP

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

Required PPE: Leather gloves, Nitrile gloves, Safety glasses

INSPECTION
RL: ____________ SO: ____________

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

- ☐ Walk on ground adjacent where launch pad will be located to ensure it is hard and stable.

If soft or muddy, move launch pad location with approval from RSO.

☐ Make sure launch rail is clear of dirt of debris that would inhibit vehicle launch.

☐ Inspect vehicle rail buttons to ensure there is no damage

☐ Inspect screws and knobs on launch rail structure to ensure they are adjustable are secure, and not loose. If loose, alert RSO immediately.

☐ Confirm with RSO the launch controller is satisfactory for the intended launch PM: ______________

LAUNCH SITE EVALUATION SO: ______________

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

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

☐ If weather is acceptable, proceed with launch operations.

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

LAUNCH EQUIPMENT SETUP RL: ______________ SO: ______________

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

☐ Register with LCO and RSO at the launch site PM: ______________

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

☐ Install launch pad using wrenches in toolbox.

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

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

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

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

PRE-FLIGHT CHECKLIST LM: ______________ SO: ______________

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

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

☐ Place Vehicle on Launch Rail VL: ______________

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

  - ☐ Align the rail buttons with the rail and slide the vehicle onto the rail with the fin can towards the ground
- ☐ Activate Recovery Electronics RL: ______________
  - ☐ Recovery Lead arms recovery electronics using power keys. There should be 3 LEDs visible on the CRAS-M and 2 LEDs visible on the CRAS-S through the LED holes after arming the power switches. **If less than 5 Recovery LEDs are visible through LED holes, see "Troubleshooting", below.**
- ☐ Verify ACS Power AL: ______________
  - ☐ ACS Lead ensures power LED is not in launched state through barometric hole. **If LED indicates the vehicle is in launched state vehicle must be taken off launch pad, disassembled, and team must revisit "ACS Preparation".**
- ☐ Ensure all electronics are prepared for launch one additional time. SO: ______________
  - ☐ Set rail angle to be perpendicular to the ground with an added maximum 5 degrees into the wind
  - ☐ Lock rail in position using adjustable knobs.
- ☐ Proceed to "Igniter Installation" to complete next steps

TROUBLESHOOTING RL: ______________ SO: ______________

- ☐ The Raven altimeter performs a continuity check before flight to ensure that all ejection charges are properly connected. Should the altimeter fail this check on the launch pad, the altimeters may need to be removed and examined.

⚠**Ensure that the battery box switches are in the "off" position. Failure to turn off the altimeters could result in unintentional black powder ignition.**

- ☐ Take the rocket off of the launch pad and back to the preparation table.
- ☐ Remove the shear pins from the rocket and separate the sections.
- ☐ Remove the parachute, Nomex protector and shock cords from the rocket.
- ☐ Separate the fin can and recovery tube
- ☐ Unbolt the CRAS-M from the aft recovery bulkhead.
- ☐ Slide the CRAS-M out of the rocket.

⚠**Recheck to ensure that the battery box switches are in the "off" position. Failure to do so could result in unintentional black powder ignition.**

- ☐ Disconnect the black powder charges from the lever nut wire connections.
- ☐ Unbolt and remove the CRAS-M upper bulkhead and filler.
- ☐ Remove the CRAS-M core and examine the altimeter wire connections for defects. If none are detected, plug the Raven altimeters into a computer for diagnostics. Consult the user’s manual for more information.

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

Safety Officer: ________________________________ Date: ______________

5.1.8 Igniter Installation

STANDARD LAUNCH PROCEDURE
VEHICLE DEMONSTRATION CHECKLIST
IGNITER INSTALLATION

Required Personnel: Safety Officer, Launch Manager

Required PPE: Nitrile gloves, Safety glasses

INSPECTION LM: ______________ SO: ______________

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

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

PRE-FLIGHT CHECKLIST LM: ______________ SO: ______________

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

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

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

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

Safety Officer: ____ Date: ______________

5.1.9 Launch Procedures

Standard Launch Procedure
Vehicle Demonstration Checklist
Launch Procedures

Required Personnel: Launch Manager, RSO, LCO

Required PPE: Nitrile gloves, Safety glasses

Flight Initiation Checklist

LM: ______________ SO: ______________

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

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

☐ Confirm with LCO once again the launch controller is satisfactory for the intended launch PM: ______________

☐ Launch Manager confirms successful launch preparations with LCO

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

☐ LCO commences launch countdown over loudspeaker

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

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

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

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

Troubleshooting

RL: ______________ SO: ______________

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

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

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

☐ Disconnect the igniter from the ignition clips.

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

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

Safety Officer: ______________________________ Date: __________

5.1.10 Post-Flight Recovery and Analysis

Standard Launch Procedure
Vehicle Demonstration Checklist
Post-Flight Recovery and Analysis

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

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

Inspection SO: __________

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

⚠**Personnel may only enter launch area when given permission by RSO.**

⚠**Black powder charges may still be live upon landing. Do not approach until Launch Manager verifies all charges have gone off.**

⚠**Motor is still hot upon landing. Do not touch until the checklist specifically mentions to.**

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

Post-Flight Recovery Checklist RL: __________ SO: __________

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

⚠**Personnel may only enter launch area when given permission by RSO.**

⚠**Black powder charges may still be live upon landing. Do not approach until Launch Manager verifies all charges have gone off.**

⚠**Motor is still hot upon landing. Do not touch until the checklist specifically mentions to.**

⚠**Do not touch PLS until told to do so.**

- ☐ Verify team ground station received panoramic image transmission before recovering
- ☐ After pictures have been taken from a distance, the Launch Manager must ensure that all 8 black powder charges successfully ejected. This can be done visually by confirming the tape seals are ripped or gone entirely. **If any black powder charges have not successfully fired, see "Troubleshooting" below for safe procedures.**

⚠**Recovery Lead must verify all black powder charges have gone off before proceeding.**

⚠**Recovery Lead turns all power keys to be OFF before proceeding.**

- ☐ Continue to take pictures of all components until Project Manager deems the quantity acceptable for report writing and team media.
- ☐ Begin Collecting Vehicle Sections SO: ____________
  - ☐ Disconnect quicklinks for all parachutes. At least one team member will be responsible for returning all 5 parachutes to the team staging area.
  - ☐ Disconnect CRAS-S from nose cone by undoing the quicklink. One team member will be responsible for returning the CRAS-S to the team staging area.
  - ☐ One team member will be responsible for returning the nose cone to the team staging area.
  - ☐ Disconnect the quicklink attaching the drogue recovery harness from the ACS eyebolt.
  - ☐ Remove nomex blankets and parachute bags. One team member will be responsible for returning the 2 parachute deployment bags to the team staging area. An additional one team member will be responsible for returning the 3 nomex blankets to the team staging area.
  - ☐ Two team members will be responsible for transporting the payload tube and connected drogue and main recovery harnesses to the team staging area.

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

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

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

  - ☐ One team member will be responsible for returning the PLS to the team staging area.

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

POST-FLIGHT ANALYSIS CHECKLIST SO: ____________

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

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

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

TROUBLESHOOTING SO: ____________

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

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

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

Safety Officer: ______________________________ Date: __________

5.2 Safety and Environment

All hazards will be assessed on the same scales of probability and severity to apply consistent, effective mitigations. Hazards considered include personnel hazards, failure modes and effects analysis (FMEA), and environmental hazards. Every hazard will be identified by a member of the Safety team and documented with appropriate causes, outcomes, mitigations and verifications. All hazards will be assigned a pre-assessment numerical value reflecting the combined probability and severity of the hazard before mitigation. Similarly, all hazards will be assigned a post-assessment value reflecting the combined probability and severity of the hazard after mitigation implementation. Mitigating hazards with larger pre-assessment values will be prioritized over hazards with smaller values, although the team is confident all hazards will be successfully mitigated. Table 58 displays the values and occurrence definitions for hazard probability. Additionally, Table 59 displays the values and definitions for hazard severity in multiple contexts, specifically personnel, vehicle, and environmental hazards.

An overall assessment can be made by multiplying the values of probability and severity. Table 60 displays all potential combinations of probability and severity and their respective risks, as well as assigning color values to each combination. The key and definition for each color assignment can be seen in Table 61.

When risks are identified and prioritized, mitigations will be identified to decrease the

Table 58: Probability Value Criteria

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

Table 59: Severity Value Criteria

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

Table 60: Overall Risk Assessment

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

Table 61: Risk Assessment Color Code

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

potential risks of each hazard. To ensure these mitigations are implemented and adhered to, verifications will also be applied to each mitigation. Verifications may take the form of actions taken by specific individuals or resources provided to all team members. In this way, all mitigations will be properly carried out by informed, trained, responsible individuals, thus ensuring effective risk reduction.

All risks identified are labeled with a respective code. This allows members of the Notre Dame Rocketry Team to quickly locate and utilize safety information. The alpha-numeric format for all labels is AAA.N, where A can be any amount of letters up to 3 letters, and N is a number. For example, the fifth risk in the Vehicles Structures FMEA Table is labeled as VS.5. Table 62 outlines the naming conventions for each category.

Table 62: Risk Label Naming Convention

Safety Table	Label
Construction Personnel Hazards	C
Launch Operations Personnel Hazards	L
Vehicle Structures FMEA	VS
Vehicle Flight Mechanics FMEA	VFM
Recovery FMEA	R
Apogee Control System FMEA	ACS
Planetary Landing System FMEA	PV
Plantary Landing System Deployment and Integration FMEA	PI
Launch Equipment FMEA	LE
Environmental to Vehicle	EV
Vehicle to Environment	VE
Project Risks	PR

5.2.1 Personnel Hazard Analysis

5.2.1.1 Construction

Table 63: Construction

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
C.1	Skin contact with strong adhesive materials (epoxy, etc.)	Improper application of adhesive materials	1. Severe allergic reaction 2. Severe skin irritation or permanent skin damage	3	3	9	1. All team members have completed applicable workshop safety training 2. Team members working with adhesives are required to wear chemical-resistant gloves and have been provided step-by-step procedures for safe operation 4. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operating Procedure 2.3.1 outlines the correct procedure for epoxying. 3. The NDRT Safety Data Sheet Document is readily available for all members 4. The NDRT Standard Operating Procedures is readily available for all members	2	2	4
C.2	Contact with the rotating component of a tool or machine	Improper use of a portable drill, drill press, a dremel, or other rotary tools	1. Severe injury to, or loss of, extremities 2. Severe skin abrasions or cuts	3	4	12	1. All team members participating in construction have completed applicable workshop safety training 2. Team members working with rotating tools or machines have been provided step-by-step procedures for safe operation 3. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation. 2. Standard Operating Procedures outline the correct procedure for operating a dremel (SOP 2.1.2), portable drill (SOP 2.1.4), drill press (SOP 2.2.4), lathe (SOP 2.2.6), and techno router (SOP 2.2.8) 7. The NDRT Standard Operating Procedures is readily available for all members	1	4	4
C.3	Materials become unsecured during construction	Parts are loose due to improper use of motion-restriction tools	1. Injury: cuts, abrasions, or blunt bodily damage 2. Unsecured part endangers nearby team members	3	3	9	1. All team members participating in construction have completed applicable workshop and hand tool safety training 2. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operating Procedure 2.1.1 outlines the correct procedure for using a clamp.	1	3	3

C.4	Contact with the cutting blade of any type of tool or machine	Improper use of a band saw, scroll saw, hand saw, exacto knife, or any other type of cutting tool	1. Severe damage to, or loss of, extremities 2. Cuts or abrasions to the contact region	3	4	12	1. All team members participating in construction have completed applicable workshop and hand tool safety training 2. Team members working with sharp tools or machines have been provided step-by-step procedures for safe operation 3. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operation Procedures outline the correct procedure for operating a hand saw (SOP 2.1.3), wire cutters and strippers (SOP 2.1.6), band saw (SOP 2.2.2), and scroll saw (SOP 2.2.7) 6. The NDRT Standard Operating Procedures is readily available for all members	1	4	4
C.5	Contact with the abrasive surface of any type of tool or machine	Improper use of a belt sander, circular sander, portable sander, sandpaper, and other tools or machines with abrasive surfaces	1. Injury including cuts and abrasions 2. Burns on skin	3	4	12	1. All members participating in construction have completed applicable safety training 2. Team members working with abrasive tools or machines have been provided step-by-step procedures for safe operation 3. Required PPE for given tasks are provided in respective Standard Operating Procedures	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Standard Operating Procedures outline the correct procedure for operating a belt and disc sander (SOP 2.2.3), and sandpaper (SOP 2.3.2) 4. The NDRT Standard Operating Procedures is readily available for all members	1	4	4
C.6	Inhalation of airborne particulates resulting from part manufacturing	Performing work such as sanding or cutting that creates harmful airborne particulates, such as carbon fiber and fiberglass	Short and long term respiratory health issues	4	4	16	1. All team members participating in construction have completed applicable safety training 2. Members working with airborne particles must wear a respirator 3. Required PPE for given tasks are provided in respective Standard Operating Procedures 4. PPE usage information is available in the NDRT Safety Handbook 5. Material properties are listed in the NDRT Safety Data Sheet Document	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. The NDRT Standard Operating Procedures are readily available for all members 3. The NDRT Safety Handbook is readily available for all members 4. The NDRT Safety Data Sheet Document is readily available for all members	2	3	6
C.7	Inhalation of toxic fumes from glue, epoxy, or spray paint	Performing work such as sanding or heating that creates harmful toxic fumes	Short and long term respiratory health issues	4	4	16	1. All team members participating in construction have completed applicable safety training 2. Team members working with any toxic fumes must wear a respirator 3. Required PPE for given tasks are provided in respective Standard Operating Procedures 4. PPE usage information is available in the NDRT Safety Handbook 5. Material properties are listed in the NDRT Safety Data Sheet Document	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. The NDRT Standard Operating Procedures are readily available for all members 3. The NDRT Safety Handbook is readily available for all members 4. The NDRT Safety Data Sheet Document is readily available for all members	2	3	6

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

C.12	Prolonged exposure to loud machinery or construction tools	Operating a tool or machine that generates unsafe levels of sound during use	Temporary or long-term hearing loss	3	3	9	1. All team members have completed applicable workshop safety training 2. Members participating in construction producing loud noise must wear hearing protection 3. Required PPE for tasks is provided in Standard Operating Procedures 4. PPE usage information is available in the NDRT Safety Handbook	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. The NDRT Standard Operating Procedures are readily available for all members 3. The NDRT Safety Handbook is readily available for all members	1	3	3
C.13	Tripping or falling	Obstacles on the floor such as loose cords, fluid spills, or build materials	Potential injury or disruption of other work, leading to consequent injuries	4	2	8	1. All team members have completed applicable workshop safety training 2. Team members are required to clean up the entire workspace and any mess after performing a task 3. Required clean up procedures for given tasks are provided in respective Standard Operating Procedures 4. PPE usage information is available in the NDRT Safety Handbook	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. The NDRT Standard Operating Procedures are readily available for all members 3. The NDRT Safety Handbook is readily available for all members	1	2	2
C.14	Fire	Overheating parts, electric components short-circuiting, Lithium-Polymer battery explosion, sparks during metal cutting, improper soldering iron placement	1. Burns leading to short term health effects or death 2. Smoke inhalation leading to short and long term health effects or death	2	4	8	1. All team members have completed applicable workshop safety training 2. Team members must consult the NDRT Safety Data Sheet Document before handling flammable materials 3. Team members are required to clean up the entire workspace and any mess after performing a task 4. Fire-prevention materials are always present in the NDRT Workshop 5. Required cleaning procedures are provided in respective SOPs 6. PPE usage information is available in the NDRT Safety Handbook 7. Material properties are listed in the NDRT Safety Data Sheet Document	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. The NDRT workshop adheres to all University of Notre Dame building codes and maintains a fire extinguisher and fire blanket in the event of a fire 3. The NDRT Standard Operating Procedures are readily available for all members 4. The NDRT Safety Handbook is readily available for all members 5. The NDRT Safety Data Sheet Document is readily available for all members	1	4	4
C.15	Contracting Sickness, specifically SARS-CoV-2	Respiratory transmission of a highly contagious virus	1. Contracting SARS-CoV-2 potentially leading to long-term health effects or death 2. Increased chance of transmission to other team members	3	4	12	1. All team members have completed applicable workshop safety training 2. Workshop capacity is set at 20 persons at all times 3. All persons must sign in and out of the workshop for contact tracing 4. Masks must be worn at all times 5. All non construction team meetings will be held on Zoom or other video chat platforms	1. The Safety Officer and team officers have verified all pandemic prevention procedures issued by NDRT the University of Notre Dame, St. Joseph's County, and. the State of Indiana are followed at all times. 2. All team members were required to sing and agree to all guidelines and are held accountable with University of Notre Dame officials	1	4	4

5.2.1.2 Launch Operations

Table 64: Launch Operations

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
L.1	Catastrophic Failure	1. Imperfections in motor 2. Motor improperly integrated into vehicle body	1. Motor explosion occurs near launch area	3	4	12	1. All motors will be thoroughly inspected prior to launch 2. All motors will be correctly and carefully installed 3. The motor has been purchased from a reputable vendor that has successfully fired this motor model thousands of times	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Motor Preparation contains guidelines for proper motor handling and installation 3. All members ordering a motor must consult the trusted vendor list and past motor data	1	4	4
L.2	Uncontrollable launch towards any personnel	1. Launch rail leans over during launch sequence 2. Vehicle stability is unacceptable for launch conditions	1. Potential high velocity impact with personnel and property	3	4	12	1. The launch rail will be carefully inspected prior to launch 2. The motor will be installed correctly and carefully by a qualified individual 3. The static stability will be within 2 to 3 calipers, per requirements 2.14 and VD. 8 4. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail and is made available to all members 3. Calculations in Section 3.9.2 show the static stability value of the vehicle is 2.17, which is within the acceptable range of 2 to 3 4. The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications	1	4	4

L.3	Uncontrollable vehicle descent towards personnel	1. The vehicle lands on personnel upon descent under parachute 2. The parachute does not deploy and the vehicle body descends vertically from apogee	1. High velocity impact with personnel and property leading to injury or death	3	4	12	1. All energetics will be installed correctly and carefully by a qualified individual 2. The recovery design will be tested to show reliability and redundancy 3. Vehicle drift will be restricted to 2,500 feet, per NASA req. 3.10 4. Maximum kinetic energy of the vehicle will be 75 ft-lbf, per NASA req. 3.3 5. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to handle energetics and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail and is made available to all members 3. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 4. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 5. Test TR.3 outlines proper procedures and success criteria for testing black powder separation and is readily available for all members 6. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy and is readily available for all members 7. Calculations in Section 3.9.5.1 show the maximum expected drift radius of the vehicle is 2,397 ft, which is within the acceptable range of 2,500 ft and satisfies NASA req. 3.10 8. Calculations in Section 3.8.5.2 shows main parachute sizing to be 12 ft in diameter and and Section 3.9.4.1 shows maximum expected kinetic energy of the vehicle to be 73.98 ft-lbf, within the acceptable range of 75 ft-lbf and satisfies NASA req. 3.3 9. The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications	2	3	6

L.4	PLS uncontrolled descent	1. PLS separates from vehicle during launch 2. PLS recovery fails	1. Personnel injury and building damage via impact	3	3	9	1. All energetics will be installed correctly and carefully by a qualified individual 2. The recovery design will be tested to show reliability and redundancy 3. Payload drift will be restricted to 2,500 feet, per requirement 3.10 4. Maximum kinetic energy of the PLS will be 75 ft-lbf, per requirement 3.3 5. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to handle energetics and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail and is made available to all members 3. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 4. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 5. Test TR.3 outlines proper procedures and success criteria for testing black powder separation and is readily available for all members 6. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy and is readily available for all members 7. Calculations in Section 3.9.5.2 show the maximum expected drift radius of the PLS is 830 ft, which is within the acceptable range of 2,500 ft and satisfies NASA req. 3.10 8. Calculations in Section 4.4.2 shows PLS parachute sizing to be 3 ft in diameter and and Section 3.9.4.2 shows expected maximum kinetic energy of the PLS to be 18.5 ft-lbf, within the acceptable range of 75 ft-lbf and satisfies NASA req. 3.3 9. The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications	2	2	4

L.5	Nose cone uncontrolled descent	1. Nose cone separated from vehicle during launch 2. Nose cone recovery fails	1. Personnel injury and building damage via impact	3	3	9	1. All energetics will be installed correctly and carefully by a qualified individual 2. The recovery design will be tested to show reliability and redundancy 3. Nose cone drift will be restricted to 2,500 feet, per requirement 3.10 4. Maximum kinetic energy of the nose cone will be 75 ft-lbf, per requirement 3.3 5. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to handle energetics and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail and is made available to all members 3. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 4. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 5. Test TR.3 outlines proper procedures and success criteria for testing black powder separation and is readily available for all members 6. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy and is readily available for all members 7. Calculations in Section 3.9.5 show the maximum expected drift radius of the nose cone is 2,094 ft, which is within the acceptable range of 2,500 ft and satisfies NASA req. 3.10 8. Calculations in Section 3.8.5.3 shows nose cone parachute sizing to be 2 ft in diameter and Section 3.9.4.1 shows expected maximum kinetic energy of the nose cone to be 27.74 ft-lbf, within the acceptable range of 75 ft-lbf and satisfies NASA req. 3.3 9. The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications	2	2	4
L.6	High temperature of motor when ignited	1. Motor is hot after landing 2. Personnel are located too close to launchpad during motor burn	1. Potential skin burns and scarring	3	3	9	1. Personnel will not touch the vehicle immediately after landing 2. Personnel will not enter launch field until RSO grants permission 3. Personnel will stand a safe distance as designated by the RSO at launch (at least 300 ft. as required by the NAR).	1. Launch Checklist: Post-Flight Recovery and Analysis outlines proper procedures for safely recovering the vehicle and PLS after landing and is made available to all members 2. The Range Safety Officer will designate safe viewing zones at least 300 ft from the launch pad, in accordance with NAR specifications 3. The Range Safety Officer will be the only individual controlling movement of personnel on or off of the launch pad and launch field	1	2	2

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

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

5.2.2 Failure Modes and Effects Analysis

5.2.2.1 Vehicle Flight Mechanics

Table 65: Vehicle Flight Mechanics

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VFM.1	Motor ignition failure	1. E-match malfunction 2. Motor imperfections	No launch results in mission failure	3	1	3	1. All motors will be thoroughly inspected prior to launch 2. Only qualified individuals will handle and install the motor and igniter 3. The motor is to be purchased from a well reputable vendor that has successfully fired this motor model thousands of times	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Launch Setup outlines a checklist for setting up launch equipment and is readily available for all members 3. Launch Checklists: Motor Preparation and Igniter Installation outline checklists and plans for installing the motor and igniter and is readily available for all members 4. The selected motor is shown in Section 3.3.3 and has been successfully flown thousands of times by the manufacturer	1	1	1
VFM.2	Vehicle fails to clear launch rail	1. Deformation of launch rail 2. Improper motor selection 3. Motor imperfections 4. Rail buttons deform or break during motor burn	Failed launch results in mission failure and potential harm to vehicle or personnel	2	3	6	1. All computer simulations involved the Vehicles Design Lead, Chief Engineer, and Graduate Student Mentor when applicable 2. The design of the vehicle has been derived from available motors 3. The center of mass is determined on launch day prior to launch when the vehicle is fully assembled 4. The static stability margin of the vehicle will at least 2.0, per NASA Req. 2.14 5. The motor has been selected based on calculations and simulations to achieve a minimum velocity of 52 feet per second at rail exit	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Calculations in Section 3.9.2 show the static stability value of the vehicle is 2.17 and the off-rail stability is 2.33, which is within the acceptable range of 2 to 3 (NASA Req. 2.14). 3. Launch Checklist: Launch Setup outlines proper procedures for setting up and inspecting the launch rail 4. Launch Checklist: Launch Vehicle Preparation outlines proper procedures for determining center of mass on launch day and is made available to all members 5. Construction procedures outlining proper steps for fabricating and attaching rail buttons will be created and made readily available 6. The selected motor (Section 3.3.3) has been successfully flown thousands of times	1	3	3

VFM.3	Failure of vehicle to reach sufficient velocity upon exiting launch rail	1. Improper motor selection 2. Motor imperfections 3. Excessive weight in vehicle 4. External forces acting on the launch vehicle are larger than expected	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	2	3	6	1. The motor has been selected based on calculations and simulations to achieve a minimum velocity of 52 feet per second at rail exit 2. Only qualified individuals will handle and install the motor and igniter 3. The motor is to be purchased from a well reputable vendor that has successfully fired this motor model thousands of times 4. Weight budgets have been allocated to each subsystem with a 21.61% total margin 5. Camera shroud shape and location were designed to minimize drag 6. Wind tunnel testing will be done to determine an accurate coefficient of drag, depending on wind tunnel availability to undergraduate student design teams at the University of Notre Dame in february 2021	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklist: Launch Setup outlines a checklist and plan for setting up launch equipment and is readily available for all members 3. Launch Checklists: Motor Preparation and Igniter Installation outline checklists and plans for installing the motor and igniter and is readily available for all members 4. Mass budgets for each subsystem were strictly enforced by the Chief Engineer and can be located in Section ____ 5. Construction procedures outlining proper steps for fabricating and attaching the camera shroud will be created and made readily available for all members 6. The selected motor (Section 3.3.3) and has been successfully flown thousands of times by the manufacturer 7. Test TV.6 outlines proper procedures and success criteria for testing the motor capability during a demonstration flight and is readily available for all members	1	3	3
VFM.4	Fin Flutter	1. Fins are not manufactured to specifications 2. Fins are not properly secured to the vehicle	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	3	3	9	1. Fin design and material are chosen based on calculations, simulations and testing to reach a static stability margin of at least 2.0, per NASA Req. 2.14 2. Fin can will be constructed carefully and accurately 3. Fins will be properly attached and adhered to the fin can and vehicle body	1. Calculations and simulations for fin can design can be found in Section 3.4.5 and have been verified and approved by the Safety Officer and Chief Engineer 2. Calculations and simulations for fin design can be found in Section 3.4.7 and have been verified and approved by the Safety Officer and Chief Engineer 3. Calculations in Section 3.9.2 show the static stability value of the vehicle is 2.17 and the off-rail stability is 2.33, which is within the acceptable range of 2 to 3 and satisfies NASA Req. 2.14. 4. Construction procedures outlining proper steps for fabricating and assembling the fin can will be created and made readily available for all members 5. Construction procedures outlining proper steps for fabricating and attaching fins will be created and made readily available for all members	2	1	2

VFM.5	Failure of launch vehicle to travel in intended direction	1. Incorrect motor alignment 2. Improper rail buttons alignment	Vehicle moves along an unintended line of motion causing potential harm to vehicle or personnel	3	3	9	1. Centering rings will be constructed using proper procedures and techniques 2. Rail buttons will be properly attached and adhered to the fin can and vehicle body 3. The motor will be installed correctly and carefully 4. The static stability will be within 2 to 3 calipers, per requirements 2.14 and VD. 8	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. Launch Checklists: Launch Setup outlines a checklist and plan for setting up launch equipment and is readily available 3. Launch Checklists: Motor Preparation and Igniter Installation outline checklists and plans for installing the motor and igniter and is readily available for all members 4. The selected motor (Section 3.3.3) has been successfully flown thousands of times 5. Calculations in Section 3.9.2 show the static stability value of the vehicle is 2.17 and the off-rail stability is 2.33, which is within the acceptable range of 2 to 3 and satisfies NASA Req. 2.14. 6. Construction procedures outlining proper steps for fabricating and assembling centering rings will be created and made readily available for all members 7. Construction procedures outlining proper steps for fabricating and attaching rail buttons will be created and made readily available for all members	2	1	2
VFM.6	Vehicle is over-stable	Center of pressure is too far below the center of mass	Vehicle turns into the wind, may not reach the desired apogee, resulting in potential harm to vehicle or personnel	3	2	3	1. All computer simulations involved the Vehicles Design Lead, Chief Engineer, and Graduate Student Mentor when applicable 2. Center of pressure was mathematically determined using Open Rocket software 3. Center of mass was calculated in CAD software and by physically balancing the vehicle before launch 4. Fin shape and placement carefully considered stability	1. Calculations and simulations for the center of pressure can be found in Section 3.9.3 and have been verified and approved by the Safety Officer and Chief Engineer 2. Calculated expected center of mass is depicted in Section 3.3.1 and have been verified and approved by the Safety Officer and Chief Engineer 3. Calculations and simulations for fin design can be found in Section 3.4.7 and have been verified and approved by the Safety Officer and Chief Engineer 4. Calculations in Section 3.9.2 show the static stability value of the vehicle is 2.17 and the off-rail stability is 2.33, which is within the acceptable range of 2 to 3 and satisfies NASA Req. 2.14. 5. Launch Checklists: Launch Vehicle Preparation outlines proper procedures for determining center of mass on launch day and is made available to all members	1	2	2

5.2.2.2 Vehicle Structures

Table 66: Vehicle Structures

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VS.1	Bulkhead failure	1. Improper construction 2. Adhesive failure to secure bulkheads 3. Bulkhead material and design cannot withstand loading	1. Internal components damaged 2. Unintentional vehicle separation	3	3	9	1. The material and design of each bulkhead will be carefully selected based on mathematical calculations and structural FEA 2. The application of adhesives will be precise and thorough, with fillets applied to reduce stress concentrations	1. Calculations and safety factors for the vehicle structural bulkhead can be located in Section 3.4.8 and have been approved by both the Safety Officer and Chief Engineer 2. Construction procedures outlining proper steps for fabricating and assembling bulkheads will be created and made readily available for all members 3. Standard Operating Procedure 2.3.1 outlines the correct procedure for epoxying.	1	2	2
VS.2	Motor explosion	1. Improper installation of motor casing 2. Imperfections within the motor	1. Vehicle and payload sustain considerable damages during flight 2. People nearby are potentially injured	2	4	8	1. All motors will be thoroughly inspected prior to launch 2. The motor will be installed correctly and carefully by a qualified individual 3. The motor is to be purchased from a reputable, high fidelity vendor that has successfully fired this motor model thousands of times in the past	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. The chosen motor has been sourced from a trusted vendor and been approved by the Vehicles Design Lead and Chief Engineer 3. Launch Checklist: Motor Preparation outlines a checklist and plan for installing the motor into the vehicle body and is readily available for all members	1	4	4

VS.3	Nose cone detachment	1. Shear pin failure 2. Premature CRAS-S black powder charge	1. Unpredictable flight path leads to potential high velocity impact, which may damage internal components 2. Loss of PLS structure during flight	2	3	6	1. Calculations and simulations were performed to determine proper nose cone size and shape 2. Each black powder charge and altimeter combination is entirely independent 3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding 4. All components in the nose cone and payload bay will be properly secured to the vehicle body, not the nose cone	1. Calculations and simulations for nose cone design (Section 3.4.1) have been approved by both the Safety Officer and Chief Engineer 2. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 3. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 4. Test TR.3 outlines proper procedures and success criteria for testing separation 5. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy 6. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures 7. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for attaching the nose cone and securing with shear pins and is readily available	1	3	3
VS.4	Structural failure upon landing	1. Vehicle body is constructed with improper materials	1. The vehicle may be damaged or entirely destroyed upon impact 2. Nearby property and people may be damaged or injured	3	3	9	1. The material and design of vehicle structural components will be carefully selected based on mathematical calculations and structural FEA 2. The vehicle structures will be tested to ensure structural integrity upon landing 3. Procedures for properly constructing the launch vehicle will be created	1. Calculations and simulations for vehicle structural components (Section 3.4) have been approved by both the Safety Officer and Chief Engineer 2. Test TV.3 outlines proper procedures and success criteria for testing fin structural integrity during impact 3. Test TV.4 outlines proper procedures and success criteria for testing nose cone structural integrity during impact 4. Test TV.5 outlines proper procedures and success criteria for testing vehicle structural integrity during a shake test 5. Construction procedures outlining proper steps for fabricating and assembling the vehicle will be created and made available	1	3	3
VS.5	Fin failure	Fins are improperly attached to the vehicle body	Flight path becomes unpredictable and vehicle does not follow the intended trajectory	3	3	9	1. The material and design of fins will be carefully selected based on mathematical calculations and structural FEA 2. Fins will be properly fabricated and attached to the fin can and vehicle body using detailed procedures 3. Fin structural integrity will be tested prior to launch	1. Calculations and simulations for the fin design (Section 3.4.7) have been approved by both the Safety Officer and Chief Engineer 2. Test TV.3 outlines proper procedures and success criteria for testing fin structural integrity during impact 3. Construction procedures outlining proper steps for fabricating and assembling the fins will be created and made readily available	1	2	2

VS.6	Dropping vehicle	1. Carelessness of team members when transporting the vehicle 2. High winds cause vehicle to fall off of staging table	1. Potential damages to interior payload components 2. Potential damages to exterior vehicle body, especially components such as fins and the nose cone	2	3	6	1. Multiple team members will be required to transport the vehicle	1. Launch Procedure: Launch Vehicle Preparation outlines a checklist for transporting the vehicle to and from the launch site and is readily available for all members 2. Launch Procedure: Launch Vehicle Preparation outlines a checklist for handling the vehicle at the launch site and is readily available for all members	1	1	1
VS.7	Centering Ring Failure	1. Centering rings improperly attached 2. Centering ring imperfections	1. Motor is not properly aligned and the vehicle does not reach the desired apogee 2. Potential injury and harm to people nearby due to unexpected flight path	3	4	12	1. The materials and design of the centering rings were carefully selected based on calculations 2. The centering rings will be properly and carefully installed based on created procedures	1. Calculations and simulations for the centering ring designs can be located in Section 3.4.9 and have been approved by both the Safety Officer and Chief Engineer 2. Construction procedures outlining proper steps for fabricating and assembling centering rings will be created and made readily available for all members	1	4	4
VS.8	Coupler Failure	1. Couplers sized incorrectly 2. Couplers improperly attached to vehicle body tube	1. Improper vehicle separation resulting in damage to vehicle and payload	3	4	12	1. The materials and design of the couplers were carefully selected based on calculations 2. The couplers will be properly and carefully installed based on created procedures	1. Calculations and simulations for the fin design can be located in Section 3.4.7 and have been approved by both the Safety Officer and Chief Engineer 2. Construction procedures outlining proper steps for fabricating and assembling centering rings will be created and made readily available for all members	1	4	4
VS.9	Electronic tracking devices fail to transmit the positions of each independent section of the vehicle	1. Radio frequency interference from shielding material inhibits transmission 2. Tracking devices are disrupted by transmitters in other components of the vehicle	NASA Req. 3.12 to track the vehicle and its components accurately during the flight is not fulfilled.	3	2	6	1. Materials surrounding the electronic tracking device will be chosen both for strength and for radio frequency transparency 2. The transmitting frequencies of other electronic devices will be carefully chosen to avoid potential interference	1. All transmitters are designed to be located in unshielded locations on the PLS 2. Launch Procedure: Planetary Landing System Preparation outlines a checklist and plan for installing and arming transmitters in the PLS and is readily available for all members 3. All transmitter frequencies will be reported to NASA prior to launch and compared to other devices at the launch site 4. Test TR.6 outlines proper procedures and success criteria for testing GPS transmitters and is readily available for all members	1	1	1

5.2.2.3 Apogee Control System

Table 67: Apogee Control System

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
ACS.1	Power system failure	1. Damaged circuits from poor construction 2. Damaged circuits during launch and/or flight 3. Insufficiently charged batteries	An overshoot of target apogee due to electrical system system and loss of control of extending tab	4	3	12	1. All electronic components will be checked thoroughly prior to launch 2. All batteries used during launch will be fully charged and tested prior to launch	1. Launch Checklist: Packing List outlines a checklist and plan for ensuring all batteries are fully charged prior to departure from the workshop and is readily available for all members 2. Launch Checklist: Packing List outlines a packing list for all ACS components, including charged batteries, and is readily available for all members 3. Launch Checklist: Apogee Control System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members 4. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing ACS electronics into the vehicle and is readily available for all members	2	2	4
ACS.2	Incorrect or unavailable sensor data	1. Sensors are improperly installed and programmed prior to launch 2. Loss of power to the electrical system	The launch vehicle will reach an apogee outside of the acceptable range of 5300 ± 30 ft	4	3	12	1. All system code operating in the apogee control system will be tested prior to launch 2. All electrical sensors in the apogee control system will be tested prior to launch	1. Test TA.4 outlines proper procedures and success criteria for testing a control algorithm with sample data 2. Test TA.5 outlines proper procedures and success criteria for testing servo actuation with sample data 3. Test TA.7 outlines proper procedures and success criteria for testing sensors and a data filter during subscale flight	2	2	4
ACS.3	Improper command signals from microcontroller	1. Electronic system is incorrectly programmed 2. Computations of live sensor data result in unexpected errors	The launch vehicle will reach an apogee outside of the acceptable range of 5300 ± 30 ft	3	3	9	1. All system code operating in the apogee control system will be tested prior to launch	1. Test TA.4 outlines proper procedures and success criteria for testing a control algorithm with sample data and is readily available for all members 2. Test TA.5 outlines proper procedures and success criteria for testing servo actuation with sample data and is readily available for all members	2	2	4

ACS.4	Mechanical tab extension mechanism failure	1. Insufficient material strength 2. Improper construction techniques	Tab extensions cannot correctly deploy, resulting in the launch vehicle reaching an apogee outside of the acceptable range of 5300 ± 30 ft.	3	3	9	1. Tab extension materials are chosen based on simulations and calculations 2. Construction procedures will be written prior to beginning construction	1. Calculations for tab extensions can be located in Section 3.7.4.1 and have been approved by both the Safety Officer and Chief Engineer 2. Test TA.2 outlines proper procedures and success criteria for testing tab extensions during demonstration flight loads and is readily available for all members 3. Construction procedures outlining proper steps for fabricating and assembling the tab extension tabs will be created and made readily available for all members	2	2	4
ACS.5	Shearing of structural components that anchor the Apogee Control System within the launch vehicle via a twist-to-lock mechanism	1. Insufficient material strength 2. Improper construction techniques	Apogee Control System is unable to properly deploy and potentially shifts inside the vehicle body, resulting in internal component damage and unexpected changes in mass distribution	3	4	12	1. Structural components are chosen based on simulations and calculations 2. Construction procedures will be written prior to construction	1. The twist-to-lock mechanism design can be located in Section 3.7.4.3 and has been approved by both the Safety Officer and Chief Engineer 2. Test TA.2 outlines proper procedures and success criteria for testing structural integrity during demonstration flight and is readily available for all members 3. Test TV.5 outlines proper procedures and success criteria for testing structural integrity during a vehicle shake test and is readily available for all members 4. Construction procedures outlining proper steps for fabricating and assembling the ACS structure will be created and made readily available for all members	2	2	4
ACS.6	Apogee Control System has a slow response time, preventing effective adjustments being made in flight	1. Data filters leave too much data for the control system to quickly process 2. The amount of flight data collected in flight exceeds the Apogee Control System's memory	Loss of effective ACS function leading to an apogee likely outside of the acceptable range of 5300 ± 30 ft.	3	2	6	1. Data filtration system will be chosen with significant considerations of speed and memory. 2. The software program for the Apogee Control System system will be tested before launch	1. Test TA.4 outlines proper procedures and success criteria for testing a control algorithm with sample data and is readily available for all members 2. Test TA.5 outlines proper procedures and success criteria for testing servo actuation with sample data and is readily available for all members 3. Test TA.7 outlines proper procedures and success criteria for testing sensors and a data filter during subscale flight and is readily available for all members	2	1	2

ACS.7	Friction on tab extensions	1. The servo motor lacks the torque to overcome the reactionary friction force on the tab extensions during deployment and withdrawal 2. Batteries are insufficiently charged to effectively power the servo motor	Tab extensions completely, or partially, fail to extend resulting in an apogee outside of the acceptable range of 5300 ± 30 ft.	3	2	6	1. Materials are chosen based on simulations and calculations results 2. Construction procedures will be written prior to construction and followed throughout the process 3. The servo motor is selected based on simulations and calculations, and is tested prior to construction 4. All batteries used during launch will be fully charged	1. Calculations for tab extension friction can be located in Section 3.7.6.2 and have been verified by both the Safety Officer and Chief Engineer 2. Test TA.5 outlines proper procedures and success criteria for testing servo actuation with sample data and is readily available for all members 3. Team members selecting a servo motor have consulted the trusted vendor document and past servo motor data prior to selection 4. Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members 5. Launch Checklist: Packing List outlines a packing list for all ACS components, including charged batteries, and is readily available for all members 6. Launch Checklist: Apogee Control System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members	2	1	2
ACS.8	Incorrectly assembled battery pack leads to the destruction or damage of the microcontroller	1. The battery pack fails to consistently output a voltage within the microcontroller's acceptable range 2. Improper construction techniques	Shutdown of the electrical system and loss of control of tab extensions resulting in an apogee outside of the acceptable range of 5300 ± 30 ft.	3	3	9	1. All electronic components will be carefully inspected prior to launch 2. All batteries will be fully charged immediately prior to launch	1. Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members 2. Launch Checklist: Packing List outlines a packing list for all ACS components, including charged batteries, and is readily available for all members 3. Launch Checklist: Apogee Control System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members 4. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing ACS electronics into the vehicle and is readily available for all members 5. Construction procedures outlining proper steps for securing the battery to the ACS structure will be created and made readily available for all members	1	2	2

5.2.2.4 Recovery

Table 68: Recovery

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

R.3	Vehicle separation during motor burn	1. Shear pins fail prematurely under launch loading 2. Incorrect altimeter reading cause premature black powder ignition	1. The vehicle would shear causing interior and exterior components to be damaged 2. Potential shrapnel and debris could seriously injure personnel and damage property	3	4	12	1. Shear pins are to be supplied from a trusted vendor with a history of successful operations 2. Shear pins are to be carefully selected based on calculations 3. Altimeters are to be supplied from trusted vendors and will be surrounded by electromagnetic shielding 4. Black powder will be properly installed prior to launch	1. Calculations and safety factors for shear pins can be located in Section ____ and have been approved by both the Safety Officer and Chief Engineer 2. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 3. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 4. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures when doing so	1	4	4
R.4	Vehicle components fully separate after apogee	1. Shock cords connecting separating components fail 2. Structural component failure due to high loading 3. Black powder detonation damages shock cords	Vehicle components descend with unacceptably high kinetic energy (failing to comply with NASA Req. 3.3) with potential for vehicle component damage and personnel injury	3	4	12	1. Shock cords are to be supplied from a trusted vendor with a history of successful operations 2. Shock cords are to be carefully selected based on calculations 3. Shock cords are securely connected to CRAS-M using secure connections 4. Vehicle separation will be tested and repeated on the ground prior to demonstration launches to be shown to be reliable 5. The material, model, and design of each structural component will be carefully selected based on mathematical calculations 6. All avionics will be properly sealed from any black powder residue following detonation	1. Calculations and safety factors for shock cords can be located in Section 3.8.5 and have been approved by both the Safety Officer and Chief Engineer 2. Calculations and safety factors for recovery structural components can be located in Section 3.8.6 and have been approved by both the Safety Officer and Chief Engineer 3. Test TR.4 outlines proper procedures and success criteria for testing CRAS-M structural integrity during a separation ground test and is readily available for all members 4. Construction procedures outlining proper steps for assembling the CRAS-M will be created and made readily available for all members 5. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures when doing so	1	4	4

R.5	Main parachute fails to properly reduce descent velocity after deployment	1. Improperly sized main parachute 2. Main parachute is deployed at an improper time 3. Main parachute shroud cords tangle and the main parachute chute does not deploy correctly 4. Black powder charges damage some or all of the main parachute upon deployment	Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req. 3.3) with potential for vehicle damage and personnel injury	3	4	12	1. Calculations and simulations have been performed to determine proper main parachute size and shape 2. Altimeters are to be supplied from trusted vendors and will be surrounded by electromagnetic shielding 3. Parachute folding is practiced and performed in accordance with manufacturer instructions 4. Nomex cloth and insulation is used to protect the parachute from damage	1. Calculations and simulations for main parachute size can be found in Section 3.8.5.2 and have been verified and approved by the Safety Officer and Chief Engineer 2. Launch Checklist: Recovery Preparation outlines a checklist and plan for folding, protecting, and insulating the main parachute and is readily available for all members 3. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures when doing so	2	2	4
R.6	Drogue and pilot parachutes fail to properly reduce descent velocity after apogee	1. Improperly sized drogue or pilot parachute 2. Drogue or pilot parachute is deployed at an improper time 3. Pilot parachute shroud cords tangle and the main parachute chute does not deploy correctly 4. Black powder charges damage drogue or pilot parachute upon deployment at apogee	Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req. 3.3) with potential for vehicle damage and personnel injury	3	4	12	1. Calculations and simulations have been performed to determine proper drogue and pilot parachute sizes and shapes 2. Altimeters are to be supplied from trusted vendors and will be surrounded by electromagnetic shielding 3. Parachute folding is practiced and performed in accordance with manufacturer instructions 4. Nomex cloth and insulation is used to protect the parachute from damage	1. Calculations and simulations for drogue parachute size can be found in Section 3.8.5.1 and have been verified and approved by the Safety Officer and Chief Engineer 2. Calculations and simulations for pilot parachute size can be found in Section 3.8.5.2 and have been verified and approved by the Safety Officer and Chief Engineer 3. Launch Checklist: Recovery Preparation outlines a checklist and plan for folding, protecting, and insulating the drogue and pilot parachutes and is readily available for all members 4. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures when doing so	1	4	4

R.7	Nose cone parachute fails to properly reduce descent velocity after apogee	1. Improperly sized nose cone parachute 2. Nose cone parachute is deployed at an improper time 3. Nose cone parachute shroud cords tangle and the nose cone parachute chute does not deploy correctly 4. Black powder charges damage some or all of the nose cone parachute upon deployment	Nose cone descends with unacceptably high kinetic energy (failing to comply with NASA Req. 3.3) with potential for nose cone or payload damage, or personnel injury	3	3	9	1. Calculations and simulations have been performed to determine proper nose cone parachute size and shape 2. Altimeters are to be supplied from trusted vendors and will be surrounded by electromagnetic shielding 3. Parachute folding is practiced and performed in accordance with manufacturer instructions 4. Nomex cloth and insulation is used to protect the parachute from damage	1. Calculations and simulations for nose cone parachute size can be found in Section 3.8.5.3 and have been verified and approved by the Safety Officer and Chief Engineer 2. Launch Checklist: Recovery Preparation outlines a checklist and plan for folding, protecting, and insulating the nose cone parachute and is readily available for all members 3. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures when doing so	1	3	3
R.8	Main parachute separates from vehicle	1. Structural component failure due to high loading 2. Shock cord failure due to high loading	1. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req. 3.3) with potential for vehicle damage and personnel injury 2. Structural component failure; damage to vehicle	2	4	8	1. Material, design, and model of structural components will be selected based on careful calculations 2. Shock cords are to be supplied from a trusted vendor with a history of successful operations 3. Shock cords are to be carefully selected based on calculations 4. Shock cords are securely connected to CRAS-M using secure connections	1. Calculations and simulations for shock cords can be found in Section 3.8.5 and have been verified and approved by the Safety Officer and Chief Engineer 2. Calculations and safety factors for recovery structural components can be located in Section 3.8.6 and have been approved by both the Safety Officer and Chief Engineer 3. Test TR.3 outlines proper procedures and success criteria for testing CRAS-M structural integrity during a separation ground test and is readily available for all members 4. Construction procedures outlining proper steps for assembling the CRAS-M will be created and made readily available for all members	1	4	4

R.9	Drogue parachute separates from vehicle	1. Structural component failure due to high loading 2. Shock cord failure due to high loading	1. Vehicle descends with unacceptably high kinetic energy (failing to comply with NASA Req. 3.3) with potential for vehicle damage and personnel injury 2. Structural component failure; damage to vehicle	2	4	8	1. Material, design, and model of structural components will be selected based on careful calculations 2. Shock cords are to be supplied from a trusted vendor with a history of successful operations 3. Shock cords are to be carefully selected based on calculations 4. Shock cords are securely connected to CRAS-M using secure connections	1. Calculations and simulations for shock cords can be found in Section 3.8.5 and have been verified and approved by the Safety Officer and Chief Engineer 2. Calculations and safety factors for recovery structural components can be located in Section 3.8.6 and have been approved by both the Safety Officer and Chief Engineer 3. Test TR.3 outlines proper procedures and success criteria for testing CRAS-M structural integrity during a separation ground test and is readily available for all members 4. Construction procedures outlining proper steps for assembling the CRAS-M will be created and made readily available for all members	1	4	4
R.10	Pilot parachute separates from vehicle	1. Structural component failure due to high loading 2. Shock cord failure due to high loading	1. Vehicle impacts ground at high velocity damaging vehicle and/or personnel 2. Structural component failure; damage to vehicle	2	4	8	1. Material, design, and model of structural components will be selected based on careful calculations 2. Shock cords are to be supplied from a trusted vendor with a history of successful operations 3. Shock cords are to be carefully selected based on calculations 4. Shock cords are securely connected to CRAS-M using secure connections	1. Calculations and simulations for shock cords can be found in Section 3.8.5 and have been verified and approved by the Safety Officer and Chief Engineer 2. Calculations and safety factors for recovery structural components can be located in Section 3.8.6 and have been approved by both the Safety Officer and Chief Engineer 3. Test TR.3 outlines proper procedures and success criteria for testing CRAS-M structural integrity during a separation ground test and is readily available for all members 4. Construction procedures outlining proper steps for assembling the CRAS-M will be created and made readily available for all members	1	4	4
R.11	Nose cone parachute separates from nose cone	1. Structural component failure due to high loading 2. Shock cord failure due to high loading	1. Nose cone impacts ground at high velocity damaging vehicle and/or personnel 2. Potential damage to payload during separation	2	3	6	1. Material, design, and model of structural components will be selected based on careful calculations 2. Shock cords are to be supplied from a trusted vendor with a history of successful operations 3. Shock cords are to be carefully selected based on calculations 4. Shock cords are securely connected to CRAS-M using secure connections	1. Calculations and simulations for shock cords can be found in Section 3.8.5 and have been verified and approved by the Safety Officer and Chief Engineer 2. Calculations and safety factors for recovery structural components can be located in Section 3.8.6 and have been approved by both the Safety Officer and Chief Engineer 3. Test TR.3 outlines proper procedures and success criteria for testing CRAS-S structural integrity during a separation ground test and is readily available for all members 4. Construction procedures outlining proper steps for assembling the CRAS-S will be created and made readily available for all members	1	3	3

R.12	Vehicle drift exceeds allowed drift radius of 2,500 ft (per NASA req 3.10)	1. Main, drogue, or pilot parachutes deploy early (before 600 ft AGL; 5000 ft AGL respectively) 2. Main, drogue, or pilot parachutes are too large	1. Vehicle could cause personnel or property damage while drifting outside the allowable range 2. Payload mission success is compromised due to a landing zone outside the allowable range	3	2	6	1. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding 2. The black powder charges and altimeters are designed to be twice redundant 3. Main, drogue, and pilot parachutes are sized based on calculations and simulations	1. Calculations in Section 3.9.5.1 show the maximum expected drift radius of the vehicle is 2,397 ft, satisfying NASA req. 3.10 2. Calculations and simulations for all parachute sizes (Sections 3.8.5.1, 3.8.5.2) have been verified and approved by the Safety Officer and Chief Engineer 3. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life 4. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight 5. Test TR.3 outlines proper procedures and success criteria for testing black powder separation 6. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy 7. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures	1	2	2
R.13	Avionics System - Main (CRAS-M) separates from vehicle body	1. The material and design used to construct the CRAS-M is insufficient in supporting the loads of the main, drogue, and pilot parachutes	1. Damaged internal components of vehicle 2. Vehicle descends with unacceptably high kinetic energy, potential for vehicle damage or injury	3	4	12	1. CRAS-M will be designed and manufactured according to calculations and simulations 2. The CRAS-M will be secured to the vehicle body using components that are chosen according to calculations	1. CRAS-M and CRAS-M securing mechanism design analysis (Section 3.8.6.1) has been verified and approved by the Safety Officer and Chief Engineer 2. Construction procedures for the fabrication of the CRAS-M will be created and made readily available to all team members prior to construction beginning 3. Construction procedures for the fabrication of the CRAS-M securing mechanisms will be created and made readily available to all team members prior to construction beginning	1	4	4
R.14	Avionics System - Secondary (CRAS-S) separates from vehicle body	1. The material and design used to construct the CRAS-S is insufficient in supporting the loads of the nose cone parachute	1. Damaged internal components of vehicle 2. Nose cone descends with unacceptably high kinetic energy, potential for vehicle damage or injury	3	3	9	1. CRAS-S will be designed and manufactured according to calculations and simulations 2. The CRAS-S will be secured to the vehicle body using components that are chosen according to calculations	1. CRAS-S and CRAS-S securing mechanism design analysis (Section 3.8.6.2) has been verified and approved by the Safety Officer and Chief Engineer 2. Construction procedures for the fabrication of the CRAS-S will be created and made readily available to all team members prior to construction beginning 3. Construction procedures for the fabrication of the CRAS-S securing mechanisms will be created and made readily available to all team members prior to construction beginning	1	3	3

5.2.2.5 Planetary Landing System

Table 69: Planetary Landing System Vehicle

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PV.1	Power system failure	1. Damaged circuits from poor construction 2. Damaged circuits during launch and/or flight 3. Insufficiently charged batteries	Payload is unable to complete mission	3	3	9	1. All electronic components will be checked thoroughly prior to launch 2. All batteries used during launch will be fully charged and tested prior to launch 3. Batteries will remain OFF until just prior to launch	1. Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members 2. Launch Checklist: Packing List outlines a packing list for all PLS components, including charged batteries, and is readily available for all members 3. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members 4. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing and arming PLS electronics into the vehicle and is readily available for all members	1	3	3
PV.2	Radio transmission signal disruption	1. Radio frequency interference from shielding material inhibits transmission 2. Tracking devices are disrupted by transmitters in other components of the vehicle	PLS is unable to transmit the image from the system to a team device, failing to comply with NASA req. 4.3.4	3	2	6	1. Materials surrounding the transmitter will be chosen both for strength and for radio frequency transparency 2. The transmitting frequencies of other electronic devices will be chosen so as not to interfere with transmitters	1. All transmitters are designed to be located in unshielded locations on the PLS 2. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for installing and arming transmitters in the PLS and is readily available for all members 3. All transmitter frequencies will be reported to NASA prior to launch and compared to other devices at the launch site 4. Test TP.3 outlines proper procedures and success criteria for testing image transmission between PLS and a team device and is readily available for all members	2	2	4

PV.3	Electronic tracking device on the payload fails to transmit the position of the PLS	1. Radio frequency interference from shielding material inhibits transmission 2. Tracking devices are disrupted by transmitters in other components of the vehicle	PLS fails to comply with NASA req. 3.12, which states that all independent components of the launch vehicle contain and electronic tracker	3	2	6	1. Materials surrounding the electronic tracking device will be chosen both for strength and for radio frequency transparency 2. The transmitting frequencies of other electronic devices will be carefully chosen to avoid potential interference	1. All transmitters are designed to be located in unshielded locations on the PLS 2. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for installing and arming transmitters in the PLS and is readily available for all members 3. All transmitter frequencies will be reported to NASA prior to launch and compared to other devices at the launch site 4. Test TR.6 outlines proper procedures and success criteria for testing GPS transmitters and is readily available for all members	1	2	2
PV.4	Camera Obstruction	1. PLS system fails to secure the parachute in an area outside of the camera's line of sight upon landing 2. Parachute or parachute cords get caught in the camera rotation mechanism	The captured image does not include a full 360 degrees of view, failing to comply with NASA req. 4.3.4	4	2	8	1. Parachute and parachute cords will be packed correctly and carefully to prevent entanglement	1. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for folding, protecting, and insulating the PLS parachute and is readily available for all members 2. Test TP.3 outlines proper procedures and success criteria for evaluating transmitted image quality between PLS and a team device and is readily available for all members	2	1	2
PV.5	Low quality image	1. Image is unviewable due to the glare created by the reflection of the sun 2. Dust interferes with the camera lens 3. Camera is not turned on	Camera unable to capture an acceptable image, failing to comply with NASA req. 4.3.4	3	2	6	1. Camera housing will prevent debris from affecting the overall quality of the image 2. Only fully charged batteries will be used during flight operations 3. Electrical connections will be checked before flight	1. Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members 2. Launch Checklist: Packing List outlines a packing list for all PLS components, including charged batteries, and is readily available for all members 3. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members 4. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing PLS electronics into the vehicle and is readily available for all members 5. Camera selection can be located in Section 4.5.1 and has been approved by the Payload Design Lead and Chief Engineer	1	1	1

PV.6	Active Orientation Failure	1. Parachute restricts leg movement due to entanglement 2. Debris buildup restricts leg movement 3. Power Failure will be prevent servo motors from running 4. Improper circuitry configuration will result in active orientation failure	Orientation will not be within the 5 degree allowance, failing to comply with NASA req. 4.3.4	3	2	6	1. Parachute and parachute cords will be packed correctly and carefully to prevent entanglement 2. Active orientation system will be built to protect against outside debris 3. Active orientation system will be tested in multiple starting positions to ensure orientation ability can overcome exaggerated obstacles 4. Only fully charged batteries will be used during flight operations 5. Electrical connections will be checked before flight	1. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for folding, protecting, and insulating the PLS parachute and is readily available for all members 2. Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop and is readily available for all members 3. Launch Checklist: Packing List outlines a packing list for all PLS components, including charged batteries, and is readily available for all members 4. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for testing batteries with a multimeter prior to launch and is readily available for all members 5. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing PLS electronics into the vehicle and is readily available for all members 6. Active orientation design can be located in Section 4.5 7. Test TP.5 outlines proper procedures and success criteria for testing PLS leg deployment and is readily available for all members 8. Test TP.6 outlines proper procedures and success criteria for testing PLS orientation and is readily available for all members	2	1	2
PV.7	Damaged Camera	1. Large forces before or during deployment 2. Large impact force	Camera components damaged and the camera is unable to capture an image, failing to comply with NASA req. 4.3.4	3	3	9	1. Camera will be chosen for both durability and quality of image 2. PLS recovery system will be tested prior to launch for proper reduction in descent kinetic energy, in compliance with NASA req. 3.3	1. Test TP.8 outlines proper procedures and success criteria for testing PLS structural integrity during a shake test and is readily available for all members 2. Camera selection can be located in Section 4.5.1 and has been approved by the Payload Design Lead and Chief Engineer	1	3	3

PV.8	Failure for all support legs to deploy	1. Launch vehicle leg retention system retains one or multiple legs in locked position 2. Servo motors do not successfully deploy legs	Orientation will not be within the 5 degree allowance, failing to comply with NASA req. 4.3.3	2	4	8	1. Servo motors will be chosen with multiple considerations, including torque, reliability, and weight 2. Leg deployment and orientation will be tested before launch	1. Servo motor selection can be located in Section 4.5 and has been approved by the Payload Design Lead and Chief Engineer 2. Test TP.2 outlines proper procedures and success criteria for testing PLS ejection and is readily available for all members 3. Test TP.5 outlines proper procedures and success criteria for testing PLS leg deployment and is readily available for all members 4. Test TP.6 outlines proper procedures and success criteria for testing PLS orientation and is readily available for all members	1	2	2
PV.9	Failure of image receiving hardware, specifically a laptop	1. The data file containing the image is corrupted through the process of file transmission 2. The competition is unable to process the photo obtained from the PLS 3. The PLS sends a photo to the competition viewing platform, however does not save one to its own files	The image capturing and processing systems are unable to adequately receive and distribute the PLS image	2	3	6	1. The file format of the photograph will be chosen to be easily viewable 2. The image distribution will be tested in order to ensure viability 3. The image capture program will be tested to ensure it saves a copy of the image	1. Launch Checklist: Post-Flight Recovery and Analysis outlines a checklist and plan for distributing the final image to competition officials and is readily available for all members 2. Test TP.3 outlines proper procedures and success criteria for evaluating transmitted image quality between PLS and a team device and is readily available for all members	1	2	2

5.2.2.6 Planetary Landing System Deployment and Integration

Table 70: Planetary Landing System Deployment and Integration

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PI.1	Nose cone separation failure	Black powder charges do not generate enough force to properly separate the nose cone from the vehicle body	PLS is unable to deploy and exit from the vehicle body payload bay	2	4	8	1. The black powder charges and altimeters are designed to be redundant 2. Each black powder charge and altimeter combination is entirely independent 3. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding.	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to handle any energetics and will obey NAR/TRA guidelines and procedures when doing so 2. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 3. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 4. Test TR.3 outlines proper procedures and success criteria for testing black powder separation and is readily available for all members 5. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy and is readily available for all members	1	4	4

PI.2	Excessive drag from PLS legs against vehicle body interior	PLS legs deploy while PLS is secure in the vehicle body	1. Payload cannot deploy from vehicle body, violating NASA req. 4.3.1 2. Total mass under the main parachute is larger than intended resulting a larger descent velocity than intended, potentially violating NASA req. 3.3	3	4	12	1. PLS legs will be restrained during flight by an in-flight locking mechanism 2. A jumper cable ejection detection system will disengage the in-flight locking system and inform PLS to rotate legs to landing position only after ejection 3. Main parachute will be designed to account for a total vehicle mass including the PLS	1. Test TP.2 outlines proper procedures and success criteria for testing PLS ejection and is readily available for all members 2. Test TP.5 outlines proper procedures and success criteria for testing PLS leg deployment and is readily available for all members 3. Test TP.7 outlines proper procedures and success criteria for testing PLS retention and is readily available for all members 4. Calculations and simulations for main parachute size can be found in Section 3.8.5.2 and have been verified and approved by the Safety Officer and Chief Engineer 5. Launch Checklist: Recovery Preparation outlines a checklist and plan for folding, protecting, and insulating the main parachute and is readily available for all members 6. Launch Checklist: Vehicle Preparation outlines a checklist and plan for integrating the PLS into the vehicle body prior to launch, including engaging the jumper cable ejection detection system, and is readily available for all members	1	4	4
PI.3	PLS retention failure	Structural components in the retention mechanism fail during flight	PLS moves freely in the payload bay, potentially damaging internal components or the vehicle and shifting stability margin of the vehicle, potentially violating NASA req. 2.14	3	4	12	1. Structural components will be designed to adequately secure the PLS in place prior to deployment	1. Calculations and simulations for PLS structural components can be found in Section 4.4 and have been verified and approved by the Safety Officer and Chief Engineer 2. Test TP.7 outlines proper procedures and success criteria for testing PLS retention and is readily available for all members 3. Test TV.8 outlines proper procedures and success criteria for testing PLS structural integrity during a vehicle shake test and is readily available for all members	1	4	4

PI.4	PLS parachute fails to properly reduce descent velocity after apogee	1. Improperly sized PLS parachute 2. PLS parachute is not deployed at 550 ft. AGL 3. PLS parachute shroud cords tangle and the PLS parachute chute does not deploy correctly 4. Black powder charges damage some or all of the PLS parachute upon deployment	Nose cone descends with unacceptably high kinetic velocity, violating NASA req. 3.3	3	4	12	1. Calculations and simulations have been performed to determine proper PLS parachute size and shape 2. Each black powder charge and altimeter combination is redundant and entirely independent, in compliance with NASA req. 3.4 3. Altimeters are to be supplied from trusted vendors and will be surrounded by electromagnetic shielding 4. Parachute folding is practiced and performed in accordance with manufacturer instructions 5. Nomex cloth and insulation is used to protect the parachute from damage	1. Calculations and simulations for PLS parachute size can be found in Section 4.4.2 and have been verified and approved by the Safety Officer and Chief Engineer 2. Test TR.2 outlines proper procedures and success criteria for testing altimeters shielding and is readily available for all members 3. Launch Checklist: Planetary Landing System Preparation outlines a checklist and plan for folding, protecting, and insulating the PLS parachute and is readily available for all members 4. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures when doing so	1	4	4
PI.5	PLS parachute separates from PLS	1. Structural component failure due to high loading 2. Shock cord failure due to high loading	1. PLS impacts ground at high velocity damaging vehicle and/or personnel 2. Damage to PLS due to component failure	3	4	12	1. Material, design, and model of structural components will be selected based on careful calculations 2. Structural components are to be supplied from a trusted vendor with a history of successful operations	1. Calculations and safety factors for PLS structural components can be located in Section 4.4 and have been approved by both the Safety Officer and Chief Engineer 2. Test TR.4 outlines proper procedures and success criteria for testing PLS structural component integrity during a separation ground test and is readily available 3. Construction procedures outlining proper steps for assembling the PLS will be created	1	4	4
PI.6	Nose cone separation during motor burn	1. Shear pins fail prematurely under launch loading 2. Incorrect altimeter reading cause premature black powder ignition	1. The PLS would shear causing interior and exterior components to be damaged 2. Potential shrapnel and debris could seriously injure personnel	3	4	12	1. Shear pins are to be supplied from a trusted vendor with a history of successful operations 2. Shear pins are to be carefully selected based on calculations 3. Altimeters are to be supplied from trusted vendors and will be surrounded by electromagnetic shielding 4. Black powder will be properly installed prior to launch	1. Shear pins will be selected using verified calculations and a safety factor approved by both the Safety Officer and Chief Engineer 2. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 3. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 4. Test TR.3 outlines proper procedures and success criteria for testing black powder separation and is readily available 5. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy and is readily available 6. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures	1	4	4

PI.7	PLS drift exceeds allowed drift radius of 2,500 ft, violating NASA req. 3.10	1. PLS parachute deploys from vehicle body at a higher altitude than 550 ft AGL 2. PLS parachute is too large	1. PLS could cause personnel or property damage while drifting outside the allowable range 2. PLS mission success is compromised due to a landing zone outside the allowable range	3	2	6	1. Altimeters are supplied from trusted vendors and are surrounded by electromagnetic shielding 2. The black powder charges and altimeters are designed to be twice redundant, and entirely independent, in accordance with NASA req 3.4 3. PLS parachute size is based on calculations and simulations	1. Calculations in Section 3.9.5.2 show the maximum expected drift radius of the PLS is 830 ft, which is within the acceptable range of 2,500 ft 2. Calculations and simulations for PLS parachute size can be found in Section 4.4.2 and have been verified and approved by the Safety Officer and Chief Engineer 3. Test TR.1 outlines proper procedures and success criteria for testing altimeters battery life and is readily available for all members 4. Test TR.2 outlines proper procedures and success criteria for testing altimeters simulated flight and is readily available for all members 5. Test TR.3 outlines proper procedures and success criteria for testing black powder separation and is readily available for all members 6. Test TR.5 outlines proper procedures and success criteria for testing deployment charge redundancy and is readily available for all members 7. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any energetics and will obey NAR/TRA guidelines and procedures when doing so	1	2	2
PI.8	Orientation legs fail to deploy in air during descent	1. Servo motor power failure 2. Servo motor torque insufficient for overcoming opposing forces during descent	1. PLS tips laterally onto the ground due to no leg stability 2. Legs are unable to orient PLS within the acceptable 5° range from vertical	3	2	6	1. PLS legs will not deploy until after the PLS has exited the vehicle body 2. The PLS legs will be tested for deployment in a descent simulation 3. The jumper cable ejection detection system will be redundant	1. Test TP.2 outlines proper procedures and success criteria for testing PLS ejection and is readily available for all members 2. Test TP.5 outlines proper procedures and success criteria for testing PLS leg deployment and is readily available for all members 3. Test TP.6 outlines proper procedures and success criteria for testing PLS orientation and is readily available for all members	1	2	2

5.2.2.7 Launch Support Equipment

Table 71: Launch Support Equipment

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

5.2.3 Environmental Risks

5.2.3.1 Environmental Risks to Vehicle

Table 72: Environmental Risks to Vehicle

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

EV.4	Excessive vehicle drift under parachute	High winds (greater than 20 mph)at the launch site	Vehicle lands outside the allowable drift radius, violating NASA req. 3.10, and potentially harming personnel or property in the area	3	2	6	1. The parachute is designed primarily to properly reduce descent velocity, but also limit drift radius when possible 2. Launch will be postponed if wind speeds exceed 20 miles per hour	1. Calculations and simulations for main (Section 3.8.5.2), drogue (Section 3.8.5.1) nose cone (Section 3.8.5.3), and PLS (Section 4.4.2) parachutes have been verified by the Safety Officer and Chief Engineer 2. Expected drift calculations can be located in Section 3.9.5 and have been verified and approved by the Safety Officer and Chief Engineer 3. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, espectially wind speed	1	2	2
EV.5	Unexpected loss of battery charge	Cold temperatures	Loss of power to electronics in the vehicle	2	4	8	1. Batteries will be stored in a temperature-controlled environment until installation during assembly 2. Batteries will be fully charged prior to transportation to launch site 3. Batteries will not be charged at temperatures below freezing (32°F) 4. Multiple batteries will be packed in case a battery loses charge 5. The launch vehicle will be assembled in a manner which allows electronics to be installed immediately prior to launch 6. Launch will not occur if the RSO deems the temperature to be too cold	1. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially wind speed 2. Launch Checklist: Packing List outlines a checklist and plan for charging batteries prior to departure from the workshop 3. Launch Checklist: Packing List outlines a packing list for all vehicle components, including extra charged batteries 4. Launch Checklist: Packing List outlines a checklist and plan for testing batteries with a multimeter prior to launch 5. Launch Checklist: Packing List outlines a checklist and plan for installing and arming PLS electronics into the vehicle	1	2	2
EV.6	Weakening of Bonding Materials	Humidity, Rain, and Heat	1. Bulkhead failure 2. Shifting interior components 3. Changes to static stability margin, potentially violating NASA req. 2.14	2	4	8	1. All adhesives will be purchased from reputable vendors with past success in high-load scenarios 2. Structures with bonding materials such as epoxy will be kept in dry, cool environments until assembly when possible 3. Bonding materials will be allowed to set and cure for the maximum necessary curing time before launch day 4. Team members working with adhesives have been provided step-by-step procedures for safe operation 5. Important material properties are listed in the NDRT Safety Data Sheet Document	1. Construction procedures outlining proper steps for bonding components will be created and made readily available for all members 2. Standard Operating Procedure 2.3.1 outlines the correct procedure for epoxying 3. NDRT Safety Data Sheet Document Sections 4.11, 4.14, and 4.15 contains the SDS documents for multiple bonding materials in the NDRT Workshop, and is readily available for all members	1	3	3

EV.7	Wetting of launch vehicle propulsion materials	High humidity, contact with swampy ground, snow, rain	Complete or partial failure to ignite motor	3	2	6	1. Motors stored by the team mentor in protective case until integration 2. Motors will be stored with silica gel desiccant for moisture absorption in event that water enters the bag	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to store and handle motors and will obey NAR/TRA guidelines and procedures	1	3	3
EV.8	Electronics UV exposure	Long exposure to sunlight	Potentially severe damage to electronics and sensors within the launch vehicle	2	4	8	1. Electronics will be stored in ESD bags, which reflect UV rays, before assembly 2. All electronics will not be exposed to direct sunlight once integrated into vehicle	1. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation List outline checklists and plans for setting up electronic systems on launch day, and is readily available for all members 2. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for installing electronics in the vehicle, and is readily available for all members	1	4	4
EV.9	Blunt Force Damage to Vehicle	Hail	1. Vehicle geometry is altered resulting in changed flight dynamics 2. Structural integrity of the vehicle is compromised, points of high stress created along the length of the vehicle	2	3	6	1. All adhesives will be approved for strength and reliability 2. All adhesives will be purchased from reputable vendors with past success in high-load scenarios 3. Structures with bonding materials such as epoxy will be kept in dry, cool environments until assembly when possible 4. Launch will not occur if the RSO deems the weather to be unfavorable, especially in the event of precipitation	1. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially wind speed, and is readily available for all members 2. The RSO will have full authority on when launches may proceed	1	1	1
EV.10	Animal Interference	Local animal population in and around the launch site	1. Potential structural damage to the launch vehicle before or after flight 2. Potential injury or death to nearby animals	3	2	6	1. Launches will occur in an open field away from any animals	1. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, including checking for wildlife, and is readily available for all members	2	1	2

EV.11	Structural components change geometry due to swelling	Humidity or temperature changes	Components do not fit together properly, causing difficulty in assembly	2	3	6	1. Parts will be transported in a safe before assembly and construction 2. Tools will be brought to launch to make minor adjustments, if absolutely necessary, so that parts fit properly together	1. Launch Checklists: Packing List outlines a packing list for launch, including necessary tools and equipment 2. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for assembling the vehicle on launch day 3. Launch Checklists: Packing List outlines a checklist and plan for storing components prior to integration in the vehicle	1	2	2
EV.12	Launch pad is not level	Soft or uneven ground under launch pad	1. Apogee is less than the target of 5300 ft 2. Moment acting on the vehicle is greater than expected, altering flight direction	3	3	9	1. A level will be used to ensure launch pad is even with respect to the ground	1. Launch Checklist: Launch Setup outlines a checklist and plan for setting up launch equipment, specifically launch pad and rail, and is readily available for all members	1	1	1
EV.13	Poor visibility of vehicle during flight	Low cloud cover	Failure of team to track flight path, leading to potential loss of vehicle	3	4	12	1. Launch will not occur when cloud cover prohibits the team from maintaining sight of the vehicle during the entire flight	1. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially cloud cover, and is readily available for all members 2. The RSO will have full authority on when launches may proceed	1	3	3
EV.14	Vehicle landing in trees	1. Trees in launch area 2. Vehicle drift exceeds allowed drift radius, violating NASA req. 3.10	Loss or damage of vehicle and/or payload components	3	4	12	1. Main and drogue parachute sizing is based on calculations and flight simulations 2. Launches will occur in an open field away from any trees	1. Calculations in Section 4.4.2 show the maximum possible simulated drift of the vehicle is 2,397 ft, which is within the acceptable range of 2,500 ft (NASA Req 3.10) 2. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially launch area terrain	1	3	3
EV.15	Wireless Signal Interference	Fog, trees, or other teams	Disrupted communication between systems	3	4	12	1. Launch will not occur when fog or landscape prohibits the transmitters from operating properly during the entire flight 2. All transmission frequencies will be reported prior to flight 3. Transmitters will be tested prior to launch 4. Electronics will be transported in ESD bags unless assembly	1. All transmitter frequencies will be reported to NASA prior to launch and compared to other devices at the launch site 2. Test TP.3 outlines proper procedures and success criteria for testing image transmission between PLS and a team device 3. Test TR.7 outlines proper procedures and success criteria for testing GPS transmitters 4. Launch Checklist: Launch Setup outlines a checklist and plan for evaluating launch conditions, especially cloud and fog cover members 5. The RSO will have full authority on when launches may proceed	1	4	4

5.2.3.2 Vehicle Risks to Environment

Table 73: Vehicle Risks to Environment

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
VE.1	Airborne fiberglass particulates (styrene gas)	Sanding of bulkhead or other fiberglass materials inside launch vehicle	1. Emission of toxins depletes local air quality 2. Contaminating land used for agriculture	3	4	12	1. Quantity of styrene gas produced in environment will be minimal so as to make effects on personnel or environment negligible 2. Components that require possible sanding, and styrene gas production, will be made clear in step-by-step fabrication procedures 3. All potential styrene gas production will be completed in a space with capable ventilation and air filtration 4. Important material properties are listed in the NDRT Safety Data Sheet Document	1. All members participating in construction have passed a Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation 2. Construction procedures outlining proper steps for sanding fiberglass materials will be created and made readily available 3. NDRT Safety Data Sheet Document Section 4.10 contains the Fiberglass G10 SDS, and is readily available for all members	1	3	3
VE.2	Excessive Carbon Dioxide emission	1. Motor and black powder charges in the recovery system will produce carbon dioxide emissions when ignited	Increased levels of carbon emissions contributes to expedited climate change	5	2	10	1. Carbon dioxide emissions from the motor and black powder charges will be minimal so as to make effects on environment negligible 2. Motor propellant safety documentation will be kept available for team members 3. Black powder safety documentation will be kept available for team members	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will inspect all motors and energetics before use and will obey NAR/TRA guidelines and procedures 2. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install any motors or energetics and will obey NAR/TRA guidelines and procedures 3. NDRT Safety Data Sheet Document contains the Cesaroni L1395 (Section 4.6) and Black Powder (Section 4.4) SDS	5	1	5
VE.3	Hydrogen Chloride emission	Ammonium perchlorate motor produces hydrogen chloride	Hydrogen chloride reacts with water to form hydrochloric acid leading to contaminated water and habitat	3	2	6	1. Hydrogen Chloride emissions from black powder charges will be minimal so as to make effects on environment negligible 2. Motor propellant safety documentation will be kept available for team members	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will inspect all motors and energetics before use and will obey NAR/TRA guidelines and procedures when doing so 2. NDRT Safety Data Sheet Document Section 4.6 contains the Cesaroni L1395 Motor Propellant SDS, and is readily available for all members 3. The RSO will ensure the launch site located so as to leave no trace on surrounding wildlife habitats or water sources	3	1	3

VE.4	Components detach from vehicle	Components within vehicle are improperly secured	1. Wildlife could ingest small components 2. Wildlife could be harmed by sharp or abrasive materials 3. Crops could be harmed or destroyed on agricultural land surrounding launch site	3	3	9	1. Components in the vehicle are designed to be secured using fasteners, adhesives, shear pins, or twist-to-lock mechanisms 2. Vehicle will be tested to ensure components do not detach during launch or induced vibrations 3. Recovery hardware will be tested to ensure components do not detach during separation, descent, or induced vibrations	1. Calculations and simulations for vehicle structural components(Section 3.4) and recovery structural components (Section 3.8.6) have been approved by both the Safety Officer and Chief Engineer 2. Calculations and simulations for the ACS twist-to-lock mechanisms can be located in Section 3.7.4.3 and have been approved by both the Safety Officer and Chief Engineer 3. Test TR.3 outlines proper procedures and success criteria for testing recovery structural integrity during a separation ground test and is readily available for all members 4. Test TV.1 outlines proper procedures and success criteria for testing vehicle structural integrity during a bulkhead assembly strength test and is readily available for all members 5. Test TV.5 outlines proper procedures and success criteria for testing vehicle structural integrity during a shake test and is readily available for all members 6. Construction procedures outlining proper steps for assembling the vehicle will be created and made readily available for all members 7. Construction procedures outlining proper steps for assembling the CRAS-M and CRAS-S will be created and made readily available for all members	1	2	2
VE.5	Battery acid leak	Battery ruptured by sharp object or impact	1. Battery acid contaminates soil 2. Battery acid contaminates groundwater 3. Contaminating land used for agriculture	2	4	8	1. Batteries will be housed in battery bag when not in use 2. All batteries will be thoroughly inspected before being placed in the vehicle 3. Batteries will be properly installed in the vehicle assembly 4. Battery safety documentation will be kept available for team members	1. Launch Checklist: Packing List outlines a checklist and plan for storing and transporting batteries and is readily available for all members 2. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outline checklists and plans for testing batteries with a multimeter prior to launch and is readily available for all members 3. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outlines a checklist and plan for installing batteries into sub-systems and is readily available for all members 4. NDRT Safety Data Sheet Document Section 4.12 contains the Lithium Polymer Battery SDS, and is readily available for all members	1	4	4

VE.6	Paint chips off of vehicle body during transportation or flight	Paint is used to design the exterior of the vehicle	1. Paint chips scatter in the local area, becoming a danger to wildlife through ingestion 2. Contaminating land used for agriculture	2	2	4	1. Quantity of paint contaminated in the environment will be minimal so as to make effects on personnel or environment negligible 2. If possible, painting will be done professionally in a proper paint shop with appropriate coatings 3. If professional painting is unavailable, the spray booth at the University of Notre Dame will be used to properly paint and cure the exterior design of the vehicle 4. Motor propellant safety documentation will be kept available for team members 5. Vehicle exterior will be tested for paint loss from impact	1. All professional paint shops must licensed vendors with proper certifications 2. Launch Checklist: Launch Vehicle Preparation outlines a checklist and plan for safely transporting the vehicle and is readily available for all members 3. Test TV.3 outlines proper procedures and success criteria for testing paint loss during a fin impact test and is readily available for all members 4. Test TV.4 outlines proper procedures and success criteria for testing paint loss during a nose cone impact test and is readily available for all members 5. Construction procedures outlining proper steps for painting the vehicle will be created and made readily available for all members 6. NDRT Safety Data Sheet Document Section 4.1 contains the Acrylic Enamel Paint SDS, and is readily available for all members	1	1	1
VE.7	Plastic Waste	Prototyping and subscale construction use plastic due to lost cost and high functionality	1. Wildlife could potentially ingest or be harmed by plastic 2. Contaminating agricultural land 3. Plastics disposed in a landfill can take over 1,000 years to decompose	4	3	12	1. When possible, all plastics will be disposed of properly according to local recycling guidelines to avoid landfill contribution 2. If recycling is not an option,, all plastics will be disposed of properly according to local landfill guidelines 3. All members completing construction using plastics will minimize plastic waste	1. All members participating in construction have passed a University of Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. A recycling bin will always be present in the team workshop, and the NDRT Workshop Safety Agreement requires team members to prioritize recycling when possible 3. Construction procedures outlining proper steps for fabricating the vehicle and disposing of consequent paste waste will be created and made readily available for all members 4. The NDRT Safety Handbook is readily available for all members 5. The NDRT Safety Data Sheet Document is readily available for all members	2	1	2

VE.8	Wire Waste	Wires are used as connections in all electrical components	1. Wildlife could potentially ingest or be harmed by wires 2. Contaminating agricultural land 3. Electronics disposed in a landfill may never fully decompose	4	3	12	1. When possible, wires will be disposed of properly according to local recycling guidelines to avoid landfill contribution 2. If recycling is not an option, wires will be disposed of properly according to local landfill guidelines 3. All members completing construction using wires will minimize plastic waste	1. All members participating in construction have passed a Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement acknowledging all team safety documentation and policies 2. A recycling bin will always be present in the team workshop, and the NDRT Workshop Safety Agreement requires team members to prioritize recycling when possible 3. Construction procedures outlining proper steps for disposing of wire waste will be created and made available	2	1	2
VE.9	Solder Waste	Solder is used to secure wire connections in many electrical components	1. Wildlife could potentially ingest or be harmed by solder 2. Contaminating land used for agriculture 3. Electronics disposed in a landfill may never fully decompose	4	3	12	1. When possible, solder will be disposed of properly according to local recycling guidelines to avoid landfill contribution 2. If recycling is not an option, solder will be disposed of properly according to local landfill guidelines 3. All members completing construction using solder will minimize solder waste 4. When possible, alternative wire connection mechanisms will be used instead of solder, such as lever wire connectors	1. All members participating in construction have passed a Notre Dame Workshop Safety and Tools Quiz and signed the NDRT Workshop Safety Agreement 2. A recycling bin will always be present in the team workshop, and the NDRT Workshop Safety Agreement requires team members to prioritize recycling when possible 3. Construction procedures outlining proper steps for fabricating the vehicle and disposing of consequent solder waste will be created and made readily available for all members 4. The NDRT Safety Handbook is readily available for all members 5. The NDRT Safety Data Sheet Document is readily available for all members	2	1	2
VE.10	Fire	1. Motor burnout 2. Electrical components short circuit	1. Damage to surrounding vegetation 2. Damage to animals' natural habitats 3. Greenhouse emissions as a result of combustion 4. Destroying land used for agriculture	2	4	8	1. Motor will be installed by a qualified individual with proper NAR/TRA certifications 2. Fire extinguishers will be included on the launch checklists to be packed for launch 3. All electronics will be carefully inspected prior to launch 4. All electronics will remain OFF until power is necessary for mission success 5. The launch pad will be positioned in a location free of debris or flammable objects	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will inspect all motors and energetics before use 2. Launch Checklist: Packing List outlines a packing list for all necessary launch materials, including fire extinguishers 3. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outline checklist and plans for testing electronics with a multimeter prior to launch 4. Launch Checklists: Apogee Control System Preparation, Planetary Landing System Preparation, and Recovery Preparation outline checklists and plans for installing ACS, recovery, and PLS electronics into the vehicle 5. The Range Safety Officer will designate staging zones at least 300 ft from the launch pad	1	4	4

VE.11	High velocity impact, in violation of NASA req. 3.3	1. High wind speeds cause vehicle to enter an unexpected trajectory flight path 2. Recovery fails to properly reduce vehicle descent velocity	1. Damage to nearby personnel or property 2. Damage to power lines leading to potential fires 3. Destroying habitats or injuring wildlife in the area 4. Destroying land used for agriculture	3	4	12	1. The motor will be installed correctly and carefully 2. The launch rail will be inspected prior to launch 3. The recovery system is designed to be reliable and redundant for all separations, in accordance with NASA req. 3.4 4. The recovery system will be tested to ensure reliability and redundancy for all separations 5. Personnel will stand at least 300 ft. from the launch pad to view the launch as required by the NAR	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. The chosen motor has been sourced from a trusted vendor and been approved by the Vehicles Design Lead and Chief Engineer 3. Launch Checklist outlines a checklist and plan for installing the motor into the vehicle body (Motor Preparation), and inspecting and setting up launch equipment (Launch Setup) 4. Recovery design can be located in Section 3.8 and has been approved by the Chief Engineer and Safety Officer 5. Proper procedures and success criteria for testing: altimeter battery life (TR.1), altimeter simulated flight (TR.2), Separation (TR.3), and charge redundancy (TR.5) have been made 6. The Range Safety Officer will designate safe staging zones at least 300 ft from the launch pad, in accordance with NAR specifications	1	4	4
VE.12	Noise Impact	Excessive noise generation from the launch vehicle's motor on launch or from team during launch operations	Noise could permanently harm wildlife, bystanders, and nearby structures	1	4	4	1. Noise produced will be temporary and will not exceed EPA regulations, as stipulated by the Noise Control Act of 1972 (42 U.S.C §4901 et. seq.)	1. Launch Checklist: Launch Setup outlines a checklist and plan for inspecting the launch site and ensuring no wildlife are in the area and is readily available for all members 2. The Range Safety Officer will designate safe staging zones at least 300 ft from the launch pad, in accordance with NAR specifications 3. The Rocketry Association will affirm that it maintains the correct noise permits to launch at the site prior to launch day	1	2	2
VE.13	Vehicle and PLS debris	Motor explosion during flight	1. Sharp or abrasive debris can harm wildlife 2. Small components could be ingested by wildlife 3. Contamination of agricultural land	2	4	8	1. The motor will be installed correctly and carefully 2. The launch rail will be inspected prior to launch 3. Personnel will stand at least 300 ft. from the launch pad to view the launch as required by the NAR	1. NDRT Mentor Dave Brunsting (NAR/TRA Level 2 Certification) will be the only individual to install motors and will obey NAR/TRA guidelines and procedures when doing so 2. The chosen motor has been sourced from a trusted vendor and been approved by the Vehicles Design Lead and Chief Engineer 3. Launch Checklist: Motor Preparation outlines a checklist and plan for installing the motor into the vehicle body 4. Launch Checklist: Launch Setup outlines a checklist and plan for inspecting and setting up launch equipment 5. The Range Safety Officer will designate safe staging zones at least 300 ft from the launch pad, in accordance with NAR specifications	1	4	4

5.3 Project Plan Risk Analysis

Table 74: Project Risks

Label	Hazard	Cause	Outcome	Probability	Severity	Pre	Mitigations	Verification	Probability	Severity	Post
PR.1	Complete destruction or loss of full scale or subscale vehicle	1. Uncontrolled descent 2. Energetics improperly installed or used	Team must build an entirely new vehicle causing project delays and doubling the costs of the project	2	4	8	1. All components will be tested individually prior to full-scale assembly 2. Construction procedures will be written prior to construction	1. A complete test operation plan can be found in Section 6.1 2. Procedures for fabrication and assembly of all components will be created and made readily available to all team members prior to the beginning of construction	1	4	4
PR.2	Failure to conduct subscale flight by January 4th and/or vehicle demonstration flight by March 8th	1. Poor weather conditions 2. Incomplete construction 3. Failure to schedule a launch date that is suitable for both the team and mentor	Inability to participate in competition	2	3	6	1. Multiple dates and locations have been chosen for flights to provide the team with multiple options 2. The team has implemented a Technology Readiness Level schedule to ensure that all subsystems are meeting each deadline comfortably 3. The team intends to launch on the first available date for subscale and demonstration flights.	1. The team has completed a subscale flight on November 13th in order to meet the subscale flight deadline 2. The team has chosen demonstration flights on February 13th and 20th in order to meet the vehicle demonstration flight deadline. 3. The team uses a Gantt chart to track TRLs of individual subsystems in order to identify potential obstacles prior to deadlines. 4. The team began subscale construction two weeks prior to subscale flight. 5. The team will begin full scale construction at least two weeks prior to the first potential demonstration flight date.	1	3	3
PR.3	Lack of funds/ exceeding budget	1. Allocation of funds to a subsystem is insufficient 2. Parts are not properly sourced	Team takes on debt or funds from travel or other subsystems diminish	3	3	9	1. The allocation of funds will be based off of previous years' spending and designs 2. Parts will be sourced to find the best combination of quality and cost 3. Each part will be considered from at least three vendors when possible	1. To limit excessive spending from the team account, the team card will have a spending cap of $2500 which can be replenished given a request to department administrators 2. Team members submit their receipts and report all purchases to ensure all spending is properly tracked	2	2	4
PR.4	Shipping/ manufacturing delays from vendors	1. Parts have an anticipated arrival date in direct conflict with team deadlines 2. The shipped part is incorrect or does not meet the team needs	Project delays and/or mission failure	3	3	9	1. Custom parts have been ordered in advance to avoid project delays and large shipping costs 2. Extra components will be ordered in the event a custom part is defective 3. NDRT has compiled a trusted vendor list to ensure quality of parts	1. All custom parts have been ordered before December 15 2. Design leads have ordered additional stock material if they determined additional stock was required 3. All team members ordering parts have consulted the trusted vendor document 4. All purchases from new vendors have been approved by the Project Manager and Chief Engineer	2	2	4

PR.5	Team member leaves team	1. Injury or illness 2. Covid-19 quarantine or isolation 3. Member prioritizes other commitments	Project delays and/or incomplete work	4	2	8	1. Multiple tem members will be assigned to the same task to ensure completion 2. Multiple members will be made aware of the details and expectations of each task	1. All progress of designs and tests have been, and will continue to be, well documented in a team Google Drive in the event a reallocation of tasks occurs	2	1	2
PR.6	Safety violations	1. Insufficient PPE 2. Insufficient training	Injury to personnel and the potential revocation of workshop space	3	3	9	1. PPE will always be stocked and made readily available in the workshop and a part of the Safety budget 2. All personnel that will be participating in construction must be certified in the Student Fabrication Lab according to university regulations. 3. All personnel must initial and sign the Workshop Safety Agreement, acknowledging all team safety rules	1. The Safety Officer has taken inventory of PPE in the workshop on a bi-weekly schedule, and additional times prior to construction 2. Additional PPE has been ordered by November 11th to ensure a delivery date prior to the team returning to University of Notre Dame's campus for the Spring semester 3. Students must confirm their completion of Student Fabrication Lab training before entering the workshop to participate in construction	1	3	3
PR.7	Insufficient materials and parts to fully complete construction	1. Parts to complete the project are not ordered	Project delays or inability to complete the competition	2	4	8	1. Personnel have made an itemized list of machined and commercially sourced parts in their designs.	1. Construction assembly procedures will provide a list of all parts required to be ordered and machined 2. Detailed CAD drawings include full assemblies with all required parts 3. The construction operation plan details all parts required to be fabricated prior to the demonstration flight	1	4	4
PR.8	Violation of FAA by exceeding approved altitude	1. Launch site does not have proper waiver for the team's altitude requirement	Potential legal action	2	3	6	1. The team have not and will not use any launch sites without a proper FAA waiver	1. NDRT leadership will confirm with prospective launch sites one wee prior to launch that the proper waiver has been attained for NDRT's selected altitude of 5300 ft.	1	3	3
PR.9	Improper testing equipment	1. Equipment does not perform to standards 2. Inability to use University resources for complex testing 3. Restriction on lab access due to Covid-19 regulations	Incorrect or missing data could lead to faulty analyses and/or design decisions	3	2	6	1. The team will confirm all tests with calculated results and simulations. 2. The team has reached out to applicable test facilities early to ensure lab time and comply with regulations at each facility. 3. The team will work with campus resources to perform tests in spaces that are restricted to full-time researchers	1. the test operation plan will contain all test results and will be shared with the team 2. All test procedures are readily available for all members 3. The team has reached out to all applicable test facilities to date to schedule testing times if available	1	2	2

5.4 Workshop Safety

The Notre Dame Rocketry Team has taken proactive steps to establish effective workshop guidelines for the 2020-2021 season. All active team members, regardless of experience or contributions to construction, have completed the NDRT Workshop Safety Agreement, outlining expectations and responsibilities in the team workshop. All conventional risks associated with construction are equally valued as in past years. This year, public health risks are emphasized regularly, and all team meetings are held virtually when possible. The workshop has been outfitted with hand sanitizer stations and an attendance sheet for contact tracing purposes. Face coverings, such as masks or face shields, and physical distancing of 6ft are required at all times. Additionally, the maximum occupancy of the workshop is 20 team members as regulated by the University of Notre Dame, but all in-person NDRT meetings have been limited to 12 team members. An NDRT officer must be present in the workshop for a meeting to occur, and officers are expected to enforce all safety guidelines when the Safety Officer is not present.

For construction tasks, the University of Notre Dame provides training on hand tools, power tools, and select machines in the Aerospace and Mechanical Engineering Student Fabrication Laboratory. The Notre Dame Rocketry Team requires members to complete the Hand and Power Tools training to be eligible to participate in any construction. All machine usage will be restricted to those who have completed the proper training and demonstrated proficiency. The Aerospace and Mechanical Engineering Student Fabrication Lab training materials and quizzes can be accessed here: `https://sfl.nd.edu/tools-equipment`.

Additionally, the Notre Dame Rocketry Team Safety Handbook and SDS Document remain readily available electronically and in print in the workshop. The NDRT Safety Handbook contains guidelines for proper PPE usage, an overview of team tools and machines, launch safety, and other applicable safety guidelines. The SDS is a compilation of all materials used by NDRT at any time within the last two years, with easy-to-read synopses on PPE, handling, and first aid for all materials.

This year, NDRT has published Standard Operating Procedures (SOPs) for construction, testing, and launch operations. SOPs will better allow NDRT members to accessibly locate step-by-step instructions on operating tools or machines, assembling the launch vehicle, or completing a test properly. SOPs will be compiled into one, organized document. The compilation of SOPs be expanded upon when required, and updated for future missions. SOPs for workshop equipment, launch, and test operations have been published in parallel with the Critical Design Review. The NDRT Safety Handbook, SDS Document, and Standard Operating Procedures can be accessed at `https://ndrocketry.weebly.com/reports.html`.

6 Project Plan

6.1 Testing

NDRT intends to complete 28 tests prior to competition to ensure systems can complete the mission as designed. Table 75 outlines all 28 planned tests and relevant requirements, including those provided by NASA and team-derived. Sections 6.1.1-6.1.4 contain all testing procedures, success criteria, results, and next steps upon completion.

Table 75: Complete Testing Overview

System	Test ID	Title	Requirements Satisfied	Result
Vehicle	TV.1	Bulkhead Assembly Strength Test	2.4, VF.2	Incomplete
	TV.2	Demonstration Flight Test	2.1, 2.4, 2.6, 2.8, 2.9, 2.16, 2.18.1, 2.22.6, VF.1	Incomplete
	TV.3	Fins Impact Test	2.4	Incomplete
	TV.4	Nose Cone Impact Test	2.4	Incomplete
	TV.5	Shake Test	2.4, 3.7	Incomplete
	TV.6	Subscale Flight Test	2.17	Pass
ACS	TA.1	15 ft Drop Test	AF.1	Incomplete
	TA.2	Demonstration Flight Test	AF.1, AD.4	Incomplete
	TA.3	Flip Test	AF.1	Incomplete
	TA.4	Sample Data Control Algorithm Test	AF.1	Incomplete
	TA.5	Sample Data Servo Motor Actuation Test	AF.4	Incomplete
	TA.6	Shake Test	2.4	Incomplete
	TA.7	Subscale Data Filter Test	AF.1	Pass
Recovery	TR.1	Altimeter Simulated Flight Test	3.4, 3.8, RF.5, RF.6, PF.6	Incomplete
	TR.2	Battery Life Test	2.7, RE.2	Incomplete
	TR.3	Black Powder Separation Ground Test	3.2, VD.2, AF.4, RF.2, RF.3, RD.4, PF.7	Incomplete
	TR.4	Demonstration Flight Test	3.1, 3.3, 3.11, 3.13, RF.1, RF.4	Incomplete
	TR.5	Deployment Charge Disarm Test	3.6, RD.5, RD.6	Incomplete
	TR.6	GPS Transmitter Test	3.12	Incomplete

	TR.7	Parachute Open Test	3.1.1	Incomplete
PLS	TP.1	Demonstration Flight	2.18.2, 4.3.1,4.3.2, 4.3.3, 4.3.4, PF.10	Incomplete
	TP.2	Ejection Detection Test	4.3.2 PF.9	Incomplete
	TP.3	Image Transmission Test	4.3.4, PF.5	Incomplete
	TP.4	Landing Detection Test	4.3.2	Incomplete
	TP.5	Leg Deployment Test	4.3.2, PF.11	Incomplete
	TP.6	Orientation Test	4.3.3, PF.8, PF.14	Incomplete
	TP.7	Retention Test	PF.3	Incomplete

6.1.1 Vehicles Testing

VEHICLE: BULKHEAD ASSEMBLY STRENGTH TEST

Test ID: TV.1

Responsible Individual: Notre Dame Vehicle Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Payload tube full structural assembly
- Recovery eyebolt secured to bulkhead with nut and washer
- Mounting weights

Objective

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

Motivation

To verify the payload bay bulkhead assembly design and failure calculations To ensure the successful recovery of the launch vehicle.

Success Criteria

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

Test Setup

1. The payload tube structural assembly is mounted on two level, stable structures with a gap in the middle.
2. A loading fixture is suspended from the recovery eyebolt.

Test Procedure

1. Mounting weights are added to the payload bay assembly until the maximum predicted parachute loading value of 287.3 lb is achieved.
2. The payload bay assembly is visually inspected.
3. Weights are removed and the payload bay assembly is inspected for signs of damage.

Results

Incomplete

Next Steps

If Test TV.1 results passes success criteria, proceed to Test TV.3 to continue clearing vehicle structures for demonstration flight.

If Test TV.1 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate bulkhead design and material selection. Repeat Test TV.1 until success criteria is met.

Vehicle: Demonstration Flight Test

Test ID: TV.2

Responsible Individual: Notre Dame Vehicle Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Nose cone
- Body tube assembly
- Fin can assembly
- Cesaroni L-1395 Blue Streak motor
- Motor retainer cap
- CRAS-M
- CRAS-S
- Recovery parachutes
- PLS
- ACS

- Screws and shear pins
- Drill drill bits
- Phillips head screwdriver
- Two wood mounts
- Tape measure
- Sharpie
- Folding table
- 12-foot, 1515 Launch rail

Objective

The objective is to validate the stability and structural integrity of the launch vehicle design through all stages of flight. Additionally, to ensure accurate implementation of launch, payload subsystem, apogee control system, and recovery processes, and to verify flight profile predictions through all flight stages.

Motivation

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

Success Criteria

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

Test Setup

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

Test Procedure

1. The launch vehicle is balanced on a single wood mount, and the CG is marked using a Sharpie.
2. The separation between the CP and CG is measured using a tape measure to ensure the correct static stability margin is achieved.

3. The vehicle is mounted on the launch rail.
4. The recovery lead activates the recovery system and verifies that it is ready for launch.
5. With permission from the RSO, the motor is ignited and the full-scale demonstration flight is conducted.
6. Upon landing, all components are recovered and inspected for damage.
7. All systems are removed and lithium polymer batteries are stored in a battery bag.

Results

Incomplete

Next Steps

If Test TV.2 results passes success criteria, vehicle is prepared for competition flight.

If Test TV.2 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate vehicle and sub-system design. Repeat Test TV.2 until success criteria is met.

Vehicle: Fins Impact Test

Test ID: TV.3

Responsible Individual: Notre Dame Vehicle Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

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

Objective

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

Motivation

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

Success Criteria

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

Test Setup

1. Set up a ladder outside on grass such that the fins of the launch vehicle can be held at a height of 4.38 ft. This height is determined so that the launch vehicle will be travelling 16.8 ft/s when it hits the ground. This simulates the approximate velocity that the launch vehicle will be traveling with the parachutes deployed when it impacts the ground during the full-scale launch.
2. Members will use the ladder to hold the fin can at the determined height, with an additional member holding the base of the ladder to ensure that it remains stable during the test.

Test Procedure

1. The members holding the launch vehicle will drop the launch vehicle in an orientation such that one of the fins will contact the ground first.
2. Members will inspect the fins and launch vehicle and ensure that no part is damaged.
3. The procedure will be repeated for the remaining fins.

Results

Incomplete

Next Steps

If Test TV.3 results passes success criteria, proceed to Test TV.4 to continue clearing vehicle structures for demonstration flight.

If Test TV.3 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate fin design and material selection. Repeat Test TV.3 until success criteria is met.

Vehicle: Nose Cone Impact Test

Test ID: TV.4

Responsible Individual: Notre Dame Vehicle Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Nose cone
- 50g weight
- Ladder

Objective

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

Motivation

It is crucial that the nose cone remains structurally intact upon landing to ensure that the launch vehicle can be re-flown without repairs. Additionally, if the nose cone fails during landing, the shattering fiberglass may be a safety hazard to anyone nearby. Furthermore, the payload recovery system is stored inside the nose cone. Consequently, if the nose cone fails, damage to the payload recovery system is likely to occur.

Success Criteria

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

Test Setup

1. Load nose cone with 50 g to simulate the weight of the recovery system.
2. Set up a ladder with a height sufficient to provide the tip of the nose cone with an initial height of 8 ft.

Test Procedure

1. Climb the ladder to bring the tip of the nose cone to a height of 9.24 ft. At this height, the nose cone will be traveling 24.4 ft/s when it impacts the ground. This is the same velocity that it will be traveling when it impacts the ground during full-scale flight under the parachute. Ensure that someone is holding the base of the ladder so it does not tip over during the test.
2. Drop the nose cone such that the tip of the nose cone lands first. Be careful not to provide any additional velocity to it as it is released
3. Remove the weights from the nose cone and visually inspect the interior and exterior for dents, cracks, missing fragments, or other deformations.

Results

Incomplete

Next Steps

If Test TV.4 results passes success criteria, proceed to Test TV.5 to continue clearing vehicle structures for demonstration flight.

If Test TV.4 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate bulkhead design and material selection. Repeat Test TV.4 until success criteria is met.

Vehicle: Shake Test

Test ID: TV.5

Responsible Individual: Notre Dame Vehicle Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Payload tube full structural assembly
- Recovery eyebolt secured to bulkhead with nut and washer
- Mounting weights

Objective

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

Motivation

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

Success Criteria

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

Test Setup

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

Test Procedure

1. The members who are holding the launch vehicle start to shake the launch vehicle lightly, simulating the vibrations of an actual launch.
2. After shaking the launch vehicle for around thirty seconds, the team will verify that all components are still secured.

3. If all components are still properly secured, the members will then shake the launch vehicle more vigorously to simulate the vibrations and disturbances of a real flight.
4. After shaking the launch vehicle again for around thirty seconds, the team will verify that all components are still secured.

Results

Incomplete

Next Steps

If Test TV.5 results passes success criteria, vehicle structures are fully cleared. Proceed to Test TV.2 for demonstration flight.

If Test TV.5 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate sub-system retention in the vehicle body. Repeat Test TV.5 until success criteria is met.

VEHICLE: SUBSCALE FLIGHT TEST

Test ID: TV.6

Responsible Individual: Notre Dame Vehicle Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

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

Objective

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

Motivation

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

Success Criteria

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

Test Setup

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

15. If necessary, add ballast to move the CG and repeat steps 12-14 until the CG is measured in the correct location.
16. Mount the launch vehicle on the launch rail by sliding the rail buttons down the 1010 slots.
17. Set the launch rail to a desired rail cant angle, and record the angle.
18. Attach the ignition leads to the motor igniter.

Test Procedure

1. Record the wind speed, temperature, and humidity.
2. With the launch vehicle properly mounted on the launch rail, ignite the motor.
3. Observe the entire flight from ignition to landing, checking off predicted flight events as they occur, and noting any anomalies.
4. Inspect the launch vehicle at the landing site for any damage.
5. Listen to the Recovery Stratologger for beeps indicating the apogee altitude, and record the result.
6. Disassemble the launch vehicle and inspect once again for damage. If all components are intact, another launch may be conducted.
7. Download and save all sensor data from the previous flight.
8. Insert the 3D printed ACS half-extension drag tab configuration onto the coupler.
9. Repeat the test setup procedure.
10. Repeat steps 1-7 for the second test flight.
11. Repeat the entire process for a third test flight, instead with the full-extension drag tab configuration attached to the coupler .

Results

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

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

Table 76: Subscale Flight Test Apogee's

The apogee result of the configuration with no drag tabs was impacted by early weathercocking that occurred at the launch rail exit, and the results of the following two flights

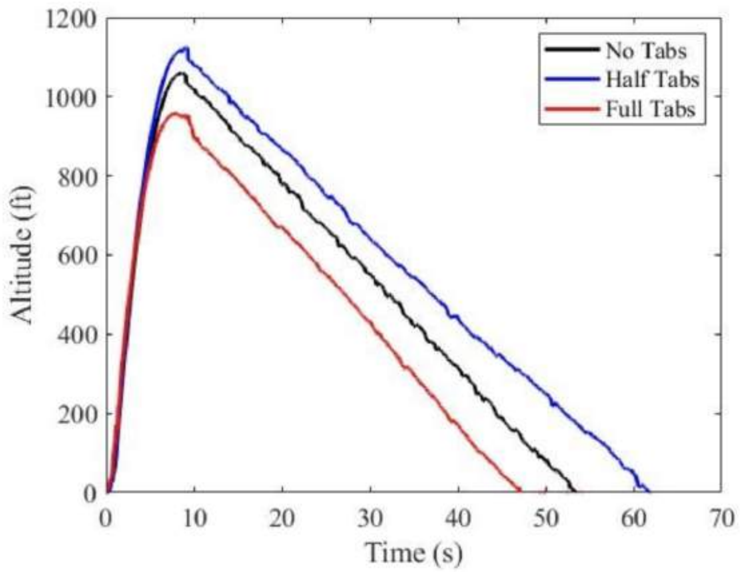


Figure 81: Subscale Flight Test Data

yielded higher apogee altitudes because a longer launch rail was used to ensure that the rail exit speed was high enough to yield stability

Next Steps

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

6.1.2 Apogee Control System Testing

APOGEE CONTROL SYSTEM: 15 FT DROP TEST

Test ID: TA.1

Responsible Individual: Notre Dame Apogee Control System Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Assembled ACS Structure
- Charged Laptop
- Sensor computer connection wires
- Tether Shock Cord
- 2 Quicklinks
- Building structure or personnel for tether

Objective

The goal of this test is to ensure that the system is able to accurately sense a change in altitude.

Motivation

A drop test allows the complete sensor array to be tested, while individual sensors can be tested in isolation. A drop test is the best way to simulate vehicle flight without a demonstration flight.

Success Criteria

Test ID	Success Description	Result
TA.1	The sensor array is able to completely and accurately detect and record altitude and acceleration data for a 15 ft free fall of the ACS structure to within an error of 5%.	Incomplete

Test Setup

1. Assemble full ACS structure.
2. Power ON all electronics. Ensure battery is sufficiently charged for at least 20 minutes of use.
3. Attach one end of the shock cord to the ACS eyebolt with a quicklink.
4. Wrap the other end of the shock cord around a building structure and use a quicklink to form a loop.
5. Allow ACS to gently fall to the ground while holding the shock cord.
6. Ensure ACS cannot hit the ground at full shock cord extension by at least 1 foot.
7. Position at least 3 members to catch ACS and prevent ground impact in case shock cord fails. ACS will not be falling fast enough to cause personnel injury.

Test Procedure

1. Verbally confirm all members performing with test are prepared for the drop to occur.
2. Ensure all sensors are on once again prior to dropping.
3. Hold ACS structure with two hands over a ledge or the chosen drop point.
4. Release both hands at the same time, allowing ACS to drop straight down.
5. Catch the system safely.
6. Connect sensors to Laptop and analyze recorded data.
7. Compare recorded data to expected data for a 15 ft free fall.
8. Record error between the actual and expected data sets.

Results

Incomplete

Next Steps

If Test TA.1 results passes success criteria, proceed to Test TA.3 to continue clearing ACS sensors and electronics for demonstration flight.

If Test TA.1 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate sensor sled and data processing and repeat Test TA.1 until success criteria is met.

Apogee Control System: Demonstration Flight Test

Test ID: TA.2

Responsible Individual: Notre Dame Apogee Control System Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

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

Objective

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

Motivation

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

Success Criteria

Test ID	Success Description	Result
TA.2	The control algorithm successfully deploys tab extensions to induce drag and reduce vehicle velocity to the target of 5,300 ft. Additionally, tabs deploy at appropriate times but do not extend and retract in an oscillatory motion.	Incomplete

Test Setup

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

Test Procedure

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

Results

Incomplete

Next Steps

If Test TA.2 results pass success criteria, ACS is fully cleared for future flight at competition launch day.

If Test TA.2 results fail success criteria, alert Chief Engineer and Safety Officer immediately. An additional Demonstration Flight may be required. Consult with NDRT Officers to determine appropriate plan of action before Flight Readiness Review and Competition.

APOGEE CONTROL SYSTEM: FLIP TEST

Test ID: TA.3

Responsible Individual: Notre Dame Apogee Control System Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

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

Objective

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

Motivation

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

Success Criteria

Test ID	Success Description	Result
TA.3	Sensors accurately detect orientation and acceleration data during rotation to within 10% of expected values. No parts are visually or audibly loose after rotations.	Incomplete

Test Setup

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

Test Procedure

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

Results

Incomplete

Next Steps

If Test TA.3 results passes success criteria, proceed to Test TA.4 to continue clearing ACS sensors and electronics for demonstration flight. Additionally, proceed to Test TA.6 to continue clearing ACS structure.

If Test TA.3 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate sensor sled and data processing and repeat Test TA.3 until success criteria is met.

APOGEE CONTROL SYSTEM: SAMPLE DATA CONTROL ALGORITHM TEST

Test ID: TA.4
Responsible Individual: Notre Dame Apogee Control System Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

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

Objective

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

Motivation

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

Success Criteria

Test ID	Success Description	Result
TA.4	The control algorithm correctly identifies flight data and initiates necessary adjustments by indicating tab extensions with 0.5 second of data transmission.	Incomplete

Test Setup

1. Assemble the ACS system

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

Test Procedure

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

Results

Incomplete

Next Steps

If Test TA.4 results passes success criteria, proceed to Test TA.5 to continue clearing ACS sensors and electronics for demonstration flight.

If Test TA.4 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate sensor sled and data processing and repeat Test TA.4 until success criteria is met.

APOGEE CONTROL SYSTEM: SAMPLE DATA SERVO MOTOR ACTUATION TEST

Test ID: TA.5

Responsible Individual: Notre Dame Apogee Control System Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

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

Objective

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

Motivation

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

Success Criteria

Test ID	Success Description	Result
TA.5	The drag tabs extend at the specific times programmed into the sample data, to within 0.5 seconds.	Incomplete

Test Setup

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

Test Procedure

1. Run the test data into the data filtering algorithm.
2. Take a video of the tab extensions as the sample data is run.
3. Compare tab extensions in the video with expected tab extensions in the sample data.

Results

Incomplete

Next Steps

If Test TA.5 results passes success criteria, sensors and electronics are cleared for demonstration flight. Proceed to Test TA.2 for demonstration flight criteria.

If Test TA.5 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate sensor sled and data processing and repeat Test TA.5 until success criteria is met.

APOGEE CONTROL SYSTEM: SHAKE TEST

Test ID: TA.6

Responsible Individual: Notre Dame Apogee Control System Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Assembled ACS Structure

- Charged Laptop
- Sensor Computer Connection Wires

Objective

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

Motivation

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

Success Criteria

Test ID	Success Description	Result
TA.6	Sensors detect orientation and acceleration data during shakes. No parts are damaged after thorough visual inspection following shakes.	Incomplete

Test Setup

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

Test Procedure

1. Ensure all sensors are on and connected prior to shaking.
2. Hold ACS structure with two hands above the table. Ensure wires are not tangled.
3. Slowly shake ACS vertically.
4. A second member must verify sensors are transmitting changes in data in the correct direction.
5. Do not proceed until sensors data transmission is operating.
6. Open a metronome on the internet using the laptop. Turn the volume up.
7. Start a metronome at 200 bpm.
8. Perform 10 vertical shakes to the metronome clicks, including both upward and downward motions in the same shake.
9. Re-orient ACS to starting position.
10. Perform 10 horizontal shakes to the same metronome clicks, including both motions, right and left, in the same shake.

11. Confirm sensors detected motion on laptop. If data anomalies are identified, return to Test TA.3 to confirm sensor accuracy.
12. Inspect ACS structure visually. Take special note of locations of possible stress concentrations, such as corners or edges of parts.

Results

Incomplete

Next Steps

If Test TA.6 results passes success criteria, ACS structure is cleared for demonstration flight. Proceed to Test TA.2 for demonstration flight criteria.

If Test TA.6 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate sensor sled and data processing and repeat Test TA.6 until success criteria is met.

Apogee Control System: Subscale Data Filter Test

Test ID: TA.7

Responsible Individual: Notre Dame Apogee Control System Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

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

Objective

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

Motivation

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

Success Criteria

Test ID	Success Description	Result
TA.7	ACS sensors are able to capture a full flight. Data filtering algorithm is able to smooth provided subscale data for effective servo motor actuation.	Complete

Test Setup

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

Test Procedure

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

Results

Passed. Three subscale flights were performed and the chosen Kalman filter is able to smooth all data, detect burnout and apogee. The sensors were able to capture accurate data for each flight as well, confirmed with recovery electronics on the same sensor sled. Figure 82 depicts both the raw and filtered subscale flight data to show the smoothed curve.

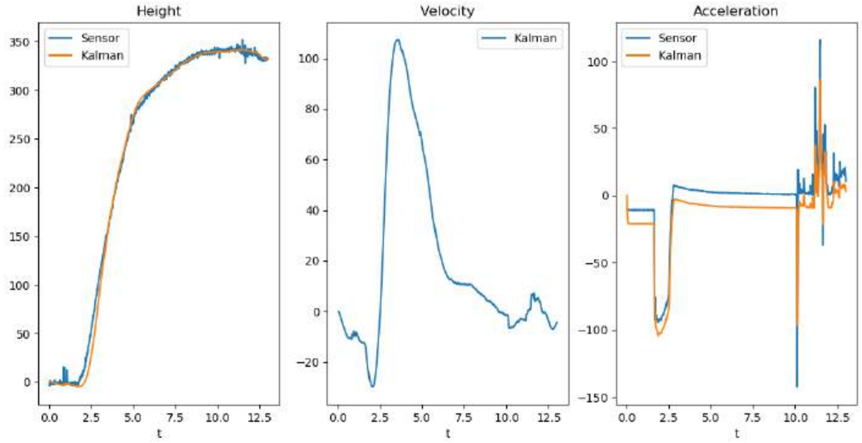


Figure 82: Kalman Filtered Subscale Data

Next Steps

Proceed to Test TA.1 to begin clearing final ACS sensors and electronics assembly for demonstration flight.

6.1.3 Recovery Testing

Recovery: Altimeter Simulated Flight Test

Test ID: TR.1

Responsible Individual: Notre Dame Recovery Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Altimeters used in CRAS-M and CRAS-S: 2 Perfectflite Stratologger SL100's, 2 Perfectflite StratologgerCF's, and 1 Featherweight Raven3
- 5 LiPo batteries
- 5 Small Incandescent Lights
- Charged Laptop
- USB connector cable

Objective

The objective of this test is to ensure that the altimeters will ignite the black powder charges at apogee and 575 feet for the altimeters in the CRAS-M and 525 feet for the altimeters used by the CRAS-S.

Motivation

This test is important to ensure that the launch vehicle is safely recovered and completes its mission, contingent on the successful operation of the altimeters. Performing a simulated flight allows for the entire system to be tested before use in a real launch.

Success Criteria

Test ID	Success Description	Result
TR.1	Altimeter lights illuminate at the correct points during a simulated flight created in a computer program.	Incomplete

Test Setup

1. Attach lights to the drogue and main ejection output terminal blocks of 1 Perfectflite

Stratologger SL100, 1 Perfectflite Stratologger CF, and the Featherweight Raven3. Attach a light to each of the main ejection output terminal blocks of 1 Perfectflite Stratologger SL100 and 1 Perfectflite Stratologger CF.

2. Connect a battery to the battery terminal block on each altimeter.

Test Procedure

1. Connect the first altimeter to be tested to the laptop with the proper software to running the altimeter through a simulated flight test using the data I/O connector on the altimeter.
2. Run the altimeter through a simulated flight using the computer generated flight data.
3. Record the height at which the altimeter light(s) illuminate and compare with the expected height of illumination in the simulated flight code.
4. Repeat steps 1-3 for all 5 altimeters.

Results

Incomplete

Next Steps

If Test TR.1 results passes success criteria, proceed to Test TR.2 to continue clearing recovery electronics for demonstration flight.

If Test TR.1 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate altimeter programming and assess any possible altimeter damages. Repeat Test TR.1 until success criteria is met.

Recovery: Battery Life Test

Test ID: TR.2

Responsible Individual: Notre Dame Recovery Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Altimeters: Stratologger SL100, Stratologger CF, and Raven3
- Eggfinder Mini
- 1S Lithium polymer battery and charger
- 2S Lithium polymer battery and charger
- Timer

Objective

The goal of this test is to ensure that the batteries for the altimeter and GPS transmitters can provide sufficient power to the electronics for at least 2 hours on the pad before launch.

Motivation

This test is being performed to verify the battery life calculations completed in Section (battery life section) and to ensure that requirement RE.3 is met.

Success Criteria

Test ID	Success Description	Result
TR.2	The altimeters and GPS transmitters remain on and powered for at least 2 hours on one battery charge.	Incomplete

Test Setup

1. Completely charge 1S lithium polymer batteries for altimeters and 2S lithium polymer batteries for Eggfinders

Test Procedure

1. Plug batteries into various electronics and start a separate timer for each battery.
2. When the electronic device powers down, stop the timer and record the time elapsed.
3. Ensure all batteries are tested for the applicable sensors or electronics as the configuration would be during demonstration flight.

Results

Incomplete

Next Steps

If Test TR.2 results passes success criteria, proceed to Test TR.6 to continue clearing recovery electronics for demonstration flight.

If Test TR.2 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate battery choice or order new batteries for express delivery. Repeat Test TR.2 until success criteria is met.

RECOVERY: BLACK POWDER SEPARATION GROUND TEST

Test ID: TR.3

Responsible Individual: Notre Dame Recovery Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Assembled Launch Vehicle
- Black powder (provided by Launch Manager)
- Wooden vehicle supports
- Timer

Objective

The objective of this test is to ensure that the calculated amount of black powder is sufficient to separate the vehicle sections and allow for parachute deployment.

Motivation

This test is performed to verify the calculations of section 3.8.4.1 before the system is launched.

Success Criteria

Test ID	Success Description	Result
TR.3	For each separation point, both sections of the vehicle fully separate. No structural damage to vehicle results from black powder charges.	Incomplete

Test Setup

1. Set altimeter to eject at a specified time.
2. Launch Manager prepared CRAS-M and CRAS-S charges as stated in Launch Checklist: Recovery Preparation
3. Place wooden vehicle supports in launch area.

Test Procedure

1. Start by testing the CRAS-M at the main parachute ejection point
2. Turn on timer for black powder ejection as programmed on the altimeter. Do not be within test zone within 1 minute of ejection.
3. Verify amount of black powder at the selected separation point with the Launch Manager and record for evaluation.
4. Assemble launch vehicle.
5. Use timer to wait for charge to go off.
6. When timer expires, expect black powder ejection.
7. If no ejection, consult with Launch Manager. Safely disarm vehicle and increase amount of black powder by 0.5 g.

8. If ejection is a success, move on to next separation point.

Results

Incomplete

Next Steps

If Test TR.3 results passes success criteria, continue black powder verifications by proceeding to Test TR.5 for a deployment charge disarm test.

If Test TR.3 results fails success criteria, re-evaluate black powder amounts until ejection occurs safely. Repeat Test TR.3 until success criteria is met.

RECOVERY: DEMONSTRATION FLIGHT TEST

Test ID: TR.4

Responsible Individual: Notre Dame Recovery Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Assembled CRAS-M
- Assembled CRAS-S
- Assembled Launch Vehicle
- E-matches
-
-

Objective

The goal of this test is to ensure that the recovery system is working properly and will allow for successful vehicle recovery on competition day.

Motivation

Testing the entire system in similar conditions to the competition launch is he most accurate way to determine if the system will work.

Success Criteria

Test ID	Success Description	Result
TR.3	For each separation point, both sections of the vehicle fully separate. All parachutes deploy successfully. No structural damage to CRAS-M or CRAS-S.	Incomplete

Test Setup

1. Complete Launch Checklist: Recovery Preparation
2. Complete Launch Checklist: Launch Vehicle Preparation
3. Complete Launch Checklist: Launch Setup

Test Procedure

1. Complete Launch Checklist: Launch Procedure
2. Complete Launch Checklist: Post-Flight Recovery and Analysis
3. Inspect CRAS-M and CRAS-S for any damages. Take pictures of all systems for further inspection.

Results

Incomplete

Next Steps

If Test TR.4 result passes success criteria, recovery system is cleared for launch at competition.

Recovery: Deployment Charge Disarm Test

Test ID: TR.5
Responsible Individual: Notre Dame Recovery Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Fully mounted and assembled recovery avionics
- Flathead Screwdriver
- Small Incandescent Lights

Objective

The objective of this test is to ensure that any ejection charges that were not set off during the flight for any reason can be safely disarmed on the ground.

Motivation

This test is performed to ensure that the most dangerous part of the system can be safely deactivated before the vehicle is launched.

Success Criteria

Test ID	Success Description	Result
TR.5	The light, a substitute for the e-match, does not illuminate at any point during the disarming of deployment charge disarming.	Incomplete

Test Setup

1. Replace the e-matches with small lights at the e-match connection slot.
2. Ensure that the batteries used to power the altimeters are fully charged and the electronics are fully assembled and ready to operate.

Test Procedure

1. With the e-match substitutes in place, power on all three recovery altimeters.
2. Listen through the start up sequence of a the altimeters, ensuring proper start up.
3. One at a time, turn off the altimeters using the power key.
4. Look for any illumination from light bulbs.
5. Record if any lights illuminate.

Results

Incomplete

Next Steps

If Test TR.5 results pass success criteria, black powder calculations are verified. Proceed to Test TR.4 for the demonstration flight.

If Test TR.5 results fail success criteria, re-evaluate altimeter e-match connections to ensure safe disarming can occur if necessary. Repeat Test TR.5 until success criteria is met.

Recovery: GPS Transmitter Field Test

Test ID: TR.6

Responsible Individual: Notre Dame Recovery Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Eggfinder RX GPS receiver
- Eggfinder Mini GPS transmitter
- Windows computer with VisualGPS installed
- USB cable

Objective

The objective of this test is to confirm that the GPS Transmitter is functioning correctly before demonstration launch.

Motivation

The motivation of this test is to ensure the GPS transmitter can transmit data on vehicle location after descent so the team can find and recover the landed vehicle.

Success Criteria

Test ID	Success Description	Result
TR.6	The VisualGPS computer program is able to receive data from the GPS transmitter through the Eggfinder RX receiver and correctly plots the location of the Eggfinder Mini transmitter to within 10 yards.	Incomplete

Test Setup

1. The Eggfinder RX GPS receiver and the Eggfinder Mini GPS transmitter are assembled following the instructions in the assembly manuals.
2. Power up the Eggfinder Mini GPS transmitter. A red LED light should begin blinking about once per second on the Eggfinder Mini transmitter's RF board.
3. Plug the USB cable of the Eggfinder RX into the Windows computer. The red light should immediately come on, indicating that the receiver is receiving power. After one or two seconds, the green light on the RF board of the Eggfinder RX should begin blinking in sync with the light on the Eggfinder Mini, indicating that it is receiving data from the Eggfinder Mini.

Test Procedure

1. Open the program VisualGPS on the windows computer. The program should begin plotting the approximate locations of the Eggfinder Mini transmitter on a grid system and displaying the satellite strength.
2. After confirming everything is functioning correctly, turn off the Eggfinder Mini transmitter by unplugging the battery. The green light on the Eggfinder RX receiver

should stop blinking.

3. Unplug the USB cable. The test is complete.
4. If any complications occur or if any of the requirements for each step are not met, refer to the troubleshooting sections of the assembly manuals for the Eggfinder Mini transmitter and Eggfinder RX receiver.

Results

Incomplete

Next Steps

If Test TR.6 results passes success criteria, recovery electronics are completely tested and prepared for the demonstration flight. Proceed to Test TR.4 for the demonstration flight.

If Test TR.6 results fails success criteria, re-evaluate VisualGPS, the Eggfinder Mini transmitter, or the GPS transmitter until accurate GPS positioning is possible. Repeat Test TR.3 until success criteria is met.

Recovery: Parachute Open Test

Test ID: TR.7

Responsible Individual: Notre Dame Recovery Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Assembled drogue parachute system
- Assembled main parachute system
- Assembled nose parachute system

Objective

The goal of this test is to ensure that the parachutes can fully open in their planned configurations

Motivation

The successful opening of the parachutes, especially of the main parachutes release from the deployment bag, is critical to a successful recovery and must be ensured before a full scale launch.

Success Criteria

Test ID	Success Description	Result
TR.3	Parachute fully opens before reaching the ground from a height of more than 35 ft.	Incomplete

Test Setup

1. Take all assembled parachute configurations to the 4th floor balcony of the Jordan Hall of Science on University of Notre Dame's campus. This is roughly 40 ft above the first floor.

Test Procedure

1. Hold parachute closed while a second member holds the recovery structure beneath the parachute.
2. Drop each parachute system from the balcony and watch for the parachute to open as it descends.
3. Ensure parachute fully opens prior to landing on the ground of the 1st floor.

Results

Incomplete

Next Steps

If Test TR.7 results passes success criteria, parachute systems are verified. Proceed to Test TR.4 for the demonstration flight.

If Test TR.7 results fails success criteria, re-evaluate parachute sizing until parachute descent occurs safely. Repeat Test TR.7 until success criteria is met.

6.1.4 Planetary Landing System Testing

Planetary Landing System: Demonstration Flight Test

Test ID: TP.1

Responsible Individual: Notre Dame Experimental Payload Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Full vehicle
- Complete PLS system
- Fully charged batteries

- Charged laptop capable of receiving image transmission

Objective

The objective is to verify that the PLS can be retained in the vehicle, jettison at 525 ft, land on the ground safely, orient to within 5 degrees from vertical, take a panoramic image, and transmit to a team computer.

Motivation

Testing the complete PLS system prior to competition enables the team to make necessary adjustments before competition launch day arrives.

Success Criteria

Test ID	Success Description	Result
TP.1	The PLS suffers no damages during jettison, descent under parachute, landing or orientation, determined by a visual inspection following the mission. The PLS is able to transmit a full panoramic image of acceptable quality to a team laptop after landing, before team recovery.	Incomplete

Test Setup

1. Follow step-by-step instructions in Launch Checklist: Planetary Landing System Preparation to prepare the PLS and PLS parachute for integration into the launch vehicle.
2. Ensure all batteries are fully charged for at least 2 hours of use and electronics are powered ON before inserting into vehicle.
3. Follow step-by-step instructions in Launch Checklist: Launch Vehicle Preparation to properly integrate PLS into vehicle and secure the retention system
4. Follow step-by-step instructions in Launch Checklist: Recovery Preparation to have Launch Manager safely arm the CRAS-S with black powder for separation.
5. Power ON laptop and ensure image receiving software program is active.

Test Procedure

1. Follow step-by-step instructions in Launch Checklist: Launch Procedures to commence the demonstration flight test.
2. Allow mission to proceed without interruption from Notre Dame personnel.
3. Wait for orientation and image to be transmitted to laptop before recovery.
4. If no image is transmitted after 15 minutes, recover vehicle.

5. If image is transmitted within 15 minutes, recover vehicle.
6. Use level and protractor to determine final PLS angle from vertical. Record this value for data analysis.
7. Use camera to record PLS parachute final location relative to PLS structure.
8. Evaluate transmitted image quality on laptop and ensure landscape is appropriately depicted in image compared to a simple look around the landing area. Image must not be significantly obstructed by parachute or
9. Compare PLS end state angle to angle detected in PLS computer.

Results

Incomplete

Next Steps

If Test TP.1 results passes success criteria, Planetary Landing System is cleared for competition flight.

If Test TP.1 results fails success criteria, alert Chief Engineer and Safety Officer immediately. Re-evaluate applicable PLS retention, recovery, orientation, imaging, or data transmission designs depending on which criteria failed to meet success criteria. Repeat Test TP.1 if necessary, or discuss alternate testing scenario with Safety Officer and Chief Engineer until success criteria is met. A repeat of TP.1 as written will require another scheduled demonstration flight and relevant FAA waiver.

Planetary Landing System: Ejection Detection Test

Test ID: TP.2

Responsible Individual: Notre Dame Experimental Payload Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Assembled PLS
- Payload Tube of Vehicle Body
- Jumper Cable
- Several Cushions or Pillows
- Small LED Light

Objective

To objective is to verify that the PLS ejection detection system can accurately and quickly determine if the PLS has ejected from the payload tube.

Motivation

The PLS must be able to verify ejection so that the legs can begin to deploy during descent. If ejection is not detected, PLS is unlikely to orient within 5 degrees from the vertical after landing.

Success Criteria

Test ID	Success Description	Result
TP.2	The Raspberry Pi LED illuminated within 3 seconds of the PLS exiting the payload tube and the detachment of the jumper cable.	Incomplete

Test Setup

1. Configure PLS with landing legs closed.
2. Attach LED to Raspberry Pi.
3. Install Raspberry Pi and jumper pins to PLS.
4. Install PLS into retention system in the payload bay.
5. Place padded cushions directly below the payload bay.
6. Position a video camera such that the payload bay and LED can be captured in the same shot.

Test Procedure

1. Lift payload bay about 1 foot in the air. Keep cushions directly below the payload bay.
2. As you lift, the PLS should slide out and the jumper cable should detach.
3. Inspect PLS for any damages.
4. Stop video.
5. In slo-motion view, determine how long the LED took to illuminate after the jumper cable released.
6. Compare this value to the 3 second limit specified in the success criteria.

Results

Incomplete

Next Steps

If Test TP.2 results passes success criteria, proceed to Test TP.5 to continue clearing PLS deployment system for demonstration flight.

If Test TP.2 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate ejection detection system design and repeat Test TP.2 until success criteria is met.

PLANETARY LANDING SYSTEM: IMAGE TRANSMISSION TEST

Test ID: TP.3

Responsible Individual: Notre Dame Experimental Payload Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Assembled PLS system
- Fully charged battery
- Charged laptop capable of receiving image transmission

Objective

To objective is to confirm that the PLS can transfer an image from the maximum allowable drift distance of 2,500 ft. Additionally, this test will verify that the PLS camera and data transmission system can transmit an image of acceptable quality.

Motivation

The PLS should be able to transmit an acceptable image from anywhere within the allowable drift radius, such that the PL image can be scored for competition.

Success Criteria

Test ID	Success Description	Result
TP.3	The PLS cab transmit a panoramic image, without obstruction, from a distance of at 2,500 ft or more.	Incomplete

Test Setup

1. Go to an open field with at least 0.5 miles of uninterrupted landscape.
2. At least one member place PLS on the ground, powered ON with legs deployed.
3. Attach parachute to eyebolt and hold up in the air.
4. Release parachute to simulate a natural landing position of the parachute.
5. Call other members to confirm laptop is powered on with image receiving software active.

Test Procedure

1. Initiate the PLS imaging process while PLS is on ground. Orientation is not critical for this test, but PLS should be upright.
2. Wait for a maximum of 5 minutes from initiation to image reception.
3. Download full panoramic image onto laptop and view.

4. Perform a visual scan of the area and confirm the transmitted image matches the landscape.
5. Evaluate quality of image and ensure the image is unobstructed, clear, and the landscape is easily identifiable.

Results

Incomplete

Next Steps

If Test TP.3 results passes success criteria, imaging and transmission systems are cleared. Proceed to Test TP.1 for demonstration flight.

If Test TP.3 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate image transmission software or camera selection and repeat Test TP.3 until success criteria is met.

Planetary Landing System: Landing Detection Test

Test ID: TP.4

Responsible Individual: Notre Dame Experimental Payload Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Assembled ACS Structure
- Small LED Light
- Shock Cord or Rope
- Timer
- Measuring Tape

Objective

To objective is to verify that the PLS can identify ground impact and initiate the orientation process.

Motivation

To meet mission criteria, the PLS must orient and transmit the image, which it will not be able to do if the PLS does not transition to the orientation process after identifying landing.

Success Criteria

Test ID	Success Description	Result
TP.4	LED illuminates when PLS lands on the ground, and the calculates kinetic energy on impact is lower than the actual expected kinetic energy on impact under parachute.	Incomplete

Test Setup

1. Attach shock cord to the PLS eyebolt.
2. Attach LED to Raspberry Pi to indicate landing sequence detection.
3. Power ACS on and set legs to descent configuration, with legs perpendicular to the PLS structure.

Test Procedure

1. Raise PLS up at least 4 ft, holding onto the cord, not the ACS structure itself.
2. Measure starting height with a measuring tape.
3. Start timer when ACS descent begins.
4. Lower ACS to the ground slowly until impact. Stop timer.
5. Observe if LED illuminates or not.
6. Calculate descent kinetic energy of ACS using timer calculations.
7. If LED illuminated, verify descent kinetic energy is less than the expected descent kinetic energy. This would result in test success.
8. If LED does not illuminate, first inspect LED and replace if necessary. If LED is good, allow PLS to descend lightly faster than the previous trial.
9. Repeat Step 8 until LED illumination or maximum possible descent kinetic energy is reached. This would result in test failure.

Results

Incomplete

Next Steps

If Test TP.4 results passes success criteria, proceed to Test TP.6 to begin clearing PLS orientation system for demonstration flight.

If Test TP.4 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate bulkhead design and material selection. Repeat Test TP.4 until success criteria is met.

Planetary Landing System: Leg Deployment Test

Test ID: TP.5

Responsible Individual: Notre Dame Experimental Payload Design Lead

Required PPE

- Safety Glasses
- Anti-static glove

Materials and Equipment

- Assembled PLS
- Jumper Cable Ejection Detection System
- Timer
- Camera
- Protractor
- Shock Cord or Rope

Objective

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

Motivation

To verify the payload bay bulkhead assembly design and failure calculations To ensure the successful recovery of the launch vehicle.

Success Criteria

Test ID	Success Description	Result
TP.5	When the jumper cable is released, the legs rotate to a 90 degree angle within 25 seconds.	Incomplete

Test Setup

1. Attach shock cord to the PLS eyebolt.
2. Place PLS in ejection configuration, such that the legs are parallel to the length of the body.
3. Insert jumper cable.
4. Power all system on.
5. Set up camera to record leg deployment.

Test Procedure

1. Raise PLS up by cord to about chest-height of the holder.
2. Turn camera on.
3. Pull jumper cable pin out while wearing an anti-static glove.
4. Start timer at the same time as jumper cable pin removal.

5. Stop timer when legs stop moving.
6. Verify time is under 25 seconds.
7. While PLS is still in the air, use a protractor to measure the angle between the PLS body and the legs.
8. Verify the angle is 90 degrees, rounding to the nearest whole degree.

Results

Incomplete

Next Steps

If Test TP.5 results passes success criteria, proceed to Test TP.4 to continue clearing vehicle structures for demonstration flight.

If Test TP.5 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate leg design, servo motor selection, or Raspberry Pi code, depending on origin of failure. Repeat Test TP.5 until success criteria is met.

Planetary Landing System: Orientation Test

Test ID: TP.6

Responsible Individual: Notre Dame Experimental Payload Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Fully Assembled Planetary Landing System
- Floor jack
- Plywood sheet
- Chair, Table, or Brick

Objective

To objective is to ensure the PLS is able to orient to within 5 degrees from vertical open landing on an uneven surface.

Motivation

The PLS mission requires an orientation to within 5 degrees of vertical, so testing this system before competition is crucial.

Success Criteria

Test ID	Success Description	Result
TP.6	System can maintain vertical orientation within 5 degrees from vertical on a 20 degree or greater incline from the horizontal.	Incomplete

Test Setup

1. Place the floor jack down on the ground.
2. Place the plywood sheet at an angle on the floor jack with the other end on the ground.
3. Place a chair, table, brick, or another heavy object at the ground end of the plywood to stop the plywood from slipping.
4. Place PLS in descent configuration, with legs perpendicular to the PLS structure.

Test Procedure

1. Use the floor jack to set the plywood to a 10 degree angle. Record this exact angle
2. Place PLS on the plywood.
3. Allow PLS to detect the surface and begin orientation.
4. When PLS stop moving, record the angle with respect to the plywood. Knowing the angle from the ground to the plywood, determine and record the angle of the PLS relative to the ground.
5. Repeat Steps 1-4 multiple times, increasing the angle of the plywood by 5 degrees each time. Stop after PLS fails or plywood is positioned at a 30 degree angle.
6. Record maximum possible starting angle for a 5 degree from vertical orientation.
7. If possible, repeat test using a textured board. Glue chunks of wood onto the plywood in random locations and re-test with same criteria.

Results

Incomplete

Next Steps

If Test TP.6 results passes success criteria, proceed to Test TP.7 to clear the PLS retention system for demonstration flight.

If Test TP.6 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate leg design, servo motor selection, Raspberry Pi code, or material selection depending on origin of failure. and material selection. Repeat Test TP.6 until success criteria is met.

PLANETARY LANDING SYSTEM: RETENTION TEST

Test ID: TP.7

Responsible Individual: Notre Dame Experimental Payload Design Lead

Required PPE

- Safety Glasses

Materials and Equipment

- Payload Tube
- Full Assembled PLS structure
- CRAS-S

Objective

To objective is to ensure the PLS retention system can restrict PLS movement during flight.

Motivation

The PLS cannot complete the mission if it is damaged during flight or is too restricted by the retention system that it does not eject.

Success Criteria

Test ID	Success Description	Result
TP.7	No components move visually or audibly during the duration of the test. No components are damaged during test.	Incomplete

Test Setup

1. Insert the PLS retention system into the payload bay and screw it in place.
2. Get the PLS to the flight configuration and connect the jumper pins.
3. Slide the PLS it into the payload bay, make sure the retention dowels fit into the PLS bulkhead holes.
4. Place the CRAS-S over the PLS legs.
5. Attach the nose cone and insert the shear pins.

Test Procedure

1. Hold payload tube and nose cone assembly with two hands such that the nose cone is pointing upwards.
2. Quiet everyone in the room. Listen closely for any noises during next step.
3. Slowly flip assembly 180 degrees so that the nose cone is pointing to the ground.
4. Disconnect nose cone and inspect the PLS for any damage.
5. Repeat Test Setup and test again, but flip quickly this time.
6. Inspect the PLS again for any damages.

Results

Incomplete

Next Steps

If Test TP.7 results passes success criteria, proceed to Test TP.8 to continue clearing the PLS for demonstration flight.

If Test TP.7 results fails success criteria, alert Chief Engineer and Safety Officer. Re-evaluate retention structure design and material selection. Repeat Test TP.7 until success criteria is met.

6.2 Requirements Compliance

Tables 77-80 show the requirements, both NASA provided and NDRT derived, that drove the design and logistical approach of the project. The tables define a unique requirement ID, provide a short description of the requirement, and the compliance plan the team has or will follow (where applicable). The tables also define the verification method used for each requirement (I for inspection, D for Demonstration, T for Testing, and A for Analysis) and a short description of the verification plan, as well as a status marker. Requirements verified through Demonstration or Testing list the relevant Test IDs as well.

6.3 NASA Requirements Compliance

6.3.1 General

Table 77: NASA General Requirements

Requirement		**Verification Method**				**Verification Plan**	**Status**
ID	**Description**	**I**	**D**	**T**	**A**		
1.1	Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor). Teams will submit new work. Excessive use of past work will merit penalties.	x				The current design is entirely independent from previous years designs, an has been entirely designed and reported by undergraduate team members,. Moving forward, it is expected that all construction an flight operations, aside from specific motor preparation, will be done by undergraduate team members.	In Progress
1.2	The team will provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations.	x				The current project plan, including scheduling and budgets, can be found in Section 6.8, while risks and mitigations can be found in Section 5.2.	In Progress
1.3	Foreign National (FN) team members must be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during launch week due to security restrictions. In addition, FN's may be separated from their team during certain activities on site at Marshall Space Flight Center.	x				All Foreign National team members that may attend launch week have been identified in the appropriate forms submitted to NASA.	Complete
1.4	The team must identify all team members attending launch week activities by the Critical Design Review (CDR). Team members will include: Students actively engaged in the project throughout the entire year, one mentor, and no more than two adult educators.	x				All team members that may attend launch week have been identified in the appropriate forms submitted to NASA.	Complete
1.5	The team will engage a minimum of 200 participants in educational, hands-on science, technology, engineering, and mathematics (STEM) activities, as defined in the STEM Engagement Activity Report, by FRR. To satisfy this requirement, all events must occur between project acceptance and the FRR due date and the STEM Engagement Activity Report must be submitted via email within two weeks of the completion of the event.	x				The team has engaged in one major educational outreach event with the Boys and Girls club of South Bend, and has several more event planned for the spring.	In Progress

Requirement		Verification Method				Verification Plan	Status
ID	Description	I	D	T	A		
1.6	The team will establish a social media presence to inform the public about team activities.	x				The team has established its own website, along with Facebook, Twitter, and Instagram accounts, and a Linkedin group.	Complete
1.7	Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient.	x				At this time, the team's Proposal, PDR, and CDR documents have been successfully emailed to NASA. The FRR and PLAR documents will be submitted in the future.	In Progress
1.8	All deliverables must be in PDF format.	x				All documents so far submitted have been in PDF format.	In Progress
1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.	x				All documents so far submitted have contained an accurate table of contents.	In Progress
1.10	In every report, the team will include the page number at the bottom of the page.	x				All documents so far submitted have contained an accurate page number at the bottom of each page.	In Progress
1.11	The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.	x				The team currently join review presentations remotely, with every individual using their own computer equipment. This is expected to continue for the CDR and FRR presentations.	In Progress
1.12	All teams will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted on the launch field. At launch, 8-foot 1010 rails and 12-foot 1515 rails will be provided. The launch rails will be canted 5 to 10 degrees away from the crowd on launch day. The exact cant will depend on launch day wind conditions.	x				The team expects to use a 12-foot 1515 rail during the competition launch.	Complete
1.13	Each team must identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The mentor must maintain a current certification, and be in good standing, through the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the rocket for liability purposes and must travel with the team to launch week.	x				The team's mentor is Dave Brunsting, who currently possesses Level 2 HPR certification from the NAR and TRA. He is currently expecte to be capable of traveling with the team for competition launch.	Complete
1.14	Teams will track and report the number of hours spent working on each milestone.	x				The team has kept track of the hours spent working on this project, and hours can be found reported in Section 1. Hours will continue to be tracked as the project progresses.	In Progress

6.3.2 Launch Vehicle

Table 78: NASA Launch Vehicle Requirements

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
2.1	The vehicle will deliver the payload to an apogee altitude between 3,500 and 5,500 ft AGL.	The launch vehicle has been designed to have a maximum apogee of 5706 ft, and a minimum apogee of 5286 ft, both of which are within the qualifying altitude range.			TV.2	x	Simulations of the launch vehicle have been performed in OpenRocket and RocketSim, and can be found in Section 3.9.1. Two instrumented full-scale test flights will be performed, in order to obtain real flight data and further qualify the performance predictions, the procedures for which can be found in Section 5.1.	In Progress
2.2	Teams shall identify their target altitude goal at the PDR milestone.	The team has chosen a target apogee of 5300 ft.	x				The team's PDR document was read through prior to submission, to ensure that the team's target apogee was clearly declared.	Complete
2.3	The vehicle will carry one commercially available, barometric altimeter.	The vehicle will carry a number of commercial barometric altimeters for recovery purposes, including 2 Stratologger CFs, 2 Stratologger SL100s, and a Featherweight Raven 3. The exact scoring altimeter will be selected and marked prior to the competition launch.	x				Prior to launch, the scoring altimeter will be checked to ensure that it has been properly marked as the scoring altimeter, and is indeed a commercially available altimeter operating based off barometric pressure.	In Progress
2.4	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.	The vehicle is designed with a recovery system capable of bringing the vehicle from apogee to the ground without significant damage. The vehicle will be capable of reflight within 2 hours.		TV.1, TV.2, TV.3, TV.4, TV.5			Two flight demonstrations are planned, during which the vehicle and all subsystems will fly in the configuration it is expected to in competition. After flight, the vehicle will be disassembled and searched for any visible damage. The general procedures for the test launches can be found in Section 5.1.	Incomplete
2.5	The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.	The vehicle is designed to have 4 independent sections: the nosecone, payload bay, recovery tube, and fin can.	x				After construction, the independent sections of the vehicle will be counted to ensure there are no more than four.	Incomplete
2.5.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.	The couplers at the bottom of the payload bay and bottom of the recovery tube, which separate in flight, are designed to be at least 6 in long.	x				After construction, the payload bay coupler and recovery tube coupler will be measured to ensure that they are at least 6 in long.	Incomplete
2.5.2	Nosecone shoulders which are located at in-flight separation points will be at least ½ body diameter in length.	The nosecone shoulder is currently designed to be 3 in long.	x				After construction, nosecone shoulder will be measured to ensure that it is at least 3 in long.	Incomplete
2.6	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens.	Detailed launch procedures have been prepared that will allow the team to prepare the vehicle for launch in less than 2 hours. These launch procedures can be found in Section 5.1.		TV.2			The team's launch preparation time during both planned full-scale launches will be timed to ensure that the vehicle is prepped in less than 2 hours.	Incomplete
2.7	The launch vehicle and payload will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components.	All electrical subsystems of the vehicle will be powered by batteries sufficiently large to allow them to remain functional for at least 2 hours.		TR.2		x	The expected power draw of vehicle electrical components have been assessed, and the minimum required battery sizes have been calculated. Demonstrations will be performed where the electrical systems will be left powered on for at least 2 hours, with functionality periodically checked during the demonstration.	In Progress
2.8	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system.	The team will use a Cessaroni L1395-BS, and will use the included motor igniter, which is designed to be fired using a standard 12 VDC system.		TV.2			A standard 12 VDC firing system will be used to launch the vehicle during both planned full-scale demonstration flights, as described in Section 5.1.	Incomplete

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
2.9	The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).	All vehicle, recovery, and payload electronics are fully internal to the vehicle, aside from the standard motor ignition circuit.		TV.2			No external circuitry or special ground support equipment will be used during any of the planned demonstration flights.	Incomplete
2.10	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).	The team will us a Cessaroni L1395-BS, which utilizes an APCP propellent and has been certified by the Canadian Association of Rocketry.	x				Prior to motor selection, the motor letter of certification was found through the CAR website.	Complete
2.10.1	Final motor choices will be declared by the Critical Design Review (CDR) milestone.	The team has selected the Cessaroni L1395-BS as its flight motor. The team currently owns several of these motors and does not anticipate any motor change.	x				The team's CDR document has been read through prior to submission, to ensure that the final motor choice has been clearly declared.	Complete
2.11	The launch vehicle will be limited to a single stage.	The vehicle is currently designed with a single rocket motor, and is not designed to separate before apogee.	x				The design has been checked for additional motor mounts or staging mechanisms.	Complete
2.12	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).	The vehicle is currently designed to use a single rocket motor with a total impulse of 4895.4 Newton-seconds.	x				The total impulse of the motor to be used was checked prior to selection.	Complete
2.13	Pressure vessels on the vehicle will be approved by the RSO and will meet a number of safety criteria.	None of the vehicle subsystems or payloads feature pressure vessels, aside from the certified rocket motor casing.	x				The design of the vehicle and all subsystems have been checked for pressure vessels.	Complete
2.14	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	The vehicle is currently designed with a minimum static stability margin of 2.33 at rail exit.				x	The location of the vehicle center of pressure at rail exit has been calculated using OpenRocket, which can be found in Section 3.9.2. The location of the vehicle center of gravity has been estimated using OpenRocket, as well as a full CAD model of the vehicle and its subsystems.	In Progress
2.15	Any structural protuberance on the rocket will be located aft of the burnout center of gravity.	The vehicle is currently designed with 2 rail buttons, both of which are located aft of the vehicle's burnout center of gravity. There are no other structural protuberances on the vehicle.	x			x	The location of the vehicle's burnout center of gravity has been estimated using OpenRocket, found in Section 3.9.2 as well as a full CAD model of the vehicle and its subsystems. This location will be marked on the vehicle, to ensure that the rail buttons are aft of this location.	In Progress
2.16	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	The vehicle is currently designed to reach a minimum velocity of 68.1 ft/s at rail exit.			TV.2	x	The vehicle's velocity at rail exit has been calculated using OpenRocket and further qualified using RockSim, as described in Section 3.9.1. Acceleration data from the planned vehicle test flights (procedures described in Section **??**) will be used to estimate the actual off-rail velocity the vehicle experienced in flight.	In Progress
2.17	All teams will successfully launch and recover a subscale model of their rocket prior to CDR. Subscales are not required to be high power rockets.	The team successfully completed three launches of its subscale model on November 13.		TV.6			Data taken from altimeters on board the subscale vehicle during its flights show altitude data indicative of a successful launch, and can be found in Section 3.6 and Test number TV.6.	Complete
2.17.1	The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.	The subscale vehicle was designed to be a 42.3% scale model of the full scale vehicle.	x				The components of the subscale vehicle were measured prior to assembly to ensure that they were constructed to the proper dimensions, the dimensions of which can be found in Section 3.6.1.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
2.17.2	The subscale model will carry an altimeter capable of recording the model's apogee altitude.	A Stratologger CF on board the subscale vehicle recorded altitude data from all three flights, showing apogees of 1060 ft, 1124 ft, and 957 ft.		TV.6, TA.7			In addition to the commercial altimeters, a team-built data recording system was on board, recording average apogees of 1063 ft, 1118 ft, and 956 ft.	Complete
2.17.3	The subscale rocket must be a newly constructed rocket, designed and built specifically for this year's project.	The vehicle has been designed and built solely by this year's team.	x				All design decisions and construction activities for the subscale vehicle have been documented and presented in the team's PDR and CDR reports.	Complete
2.17.4	Proof of a successful flight shall be supplied in the CDR report. Altimeter data output may be used to meet this requirement.	Data from the onboard Stratologger CF can be found in Section 3.6.3.	x				The team's CDR document was read through prior to submission, to ensure that the subscale flight data was clearly displayed.	Complete
2.18	**All teams will complete demonstration flights as outlined below:**	See Requirements 2.18.1–2.18.2					N/A	N/A
2.18.1	Vehicle Demonstration Flight - All teams will successfully launch and recover their full-scale rocket prior to FRR in its final flight configuration. The following criteria must be met during the full-scale demonstration flight:	See Requirements 2.18.1.1-2.18.1.9		TV.2			N/A	Incomplete
2.18.1.1	The vehicle and recovery system will have functioned as designed.	The vehicle has been designed to reach an apogee of at least 5300 ft, recover within NASA requirements, and be capable of reflight without repair.			TV.2		Data taken from onboard altimeters during the test flight will be analyzed to ensure the ascent and descent velocities are in range of the design intent. The vehicle and all subsystems will be inspected after flight to ensure no permanent deformation or damage occurred during the flight. The procedures for the Vehicle Demonstration flight can be found in Section **??**	Incomplete
2.18.1.2	The full-scale rocket must be a newly constructed rocket, designed and built specifically for this year's project.	The vehicle has been designed and built solely by this year's team.	x				All design decisions and construction activities have been documented and presented in the team's PDR, CDR, and FRR reports.	In Progress
2.18.1.3	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight. The following requirements still apply:	See Requirements 2.18.1.3.1–2.18.1.3.2					N/A	Incomplete
2.18.1.3.1	If the payload is not flown, mass simulators will be used to simulate the payload mass.	In the event that the team's payload is unable to fly in the vehicle during the vehicle demonstration flight, a mass simulator equalling the mass of the payload will be installed as a substitute.	x				Any payload substitute used during the vehicle demonstration flight will be weighed and have its weight recorded. Information about the design and weight of the substitute will be included in the team's FRR, if necessary.	Incomplete
2.18.1.3.2	The mass simulators will be located in the same approximate location on the rocket as the missing payload mass.	Any mass simulator used will be installed in the same compartment as the mass it is intended to simulate.	x				Any payload substitute used during the vehicle demonstration flight will be weighed and have its weight recorded. Information about the design and weight of the substitute will be included in the team's FRR, if necessary.	Incomplete
2.18.1.4	If the payload changes the external surfaces of the rocket (such as with camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight.	The vehicle will fly its vehicle demonstration flight with all its components, including any camera housings or airbraking systems.		TV.2			The state of the vehicle's subsystems will be assessed prior to flight to ensure all relevant components and subsystems are present, as described in Section 5.1.5.	Incomplete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
2.18.1.5	Teams shall fly the launch day motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance if the home launch field cannot support the full impulse of the launch day motor or in other extenuating circumstances (such as weather).	The team intends to fly the vehicle using a CTI L1395 during the Vehicle Demonstration flight.	x				The motor will be inspected prior to installation to ensure that it is the correct motor type, as described in Section 5.1.6.	Incomplete
2.18.1.6	The vehicle must be flown in its fully ballasted configuration during the full-scale test flight.	All subsystems will use the same amount of ballast during the test flight that they will during the competition launch.	x				The vehicle will be inspected prior to competition launch to ensure that no additional ballast has been added since the successful vehicle demonstration, as described in Section 5.1.5.	Incomplete
2.18.1.7	After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA Range Safety Officer (RSO).	The team plans to launch the vehicle in its fully completed form,with no modifications planned after the vehicle demonstration flight.	x				The vehicle will be inspected prior to competition launch to ensure that none of the critical components of the vehicle have been modified since the demonstration flight.	Incomplete
2.18.1.8	Proof of a successful flight shall be supplied in the FRR report. Altimeter data output is required to meet this requirement.	A number of commercial barometric altimeters will be active during the vehicle demonstration flight. Data from these altimeters will be displayed in the team's FRR.	x				The team's FRR will be read through prior to submission to ensure that vehicle demonstration flight data is present.	Incomplete
2.18.1.9	Vehicle Demonstration flights must be completed by the FRR submission deadline.	The team currently plans to complete the vehicle demonstration flight on Feb. 13, with a backup date on Feb. 20.		TV.2			Both vehicle demonstration dates are prior to the FRR submission deadline.	Incomplete
2.18.2	Payload Demonstration Flight - All teams will successfully launch and recover their full-scale rocket containing the completed payload prior to the Payload Demonstration Flight deadline.	The team plans to fly the final, fully active payload on Feb. 20, prior to the FRR submission deadline.		TP.1			The payload and all retention systems will be inspected after payload demonstration to ensure that no permanent deformation or damage was caused during flight or deployment.	Incomplete
2.19	An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASA required Vehicle Demonstration Re-flight after the submission of the FRR Report.	The team currently plans to complete the Payload Demonstration on Feb. 20, prior to the FRR submission date.	x				N/A	Incomplete
2.20	The team's name and launch day contact information shall be in or on the rocket airframe as well as in or on any section of the vehicle that separates during flight and is not tethered to the main airframe. This information shall be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle.	The team's name and contact information will be present on the inside of the nosecone, the inside of the payload bay, and the payload itself.	x				Prior to flight, the vehicle will be inspected to ensure that team contact information is present and easily readable on all seperately descending elements of the vehicle.	Incomplete
2.21	All Lithium Polymer batteries will be sufficiently protected from impact with the ground and will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other payload hardware.	All Lithium Polymer batteries used on the recovery, ACS, and payload systems will be clearly marked with brightly colored tape to differentiate them from other hardware.	x				Prior to flight, all systems with batteries will be inspected to ensure that the LiPo batteries are easily distinguishable from the rest of the hardware.	Incomplete
2.22	**Vehicle Prohibitions**	See Requirements 2.22.1–2.22.10					N/A	N/A
2.22.1	The launch vehicle will not utilize forward firing motors.	The current design does not feature forward-firing rocket motors.	x				The design of the vehicle and all subsystems have been checked for forward-firing motors.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
2.22.2	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)	The design currently features a CTI L1395, which does not expel titanium sponge.	x				The design of the vehicle and all subsystems have been checked for titanium-expelling motors.	Complete
2.22.3	The launch vehicle will not utilize hybrid motors.	The design currently features a CTI L1395, which does not utilize hybrid propellant.	x				The design of the vehicle and all subsystems have been checked for hybrid rocket motors.	Complete
2.22.4	The launch vehicle will not utilize a cluster of motors.	The design currently features a single rocket motor.	x				The design of the vehicle and all subsystems have been checked for additional rocket motors.	Complete
2.22.5	The launch vehicle will not utilize friction fitting for motors.	The design currently uses a screw-on Aeropack motor retainer to retain the motor during flight.	x				The vehicle will be inspected prior to demonstration flight to ensure that the motor is properly retained using the Aeropack motor retainer.	Incomplete
2.22.6	The launch vehicle will not exceed Mach 1 at any point during flight.	The vehicle is currently designed to reach a maximum Mach number of 0.6.			TV.2	x	The maximum expected velocity has been determined through analysis conducted in OpenRocket as seen in Section 3.9.1, and will be further verified through velocity data gathered through onboard altimeters during the demonstration flights.	In Progress
2.22.7	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad	The vehicle is expected to use a maximum of 22 oz lbs of ballast, which is 2.8% of the full vehicle mass.	x				The vehicle will be inspected prior to flight to ensure that the total amount of ballast is less than 10% of the total vehicle mass, as described in Section 5.1.5.	Incomplete
2.22.8	Transmissions from onboard transmitters will not exceed 250 mW of power (per transmitter).	The transmitters onboard the vehicle are expected to transmit at 100 mW of power.	x				Documentation accompanying the selected transmitters have been read to ensure that the transmission power does not exceed 250 mW.	Complete
2.22.9	Transmitters will not create excessive interference. Teams will utilize unique frequencies, handshake/passcode systems, or other means to mitigate interference caused to or received from other teams.	All active transmitters on the vehicle will use unique frequencies to mitigate interference with other transmitters.	x				Documentation accompanying the selected transmitters have been read to ensure that the transmitters all use different, unique frequencies.	Complete
2.22.10	Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses.	The vehicle design utilizes a limited amount of aluminum in structural bulkheads and standoffs, and a a small amount of steel in small structural elements like screws, eyebolts and quicklinks.	x				The design has been checked by the team, and does not feature what the team has determined to be an excessive amount of metal.	Complete

6.3.3 Recovery System

Table 79: NASA Recovery Requirements

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
3.1	The launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee, and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue stage descent is reasonable, as deemed by the RSO.	The recovery system is currently designed to deploy a 2 ft drogue parachute at the vehicle's apogee, and a 12 ft main parachute at 575 ft AGL.		TR.4			The full functionality of the recovery system will be demonstrated during the Vehicle Demonstration Flight, as described in Section 5.1.	Incomplete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
3.1.1	The main parachute shall be deployed no lower than 500 feet.	The recovery system is currently designed to deploy its main parachute at 575 ft AGL.		TR.7	TR.4		A drop test (Test TR.7) will be performed on the main parachute to ensure that they open within 35 ft of deployment. The data from the onboard barometric altimeters, taken during the Vehicle Demonstration Flight, will be analyzed to confirm that the main parachute opens before 500 ft.	Incomplete
3.1.2	The apogee event may contain a delay of no more than 2 seconds.	The recovery system is currently designed to deploy its drogue parachute at the vehicle's apogee.			TR.4		The data from the onboard barometric altimeters will be analyzed after the Vehicle Demonstration flight to confirm that the drogue parachute was deployed before 2 seconds after apogee.	Incomplete
3.1.3	Motor ejection is not a permissible form of primary or secondary deployment.	The recovery system is currently designed to use electrically triggered ejection charges.		TR.4			Proper ignition of the parachute ejection charges will be demonstrated during the Vehicle Demonstration Flight.	Incomplete
3.2	Each team must perform a successful ground ejection test for both the drogue and main parachutes. This must be done prior to the initial subscale and full-scale launches.	Ground separation demonstrations are planned to be performed just before the vehicle demonstration flight.		TR.3			Procedures for ground separation tests can be found at Test number TR.3, in Section 6.1.4.	Incomplete
3.3	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.	The maximum terminal kinetic energy of the heaviest vehicle section is expected to be 53.1, based on hand calculations.			TR.4	x	Analysis of the descent kinetic energy was performed in OpenRocket, as well as a team developed MATLAB code and hand calculations, as described in Section 3.9.4.1. The analysis will be further verified using descent velocity data from onboard commercial altimeters.	In Progress
3.4	The recovery system will contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers.	The recovery system is designed to feature three redundant commercial altimeters, each capable of deploying both the main and drogue parachutes.		TR.1			Procedures for altimeter testing, performed prior to the first demonstration flight, can be found at Test TR.1, in Section 6.1.4.	Incomplete
3.5	Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.	Each of the recovery altimeters will be powered by their own commercially-available battery.	x				Prior to assembly, the recovery altimeters will be visually inspected to ensure that they are electrically isolated and independently powered.	Incomplete
3.6	Each altimeter will be armed by a dedicated mechanical arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.	Each recovery altimeter will feature a keyed, locking rotary switch for arming.		TR.5			Accessibility of the recovery arming switches will be demonstrated during the Ejection Charge Disarming test, Test TR.5 in Section 6.1.4.	Incomplete
3.7	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).	Each recovery arming switch locks in position with the removal of the arming key.		TV.5			A shake demonstration will be performed to simulate vibrations in the recovery system during launch, and verify that the switches will not be knocked out of place.	Incomplete
3.8	The recovery system electrical circuits will be completely independent of any payload electrical circuits.	The recovery system is currently designed to be completely electrically isolated from the payload.		TR.1			Procedures for altimeter testing, performed prior to the first demonstration flight, can be found at Test TR.1, in Section 6.1.4.	Incomplete
3.9	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	The main parachute compartment is to be held together using 4 2 nylon shear pins, and the drogue compartment is to be held together with 2 2 nylon shear pins.	x				Prior to launch, the vehicle will be visually inspected to ensure the presence of the appropriate number of shear pins holding the vehicle together. Launch procedures can be found in Section 5.1.	Incomplete
3.10	The recovery area will be limited to a 2,500 ft. radius from the launch pads.	The vehicle is expected to drift a maximum of 2397 ft from the launch pad in worst-case conditions.				x	Analysis of the vehicle drift has been performed in a custom MATLAB program, OpenRocket, and through hand calculations, as described in Section3.9.4.1.	Complete
3.11	Descent time will be limited to 90 seconds (apogee to touch down).	The vehicle is expected to take a maximum of 80.8 seconds to descend from apogee to the ground.			TR.4	x	Analysis of the vehicle descent time has been performed in OpenRocket as well as a team-built MATLAB script and hand calculations, as described in Section 3.9.4.1. The descent time will be further verified using altitude data taken during the vehicle demonstration flight.	In Progress

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
3.12	An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver.	A pair of Eggfinder Minis will be used to track the independently descending vehicle and nosecone.	x	TR.6			The vehicle will be visually inspected prior to launch to ensure that the GPS trackers are present and active prior to launch. Function of the altimeters will be verified during Test TR.6.	Incomplete
3.13	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	All recovery electronics will be shielded from electromagnetic interference through the use of copper-taped boxes.		TR.4			All transmitters and recovery electronics will be active during the vehicle demonstration flight.	Incomplete

6.3.4 Payload Experiment

Table 80: NASA Payload Requirements

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
4.3	**Primary Landing System Mission Requirements:**	See Requirements 4.3.1-4.3.4					N/A	N/A
4.3.1	The landing system will be completely jettisoned from the rocket at an altitude between 500 and 1,000 ft. AGL. The landing system will not be subject to the maximum descent time requirement (Requirement 3.11) but must land within the external borders of the launch field. The landing system will not be tethered to the launch vehicle upon landing.	The payload will eject from the vehicle at 525 ft AGL, and descend from the altitude under a 48 in parachute. It is expected to drift a maximum of 2130 ft from the launch pad.		TP.1		x	Using hand calculations, analysis of the lander's drift during descent has been performed and determined to be within the 2500 ft launch field radius, as described in Section 4.4.2. The deployment system will be demonstrated in full during the the Payload Demonstration Flight, as described in Test TP.1.	In Progress
4.3.2	The landing system will land in an upright orientation or will be capable of reorienting itself to an upright configuration after landing. Any system designed to reorient the lander must be completely autonomous.	The payload legs will deploy on deployment, using three servos attached to leadscrews. After landing, the onboard microcontroller will use input from an IMU to adjust the angle of the landing legs, reorienting the lander to be vertical.		TP.1, TP.1, TP.2 TP.4, TP.5		x	Kinematic analysis on the landing legs have been performed, and they have been determined to be capable of fully deploying before the payload lands, as described in Section 4.4.3. The speed of leg deployment will be demonstrated on the ground in Test TP.5, detection of landing will be demonstrated in Test TP.4, and detection of ejection will be demonstrated in Test TP.2.	In Progress
4.3.3	The landing system will self-level to within a five-degree tolerance from vertical.	After landing, the onboard microcontroller will use input from an IMU to adjust the angle of the landing legs, reorienting the lander to be within 5 degrees of vertical.			TP.1, TP.6		The reorientation of the lander will be tested on the ground for inclines up to 30 degrees, with data from the onboard IMU confirming the initial and final orientation of the lander. This will be further verified during the Payload Demonstration flight.	Incomplete
4.3.3.1	Any system designed to level the lander must be completely autonomous.	The payload will eject from the vehicle, land, and reorient without any external input.		TP.1, TP.6			The reorientation of the lander will be tested on the ground (Test TP.6) for inclines up to 20 degrees, with data from the onboard IMU confirming the initial and final orientation of the lander. No communication to the lander will occur during reorientation.	In Progress
4.3.3.2	The landing system must record the initial angle after landing, relative to vertical, as well as the final angle, after reorientation and self-levelling. This data should be reported in the Post Launch Assessment Report (PLAR).	The orientation of the lander, both before and after landing and leveling, will be measured by an onboard IMU and recovered after successful recovery of the payload.		TP.6			Acquisition of orientation data will be demonstrated during orientation ground testing, described in Test TP.6.	Incomplete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
4.3.4	Upon completion of reorientation and self-levelling, the lander will produce a 360-degree panoramic image of the landing site and transmit it to the team.	The payload will hold 4 cameras, offset by 90 degrees, each of which will take a picture of the environment. These pictures will then be stitched into a single panoramic picture, and be transmitted to the team's ground station using the onboard radio transceiver, as described in Sections 4.5.1 and 4.5.2.		TP.3			The imaging and transmission ability of the payload will be assessed through imaging transmission tests, Test TP.3.	Incomplete
4.3.4.1	The hardware receiving the image must be located within the team's assigned prep area or the designated viewing area.	The ground station receiving the transmitted panorama will be located in the launch viewing area.	x				Prior to launch, the ground station will be checked to ensure that it is active and within the correct area.	Incomplete
4.3.4.2	Only transmitters that were onboard the vehicle during launch will be permitted to operate outside of the viewing or prep areas.	All active transmitters will be contained either within the vehicle, or within the launch viewing area.	x				Prior to launch, the ground station will be checked to ensure that it is active and within the correct area.	Incomplete
4.3.4.3	Onboard payload transmitters are limited to 250 mW of RF power while onboard the launch vehicle but may operate at a higher RF power after landing on the planetary surface. Transmitters operating at higher power must be approved by NASA during the design process.	The payload transmitters operate at an RF power of 100 mW.	x				The documentation associated with the commercial transmitters used for the payload was read, and the power emitted by the transmitters was found to be under 250 mW.	Complete
4.3.4.4	The image should be included in your PLAR.	The panoramic image produced by the payload will be included in the team's PLAR.	x				Prior to submission, the team's PLAR will be inspected to ensure that the panoramic image produced by the payload is included.	Incomplete
4.4	**General Payload Requirements**	See Requirements 4.4.1-4.4.6					N/A	Complete
4.4.1	Black Powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Energetics will not be permitted for any surface operations.	Black powder ejection charges are planned for in-flight payload/nose cone ejection only.	x				The has been thoroughly inspected, and does not contain surface-ignited energetics.	Complete
4.4.2	Teams must abide by all FAA and NAR rules and regulations.	The current design does not violate any FAA or NAR regulations.	x				Applicable regulations, including the NAR High Power Rocketry Safety Code and FAA regulation 14 CFR 101.22-101.29, have been read, and the design has been determined to be in compliance with these regulations.	Complete
4.4.3	Any experiment element that is jettisoned, except for planetary lander experiments, during the recovery phase will receive real-time RSO permission prior to initiating the jettison event.	The only experiment element to be jettisoned in flight is the planetary lander.					N/A	Complete
4.4.4	Unmanned aircraft system (UAS) payloads, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAS.	The planetary lander, as designed, is not considered an Unmanned Aerial System (UAS).					N/A	Complete
4.4.5	Teams flying UASs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112-95 Section 336; see https://www.faa.gov/uas/faqs).	The planetary lander, as designed, is not considered an Unmanned Aerial System (UAS).					N/A	Complete
4.4.6	Any UAS weighing more than .55 lbs. will be registered with the FAA and the registration num- ber marked on the vehicle.	The planetary lander, as designed, is not considered an Unmanned Aerial System (UAS).					N/A	Complete

6.3.5 Safety

Table 81: NASA Safety Requirements

Requirement		Verification Method				Verification Plan	Status
ID	Description	I	D	T	A		
5.1	Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.	x				The team's FRR will be thoroughly inspected prior to submission to ensure the presence of final launch procedures. Current procedures, to be used in the Vehicle Demonstration and Payload Demonstration flights can be found in Section 5.1.	In Progress
5.2	Each team must identify a student safety officer who will be responsible for all items in section 5.3.	x				The team's Safety Officer for this project is Jake Shapiro.	Complete
5.3	**The role and responsibilities of the safety officer will include, but are not limited to:**					N/A	N/A
5.3.1	The safety officer shall monitor team activities with an emphasis on safety during design of vehicle and payload, construction of vehicle and payload components, assembly of vehicle and payload, ground testing of vehicle and payload, full-scale launch test(s), subscale launch test(s), launch day, recovery activities, and STEM engagement activities.	x				The team has developed and implemented a team Safety Handbook and series of Standard Operating procedures to aid in team safety. Members of the team's safety sub-team are present during all construction, assembly, and testing operations, to monitor activities and ensure compliance.	In Progress
5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	x				Standard procedures and checklists have been developed for construction, test and launch activities. Members of the safety team will be present during all these activities to ensure compliance.	In Progress
5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	x				Current versions of the team's hazard analysis FMEA, procedures, and SDS data have been compiled and can be found in Sections 5.2 and 5.1.	In Progress
5.3.4	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	x				Current versions of the team's hazard analysis, FMEA, and procedures, have been compiled and can be found in Sections 5.2 and 5.1.	In Progress
5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.	x				The team works closely with the Michiana Rocketry Club to ensure that all launch operations are conducted in a safe and legal manner.	In Progress
5.5	Teams will abide by all rules set forth by the FAA.	x				The team works closely with the Michiana Rocketry Club to ensure that all launch operations are conducted in accordance with FAA CFR 14 101.21-101.29.	In Progress

6.3.6 Final Flight

Table 82: NASA Final Flight Requirements

Requirement		Verification Method				Verification Plan	Status
ID	Description	I	D	T	A		
6.1	**NASA Launch Complex Requirements**					N/A	N/A
6.1.1	Teams must complete and pass the Launch Readiness Review conducted during Launch Week.	x				The team intends to attend the Launch Readiness Review at the earliest opportunity.	Incomplete

Requirement		Verification Method				Verification Plan	Status
ID	Description	I	D	T	A		
6.1.2	The team mentor must be present and oversee rocket preparation and launch activities.	x				The team mentor, Dave Brunsting, intends to attend the launch week at this time.	Incomplete
6.1.3	The scoring altimeter must be presented to the NASA scoring official upon recovery.	x				The vehicle contains a number of altimeters capable of beeping out the official altitude for the NASA scoring official.	Incomplete
6.1.4	Teams may launch only once. Any launch attempt resulting in the rocket exiting the launch pad, regardless of the success of the flight, will be considered a launch. Additional flights beyond the initial launch, will not be scored and will not be considered for awards.		TV.2, TP.1			After successful Vehicle Demonstration and Payload Demonstration flights, the team intends to launch only once at competition.	Incomplete
6.2	**Commercial Spaceport Launch Site**					N/A	N/A
6.2.1	The launch must occur at a NAR or TRA sanctioned and insured club launch. Exceptions may be approved for launch clubs who are not affiliated with NAR or TRA but provide their own insurance, such as the Friends of Amateur Rocketry. Approval for such exceptions must be granted by NASA prior to the launch.	x				Should the team be unable to travel to Huntsville for competition, the team will carry out the competition launch with the Michiana Rocketry Club (Tripoli Michiana, NAR 721).	Incomplete

6.4 NDRT Requirements Compliance

6.4.1 Launch Vehicle

Table 83: NDRT Launch Vehicle Requirements

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
FUNCTIONAL REQUIREMENTS								
VF.1	The launch vehicle shall reach an apogee at or above 5300 ft in all NASA-defined flight conditions, including winds up to 20 mph and launch rail angles of up to 10 degrees from vertical.	As currently designed, the vehicle is predicted to reach an apogee between 5706 ft and 5286 ft, in all expected flight conditions.			TV.2	x	The predicted apogee of the vehicle has been analyzed using models in OpenRocket and Rocksim to produce the current apogee predictions, as described in Section 3.9.1. The models will be further verified using data taken during the vehicle and payload demonstration flights, Test TV.2.	In Progress
VF.2	The bottom of the payload bay shall have an aft-facing shock cord connection point, capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 1.5.	The current design features a bulkhead epoxied near the bottom of the payload bay, with an embedded eyebolt as a shock cord connection. This connection is capable of sustaining the maximum flight loads with a factor of safety of 2.55.				x	The strength of the payload bay bulkhead was assessed via finite-element analysis as described in Section 3.4.8, while the eyebolt strength was taken from manufacturer ratings.	Complete
VF.3	The fin can shall be constructed to be capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 1.5.	The current fin can is designed to sustain flight loads to a factor of safety of 7.9.				x	The strength of the fin can has been assessed through a combination of hand-shear calculations and finite-element analysis, as described in Section 3.4.5.	Complete
DESIGN REQUIREMENTS								
VD.1	The launch vehicle shall have a minimum of 3 in-flight separation points.	The current design features 3 in-flight separation points: at the bottom of the recovery tube, the top of the recovery tube, and the nosecone.	x				After construction, the number of separation points will be counted to ensure that there are three.	Incomplete

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
VD.2	The nose cone shall contain space sufficient for the placement of a parachute capable of slowing the nosecone below 20 ft/s, along with associated shock cord and thermal protection.	The current nosecone selection features a hollow interior, with more than sufficient to contain the parachute, shock cord and thermal protection required to recover the nosecone.		TR.3			Prior to launch, the nosecone recovery hardware will be packed into the nose for the nosecone separation demonstration, Test TR.3.	Incomplete
VD.3	The recovery tube of the vehicle shall have a minimum length of 30 in, and a maximum length of 48 in.	The recovery tube is currently designed to be 33in in length.	x				After construction, the recovery tube will be measured to ensure that it has been cut to the appropriate length.	Incomplete
VD.4	The vehicle fin can shall have a minimum of 10 inches of length available to house the ACS.	The vehicle is currently designed with 11 inches of space above the motor mount to accommodate the ACS.	x				After construction, the fin can will be measured to ensure that it has been cut to the appropriate length to accommodate the ACS.	Incomplete
VD.5	The vehicle fin can shall have a maximum length of 48 in.	The vehicle is currently designed with a fin can length of 45.75 in, including the aft boattail.	x				After construction, the fin can will be measured to ensure that it has been cut to the appropriate length.	Incomplete
VD.6	The payload bay of the vehicle shall have a minimum internal diameter of 6 in.	The vehicle is currently designed with an inner diameter of 6 in.	x				Prior to construction, the diameter of the payload bay will be measured to ensure that it is the appropriate diameter.	Incomplete
VD.7	The off-rail stability of the fully loaded vehicle shall be between 2 and 3 calibers.	The vehicle is currently designed with an off-rail stability of 2.33 calibers.				x	The location of the vehicle center of pressure at rail exit has been calculated using OpenRocket, as well as Ansys Fluent, as described in Sections 3.9.2 and 3.9.3, respectively. The location of the vehicle center of gravity has been estimated using OpenRocket, as well as a full CAD model of the vehicle and its subsystems.	In Progress
VD.8	The payload bay shall be constructed of EM-transparent material.	The payload bay is to be constructed of a fiberglass-Kevlar composite, which is EM-transparent.	x				Research into the fiberglass composite used for the body tubes has confirmed that is RF transparent.	Complete
VD.9	The payload bay shall have a minimum length of 21 in, and a maximum length of 48 in.	The payload bay is currently designed with a total length of 30.5 in.	x				After construction, the payload bay will be measured to ensure that it has been cut to the appropriate length.	Incomplete
ENVIRONMENTAL REQUIREMENTS								
VE.1	All airframe components shall be capable of sustaining a minimum of 54 Gs of axial acceleration.	All current airframe components are expected to be capable of sustaining a minimum of 87.5 Gs of axial acceleration.				x	A combination of and calculation and finite element analysis has been performed on all load-bearing components of the vehicle, the results of which can be seen in Section 3.5.	Complete

6.5 Apogee Control System

Table 84: NDRT ACS Requirements

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
FUNCTIONAL REQUIREMENTS								
AF.1	The ACS shall be capable of recording vehicle altitude (via barometric pressure) and vehicle acceleration.	The ACS will use a BMP388 for barometric altitude measurement and an ADXL 345 for acceleration measurement.			TA.1, TA.2, TA.3, TA.4, TA.7		A number of tests of the various sensors on the ACS are to be tested, as described in Tests TA.1, TA.2, TA.3, TA.4, and TA.7	In Progress
AF.2	ACS shall provide a connection for a recovery harness, capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 1.5.	The ACS is currently designed with an eyebolt mounted in the center of its top bulkhead as a connection point, capable of sustaining flight loads with a factor of safety of 8.4.				x	A combination of hand-calculations and finite-elements analysis has been performed to verify the structural integrity of the recovery attachment point, as described in Section 3.7.4.2.	Complete

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
AF.3	The ACS shall be capable of continuously actuating its control surfaces for a minimum of one minute.	The ACS is capable of continuously actuating its control surfaces for approximately 12.5 minutes.		x		x	Hand calculations of the theoretical maximum run time of the ACS have been performed, as seen in Section 3.7.6.4, and an actuation demonstration will be performed to confirm that the system will be capable of one minute of actuation.	In Progress
AF.4	The ACS shall create an pneumatic seal with the vehicle body tube at the fore end of the system.	The ACS to bulkhead will be carefully toleranced to seal the ACS from the black powder ejection charges in the recovery tube.		TR.3			Parachute separation demonstrations will be performed to confirm proper separation of the vehicle without damage, as described in Test TR.3	Incomplete
DESIGN REQUIREMENTS								
AD.1	ACS shall have a maximum allowable weight of 80 oz.	The ACS is currently predicted to have a weight of 77 oz, as seen in Section 3.7.5	x				The ACS will be weighed prior to installation in the vehicle, to verify that it is under 80 oz.	Incomplete
AD.2	ACS shall have a maximum length of 10 in.	The ACS is currently designed to have a length of 10 in.	x				The ACS length will be measured prior to installation in the vehicle to verify its length.	Incomplete
AD.3	ACS shall have a maximum diameter of 6 inches, with all external control surfaces retracted.	The ACS is currently designed to have a diameter of 5.9 in.	x				The ACS diameter will be measured prior to installation in the vehicle to verify its construction.	Incomplete
AD.4	The ACS shall be capable of installation and removal from the vehicle without the use of power tools.	The ACS shall be oriented within the vehicle with a twist-in mechanism at the bottom of the system, and secured into the vehicle using screws.		TA.2			Prior to the vehicle demonstration flight, the ACS will be fully installed in the vehicle without the use of power tools, as described in Test TA.2.	Incomplete
AD.5	All control surfaces extending from the exterior of the vehicle shall be a minimum of 2 calibers aft of the vehicle's on-pad Center of Mass.	The ACS drag tabs are currently designed to be 2.3 calibers behind the vehicle center of mass.	x				The distance between the vehicle center of mass and drag tabs will be measured after construction to ensure its relative location.	Incomplete
ENVIRONMENTAL REQUIREMENTS								
AE.1	All ACS components shall be capable of sustaining a minimum of 54 Gs of axial acceleration.	All current components of the ACS are expected to be capable of sustaining 91 Gs of axial acceleration.	x				A combination of hand calculations and finite element analysis have been performed on all significant load-bearing components of the ACS, as can be seen in Section 3.7.4.2	Complete
AE.2	The ACS shall be capable of remaining on the launch pad for a minimum of 2 hours prior to launch.	The ACS is expected to be capable of remaining on the launch pad for a total of 20 hours.				x	Hand calculations have been performed estimating the wait time the ACS is capable of, as seen in Section 3.7.6.4.	Complete

6.6 Recovery System

Table 85: NDRT Recovery Requirements

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
FUNCTIONAL REQUIREMENTS								
RF.1	All recovery altimeters shall store recorded data on local memory or removable storage which can readily be downloaded to a laptop computer at the launch field via a commercially available cable or adapter.	The design currently features three different models of altimeters, all of which are capable of storing and transferring altitude data to a laptop computer in the field.		TR.4			After the vehicle demonstration flight, altitude data from all the onboard altimeters will be downloaded for further analysis.	Incomplete
RF.2	All recovery parachutes and shock cords shall be thermally protected from black powder ejection charges.	The design currently features Nomex blankets that will be used to protect the parachutes and shock cords from the black powder ejection charges.		TR.3			The parachutes and shock cords will be visually inspected after the ground parachute ejection demonstrations to ensure that no damage was done to the recovery components.	Incomplete

Requirement		Verification Method					Verification Plan	Status
ID	Description	Compliance Plan	I	D	T	A		
RF.3	All recovery avionics shall be pneumatically sealed from vehicle compartments with ejection charges.	The design currently features an O-ring around both bulkheads of the avionics module, separating the electronics from the black powder charges.		TR.3			The recovery avionics will be visually inspected after the ground parachute ejection demonstrations to ensure that they are still powered and functional.	Incomplete
RF.4	The vehicle nosecone shall be recovered independently from the rest of the vehicle.	The current design features a separate parachute and shock cord for the nosecone, which will descend separately from the main vehicle.		TR.4			The function of the nosecone ejection and recovery system will be demonstrated during the Vehicle Demonstration flight.	Incomplete
RF.5	The main vehicle recovery system shall have a minimum of 3 electrically isolated systems for deploying both the main and drogue parachute.	The current design features 2 Stratologger CFs and a Raven3 altimeter for main vehicle recovery, all of which are electrically isolated from each other and capable of deploying both the main and drogue parachutes of the vehicle.		TR.1			The ability of these altimeters to independently ignite e-matches will be tested on the ground prior to flight, and full function will be demonstrated during the Vehicle Demonstration flight.	Incomplete
RF.6	The nosecone recovery system shall have a minimum of 2 electrically isolated systems for deploying its parachute.	The current design features 2 Stratologger SL100 altimeters for nosecone recovery, both of which are electrically isolated from each other and capable of ejecting the nosecone and deploying the nosecone parachute.		TR.1			The ability of these altimeters to independently ignite e-matches will be tested on the ground prior to flight, and full function will be demonstrated during the Vehicle Demonstration flight.	Incomplete
RF.7	The avionics bay shall contain 2 parachute connections, both capable of sustaining the maximum loads expected in flight to a minimum factor of safety of 1.5.	The current dessign features steel eyebolt connected to an aluminum bulkhead, with a minimum factor of safety of 1.5.				x	A combination of hand calculations and FEA have been performed to confirm the structural integrity of the parachute connection, as described in Section 3.8.6.1.	Complete
DESIGN REQUIREMENTS								
RD.1	The recovery system for the main vehicle shall have a maximum allowable mass of 165 oz.	The main recovery system is currently predicted to be 163 oz.	x				All components of the main recovery system will be weighed prior to installation, to ensure that they are under the required maximum.	Incomplete
RD.2	All recovery components shall have a maximum diameter of 6 in.	The diameter of the main recovery system is currently designed to have a diameter of 5.9 in.	x				The diameter of the main recovery module will be measured prior to installation, to ensure that is is under the maximum allowable diameter.	Incomplete
RD.3	The recovery system for the nosecone shall have a maximum allowable mass of 26 oz.	The nosecone recovery system is currently predicted to have a mass of 25.1 oz.	x				All components of the nosecone recovery system will be weighed prior to installation, to ensure that they are under the required maximum.	Incomplete
RD.4	All recovery avionics shall be removable from the launch vehicle without the use of power tools.	The main recovery module is to be retained in the vehicle with externally accessible screws.		TR.3			During parachute ejection ground testing, installation and removal of the avionics module without power tools will be demonstrated.	Incomplete
RD.5	All arming switches used for main vehicle recovery shall be accessible from one location on the rocket body.	The key switches for arming the main vehicle altimeters are vertically aligned, and externally accessible from a single location on the exterior of the vehicle.	x				The vehicle will be visually inspected after recovery installation to ensure that the main recovery arming switches are accessible from one location on the rocket body.	Incomplete
RD.6	All arming switches used for nosecone recovery shall be accessible from one location on the rocket body.	The key switches for arming the nosecone altimeters are vertically aligned, and externally accessible from a single location on the exterior of the vehicle.	x				The vehicle will be visually inspected after recovery installation to ensure that the nosecone recovery arming switches are accessible from one location on the rocket body.	Incomplete
ENVIRONMENTAL REQUIREMENTS								
RE.1	The recovery systems shall be capable of sustaining a minimum of 54 Gs of axial acceleration.	All current components of the recovery system are expected to be capable of sustaining 56 Gs of axial acceleration.				x	A combination of hand calculations and finite element analysis have been performed on all significant load-bearing components of the recovery system.	Complete
RE.2	The recovery system shall be capable of remaining on the launch pad for a minimum of 2 hours prior to launch.	The recovery system is expected to be capable of remaining on the launch pad for a total of 17 hours.				x	Hand calculations have been performed estimating the wait time the recovery system is capable of.	Complete

6.7 Payload Experiment

Table 86: NDRT Payload Requirements

Requirement		**Verification Method**					**Verification Plan**	**Status**
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
FUNCTIONAL REQUIREMENTS								
PF.1	The PLS shall descend with a maximum terminal velocity of 20 ft/s.	The lander parachute has been sized such that the lander descends at a velocity of 17.6 ft/s.				x	The descent velocity of the lander has been calculated using hand calculations, as described in Section 4.4.2.	Complete
PF.2	The PLS shall have a drift radius of less than 2500 ft from the launch pad.	The lander is expected to drift a maximum of 2130 ft from the launch pad.				x	The descent velocity of the lander has been found using simple hand calculations, as described in Section 4.4.2.	Complete
PF.3	All moving elements of the PLS shall be locked in place during flight.	The lander legs are to be locked in place through the stall torque of the leg deployment servos.		TP.7			A shake demonstration will be performed on the PLS, to ensure that all elements are properly secured when in flight configuration.	Incomplete
PF.4	The PLS shall be capable of withstanding an impact with the ground at a minimum of 20 ft/s.	The lander is expected to be capable of sustaining the expected ground impact with a factor of safety of 3.3.				x	The hinges connecting the lander legs to the body have been analyzed using finite-element analysis, as found in Section 4.4.3.	Complete
PF.5	The PLS shall be capable of transmitting data to a minimum distance of 2 km.	The lander radio transceiver has been selected to be capable of transmission to at least 2 km.		TP.3			A range demonstration will be performed using the integrated lander electronics to ensure that all they are capable of transmission to the required distance.	Incomplete
PF.6	The PLS shall contain minimum of 2 electrically isolated systems for deployment from the vehicle.	The lander will be jettisoned from the vehicle by black powder ejection charges initiated by an independent pair of Stratologger SL100s.		TR.1, TP.1			The ability of these altimeters to independently ignite e-matches will be tested on the ground prior to flight, and full function will be demonstrated during the Payload Demonstration flight.	Incomplete
PF.7	PLS legs shall be capable of sustaining forces associated with nosecone ejection.	The payload legs will be constructed of 1/8th in carbon fiber plate, supported on the bottom by an epoxied-in centering ring.		TR.3			The strength of the payload legs will be verified through the nosecone ejection ground tests, described in Test TR.3	Incomplete
PF.8	PLS leg servos shall have sufficient torque to reorient the PLS after landing.	The leg servos have a stall torque of 75 oz-in, capable reorienting the payload.		TP.6		x	The required reorientation torque was calculated using hand calculations, as found in Section 4.4.3. The system will be further verified through ground demonstrations of the orientation system, Test TP.6.	In Progress
PF.9	PLS shall be capable of detecting ejection from the vehicle.	The lander has jumper wires connected to the inside of the payload bay, which will separate as the lander is jettisoned. This separation will be detected by the lander's microcontroller.		TP.2			A ground release demonstration will be performed, verifying that the lander's mirocontroller can detect jettison from the payload bay, Test TP.2.	Incomplete
PF.10	PLS shall be capable of deploying from the vehicle without interference from the nose cone or any other vehicle elements.	The nose cone is to be fully ejected from the vehicle as the payload is jettisoned, clearing the way for payload deployment.		TP.1, TP.2			A ground release demonstration will be performed (Test TP.2), verifying the ability of the lander to release from the payload bay. This will be further verified during the Payload Demonstration flight, where the lander will be ejected in a representative flight environment (Test TP.1).	Incomplete
PF.11	PLS shall be capable of fully deploying its legs within 25 seconds of ejection.	As currently designed, the lander legs are capable of deployment within 4.2 seconds of jettison from the vehicle.		TP.5		x	Analysis of the leg deployment speed has been through hand calculations, as found in Section 4.4.3. The deployment time of the lander legs will be further tested through timing of the lander legs on the ground (Test TP.5).	In Progress
PF.12	The PLS shall contain a GPS module and method of transmitting GPS data to the team.	The PLS microcontroller has an attached standalone GPS module, and will transmit the GPS data through the Adafruit LoRa radio bonnet.		TP.3			A range demonstration will be performed using the integrated lander electronics to ensure that they are capable of transmission of GPS data to the team's ground station.	Incomplete
PF.13	The PLS ground station electrical components shall be powered via commercially available batteries or a USB connector.	The ground station will be powered by a USB connector, connected to a laptop.		TP.3			All functional tests of the lander's transmision systems will be done with the ground station only connected to a laptop computer.	Incomplete

Requirement		Verification Method					Verification Plan	Status
ID	**Description**	**Compliance Plan**	**I**	**D**	**T**	**A**		
PF.14	The PLS shall be capable of orienting on a slope less than 30 degrees.	As currently designed, the lander has leg travel sufficient to reorient on inclines of up to 20 degrees.		TP.6			The orientation system of the lander will be tested on the ground on inclines of up to 20 degrees.	Incomplete
DESIGN REQUIREMENTS								
PD.1	The PLS shall have a maximum weight of 80 oz, including the lander, retention, deployment and descent hardware.	The payload is currently predicted to have a weight of 77.7 oz.	x				The payload components will be weighed prior to installation in the vehicle, to verify that it is under 80 oz.	Incomplete
PD.2	The PLS shall have a maximum length of 21 in.	The payload is currently designed to have a length of 15.5 in.	x				The payload length will be measured prior to installation in the vehicle to verify its length.	Incomplete
ENVIRONMENTAL REQUIREMENTS								
PE.1	The PLS shall be capable of sustaining a minimum of 54 Gs of axial acceleration.	All current components of the payload are expected to be capable of sustaining 56 Gs of axial acceleration.				x	A combination of hand calculations and finite element analysis have been performed on all significant load-bearing components of the payload.	Complete
PE.2	PLS shall be capable of remaining on the launch pad for a minimum of 2 hours.	The payload is expected to be capable of remaining on the launch pad for a total of 4 hours.				x	Hand calculations have been performed estimating the pad time the PLS is capable of.	Complete
PE.3	Ground station power supply shall be capable of powering the system for a minimum of 2 hours.	The ground station is expected to be capable of remaining on the launch pad for a total of X hours.				x	Hand calculations have been performed estimating the operation time the ground station is capable of.	Complete

6.8 Budgeting and Timeline

6.8.1 Budget

The team's funding plan can be seen in Table 87. The AIAA funds previously mentioned in CDR have been used to upgrade the workspace of multiple design teams instead of being allocated to NDRT specifically. The budget reflects this and a profit from selling team merchandise this semester. The team is still pursuing more corporate sponsorships for funding opportunties.

Table 87: NDRT 2020/2021 Revenue

Source	Amount
Carryover (2019/2020)	$9,297
Electrical Engineering Department	$500
Team Merchandise	$82.05
NDRT Alumni	$1,000
ND Day Fundraising	$940
Collins Aerospace	$5,000
Total	**$16,819.05**

Table 88: Budget allocation and funds spent to date.

Item	**Allocation**	**Funds Spent**
Vehicle Design	$4,000.00	$1,813.30
Apogee Control System	$1,000.00	$618.85
Recovery System	$1,200.00	$761.40
Planetary Landing System	$1,700.00	$37.47
Vehicle Subtotal	***$7,900.00***	***$3,263.01***
Safety	$300.00	$31.99
STEM Engagement	$100.00	$0.00
Competition Travel	$8,000.00	$0.00
Total Expenses	**$16,300.00**	**$3,263.01**
Total Revenue	$16,819.05	$16,819.05
Remaining Funds	$519.05	$13,556.04

Table 89: Vehicles line-item budget.

Item	Vendor	Qty	Unit Price	Tax & Shipping	Total Cost
Rocksim v10 Licenses	Apogee Components	3	$21.25	$0.00	$63.75
Standard Rail Button (fits 1" Rail - 1010) - 2 Per Pack	Apogee Components	1	$3.48	$0.00	$3.48
Motor Mount Tubing - 29mm x 12" Motor Mount Tube	LOC Precision	2	$1.99	$0.00	$3.98
Aerotech G80 Blue Thunder 29 mm - Single Use	BuyRocketMotors.com	3	$26.99	$0.00	$80.97
Aerotech 29mm Aluminum Motor Retainer	BuyRocketMotors.com	1	$14.39	$0.00	$14.39
UPS HAZMAT Shipping Fee	BuyRocketMotors.com	1	$37.00	$0.00	$37.00
BTL-2.5-1.5	Public Missiles, Ltd.	1	$31.95	$0.00	$31.95
2.6" Tube Coupler. 5" Long for Bays	Rocketarium	2	$2.75	$0.00	$5.50
2.6" Phenolic Tube. 36" Long	Rocketarium	3	$19.95	$0.00	$59.85
Shipping of all subscale parts	Subscale Shipping	1	$57.16	$0.00	$57.16
Spray Paint	Home Depot	1	$5.33	$0.00	$5.33
(K)Frame Airframe 6" Body Tubes	Giant Leap Rocketry	3	$169.99	$65.10	$575.07
G12 Fiberglass Coupler	Apogee Components	2	$64.29	$17.57	$146.15
FNC-6.0 Nosecone	Wildman Rocketry	1	$109.95	$14.70	$124.65
Fiberglass Boattail	Public Missiles, Ltd.	1	$132.95	$14.95	$147.90
Rail Buttons	Apogee Components	1	$11.17	$0.00	$11.17
Motor Retainer	Apogee Components	1	$56.67	$5.08	$61.75
.187” Fiberglass	Curbell Plastics	1	$181.68	$30.83	$212.51
JB Weld Epoxy	eRockets	1	$7.99	$3.23	$11.22
RocketPoxy	BuyRocketMotors.com	1	$39.38	$14.95	$54.33
1/8” Fiberglass	McMaster Carr	2	$44.64	$15.91	$105.19
				Total	**$1,813.30**
				Allocation	$4,000.00
				Funds Remaining	$2,186.70

Table 90: Recovery line-item budget.

Recovery System Components	**Vendor**	**Qty**	**Unit Price**	**Tax & Shipping**	**Total Cost**
Keylock Switch (KO117A125)	Digi-Key	5	$8.19	$8.21	$49.16
StratologgerCF Altimeter	PerfectFlite Direct	2	$54.95	$9.70	$119.60
Eggfinder Starter Set with Mini Transmitter	Eggtimer Rocketry	2	$80.75	$8.00	$169.50
25Ft. Lg. 1/4" Tubular Kevlar with 2 Loops	OneBadHawk Recovery	1	$28.00	$0.00	$28.00
35Ft. Lg. 3/4" Tubular Nylon with 2 Loops	OneBadHawk Recovery	2	$31.00	$10.00	$72.00
12 Ft. Standard Parachute	Rocketman	1	$139.50	$0.00	$139.50
2 Ff. Standard Parachute	Rocketman	1	$25.65	$0.00	$25.65
Square-Profile Oil-Resistant Buna-N O-Ring (No. 256)	McMaster-Carr	1	$9.30	$0.00	$9.30
Multipurpose 6061 Aluminum (1/4"x8"x8")	McMaster-Carr	2	$18.31	$0.00	$36.62
Multipurpose 6061 Aluminum (3/8"x2"x12")	McMaster-Carr	1	$7.26	$0.00	$7.26
1/16" Garolite G-10/FR4 Sheet	McMaster-Carr	1	$10.75	$0.00	$10.75
Turnigy 2S Lipo	Hobby King	2	$7.15	$0.00	$14.30
4-40 3/4" Lg Screws, 18-8 Steel, 100 Pack	McMaster-Carr	1	$4.20	$0.00	$4.20
4-40 ½" Lg Screws, nylon	McMaster-Carr	1	$7.13	$0.00	$7.13
4-40 Washers	McMaster-Carr	1	$1.43	$0.00	$1.43
4-40 Low Strength Nuts	McMaster-Carr	1	$0.89	$0.00	$0.89
6-32 ¾" Lg Screws	McMaster-Carr	1	$3.43	$0.00	$3.43
3000 lb Swivel	Fruity Chutes	1	$9.00	$0.00	$9.00
1S Lipo Batteries	Amazon	1	$19.99	$0.00	$19.99
LED Indicator Lights	Amazon	1	$5.99	$0.00	$5.99
6-32 1-½" Lg. Steel Standoffs	McMaster-Carr	3	$3.61	$0.00	$10.83
6-32 3" Lg. Aluminum Standoffs	McMaster-Carr	3	$2.09	$0.00	$6.27
12-24 3/4" Lg. Alloy Steel Screws	McMaster-Carr	1	$10.60	$0.00	$10.60
				Total	**$761.40**
				Allocation	$1,200.00
				Remaining Funds	$438.60

Table 91: ACS line-item budget.

Apogee Control System Components	Vendor	Qty	Price Per Unit	Tax & Shipping	Total Cost
Raspberry Pi Zero W	Adafruit	1	$10.00	$0.00	$10.00
Adafruit ADXL345	Adafruit	1	$17.50	$0.00	$17.50
Adafruit MPL3115A2	Adafruit	1	$9.95	$0.00	$9.95
HiLetgo MPU9250/6500	Amazon	2	$8.99	$0.00	$17.98
SanDisk 32GB Ultra microSDHC	Amazon	1	$8.49	$0.00	$8.49
Turnigy 2000mAh LiPo Battery	Hobby King	2	$4.53	$0.00	$9.06
Zippy 1300mAh Compact LiPo Pack	Hobby King	2	$7.95	$9.60	$25.50
D980TW Servo	Servo City	2	$169.99	$6.99	$346.97
Adafruit Powerboost	Adafruit	1	$14.95	$10.42	$25.37
3/8" Aluminum Sheet	McMaster Carr	1	$26.99	$0.00	$26.99
3/8"-16 Steel Threaded Rod	McMaster Carr	1	$11.45	$0.00	$11.45
3/16" HDPE Sheet	McMaster Carr	2	$6.23	$0.00	$12.46
1/2" 6/6 Nylon	McMaster Carr	1	$58.26	$0.00	$58.26
1/4" 6/6 Nylon	McMaster Carr	1	$38.87	$0.00	$38.87
				Total	**$618.85**
				Allocation	$1,000.00
				Remaining Funds	$381.15

Table 92: PLS line-item budget.

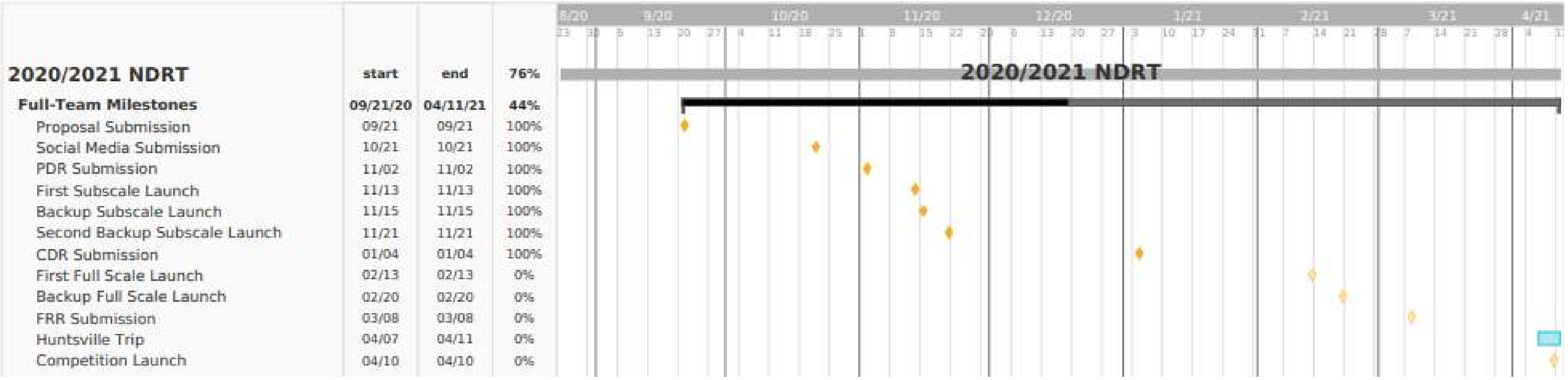
Planetary Landing System Components	Vendor	Qty	Unit Price	Tax & Shipping	Total Cost
3102 Servo Programmer	Servo City	1	$6.49	$0.00	$6.49
2000 Series Dual Mode Servo	Servo City	1	$23.99	$6.99	$30.98
				Total	**$37.47**
				Allocation	$1,700.00
				Remaining Funds	$1,662.53

Table 93: Safety line-item budget

Item	Vendor	Qty	Unit Price	Tax & Shipping	Total Cost
Solder Smoke Absorber	Kulannder Direct	1	$31.99	$0.00	$31.99
				Total	**$31.99**
				Allocation	$300.00
				Remaining Funds	$268.01

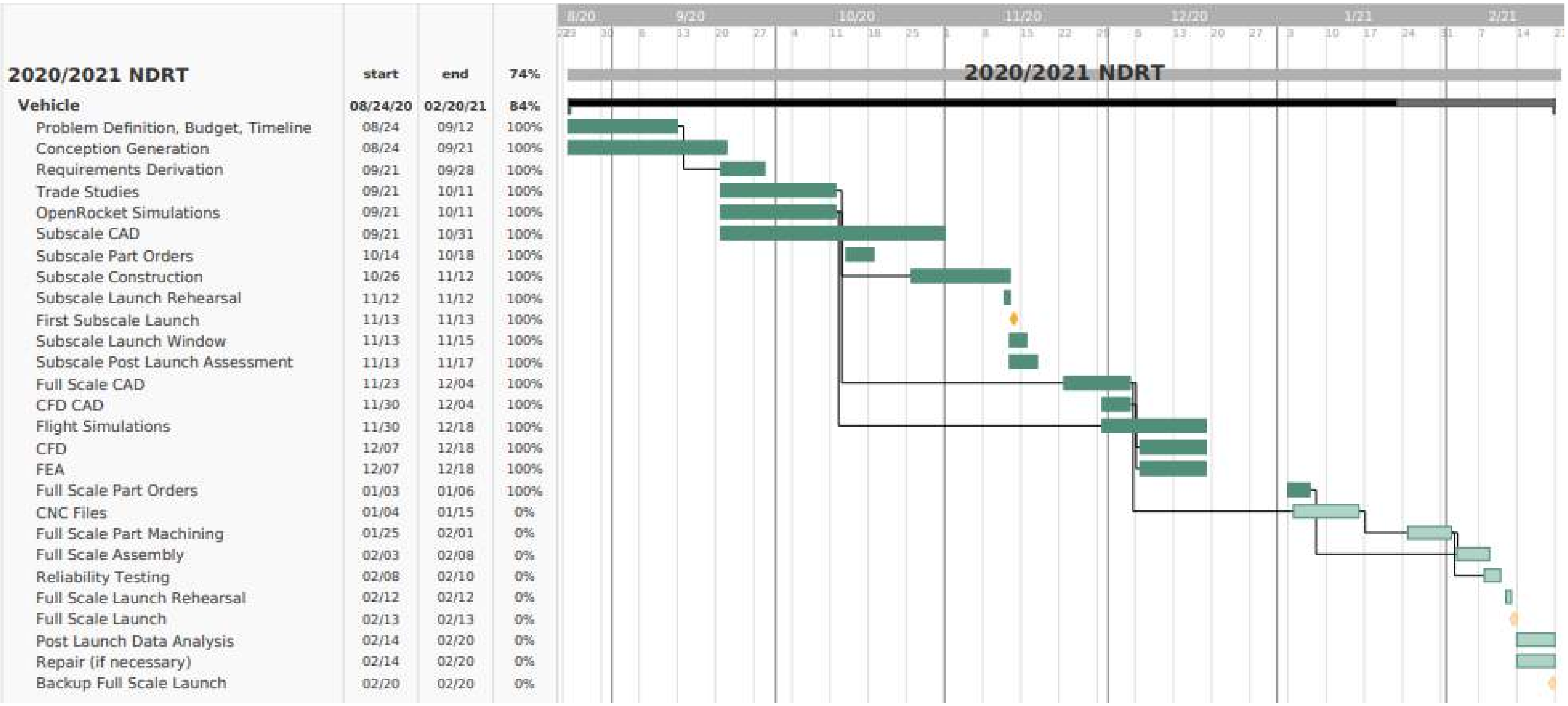
6.8.2 Timeline

The timeline shown in the figures below demonstrates adherence to NASA milestones as well as accounts for the University of Notre Dame's school schedule. The team has chosen an aggressive schedule in regards to construction, testing, and launching to accommodate for any delays. The team is preparing to launch at the first available date after returning to campus which is February 13th. This is intended to give the team additional launch opportunities prior to the FRR deadline in the case of weather, illness, or failure. The timelines run up until after the first launch. If an backup launch is required, the launch seen on Figure 83 will be used.



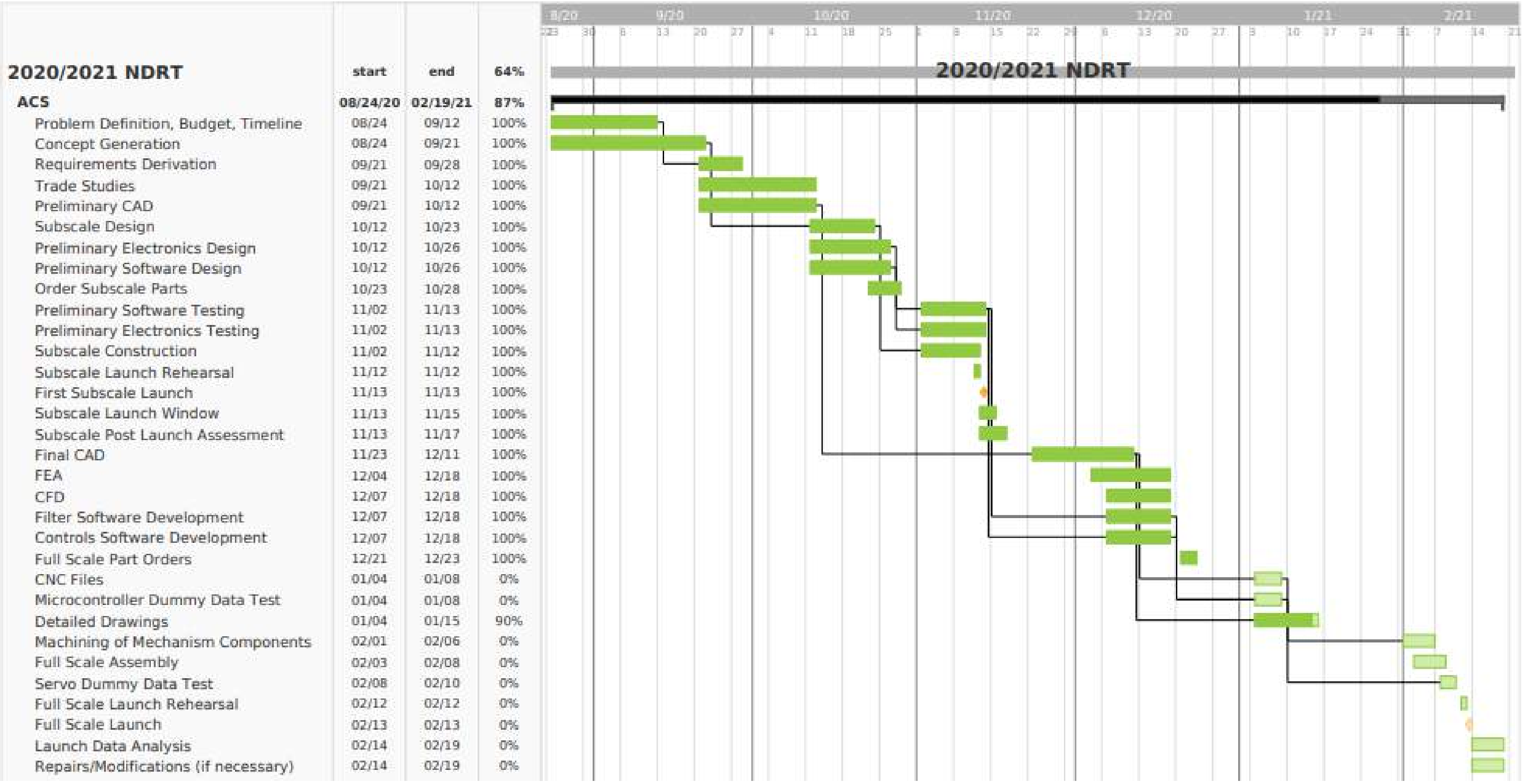
2020/2021 NDRT	start	end	76%
Full-Team Milestones	**09/21/20**	**04/11/21**	**44%**
Proposal Submission	09/21	09/21	100%
Social Media Submission	10/21	10/21	100%
PDR Submission	11/02	11/02	100%
First Subscale Launch	11/13	11/13	100%
Backup Subscale Launch	11/15	11/15	100%
Second Backup Subscale Launch	11/21	11/21	100%
CDR Submission	01/04	01/04	100%
First Full Scale Launch	02/13	02/13	0%
Backup Full Scale Launch	02/20	02/20	0%
FRR Submission	03/08	03/08	0%
Huntsville Trip	04/07	04/11	0%
Competition Launch	04/10	04/10	0%

Figure 83: Timeline of overall milestones.



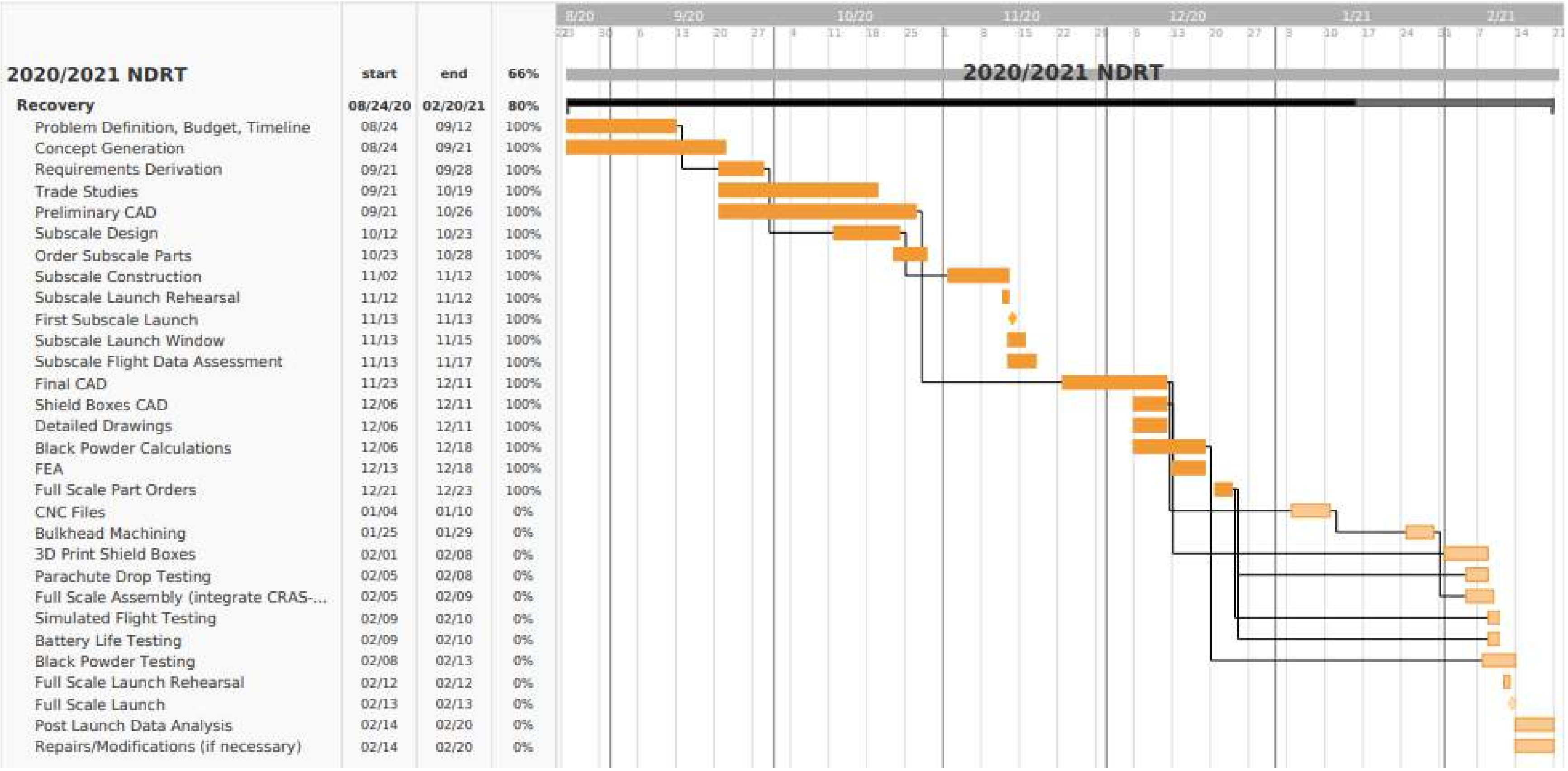
2020/2021 NDRT	start	end	74%
Vehicle	**08/24/20**	**02/20/21**	**84%**
Problem Definition, Budget, Timeline	08/24	09/12	100%
Conception Generation	08/24	09/21	100%
Requirements Derivation	09/21	09/28	100%
Trade Studies	09/21	10/11	100%
OpenRocket Simulations	09/21	10/11	100%
Subscale CAD	09/21	10/31	100%
Subscale Part Orders	10/14	10/18	100%
Subscale Construction	10/26	11/12	100%
Subscale Launch Rehearsal	11/12	11/12	100%
First Subscale Launch	11/13	11/13	100%
Subscale Launch Window	11/13	11/15	100%
Subscale Post Launch Assessment	11/13	11/17	100%
Full Scale CAD	11/23	12/04	100%
CFD CAD	11/30	12/04	100%
Flight Simulations	11/30	12/18	100%
CFD	12/07	12/18	100%
FEA	12/07	12/18	100%
Full Scale Part Orders	01/03	01/06	100%
CNC Files	01/04	01/15	0%
Full Scale Part Machining	01/25	02/01	0%
Full Scale Assembly	02/03	02/08	0%
Reliability Testing	02/08	02/10	0%
Full Scale Launch Rehearsal	02/12	02/12	0%
Full Scale Launch	02/13	02/13	0%
Post Launch Data Analysis	02/14	02/20	0%
Repair (if necessary)	02/14	02/20	0%
Backup Full Scale Launch	02/20	02/20	0%

Figure 84: Timeline of the Vehicles team.



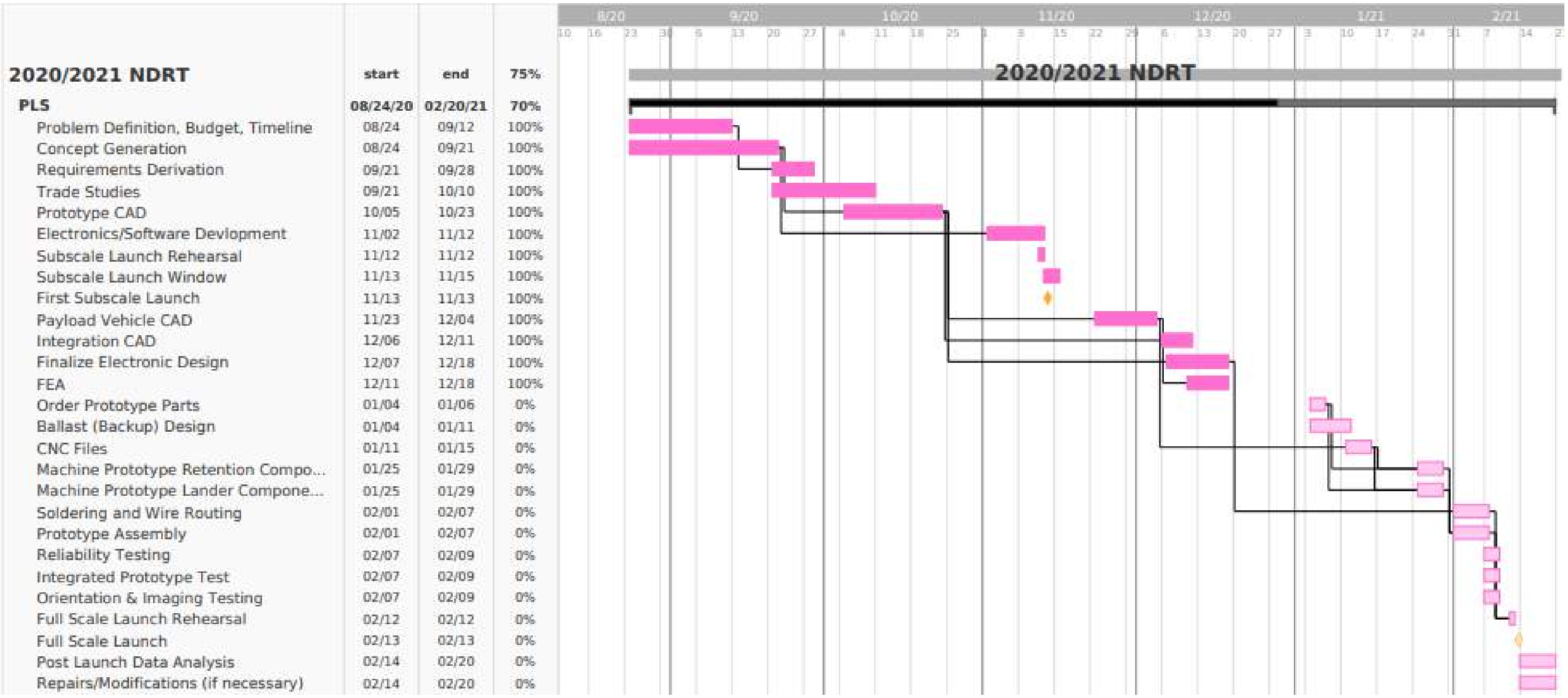
2020/2021 NDRT	start	end	64%
ACS	08/24/20	02/19/21	87%
Problem Definition, Budget, Timeline	08/24	09/12	100%
Concept Generation	08/24	09/21	100%
Requirements Derivation	09/21	09/28	100%
Trade Studies	09/21	10/12	100%
Preliminary CAD	09/21	10/12	100%
Subscale Design	10/12	10/23	100%
Preliminary Electronics Design	10/12	10/26	100%
Preliminary Software Design	10/12	10/26	100%
Order Subscale Parts	10/23	10/28	100%
Preliminary Software Testing	11/02	11/13	100%
Preliminary Electronics Testing	11/02	11/13	100%
Subscale Construction	11/02	11/12	100%
Subscale Launch Rehearsal	11/12	11/12	100%
First Subscale Launch	11/13	11/13	100%
Subscale Launch Window	11/13	11/15	100%
Subscale Post Launch Assessment	11/13	11/17	100%
Final CAD	11/23	12/11	100%
FEA	12/04	12/18	100%
CFD	12/07	12/18	100%
Filter Software Development	12/07	12/18	100%
Controls Software Development	12/07	12/18	100%
Full Scale Part Orders	12/21	12/23	100%
CNC Files	01/04	01/08	0%
Microcontroller Dummy Data Test	01/04	01/08	0%
Detailed Drawings	01/04	01/15	90%
Machining of Mechanism Components	02/01	02/06	0%
Full Scale Assembly	02/03	02/08	0%
Servo Dummy Data Test	02/08	02/10	0%
Full Scale Launch Rehearsal	02/12	02/12	0%
Full Scale Launch	02/13	02/13	0%
Launch Data Analysis	02/14	02/19	0%
Repairs/Modifications (if necessary)	02/14	02/19	0%

Figure 85: Timeline of the ACS team.



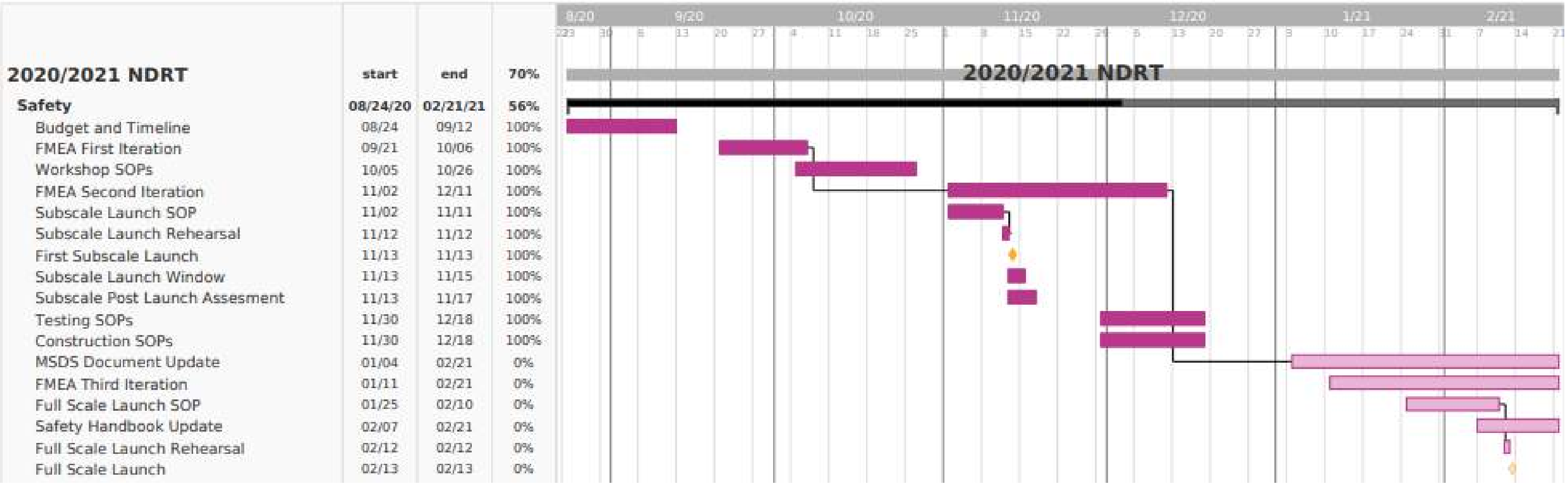
2020/2021 NDRT	start	end	66%
Recovery	**08/24/20**	**02/20/21**	**80%**
Problem Definition, Budget, Timeline	08/24	09/12	100%
Concept Generation	08/24	09/21	100%
Requirements Derivation	09/21	09/28	100%
Trade Studies	09/21	10/19	100%
Preliminary CAD	09/21	10/26	100%
Subscale Design	10/12	10/23	100%
Order Subscale Parts	10/23	10/28	100%
Subscale Construction	11/02	11/12	100%
Subscale Launch Rehearsal	11/12	11/12	100%
First Subscale Launch	11/13	11/13	100%
Subscale Launch Window	11/13	11/15	100%
Subscale Flight Data Assessment	11/13	11/17	100%
Final CAD	11/23	12/11	100%
Shield Boxes CAD	12/06	12/11	100%
Detailed Drawings	12/06	12/11	100%
Black Powder Calculations	12/06	12/18	100%
FEA	12/13	12/18	100%
Full Scale Part Orders	12/21	12/23	100%
CNC Files	01/04	01/10	0%
Bulkhead Machining	01/25	01/29	0%
3D Print Shield Boxes	02/01	02/08	0%
Parachute Drop Testing	02/05	02/08	0%
Full Scale Assembly (integrate CRAS-...	02/05	02/09	0%
Simulated Flight Testing	02/09	02/10	0%
Battery Life Testing	02/09	02/10	0%
Black Powder Testing	02/08	02/13	0%
Full Scale Launch Rehearsal	02/12	02/12	0%
Full Scale Launch	02/13	02/13	0%
Post Launch Data Analysis	02/14	02/20	0%
Repairs/Modifications (if necessary)	02/14	02/20	0%

Figure 86: Timeline of the Recovery team.



2020/2021 NDRT	start	end	75%
PLS	08/24/20	02/20/21	70%
Problem Definition, Budget, Timeline	08/24	09/12	100%
Concept Generation	08/24	09/21	100%
Requirements Derivation	09/21	09/28	100%
Trade Studies	09/21	10/10	100%
Prototype CAD	10/05	10/23	100%
Electronics/Software Devlopment	11/02	11/12	100%
Subscale Launch Rehearsal	11/12	11/12	100%
Subscale Launch Window	11/13	11/15	100%
First Subscale Launch	11/13	11/13	100%
Payload Vehicle CAD	11/23	12/04	100%
Integration CAD	12/06	12/11	100%
Finalize Electronic Design	12/07	12/18	100%
FEA	12/11	12/18	100%
Order Prototype Parts	01/04	01/06	0%
Ballast (Backup) Design	01/04	01/11	0%
CNC Files	01/11	01/15	0%
Machine Prototype Retention Compo...	01/25	01/29	0%
Machine Prototype Lander Compone...	01/25	01/29	0%
Soldering and Wire Routing	02/01	02/07	0%
Prototype Assembly	02/01	02/07	0%
Reliability Testing	02/07	02/09	0%
Integrated Prototype Test	02/07	02/09	0%
Orientation & Imaging Testing	02/07	02/09	0%
Full Scale Launch Rehearsal	02/12	02/12	0%
Full Scale Launch	02/13	02/13	0%
Post Launch Data Analysis	02/14	02/20	0%
Repairs/Modifications (if necessary)	02/14	02/20	0%

Figure 87: Timeline of the PLS team.



2020/2021 NDRT	start	end	70%
Safety	**08/24/20**	**02/21/21**	**56%**
Budget and Timeline	08/24	09/12	100%
FMEA First Iteration	09/21	10/06	100%
Workshop SOPs	10/05	10/26	100%
FMEA Second Iteration	11/02	12/11	100%
Subscale Launch SOP	11/02	11/11	100%
Subscale Launch Rehearsal	11/12	11/12	100%
First Subscale Launch	11/13	11/13	100%
Subscale Launch Window	11/13	11/15	100%
Subscale Post Launch Assesment	11/13	11/17	100%
Testing SOPs	11/30	12/18	100%
Construction SOPs	11/30	12/18	100%
MSDS Document Update	01/04	02/21	0%
FMEA Third Iteration	01/11	02/21	0%
Full Scale Launch SOP	01/25	02/10	0%
Safety Handbook Update	02/07	02/21	0%
Full Scale Launch Rehearsal	02/12	02/12	0%
Full Scale Launch	02/13	02/13	0%

Figure 88: Timeline of Safety team.

Appendix A: Complete Black Powder Calculations

Variables:

- τ: shear strength of shear pin
- d: shear pin diameter
- n_1: number of shear pins used
- b: bulkhead diameter
- n_2: moles of gas needed
- V: chamber volume
- R: gas constant
- T: ignition temperature

Primary Separation Event: Drogue Deployment

Force needed to break shear pins:

$$F = \frac{\pi}{4}\tau d^2 n_1$$

$$F = \frac{\pi}{4}(10{,}000\,\text{psi})(0.086\,\text{in})^2(2) = \boxed{116\ \text{lbf}}$$

Convert to pressure:

$$P = \frac{F}{\frac{\pi}{4}b^2}$$

$$P = \frac{116\,\text{lbf}}{\frac{\pi}{4}(6\,\text{in})^2} = 4.11\ \text{lbf} = \boxed{0.28\,\text{atm}}$$

Calculate moles of gas needed:

$$n_2 = \frac{PV}{RT}$$

$$F = \frac{(0.28\,\text{atm})(4.52\,\text{L})}{(0.082\,\frac{\text{Latm}}{\text{mol K}})(1837\,\text{K})} = \boxed{0.0084\ \text{moles gas}}$$

Calculate black powder needed:

$$2KNO_3 + S + 3C \implies K_2S + N_2 + 3CO_2$$

$$\frac{0.0084 \text{ moles gas}}{1} \times \frac{2 \text{ mol } KNO_3}{4 \text{ mol gas}} \times \frac{101.1 \text{ g } KNO_3}{1 \text{ mol } KNO_3} = 0.075 \text{ g } KNO_3$$

$$\frac{0.0084 \text{ moles gas}}{1} \times \frac{1 \text{ mol S}}{4 \text{ mol gas}} \times \frac{32.1 \text{ g S}}{1 \text{ mol S}} = .067 \text{ g S}$$

$$\frac{0.0084 \text{ moles gas}}{1} \times \frac{3 \text{ mol C}}{4 \text{ mol gas}} \times \frac{12.0 \text{ g C}}{1 \text{ mol C}} = 0.42 \text{ g C}$$

$$0.075 \text{ g } KNO_3 + .067 \text{ g S} + 0.42 \text{ g C} = \boxed{0.566 \text{ g Black Powder}}$$

With a FOS of 25%, $\boxed{0.71 \text{ g}}$ of black powder is needed for the primary separation event. This will be rounded up to 1 g in the field for ease of measurement. The back-up charges for drogue deployment both have 1.5 g of black powder.

Secondary Separation Event: Main Deployment

Force needed to break shear pins:

$$F = \frac{\pi}{4} \tau d^2 n_1$$
$$F = \frac{\pi}{4} (10,000 \text{ psi})(0.086 \text{ in})^2 (4) = \boxed{232 \text{ lbf}}$$

Convert to pressure:

$$P = \frac{F}{\frac{\pi}{4} b^2}$$
$$P = \frac{232 \text{ lbf}}{\frac{\pi}{4}(6 \text{ in})^2} = 8.22 \text{ lbf} = \boxed{0.56 \text{ atm}}$$

Calculate moles of gas needed:

$$n_2 = \frac{PV}{RT}$$

$$F = \frac{(0.56\,\text{atm})(13.44\,\text{L})}{(0.082\,\frac{\text{L atm}}{\text{mol K}})(1837\,\text{K})} = \boxed{0.0498\text{ moles gas}}$$

Calculate black powder needed:

$$2\text{KNO}_3 + \text{S} + 3\text{C} \implies \text{K}_2\text{S} + \text{N}_2 + 3\text{CO}_2$$

$$\frac{0.0498\text{ moles gas}}{1} \times \frac{2\text{ mol KNO}_3}{4\text{ mol gas}} \times \frac{101.1\text{ g KNO}_3}{1\text{ mol KNO}_3} = 0.449\text{ g KNO}_3$$

$$\frac{0.0498\text{ moles gas}}{1} \times \frac{1\text{ mol S}}{4\text{ mol gas}} \times \frac{32.1\text{ g S}}{1\text{ mol S}} = 0.400\text{ g S}$$

$$\frac{0.0498\text{ moles gas}}{1} \times \frac{3\text{ mol C}}{4\text{ mol gas}} \times \frac{12.0\text{ g C}}{1\text{ mol C}} = 2.52\text{ g C}$$

$$0.449\text{ g KNO}_3 + 0.400\text{ g S} + 2.52\text{ g C} = \boxed{3.368\text{ g Black Powder}}$$

With a FOS of 25%, $\boxed{4.2\text{ g}}$ of black powder is needed for the primary separation event. The back-up charges for drogue deployment both have 5 g of black powder.

Tertiary Separation Event: Nosecone Jettison

Force needed to break shear pins:

$$F = \frac{\pi}{4}\tau d^2 n_1$$

$$F = \frac{\pi}{4}(10{,}000\,\text{psi})(0.086\,\text{in})^2(4) = \boxed{232\text{ lbf}}$$

Convert to pressure:

$$P = \frac{F}{\frac{\pi}{4}b^2}$$

$$P = \frac{232\,\text{lbf}}{\frac{\pi}{4}(6\,\text{in})^2} = 8.22\text{ lbf} = \boxed{0.56\,\text{atm}}$$

Calculate moles of gas needed:

$$n_2 = \frac{PV}{RT}$$

$$F = \frac{(0.56\,\text{atm})(5.93\,\text{L})}{(0.082\,\frac{\text{L atm}}{\text{mol K}})(1837\,\text{K})} = \boxed{0.022 \text{ moles gas}}$$

Calculate black powder needed:

$$2\text{KNO}_3 + \text{S} + 3\text{C} \implies \text{K}_2\text{S} + \text{N}_2 + 3\text{CO}_2$$

$$\frac{0.022 \text{ moles gas}}{1} \times \frac{2 \text{ mol KNO}_3}{4 \text{ mol gas}} \times \frac{101.1 \text{ g KNO}_3}{1 \text{ mol KNO}_3} = 0.198 \text{ g KNO}_3$$

$$\frac{0.022 \text{ moles gas}}{1} \times \frac{1 \text{ mol S}}{4 \text{ mol gas}} \times \frac{32.1 \text{ g S}}{1 \text{ mol S}} = 0.177 \text{ g S}$$

$$\frac{0.022 \text{ moles gas}}{1} \times \frac{3 \text{ mol C}}{4 \text{ mol gas}} \times \frac{12.0 \text{ g C}}{1 \text{ mol C}} = 1.11 \text{ g C}$$

$$0.198 \text{ g KNO}_3 + 0.177 \text{ g S} + 1.11 \text{ g C} = \boxed{1.49 \text{ g Black Powder}}$$

With a FOS of 25%, $\boxed{1.85 \text{ g}}$ of black powder is needed for the primary separation event. For ease of measurement, this will be rounded up to 2 g. The back-up charges for drogue deployment both have 2.5 g of black powder.