Project Voss

Flight Readiness Review

Purdue University 2021

500 Allison Road
West Lafayette, IN 47906

Purdue Space Program

Table of Contents

Table of Acronyms

Acronym or Abbreviation	Definition
PSP-SL	Purdue Space Program: Student Launch
ASL	Aerospace Sciences Laboratory
BIDC	Bechtel Innovation Design Center
GCS	Ground Control Station
FEA	Finite Element Analysis
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
FDM	Fused Deposition Modeling (3D Printing)
PLS	Planetary Lander System (Lander Team)
ABCS	Aero-Braking Control System (Airbrakes Team)
SOS	Self Orientation Subsystem
LCS	Lander Control Subsystem
PICS	Panoramic Image Capture Subsystem
R&D	Retention and Deployment Subsystem
D&L	Descent and Landing Subsystem
AGL	Above Ground Level
MSL	Mean Sea Level
COTS	Commercial Off-The-Shelf
NAR	National Association of Rocketry
PPE	Personal Protection Equipment
CFR	Code of Federal Regulations
APCP	Ammonium Perchlorate Composite Propellant
OEW	Operating Empty Weight
R&VP	Requirements and Verification Plans
MFSS	Motor and Fin Support Structure
IFVR	In-Flight Video Recording System
CTI	Cesaroni Technology Inc.
VDF	Vehicle Demonstration Flight
FOS	Factor Of Safety
AGL	Above Ground Level
CoM	Center of Mass
VDF	Vehicle Demonstration Flight
PDF	Payload Demonstration Flight
PCB	Printed Circuit Board

1 FRR Report Summary

1.1 Team Summary

Team Name	Purdue Space Program – NASA Student Launch (PSP-SL)
Team Address	500 Allison Road, West Lafayette, IN 47906
Team Mentor Name	Christopher Nilsen
Team Mentor Email	cnilsen@purdue.edu
Team Mentor Cell Phone	(813)-442-0891
Team Mentor TRA/NAR Certifications	TRA 12041, Level 3 Certified
Hours Spent ON CDR	353 Person Hours

Table 1.1: PSP-SL Team Summary

1.2 Launch Vehicle Summary

The following section will explain in-depth the launch vehicle that will be constructed for the 2020-2021 Project Voss.

Vehicle Name	All Gas, All Brakes
Target Altitude	4100' AGL
Motor Selection	Cessaroni Technologies Inc. L1115-0
Vehicle Predicted Mass	52.0 lbm
Vehicle Outer Diameter	6.17"
Vehicle Length	88.2"
Vehicle Independent Sections	3
Vehicle Recovery System	Dual Deployment: Apogee and 900' AGL

Table 1.2: Launch Vehicle Summary

1.2.1 Size and mass

The launch vehicle designed for the PSP-SL Project Voss mission is a 6.17" outer diameter launch vehicle, with an overall length of 88.2". The launch vehicle contains the following sections: a 36" booster section housing the MFSS and the ABCS, a 14" lower recovery section containing the drogue recovery system and the ABCS coupler, a 1" switch band centered on top of a 5" internal avionics bay, a 17" upper recovery section containing the main recovery system and the payload coupler, a 14" payload bay containing the R&D and PLS, and finally a 3" diameter hemispherical nose cone equipped with three on board flight recording systems. The outer airframe components are constructed with G12 filament-wound fiberglass. Many of the subsystems contain 3D printed parts, ranging from steel to ONYX for structural integrity. The current launch vehicle comes in around 49lbm, but the team expects this to rise to 52.0lbm for the final launch.

Project Voss Launch Vehicle	
Expected Mass	52.0 lbm
Length	88.2"
Outer Diameter	6.17"
Rail Size	96"

Table 1.3: Launch Vehicle

1.2.2 Launch Day Motor

The team continues to utilize the CTI L1115 motor, which is a 4-grain solid rocket motor.

Cesaroni Technology Inc. L1115	
Fuel	Ammonium Perchlorate
Oxidizer	Atomized Aluminum
Thrust Profile	Regressive
Propellant Mass	83.79oz
Gross Mass	154.14oz

Table 1.4: Motor Specifications

1.2.3 Target Altitude

The team is targeting an apogee of 4100' on the day of the final launch. This apogee was concluded after various simulations incorporating both launch day conditions and mass margins. If the vehicle is under the anticipated mass for the final launch, ballast will be added above the center of gravity, to help hit this apogee in tandem with the ABCS.

1.2.4 Recovery System
The recovery system is designed to protect the launch vehicle on descent and landing. This is achieved via a dual deploy, black powder cannon ejection system controlled by primary and redundant altimeters. These design decisions are specified in the table below and have been certified to meet the team derived and project derived requirements, including correct parachute deployment and landing practices.

Primary Altimeter	Altus Metrum TeleMetrum
Redundant Altimeter	PerfectFlite StratoLoggerCF
Main Parachute	Rocketman High Performance CD 2.2, 144” diameter
Main Parachute Deployment	900’ (700’ redundant)
Drogue Parachute	Fruity Chutes Classic Elliptical, 24” diameter
Drogue Parachute Deployment	Apogee (Apogee+2s redundant)
Ejection Charge Type	FFFFg Black Powder

Table 1.5: Recovery System Specifications

1.3 Payload Summary
PSP-SL's 2020–21 Payload experiment is titled “*Drag and Drop*,” owing to its systems’ central aerobraking and deployment concepts as well as the classic computing phrase.

The Payload team’s systems have been designed to satisfy the competition challenges, as well as challenges the team has imposed upon itself. The Payload system comprises of a middle-of-descent deploying Planetary Landing System (PLS) and an apogee-adjusting AeroBraking Control System (ABCS). These payload experiments remain completely contained within the launch vehicle until flight conditions are satisfied for them to become active. Both experiments have been designed to not interfere with the operation of the launch vehicle until their designated operation events are satisfied. The Payload team has completed construction and testing of sections which integrate directly into the launch vehicle, deemed mission critical for the VDF. However, the PLS Lander and ABCS Airbrakes are not yet able to fully meet non-critical NASA mission requirements.

1.3.1 Primary Payload
The primary payload has been designed to meet the challenge requirements as outlined in the Handbook. The PLS consists primarily of a deployable Lander Subsystem—or just “Lander”—and its associated Retention and Deployment Subsystem (R&D). The R&D contains the Lander within the Payload Bay until time of deployment, handling all associated flight loads which would otherwise be transferred through the Lander itself. When activated, the R&D ejects the Lander by mechanical means—without producing an additional independent section of the vehicle. The Lander will be fully deployed from the launch vehicle after the deployment of the vehicle’s main parachute, no lower than 500’ AGL. Afterward, the Lander will descend to the ground at a non-ballistic rate through the use of a parachute. Once grounded, the Lander will begin a coordinated orientation sequence, up righting itself within the required bounds. Afterward, the Lander’s onboard Panoramic Image Capture Subsystem (PICS) cameras will be activated, take a picture of its surroundings, and transmit the data to the Payload Team’s Ground Control Station (GCS) for image processing and display.

1.3.2 Secondary Payload
The secondary payload has been designed to meet the additional technical requirements as outlined by PSP-SL. The ABCS consists of a mechanical apparatus capable of being integrated with the airframe of the vehicle. This device actuates linkages connected to sectioned plates in order to affect the aerodynamic cross-sectional area of the vehicle after the vehicle’s burn has completed, producing increased drag. An internal control system is being developed to monitor flight conditions, and through a closed-loop control system, the control system will actuate the mechanical device to produce the desired amount of drag. The control system will utilize flight conditions to predict the current amount of drag required for the vehicle to attain the desired apogee and will modulate the mechanical system to that end. This system is being implemented to more accurately achieve the team’s apogee goal and is something that the team has not done in previous years. Furthermore, due to the lack of experience with this form of control system on a high-powered launch vehicle, the team has decided to dedicate much effort towards ensuring flight safety and stability.

2 Changes made since CDR
2.1 Changes made to Vehicle Criteria
2.1.1 Vehicle
Since CDR, the vehicle has undergone a few major design changes. The first being the implementation of a 1.25” fiberglass spacer placed between the aft motor closure and the motor flange plate. This was done to fix an overlook in the initial vehicle design. The

team was unaware of the forward motor closure, and the part was conflicting with the lower ABCS centering plate. The team believed that this was the most logical solution, and the solution was verified with the successful first launch. Another design change took place in the nose cone. As of the completion of CDR, the team was still unsure how incorporate the three cameras into the nose cone. Since then, the team has developed a design change to house the three cameras in the nose cone, which will be displayed in later sections. The changes made since CDR were all made with the predetermined requirements in mind and have been verified with the successful conclusion of the first vehicle launch.

2.1.2 **Recovery**

In terms of avionics and recovery, two changes have been made since CDR. The most significant one is the change in the drogue delay from one second to two seconds (i.e. the redundant altimeter initiates the drogue parachute ejection charge two seconds after the primary altimeter instead of one second). This change was made due to the failure to meet the Altimeter Ejection Vacuum Test success criteria in the first attempt of the test. Even though the drogue delay was set to one second, the two drogue charges would consistently ignite almost simultaneously in the test. Therefore, in the second attempt of the test, the drogue delay was set two seconds, and the measured delay consistently came out to be around one second, which adequately fulfilled the success criteria. Therefore, the team decided that permanently changing the drogue delay to two seconds would be safest to prevent simultaneous ignition and possible damage to the vehicle, while still remaining within the relevant NASA requirements.

The less significant change is one in the design of the altimeter sled. The team has decided to go back to utilizing nylon mounting posts for the purpose of altimeter retention rather than built-in 3D printed mounting posts. This change was made because manually threading the built-in mounting posts with a metal screw proved extremely difficult. The threads could not be made precise enough, and the fragile nylon altimeter screws kept stripping when screwing them into the homemade threads. Therefore, the built-in mounting posts were removed from the altimeter sled design and replaced with holes to insert and glue the nylon mounting posts. The premade threads in these are of course perfect for the nylon altimeter screws, and the altimeters could now be properly retained inside the vehicle.

2.2 Changes made to Payload Criteria

In the runup to the team's VDF, the Payload team has faced a significant challenge in the manufacturing and assembly of the Payload system. Due to resource limitations and supply line difficulties characteristic of the COVID-19 era, the Payload team has needed to make do with available materials. This issue has been documented in part by a message sent directly to NASA-SL personnel regarding possible action plans.

In short, inability to acquire Printed Circuit Boards (PCB's) in time for assembly and testing of the PLS and ABCS has resulted in a temporary change of plans. In lieu of PCB's—recent and opportune space-and-time-saving inclusions in PSP-SL's electrical designs—the team has needed to produce schematically and functionally identical electrical boards in the form of perfboards. Perfboards are manually constructed counterparts of typical PCB's, though they require much more effort from the team to construct. For the purposes of VDF, these perfboards have served as an effective stand-in for the R&D as well as the ABCS. However, perfboards, in comparison to mechanically assembled PCB's, are too structurally large to operate within the low-tolerance design of the PLS Lander. As a result, the Payload team has been unable to fully construct and test the Lander, and therefore the PLS, for the VDF. This has necessitated an additional launch for the team's PDF. By that time, the team's final PCB's should have arrived to be assembled and fully tested once again.

2.2.1 **Primary Payload**

Progressing from CDR, the PLS has received a small set of changes. While the functional structural design itself has remained the same, there is a decent amount of construction-related modifications which have been made in response to integration difficulties with the physical Lander. To illustrate, the primary challenge of the PLS's design is the Lander's difficulty exiting the R&D bay after deployment. This was predicted during the design phase, confirmed during initial integration, and proven during VDF. It was determined that, while the R&D appeared to deploy as intended, the Lander was unable to *reliably* exit the confines of the R&D bay, not constituting a full deployment by the team's standards.

In response, the Lander team has decided to rework the Lander loading methodology and modify the dimensions within the R&D bay to better make use of available space. This primarily includes the change to load the Lander into the R&D bay with the D&L parachute at the Lander's base. This was determined through testing to more reliably allow the Lander to fall outwards to its side, especially when the parachute bag is folded unevenly to serve as a ramp. In addition, the R&D Pizza Table design has been extended to allow for additional falling-space for the Lander post-R&D deployment. These changes, once fully implemented, will hopefully act to mitigate the Lander's deployment difficulty for PDF. Additional testing will be required to ensure that these new changes will perform better than during VDF.

2.2.2 **Secondary Payload**

Since CDR, the ABCS has seen minimal overall changes. Structurally speaking, the ABCS mechanical design has been under construction since before CDR, so most changes that were made were reported at that time. While the ABCS design has been minimally modified, the ABCS control system has undergone significant development. The team has been able to successfully integrate velocity and acceleration data to actuate the ABCS's aeroplates.

However, while the control system has been shown to operate on the ground, there remains the question of how well the ABCS will perform in a real launch. As will be discussed, the ABCS was fully physically tested and ensured to be flight-ready for VDF. While the VDF flight was unable to produce the desired actuation results, the team will utilize the observed behavior of the launch vehicle to better calibrate the ABCS system. Future plans include simulation testing of the ABCS on the ground as well as modifications to better ensure flight-readiness and stability of the system itself under flight loads.

2.3 Changes made to Project Plan

The main changes to the project plan were in the timeline. In the team's original timeline, the Vehicle Demonstration Flight and the Payload Demonstration Flight were both going to occur in late February. Due to issues with shipping, the PCBs for the Payload were not able to arrive on time. This caused the team to split the vehicle and payload demonstration flights, with the vehicle demonstration occurring on February 27th and the payload demonstration planned for March 19th or 21st.

3 Vehicle Criteria

3.1 Design and Construction of Vehicle

3.1.1 **Final Locations of Separation**

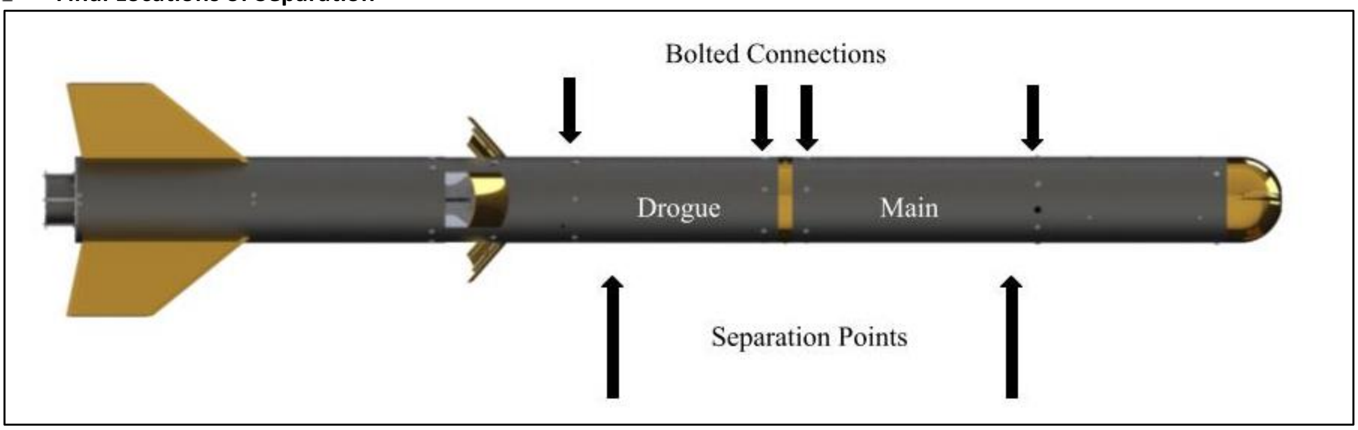

Figure 3.1: Final Locations of Separation

The launch vehicle has two separation points, both located in the recovery section. The first separation point is located in the lower recovery section, held together in flight by four shear pins that penetrate the lower recovery airframe and the ABCS coupler. The second separation point is located in the upper recovery section, where four shear pins connect the upper recovery airframe and the payload coupler. When recovery systems are deployed, the sections are held together by four eyebolts connected to coupler bulkheads: 1 on the ABCS and payload, and 2 on either side of the avionics bay. The black powder is housed on either side of the avionics bulkheads to allow for separation.

3.1.2 **Launch Vehicle Features**

3.1.2.1 Structural Elements

3.1.2.1.1 Lower Airframe

The lower airframe assembly consists of:

1. The Motor Fin Support Structure housing the motor casing and fins
2. The motor casing
3. The motor retainer
4. Three fins equally spaced 120º from each other
5. One rail button
6. The ABCS assembly and brake pads

Utilizing ANSYS and SolidWorks FEA software, the structural integrity of the lower airframe was validated. Assigning an 1800 N force in the direction of motion on the motor nozzle and an 800 N force opposite of the direction of motion on each fin leading edge, the following plots were obtained.

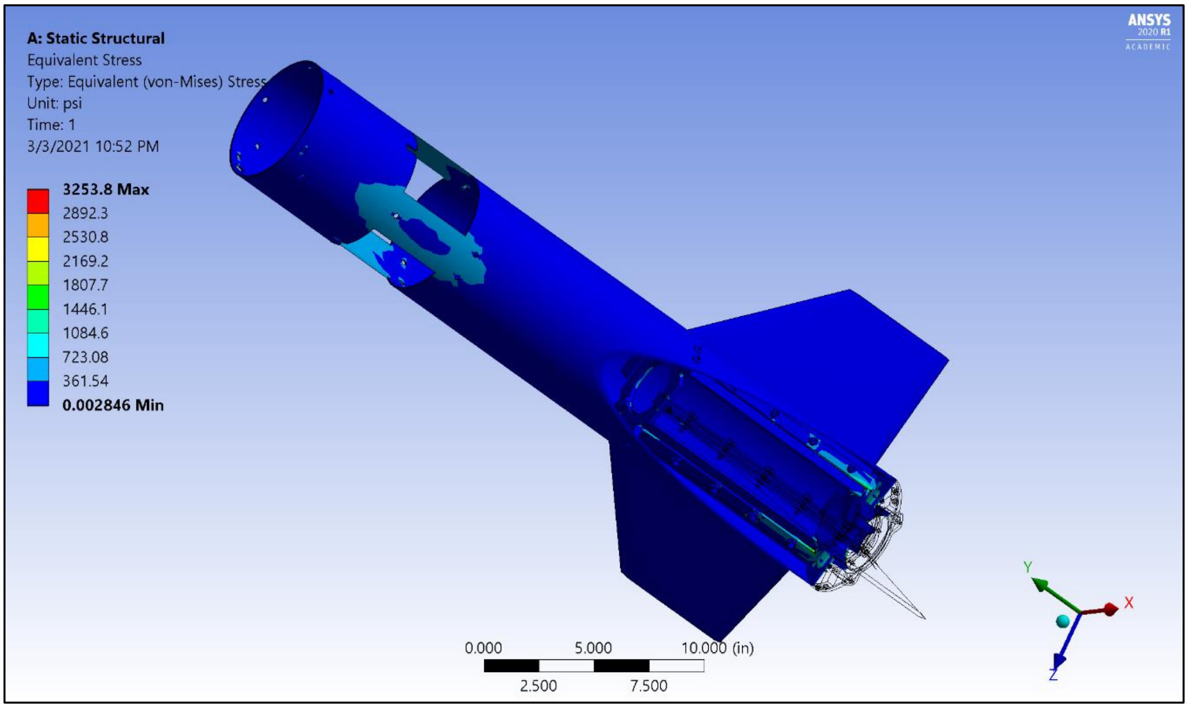

Figure 3.2: Von Mises stress contour plot of the lower airframe from thrust-drag load

In the simulation, the airframe experiences a nearly uniform stress load anywhere between 0.0029 psi (dark blue region) to 361.54 psi (dark cyan region). Higher areas of stress are indicated around the ABCS region, which is likely due to the lack of structural components included in the ABCS assemblies that were not introduced in the software during the simulation. Near the motor fin support structure (MFSS), the indicated stress is low and well distributed across the airframe.

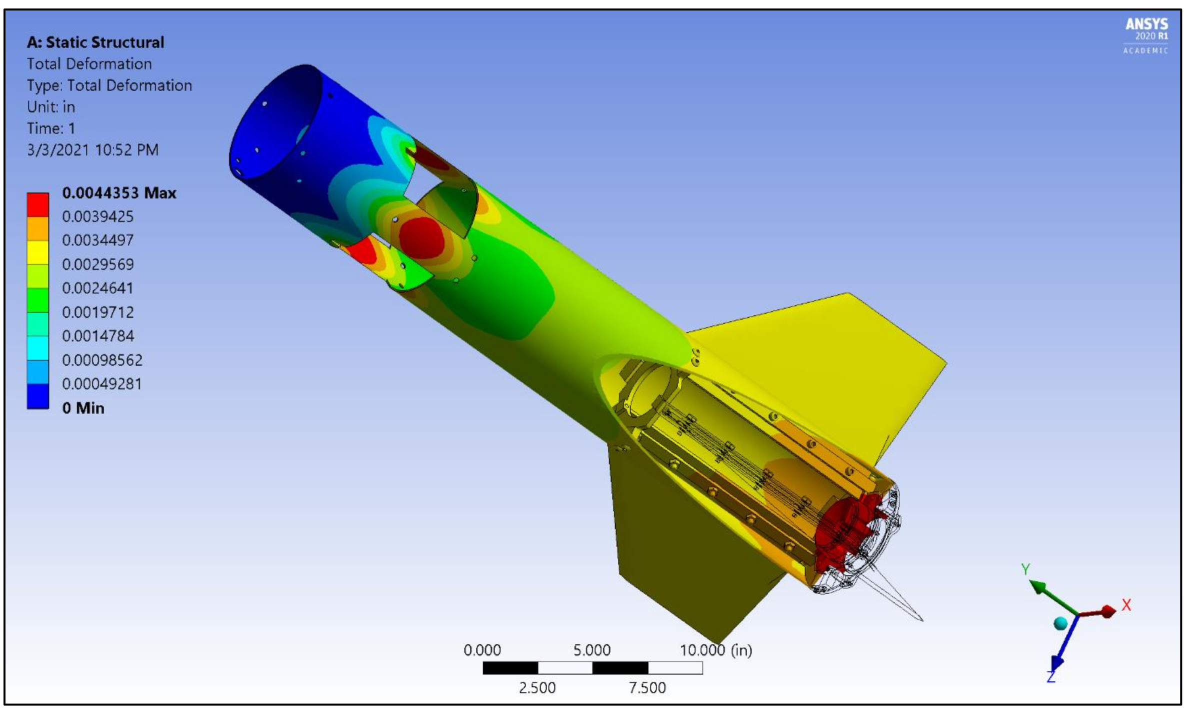

Figure 3.3: Total deformation contour plot of the lower airframe from thrust-drag load

The total deformation of the lower airframe is relatively low, reaching a maximum deformation of 0.0044 inches. Most of this deformation is near the thrust plate and thrust plate flange, the area where the motor thrust load is transferred to during the flight.

3.1.2.1.2 Motor Fin Support Structure

The MFSS contains seven main components: an upper centering plate, three fin spars, a lower thrust plate, a thrust plate flange and the motor retainer plate. The MFSS also includes three 2” long #6-32 standoffs that connect the retainer plate to the thrust plate. The centering and thrust plates provide structural support to the fin spars, which are mounted radially along the plates. During the burn, the motor contacts the thrust plate flange, which is secured to the thrust plate. The thrust/drag forces were simulated using the same parameters outlined in the previous section.

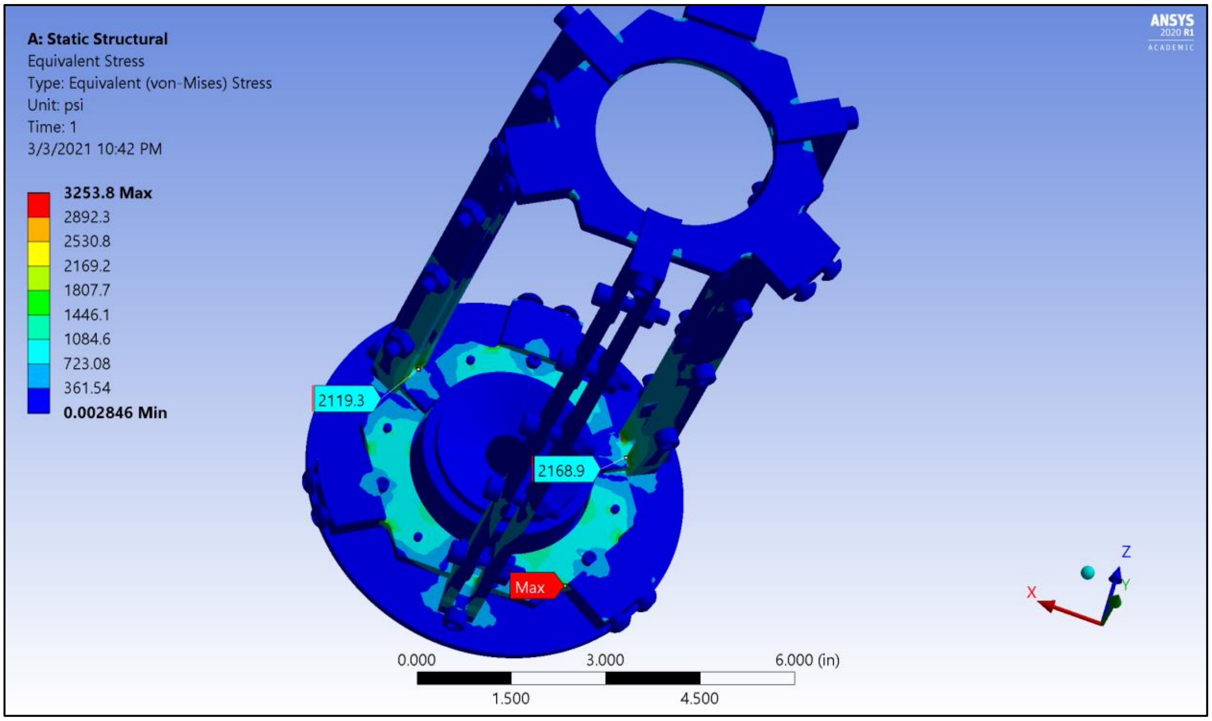

Figure 3.4: Von Mises Stress contour plot of MFSS assembly from thrust-drag load

This simulation verifies the stress applied to the structure is uniformly distributed. The majority of the structure experiences stress between 0.0028 psi (dark blue region) and 723.08 psi. The fin spars indicate the uniform distribution of stress except for the points of contact with the spars and the thrust plate flange. These points that potentially connect with the flange due to the plates' minor deformation indicate stresses of up to 2200 psi. The maximum indicated stress during the study was estimated at 3253.8 psi in the thrust plate's rounded corners.

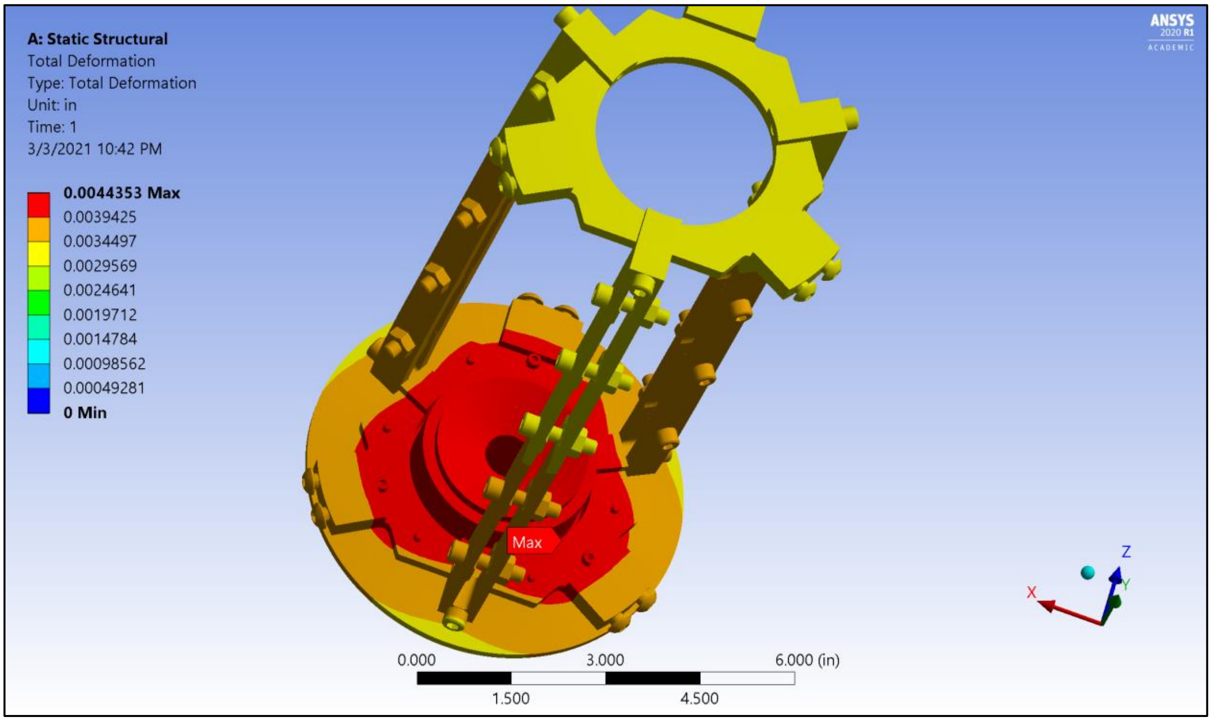

Figure 3.5: Total deformation contour plot of MFSS assembly from thrust-drag load

This simulation indicates the total deformation from the thrust/drag load. Most deformation occurs near the thrust plate and increases radially inwards, with the maximum deformation being at the surface that contacts the motor casing.

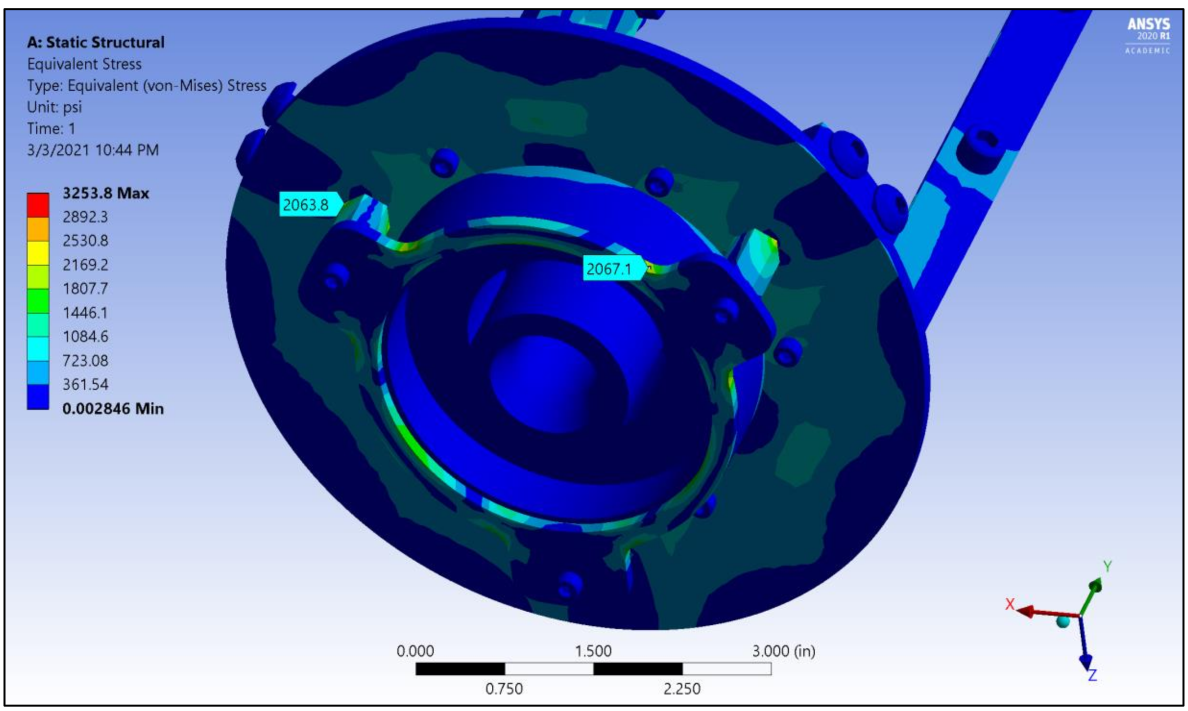

Figure 3.6: Von Mises Stress contour plot of thrust plate flange from thrust-drag load

This simulation plots the stress on the thrust plate flange from the motor. The largest stresses are located near the standoffs of the motor retainer. The stress reaches anywhere between 2169.2 psi and 2530.8 psi at these points, indicating the load is transferred from the flange plate to the standoffs and into the retainer. Besides this maximum, the stress is relatively uniform across the plate between 0.0028 psi and 723.08 psi.

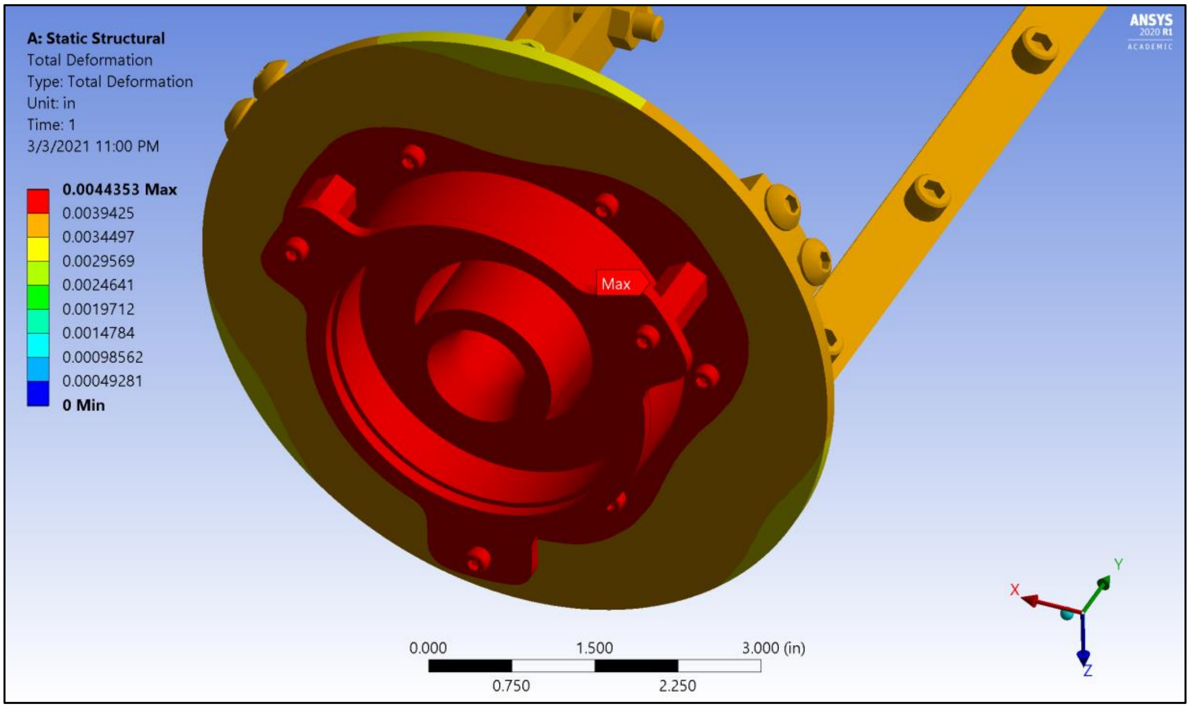

Figure 3.7: Total deformation contour plot of thrust plate flange from thrust-drag load

The total deformation plot indicates most deformation occurs near the center of the flange, the standoffs, and the motor retainer itself. The maximum indicated deformation is 0.0044 inches in this region, where the rest of the plate is indicated around 0.00344 inches to 0.00394 inches.

3.1.2.1.3 Fins

The fins mounted to the MFSS provide stability for the launch vehicle during flight. Much of the support is a result of the rigidity of the MFSS. The fins' design integrity has been validated using Ansys Finite Element Analysis for static drag on the fins (800 N) and lift forces (1800 N) in addition to in-flight verification.

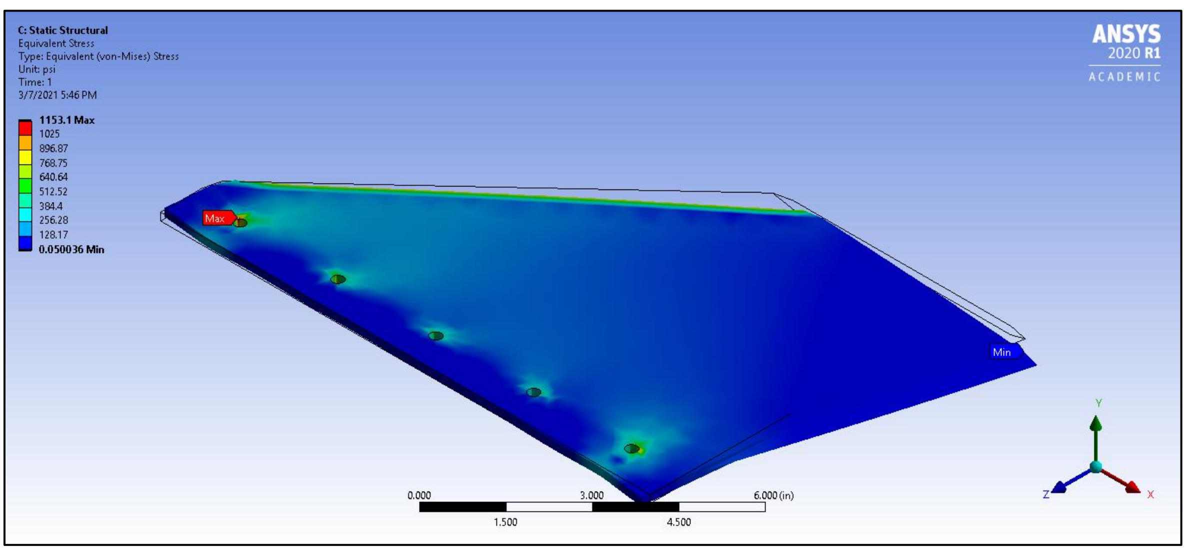

Figure 3.8 Von Mises Stress contour plot of fin drag force

The figure above shows the Von Mises stress test applied to the fin representing the flight's drag force. The test was very successful, with most of the fin only experiencing anywhere between 0.05 psi and to 384.4 psi. A slightly higher 384.4-512.5 psi range is experienced around the attachment points, which is far below the minimum tensile strength of 38,000 psi. This test's results clearly show the integrity of this fin design and the benefit of using spars to mount the fins.

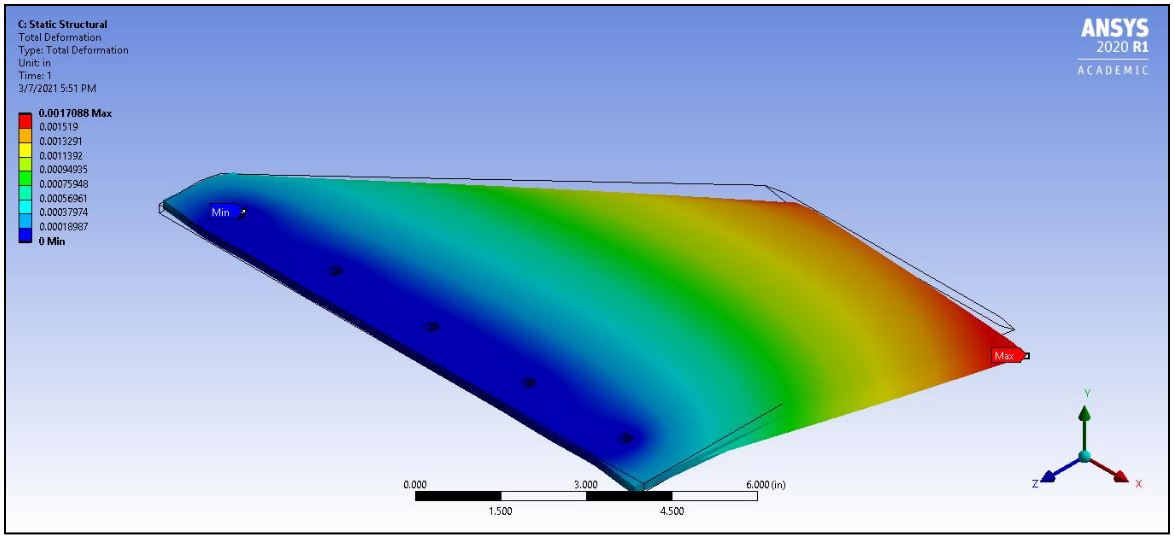

Figure 3.9: deformation contour plot of Fin Drag force

The figure above shows the total deformation test applied to the fin to represent the flight's drag force. This test behaved as expected, with the lowest displacement, 0 - 1.8e-4 in, being around the attachment points and slowly increasing until it reached its maximum displacement, 0.0017 in, at the fin tip. This test's maximum displacement is still well below the critical displacement for this design and confirms its structural integrity.

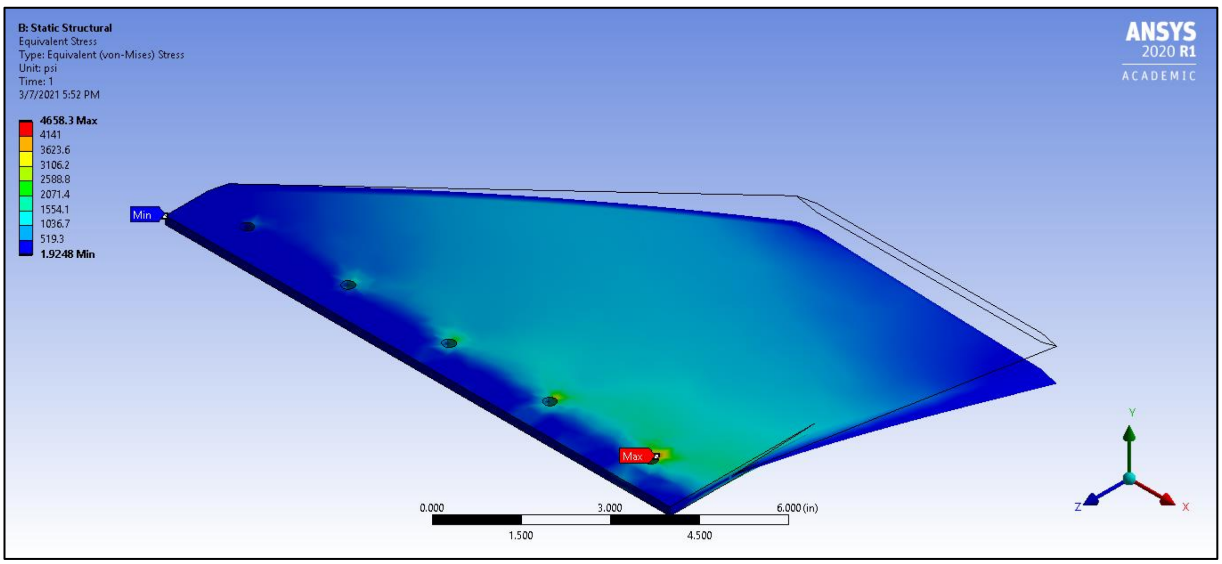

Figure 3.10: Von Mises Stress contour plot of fin from lift force

The figure above shows the Von Mises stress test done on the fin representing the flight's lift force. As shown in the figure, the fin shows stress having a minimum of 1.9248 psi and a maximum 4658.3 psi around the attachment points, far below the minimum tensile strength of 38,000 psi. This test shows the great advantage of the new fin mounting spars and validates the design's integrity.

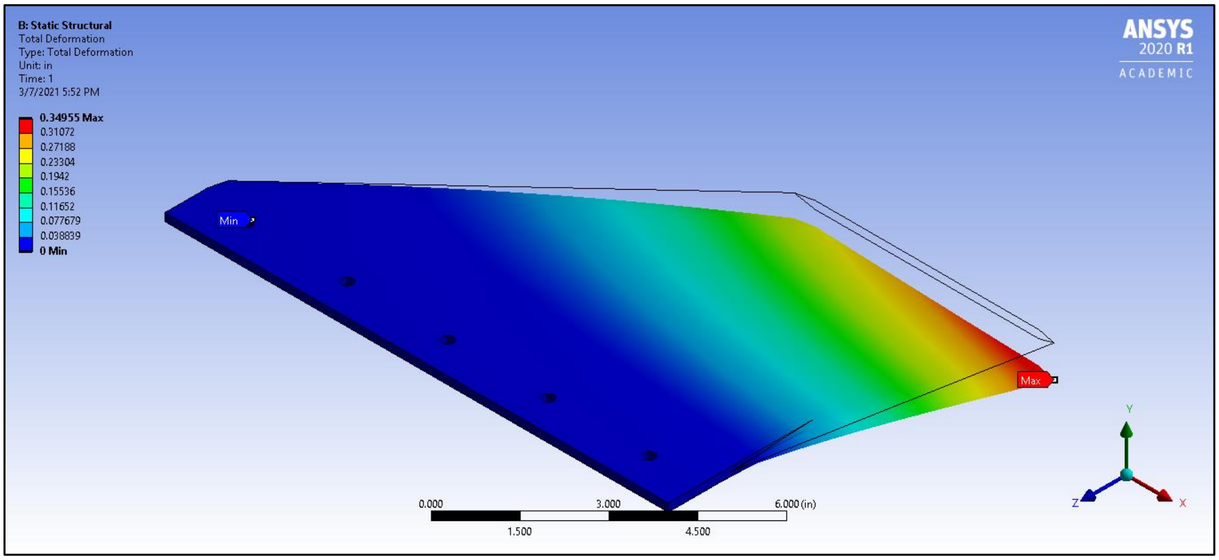

Figure 3.11: deformation plot of fin from lift force

The figure above shows the total deformation of the fin when lift force is applied. The deformation is applied as expected, with very low deformation at the attachment points and steadily increasing until it reaches its highest deformation at the bottom corner of the tip chord. The minimum fin displacement was between 0 and 0.038 psi, and the maximum fin displacement was 0.349 in. Thus, the fin shows no sign of being irreparably damaged by the flight.

3.1.2.1.3.1 Fin Flutter

Aeroelastic fin flutter is a phenomenon where there exists a dynamically unstable interaction of aerodynamic, elastic and inertial forces. When the launch vehicle is diverted from the stable flight path, a lift force is generated on each fin, which creates a bending moment on the fin and a pitching moment on the launch vehicle. This bending moment causes the fin to oscillate, which then in turn comes in contact with the air at an increased angle of attack due to the displacement from the lift and due to the pitching moment created on the whole launch vehicle, which behaves as a free body. The result is that the lift force also oscillates. When a certain frequency is reached, depending on the geometry and material of the fin, the system can start oscillating in resonance with the natural frequency of the fin material. This will usually result in structural failure of the fin. The resonance phenomenon, that is fin flutter, occurs at a certain velocity, which is predicted by the model which is derived in NACA Technical Note 4197. The equation given is:

$$v_{flutter} = \alpha * \sqrt{\frac{G}{\frac{24}{\pi} * \varepsilon * \rho_{sea} * a_{sea}^2 * \frac{p}{p_{sea}} * \frac{AR^3 * (\lambda + 1)}{\left(\frac{t}{c}\right)^3 * (AR + 2) * 2}}}$$

where α is the speed of sound at a geopotential altitude h, ε = 0.25 as given in the technical report, G is the shear modulus of the fin material, ρ_{sea} is the density of the air at sea level, α_{sea} is the speed of sound at sea level, p is the atmospheric pressure at geopotential altitude h, p_{sea} is the atmospheric pressure at sea level, AR is the panel aspect ratio of the fin, λ is the taper ratio of the fin, $\frac{t}{c}$ is the thickness ratio of the fin.

The team created a MATLAB script where the fin geometric characteristics were input. For the fin material, G10 fiberglass, two different values of G were used, one for lengthwise and one for crosswise properties, since the material is anisotropic. The values used for each parameter can be seen in the appendix, in the MATLAB script. They were derived from the sources listed in the commented description section of the code.

Using the standard atmosphere values, the team obtained the following maximum and minimum predicted values for fin flutter velocities:

NACA TN 4197 equation results	Flutter Velocity (ft/s)
Minimum	1052.983
Maximum	1260.808

Table 3.1 Flutter Velocity

The minimum flutter velocity is observed to be well above the maximum velocity measured from the full scale vehicle demonstration flight (541.47ft/s according to Telemetrum) and the maximum velocity predicted (550ft/s) by OpenRocket for the full scale launch. The plot of fin flutter velocity vs geometric altitude for the two different shear moduli can be seen below:

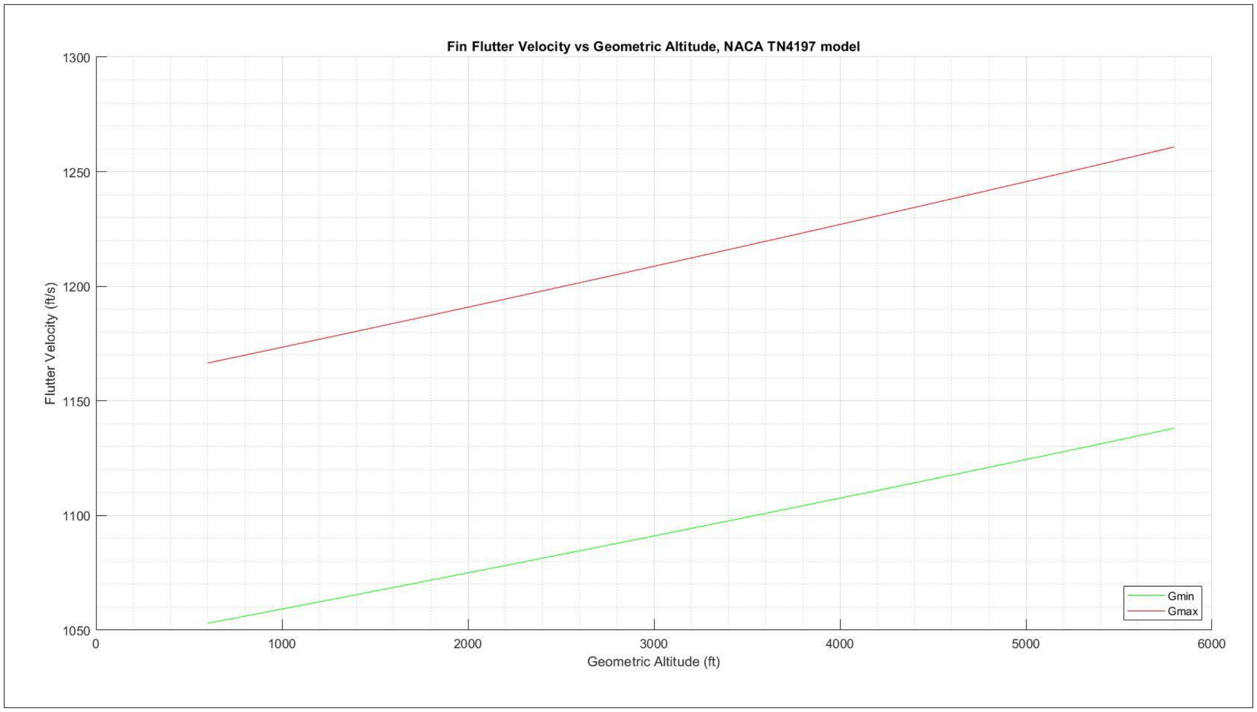

Figure 3.12: Fin Flutter Velocity Range for each shear modulus value of G10 fiberglass and as a function of geometric altitude. Results from NACA TN4197 equation.

It is worth noting that another equation is proposed in the newsletter issue 291 of Apogee Components. In this equation, the author proceeds to alter part of the denominator, claiming that the equation obtained uses a more accurate approximation of the torsional stiffness constant, which results in the following equation:

$$v_{flutter} = \alpha * \sqrt{\frac{G}{1.337 * p * \frac{AR^3 * (\lambda + 1)}{\left(\frac{t}{c}\right)^3 * (AR + 2) * 2}}}$$

where α is the speed of sound at a geopotential altitude h, G is the shear modulus of the fin material, p is the atmospheric pressure at geopotential altitude h, AR is the panel aspect ratio of the fin, λ is the taper ratio of the fin, $\frac{t}{c}$ is the thickness ratio of the fin. The team decided to use this equation as a complement to the equation derived in NACA Technical Note 4197. The following results were obtained, using a different MATLAB script:

Apogee Components Newsletter #291 equation results	Flutter Velocity (ft/s)
Minimum	1489.089
Maximum	1782.987

Table 3.2 Flutter Velocity

Once more, the minimum flutter velocity is observed to be well above the maximum velocity measured from the full scale vehicle demonstration flight (541.47ft/s according to Telemetrum) and the maximum velocity predicted (550ft/s) by OpenRocket for the full scale launch. The plot of fin flutter velocity vs geometric altitude for the two different shear moduli can be seen below, for this model:

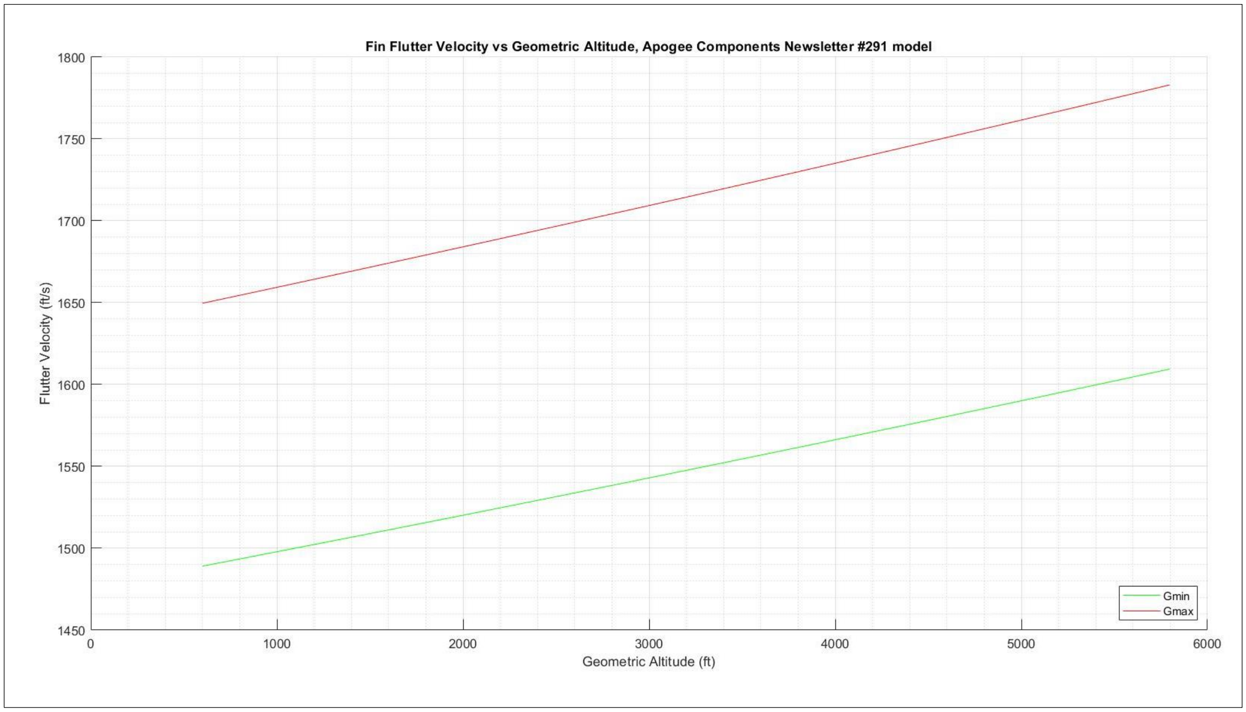

Figure 3.13: Fin Flutter Velocity Range for each shear modulus value of G10 fiberglass and as a function of geometric altitude. Results from Apogee Components Newsletter Issue 291 Equation.

In conclusion, both models show that the launch vehicle will never reach the fin flutter velocity, as the minimum flutter velocity predicted in both equations is approximately (at least) two times larger than the maximum measured and predicted velocities that the launch vehicle reaches, meaning the fins are safe from resonance phenomena and structural failure. This was also proven by demonstration, as the fins were filmed during the ascent stage from the rear-facing camera at the nose cone, where no violent oscillations were observed. Thus, no fin flutter occurred during ascent, which is the part of the flight that the fins have to ensure that the launch vehicle flies in a stable trajectory. Below, a picture of the fins during ascent, almost at maximum velocity at the end of burnout, can be seen:

Figure 3.14: Fins during ascent. Screenshot obtained from aft nosecone camera video.

3.1.2.1.4 Bulkheads

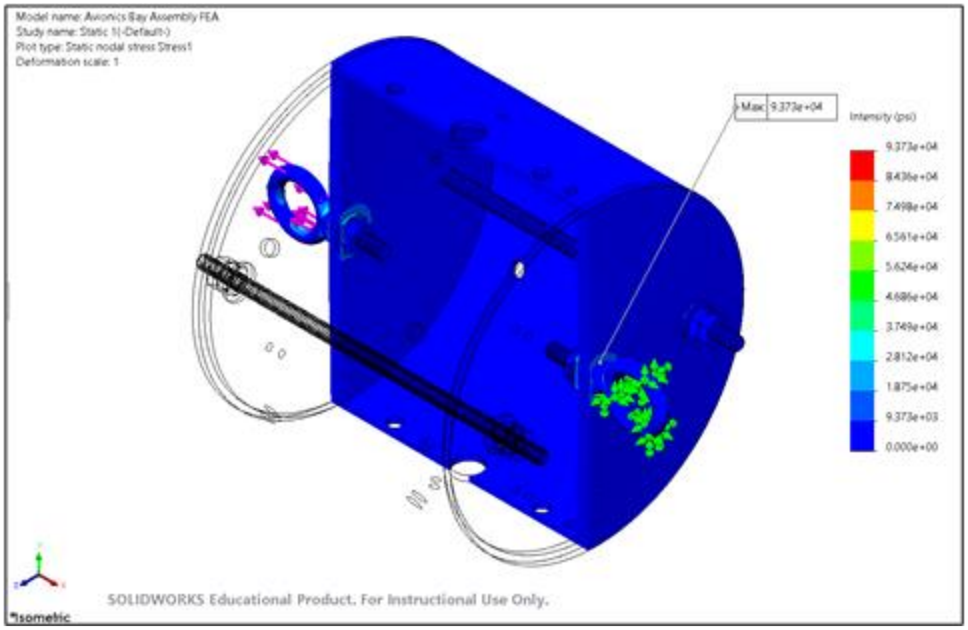

Figure 3.15: Avionics Bay Bulkhead Stress Intensity Contour Plot

The main parachute deployment simulation static study focused on the avionics bay assembly bulkheads, assuming one eye bolt is fixed while the other eye bolt is under a force of 500 lbf, which is the maximum force rating for the eye bolts. This force is part of the tension force from the main parachute deployment. The intensity stress does not overcome the minimum tensile strength of 38,000 psi for G10 fiberglass. It reaches a maximum near the cyan range on the bulkheads themselves, at the contact points with the eye bolt and the other fasteners (28120-37490 psi). This value is very close to the tensile strength value of G10 fiberglass, though in this case, the eye bolts are expected to fail first. The rest of the assembly remains below the value of 18,750 psi, in the darker blue ranges. The team is confident that the bulkhead and the eye bolts will not fail, as the design has been proven to be functional and safe from the final two successful full-scale launches that were conducted last year, where no damage was observed in the bulkheads. Note that the avionics bay shares the load from the main parachute's deployment with the upper coupler bulkheads in the payload section of the upper airframe. These bulkheads are nearly identical, and their assembly is also very similar to the avionics bay. The simulation of the payload coupler bulkhead is very similar, with higher stress appearing mostly on the point of contact and the larger part of the bulkhead remaining under 24,280 psi, in the dark blue region.

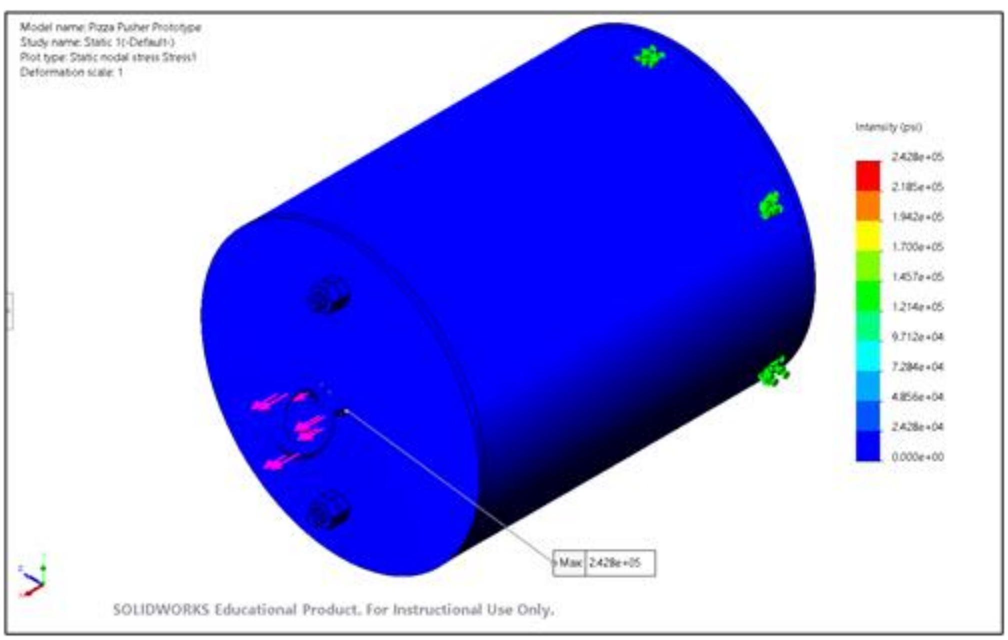

Figure 3.16: Payload Bay Bulkhead Stress Intensity Contour Plot

3.1.2.2 Electrical Elements

3.1.2.2.1 Wiring

In the nose cone, three Raspberry Pi Zeros are connected in parallel to the nose cone battery, and each Pi is connected to a camera (pointing forward, outward, and aft). This configuration minimized the complexity of the wiring and assured redundancy within the system so that a camera could fail without compromising the entire camera system. The cameras are made to begin recording as soon as they are connected to a power source. Given the limited complexity of the Raspberry Pi Zeros and the cameras, this was the most efficient way to ensure the cameras functioned reliably and with limited interaction.

3.1.2.2.2 Switches

The nose cone recording system has a button on the battery that is used to turn on the video recording system. This button is activated as the battery is loaded into the nose cone, and thus the recording is started as the battery is loaded into the nose cone. Integration of a key switch is planned for the final version of the nose cone so that the system can be activated from the launch pad, but as of now, the camera system must be activated as it is loaded into the nose cone.

3.1.2.2.3 Battery Retention

The batteries necessary to power the avionics boards are located on the altimeter sled, in two compartments, sized appropriately for each battery. To secure the batteries to the altimeter sled, the battery guard slides onto the threaded rods that run axially along the avionics bay. The battery guard has a similar shape to the altimeter sled and has the necessary slots to permit the batteries' wires to connect to their respective altimeters.

The battery necessary for the nose cone recording system is located in the nose cone with the recording equipment. This battery is placed between four vertical spars, and then two horizontal spars are screwed into place, securing the battery.

3.1.2.2.4 Retention of Avionics Boards

The avionics boards are secured to the altimeter sled using nylon mounting posts and screws. The mounting posts are hot glued to the sled and are located to allow each avionics board's respective batteries to connect. The altimeter sled is secured to the vehicle along two threaded rods and with pairs of nuts to lock it into place.

3.1.3 **Flight Reliability Confidence**

The entirety of the launch vehicle was always designed and constructed with the confidence of a successful launch. There were no shortcuts made to expedite the construction process, and all construction was done up to engineering standards. Previous years' successful launches instilled this confidence and the many simulation software's used. Whether it be SolidWorks or ANSYS used to conduct structural tests, or OpenRocket or Simulink to predetermine flight profiles, the team was never under the perception that a failure would occur. Through all simulation software, no abnormalities occurred, and a failure never posed a risk. The successful VDF and recovery of the launch vehicle demonstrated that this confidence was not for nothing.

3.1.4 **Documentation of Construction Process**

The following section will encompass the construction of the main components of the launch vehicle. The construction documentation of each sub system will be discussed in larger sections. The process also assumes that all material required had already been obtained. The steps were as followed:

- All airframes and couplers were measured and cut to length. The edges were then sanded to keep consistency between the sections.

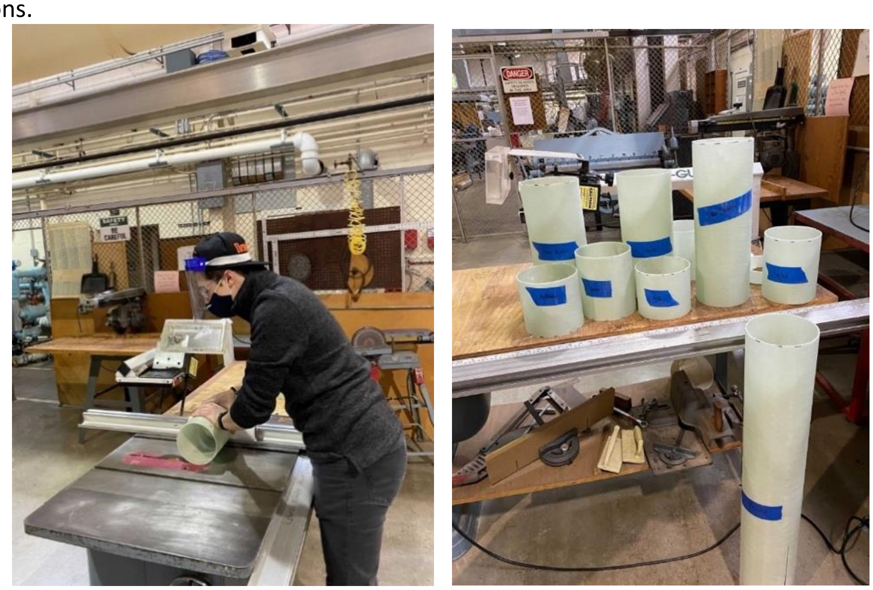

Figure 3.17: Cutting airframes and couplers to the proper length

- Bulkheads were built by epoxying a 5.777" diameter bulkhead onto a 5.998" diameter bulkhead.

Figure 3.18: Epoxying bulkheads

- Jigs were then 3D printed to allow the bulkhead to fit snug into a cylindrical extrusion. The print had the exact dimensions of all holes located on the bulkhead, which allows for much higher precision when drilling holes and keeping consistency.
- Jigs again were used to drill the radial holes on the airframe and couplers. To do this, the couplers were aligned into their respective positions in the airframe, and the jigs were placed over the airframe. The jigs were then hot glued onto the airframe to mitigate any rotational movement when drilling. Once everything was positioned, the drills were holes in their exact positioning relative to the CAD.
- After all holes were drilled, lock nuts were then epoxied into the couplers, to allow for the bolts to be threaded when the vehicle is assembled. This step is necessary because the couplers' inside is not accessible once they are put together, so the nuts would not be able to put into position otherwise.
- Once the nuts were dry, the couplers were then constructed. This requires to bulkheads that were built, two threaded rods cut to length, and then two washers and four nuts to hold them shut. This can be seen in the picture below.

Figure 3.19: Assembled Couplers

- After the couplers were built, the launch vehicle was essentially ready to be completely assembled, disregarding the other sub systems. To do this, the ABCS coupler was bolted into the booster section, the avionics bay was bolted into the lower and upper recovery sections, and the payload coupler was bolted into the payload section. The lower recovery section then slid over the top of the ABCS coupler to be held together with shear pins, and the same process was done for the upper recovery sections and payload coupler. The constructed launch vehicle can be seen below.

Figure 3.20: Fully constructed launch vehicle with PSP SL Team Leads

MFSS Manufacturing:
The following procedures were done in no particular order as the machining processes were often done simultaneously by various construction members at the Bechtel Innovation Design Center.

- The thrust plate flange and motor retainer were waterjet to design specifications.

Figure 3.21: Motor Retainer and Thrust Flange

- The fin spars were each machined in a 3-axis mill for further assembling. Each fin spar required three different operations, where the part was rotated 90 degrees with respect to its longitudinal axis, so each face could be machined. Due to the length of the part, twin vises were used as work holding.

Figure 3.22: Fin Spars Machined

- The thrust plate and the centering plate were designed and machined to fit specifically the CTI L1115 motor case. Each part required three toolpaths after the initial dovetail maker. The first toolpath created a rough geometry of the part on the top side, which allowed the team to hand-tap the radial holes. The second toolpath finished the top side contours. The last toolpath removed the bottom side (dovetail and excess material) and further finished the inner bore with shallow passes, to ensure the motor would tightly fit the inner bore. For the thrust plate, there was the added final step of hand-tapping the nine vertical holes. The eventual tolerance on the inner diameter allowed for a snug fit, which was viable to assemble with no significant force from a single person.

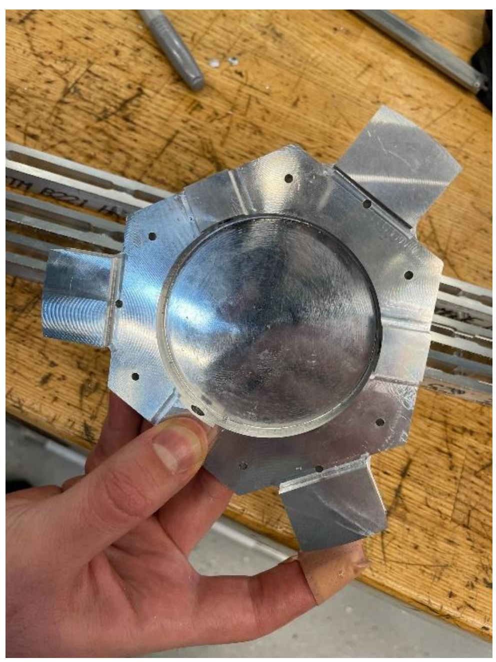

Figure 3.23: Thrust Plate before the last operation to remove the dovetail and excess material on the bottom side.

- After all components were machined to design specifications, the MFSS was assembled and integrated into the booster section. Assembly was as follows:

- Insert fin into spar slot and place nut and screw through the 5 retention holes. Repeat for other 2 fins.
- Align bottom radial spar hole with thrust plate, and thread the spar bolt through the spar and thrust plate. Repeat for other 2 fins.
- Repeat the above process for the top centering ring.
- Align thrust flange with the thrust plate and thread 6 retention bolts.
- Insert assembled MFSS into booster section.

Figure 3.24: Integration of MFSS into Booster Section

3.1.5 As-built Schematics

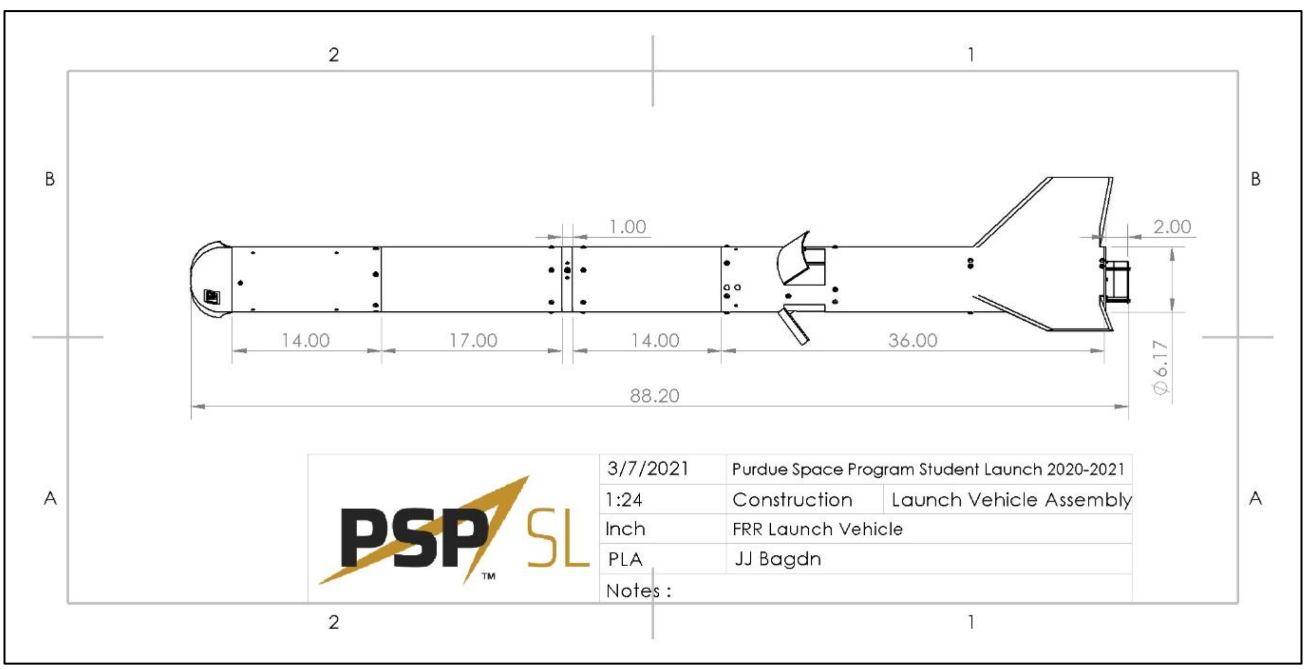

Figure 3.25: Completed Launch Vehicle

The launch vehicle is 88.2" long, measured from nose to motor, and has an outer diameter of 6.17". The vehicle is comprised of our main sections: the nosecone, payload, recovery, and booster, with the new airbrakes housed within the booster.

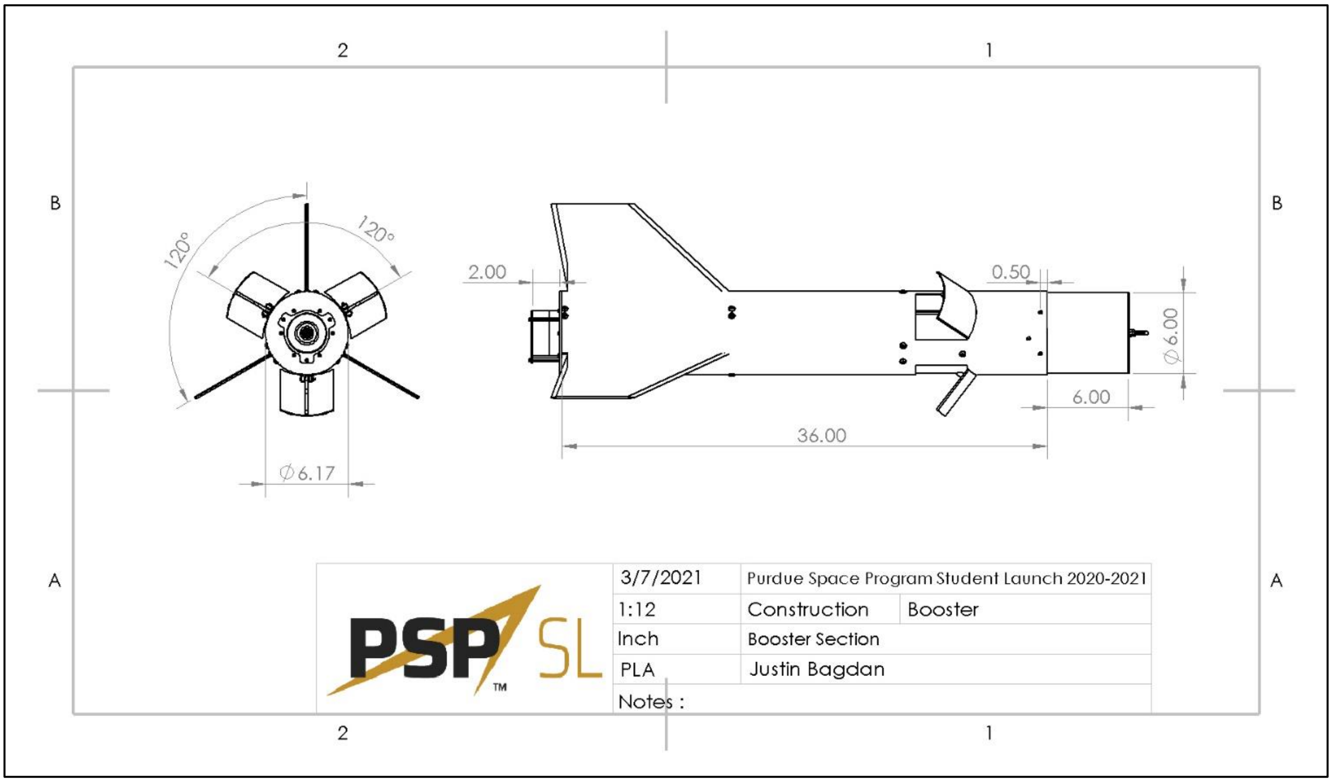

Figure 3.26: Booster Section

The booster section is the longest of the main sections at 36” and houses the airbrakes system. The fins are placed at the bottom of the booster section with 120 degrees between each one, evenly spacing them. The airbrake flaps are placed near the top of the booster and are also evenly spaced 120 degrees with 60 degrees offset from the fins so as to not interfere with each other.

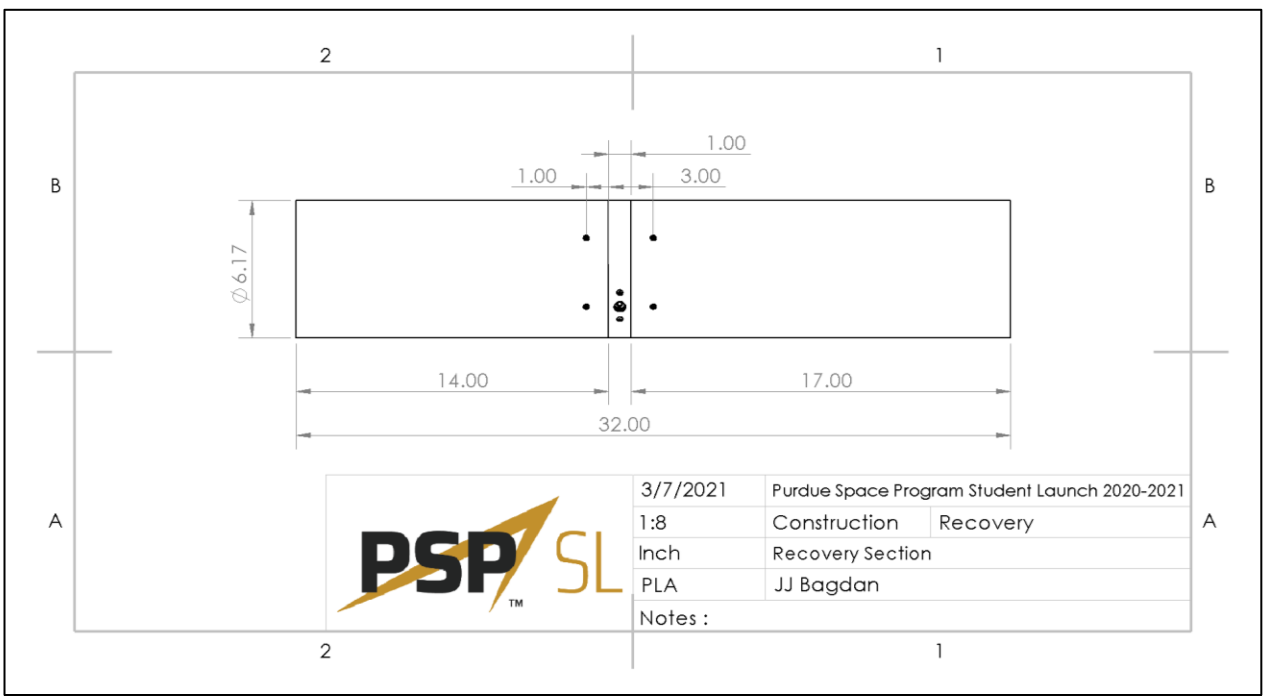

Figure 1.27. Recovery Section

The recovery section is 32” long and is split down the middle by a coupler, creating a 14” long sub-section and a 17” long sub-section. This section contains the parachutes and shock cords needed to recover the vehcile safely. It also contains the avionics bay, which houses the altimeter and ejection systems.

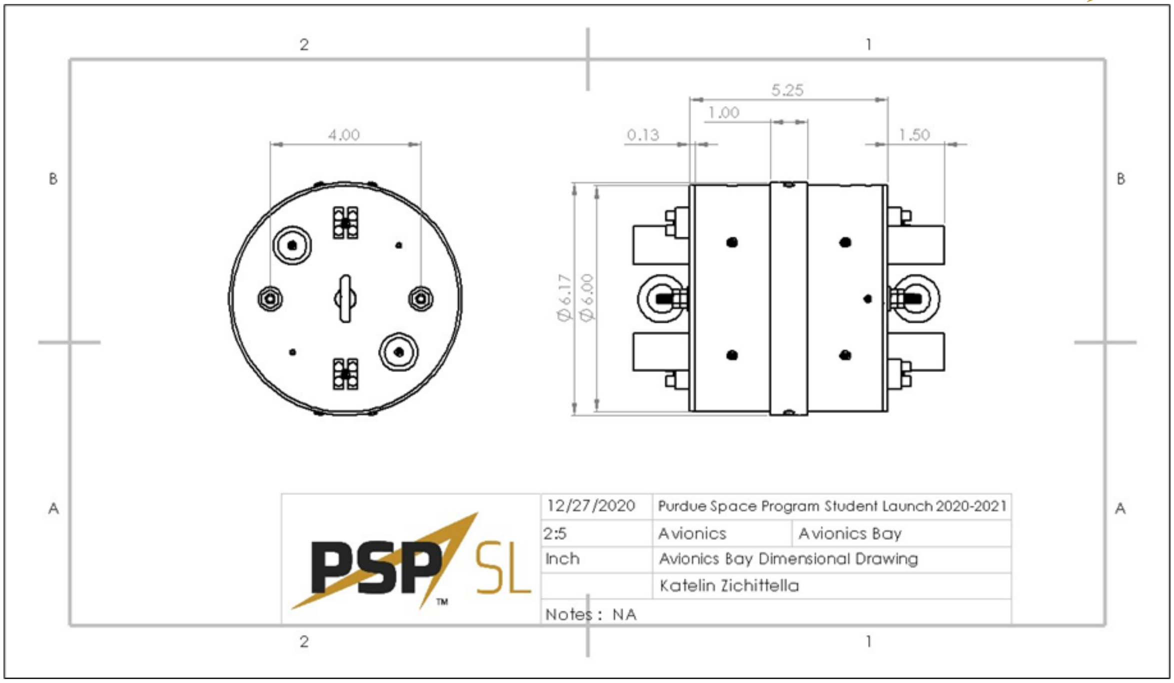

Figure 3.28: Avionics Bay Dimensional Drawing

The avionics bay has a coupler outer diameter of 6”, a coupler length of 5”, and a total length of 8.25”, including the black powder canisters. It also has a switch band around the center with a width of 1”. The avionics bay's purpose is to house the primary and redundant altimeter/ejection systems and provide an attachment point for the drogue and main parachutes.

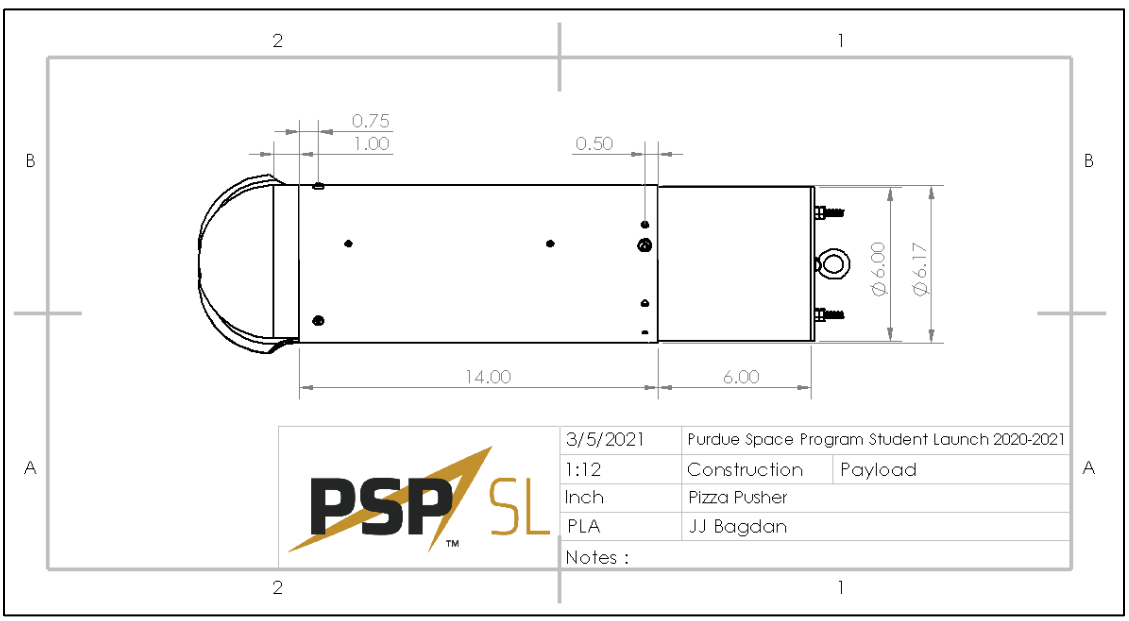

Figure 3.29: Payload Section

The payload section sits right below the nosecone and is split into a 14” and 6” sub-section, totaling 20”. The 14” sub-section has two sets of screws spaced around the body of the launch vehicle, one set in a ring .5” from the bottom of the section and the other 1” from the top. This section houses the self-righting lander and the mechanisms needed to hold and deploy it.

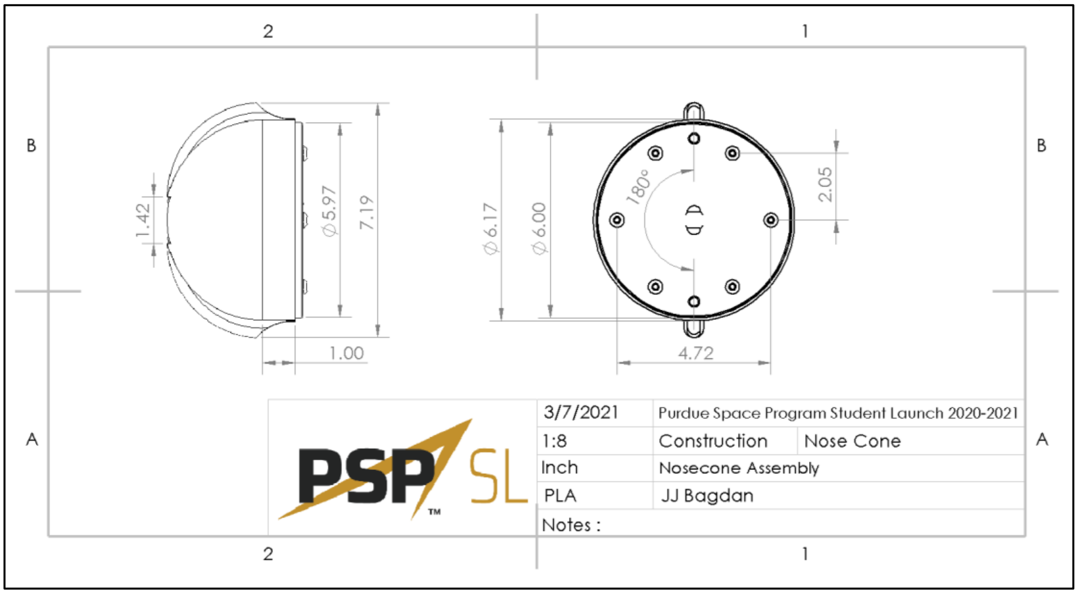

Figure 3.30: Nose Cone

The nosecone is located at the top of the launch vehicle and has a 7.19" outer and 5.97" inner diameter. It is dome-shaped to reduce surface area-induced drag and house the camera bay, which films the launch vehicle in flight.

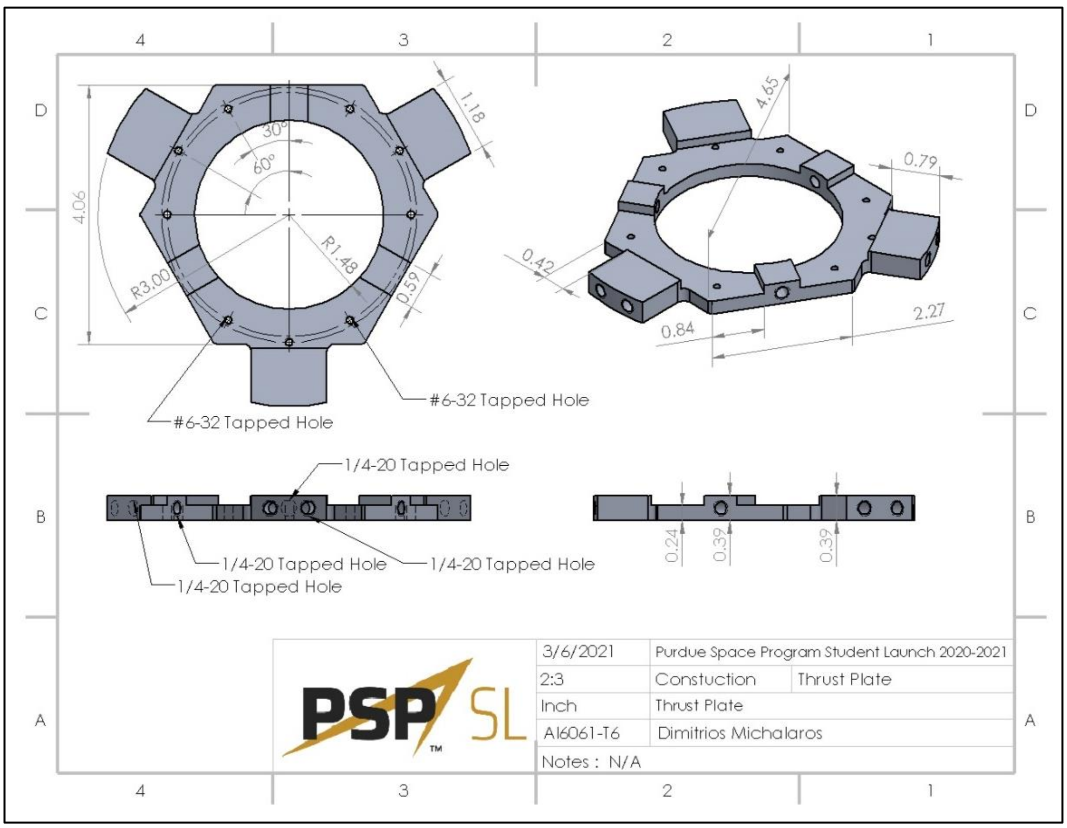

Figure 3.31: Thrust Plate

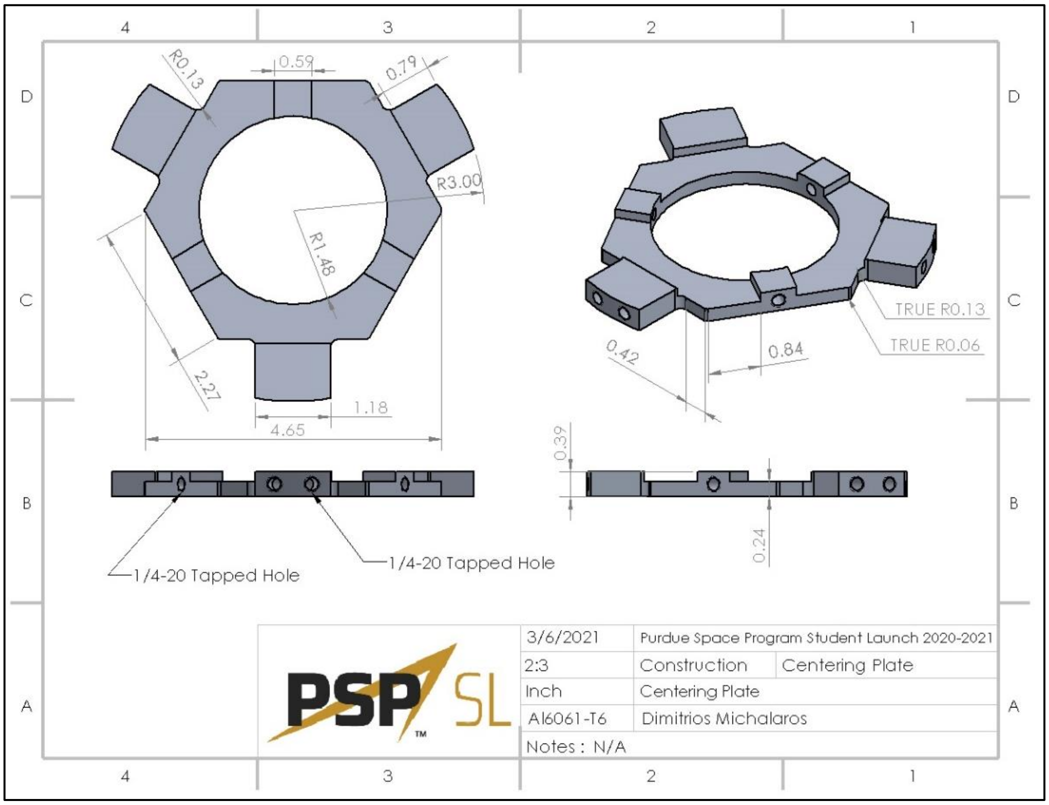

Figure 3.32: Centering Plate

The centering plate is part of the MFSS located in the booster section of the launch vehicle. The motor is placed inside the center plate, which keeps it in line and prevents dangerous vibration. It also acts as a mounting plate to connect the fin spars.

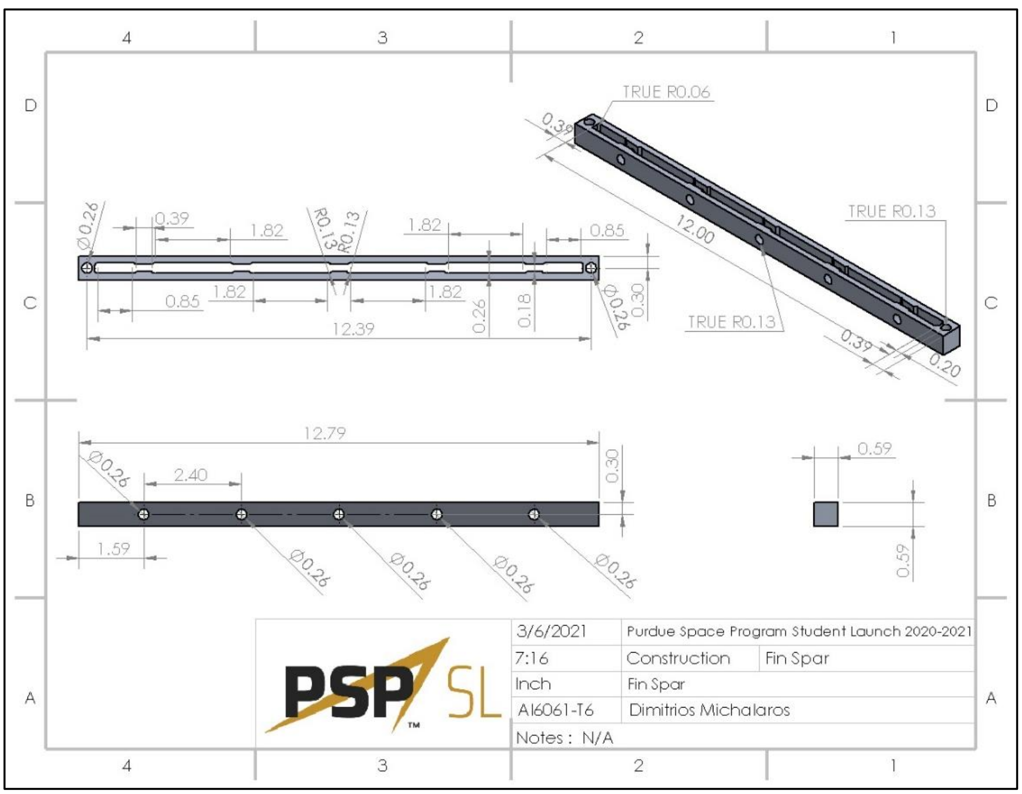

Figure 3.33: Fin Spar

The fin spars are the main feature of the MFSS and house the fins to avoid epoxy construction. The fins fit into spars and are bolted into place, while the spars themselves are attached to the centering plate.

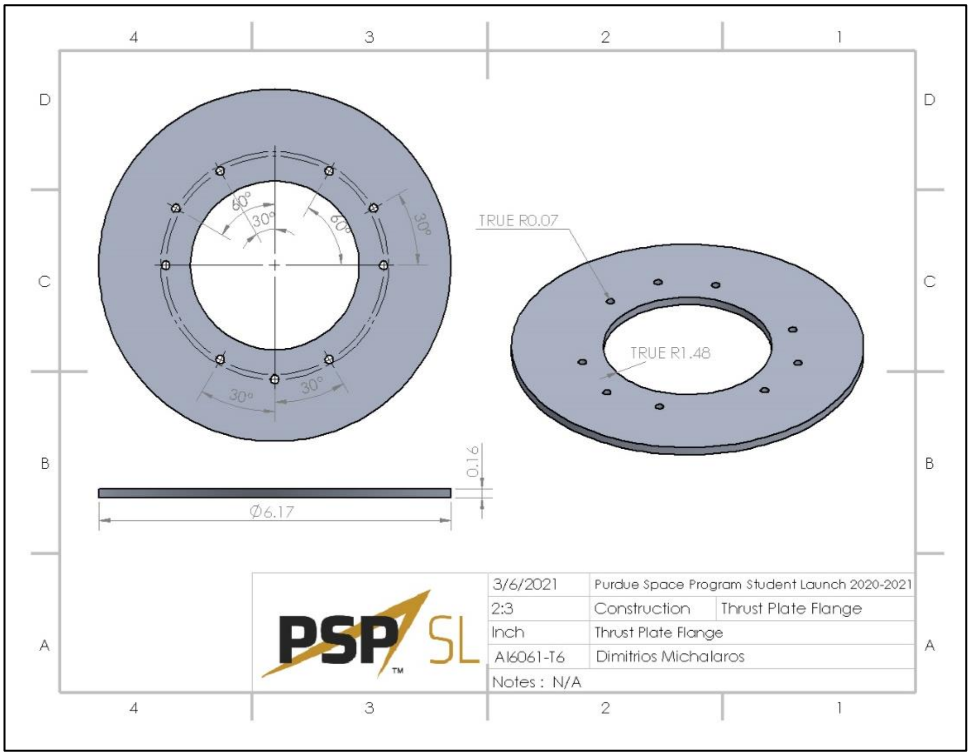

Figure 3.34: Thrust Plate Flange

The thrust plate flange is located at the bottom of the MFSS and seals the booster's bottom to prevent potentially harmful airflow into the launch vehicle. It also helps to support the MFSS and evenly distribute the force of launch throughout the body tube.

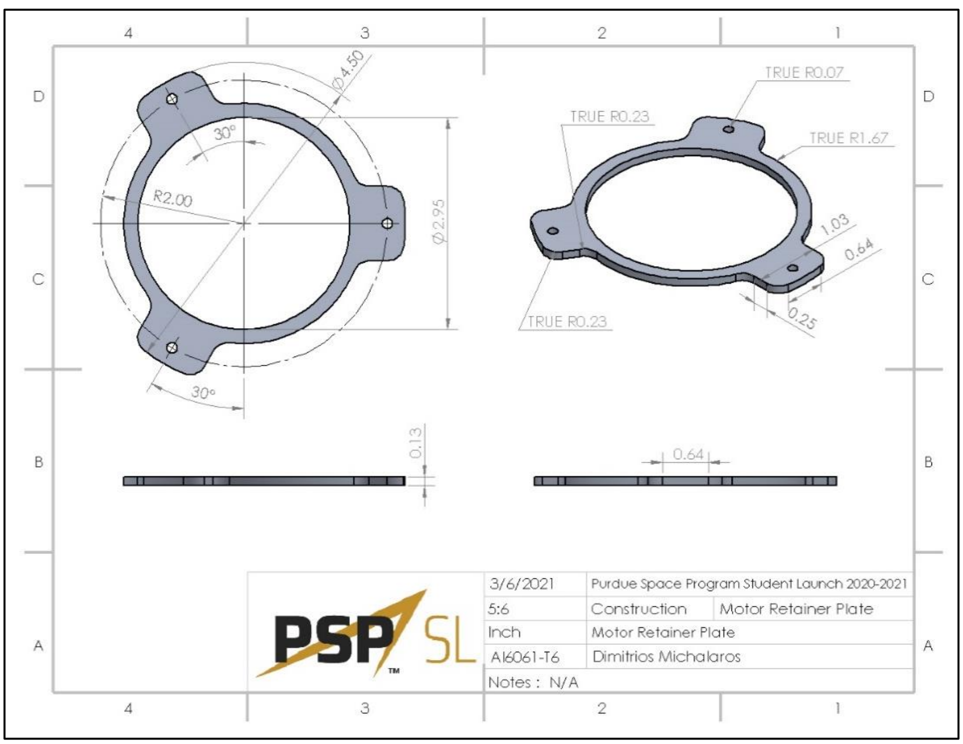

Figure 3.35: Motor Retainer Plate

The motor retainer plate is located at the very bottom of the MFSS below the motor itself. It prevents the motor from falling out of the booster once its propellent has been spent.

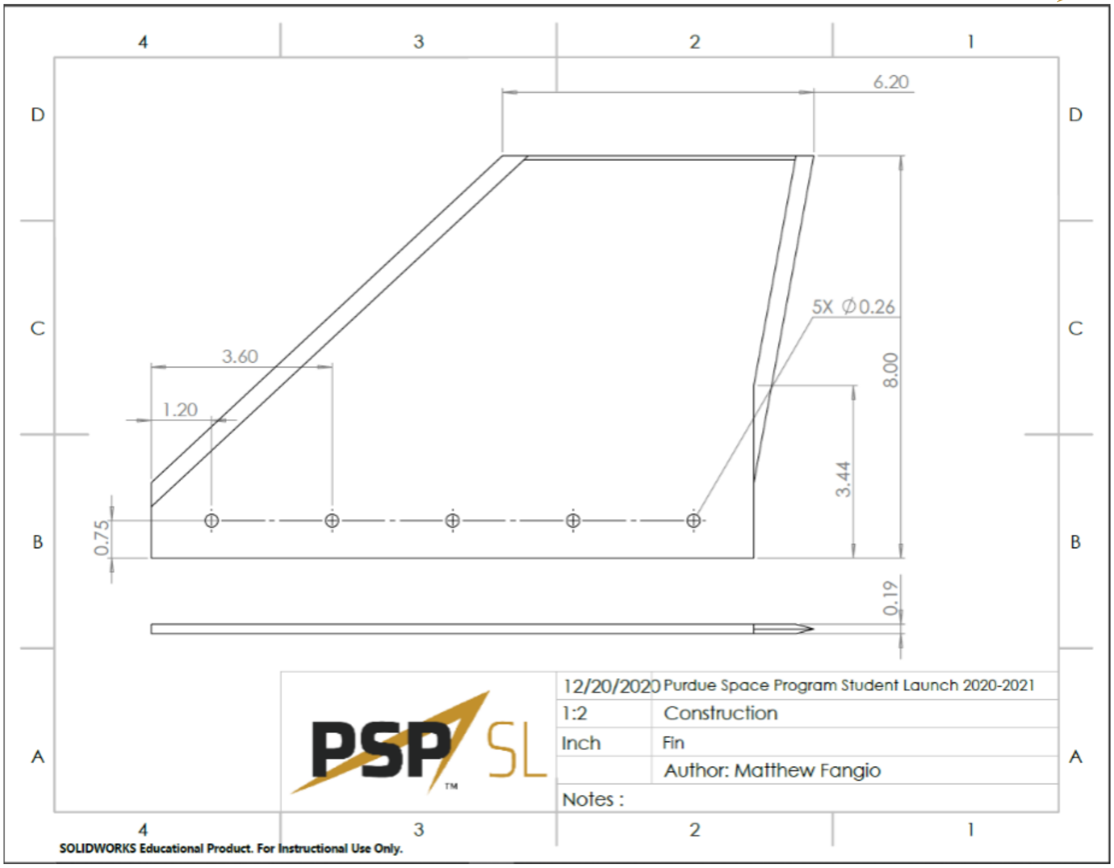

Figure 3.36: Fin

This design's fin set consists of three trapezoidal fins placed symmetrically around the launch vehicle base and constructed of G10 fiberglass. This arrangement will create the best balance between effective surface area and additional weight, allowing the launch vehicle to reach its highest altitude with an acceptable amount of stability. The entire structure is estimated to weigh 2.775 lbm, which is less than last year, as the current launch vehicle has a dedicated fin mounting structure rather than using epoxy for each fin.

3.1.6 Differences between Constructed Rocket and Earlier Models

The constructed launch vehicle differs very slightly from the early models. First, the nose cone has been updated to its final iteration. For CDR, the nose cone was continuing to go through designs to best suit the three cameras' housing. Now, the nose cone has two cut outs for the forward and outward cameras and two aerodynamic protrusions to house the aft camera while maintaining aerodynamic symmetry. This update was needed to fulfill the requirement of recording the three flight profiles, which the team decided to allocate to the nose cone.

Another design difference was the MFSS centering rings. The team utilized a CAD of the motor case from the motor supplier's website, which was used to determine the centering rings' CAD. However, after the centering rings were machined, the inner diameter's tolerance was too small, and the motor case did not fit. This required a second pass on the 4-axis mill with the centering rings so that the MFSS could securely house the motor.

The last outlying design change was incorporating a motor spacer between the aft closure and the flange plate. Again, the change was made based off the CAD provided online. The CAD did not include the top motor closure, which gave less tolerance for the ABCS in the tube's axial direction than expected. To solve this, a spacer was required to extend the motor out of the launch vehicle by just over an inch.

All these design changes were made after long discussions. Each change was thoroughly considered, and many other solutions were also considered. In the end, the choice the team made was made with the vehicle integrity kept in mind, and no shortcuts were taken. At the conclusion of the successful VDF, the team deemed these design changes justifiable.

31

3.2 Recovery Subsystem

3.2.1 As-Built and As-Tested Recovery System

3.2.1.1 Structural Elements

3.2.1.1.1 Coupler

To connect the upper and lower recovery sections of the vehicle and house all avionics components, a coupler with an outer diameter of 5.998", an inner diameter of 5.775", and an overall length of 5" is used. The coupler is made of the same material as the rest of the airframe (G12 fiberglass), and its dimensions were chosen to provide the required volume for all the necessary avionics components. Additionally, the coupler has two bulkheads on the forward and aft ends to provide support for the rest of the recovery components.

The coupler includes two ½” holes for access to the key switches used for the altimeters, four corresponding holes used to secure the switch holders to the coupler with ½” 6-32 screws and hex nuts, twelve ¼” holes for attaching the coupler to the upper and lower recovery sections of the vehicle, and four #8 static port holes on the forward end of the coupler to allow the altimeters to determine the current altitude.

3.2.1.1.2 Switch Band

The switch band has an inner diameter of 6”, an outer diameter of 6.17” (allowing it to slide over the coupler), and a length of 1” (allowing it to accommodate the key switch holes while adding as little additional length to the vehicle as possible). Likewise, it has ½” holes for accessing the key switches and four holes for the 6-32 screws and hex nuts. The switch band is epoxied around the center of the coupler and is also made of G12 fiberglass.

3.2.1.1.3 Bulkheads

One G10 fiberglass bulkhead with the same outer and inner diameters as the coupler and an overall thickness of 0.25” seals each end of the avionics bay. Each bulkhead has one ¼” hole in the center to fit an eyebolt, two ¼” holes located 2” away on either side to fit the threaded rods, and six additional holes of varying sizes spaced evenly about the same circumference as the threaded rod holes. These holes are used to secure two 8g capacity black powder canisters (#8 holes) and two terminal blocks (#4 holes), which are placed on opposite sides from each other on the bulkhead. The remaining two holes (#6 holes) are used to feed the lighter connection wires from the coupler's interior to the terminal blocks.

3.2.1.1.4 Switch Holder

In order to retain the key switches which will activate the altimeters, two switch holders were designed to be secured to the interior of the avionics coupler under the switch band, allowing access once the vehicle was fully assembled. The switch holders have the same radius as the coupler's interior and have two holes each for the 6-32 screws and hex nuts which secure them to the switch band. Finally, each switch holder has a ½" hole, which allows the key switches to be securely fastened to them. The switch holder was 3D printed out of PLA since it is not a major structural component.

3.2.1.1.5 Altimeter Sled and Battery Guard

Both altimeters and their respective batteries are mounted to the vehicle using the altimeter sled, with the batteries being secured by the battery guard. The altimeter sled was designed with holes to insert nylon mounting posts for the altimeters and compartments to hold the batteries. It was 3D printed out of PLA and attaches to the vehicle via the two threaded rods that run axially through the avionics bay. Finally, the battery guard attaches to the avionics bay in a similar fashion, following the altimeter sled in order to retain the batteries and permit the wires to connect to their respective altimeters.

3.2.1.1.6 Attachment Hardware and Heat Shielding

The drogue parachute is attached to a 30’ long, 3/8” wide tubular Kevlar shock cord, while the main parachute is attached to a 60’ long, 3/8” wide tubular Kevlar shock cord. The shock cords are attached to the parachutes and ¼” stainless steel bulkhead eyebolts via ¼” stainless steel quick links. To protect the parachutes from hot ejection charge gases, an 18” to a side square Nomex blanket is wrapped around each parachute while they are packed inside the airframe sections.

3.2.1.2 Electrical Elements

3.2.1.2.1 Primary and Redundant Altimeters and Batteries

The primary altimeter is the Altus Metrum TeleMetrum, which operates with a 3.7V LiPo battery. This altimeter was chosen because of its high reliability in many past launches as well as its GPS/live telemetry capabilities. The redundant altimeter is the PerfectFlite StratoLoggerCF, which differs from the Missile Works RRC3+ Sport used in past years. This change was made due to configuration changes in the vehicle that necessitated a relatively short avionics bay (5” in length), so the RRC3+ Sport would be a tight fit. The StratoLoggerCF is much shorter (only 2”) and has all of the capabilities of the RRC3+ Sport, so it was chosen instead to serve as the redundant altimeter. The team prioritizes utilizing two altimeters of different makes/models in order to increase the likelihood that if a failure occurs in the primary system, the same one will not also occur in the redundant system, resulting in catastrophic failure.

Figure 3.37: TeleMetrum Altimeter

Figure 3.38: StratoLoggerCF Altimeter

3.2.1.2.2 Switches

Key switches are mounted on radially opposite sides of the coupler and allow for the activation of the avionics systems. Key switches were selected because they cannot be deactivated without a key, preventing accidental in-flight disarmament. The switches are located entirely within the coupler in switch holders to reduce their aerodynamic effect, keep them protected from external forces and debris, and prevent landing damage. These key switches replace previously used rocker switches, which had a high risk of in-flight disarmament.

Figure 3.39: Key Switch

3.2.1.2.3 Connectors

3.2.1.2.3.1 Switch JST Connectors

The key switches are connected to the altimeters via wires with JST connections. One connector is located on the end of the switch wiring while the other connector is located on the end of the wire connecting to each altimeter. JST connectors allow for easier placement of components in the avionics bay while preserving the wired connection between the switches and the altimeters.

3.2.1.2.3.2 Exterior Terminal Blocks

Because the lighters are not long enough to reach from the altimeters to the black powder canisters, exterior terminal blocks have been implemented on the outside of the avionics bay bulkheads, one primary and one redundant for each bulkhead. Simple wires connect the drogue and main ports of each altimeter to the terminal blocks through a small hole in the bulkhead, and lighters connect the terminal blocks to the black powder in the black powder canisters.

3.2.1.3 Redundancy

Full redundancy is achieved in the avionics electrical components by utilizing completely independent circuits for the primary and redundant deployment systems. These circuits include wiring from each altimeter to its dedicated switch, battery, terminal block, and black powder canister for drogue parachute deployment, and terminal block and black powder canister for main parachute deployment. Two altimeters of different makes/models are used in order to increase the likelihood that if a failure occurs in the primary system, the same one will not also occur in the redundant system, resulting in catastrophic failure. Additionally, the redundant main ejection charge is programmed to go off 200' lower than the primary main ejection charge, the redundant drogue ejection charge is programmed to go off 2s after the primary drogue ejection charge, and the redundant ejection charges for both parachutes contain 1g more of black powder than the primary ejection charges. These factors all work together to contribute to overall reliability and success in separation and deployment processes as prescribed in the mission requirements.

3.2.1.4 As-Built Parachute Sizes and Descent Rates

3.2.1.4.1 Parachutes

The selected drogue parachute is a 24" diameter Fruity Chutes Classic Elliptical parachute. This parachute was chosen because it is especially compact and lightweight, and it has a relatively high drag coefficient for its size (1.55). It was also used last year with great success. The selected main parachute is a 144" diameter Rocketman High-Performance CD 2.2 parachute, which differs from the 120" SkyAngle CERT-3 XXL parachute used last year. The reason this change was made was that it was retroactively determined that the SkyAngle parachute was undersized for the vehicle last year, and the team is sizing the vehicle similarly this year. Therefore, a search was made for a larger main parachute that was not excessively expensive. Considering factors such as cost, diameter, and maximum vehicle weight, the search was narrowed down to the aforementioned Rocketman parachute. This parachute can support a vehicle with a maximum weight of around 54lbm, is also quite compact and lightweight, and has a strong listed drag coefficient (2.2). Both main and drogue parachutes are made of 1.1 oz ripstop nylon.

With the current designed vehicle weight, the chosen 144" diameter Rocketman High-Performance parachute was verified with the Simulink simulation to balance the maximum landing kinetic energy and maximum descent time requirements. Also, deploying the main parachute specifically at 900' AGL balances the payload system's need to have enough time to separate from the vehicle and the requirement that the descent time is under 90 seconds.

Figure 3.40: Drogue Parachute

Figure 3.41: Main Parachute

3.2.1.4.2 Descent Rate Table

Descent Under	Descent Velocity (ft/s)
Drogue	89.9
Main	15.0
Lander	21.6

Table 3.3: Simulink Vehicle and Lander Descent Velocities

3.2.1.5 Ejection Charges and Sizing

3.2.1.5.1 Ejection Charges

The ejection charge type used is FFFFg black powder stored in black powder canisters on the bulkheads of the avionics bay. Each bulkhead supports the ejection canisters for either the drogue or the main parachute and has both a primary and a redundant charge in separate canisters. The forward charges eject the main parachute, and the aft charges eject the drogue parachute. These charges have been sized based on the airframe's interior volume on either side of the avionics bay. The redundant charges contain 1g more of black powder to ensure ejection occurs at the expected times in flight. Black powder was chosen as the ejection charge because it is relatively lightweight, quite reliable, has been used successfully in many past launches, and avoids highly regulated high-pressure gas. The team avoids the use of pressurized gas ejection systems due to the regulatory complexity around its use. The ideal calculated amounts of black powder to use are 3g for the main parachute's primary charge, 4g for the redundant charge for the main parachute, 2g for the primary charge for the drogue parachute, and 3g for the redundant charge for the drogue parachute.

3.2.1.5.2 Ejection Charge Sizing

Both parachutes are deployed via black powder charges initiated by redundant altimeters. The primary drogue charge ignites at apogee with the redundant at apogee plus two seconds, and the primary main charge ignites at 900' AGL with the redundant at 700' AGL. The primary main charge contains 3g of FFFFg black powder, and the redundant main charge contains 4g of black powder (3g + 1g) to ensure complete separation. Similarly, the primary drogue charge contains 2g of black powder, and the redundant drogue charge contains 3g of black powder.

By calculating the cross-sectional area of a single 4-40 shear pin and multiplying it by the shear strength of nylon, it is possible to calculate the force necessary to shear a single shear pin.

$$Area_{Pin} = \pi R^2$$
$$Area_{Pin} = 3.1415 \cdot (0.056in)^2 = 0.009852in^2$$
$$Force_{Pin,Failure} = Area_{Pin} \cdot \tau_{Nylon}$$
$$Force_{Pin,Failure} = 0.009852in^2 \cdot 10000psi = 98.52lbf$$

From there, one can determine how much force is required to shear four pins and use that to calculate how much pressure is necessary on a 6" diameter bulkhead to sufficiently shear all four pins.

$$4 \cdot Force_{Pin,Failure} = 394.1lbf$$
$$Area_{Bulkhead} = \pi R^2$$
$$Area_{Bulkhead} = 3.1415 \cdot (3in)^2 = 28.27in^2$$
$$P_{Bulkhead} = \frac{4 \cdot Force_{Pin,Failure}}{Area_{Bulkhead}} = \frac{394.1lbf}{28.27in^2} = 13.94psi$$

By using the equation below (where 0.006 is the pressure coefficient corresponding to a desired pressure on the bulkhead of 13.94psi, D is the diameter of the airframe, L is the length of the airframe section, and G is the mass of black powder in each canister in grams), the amount of black powder needed to sufficiently shear all the nylon shear pins can be calculated. The final value is multiplied by 1.2 and always rounded up as a safety factor.

$$G = Mass_{BP} = C_P \cdot D^2 \cdot L \cdot 1.2$$

Upper Recovery Section Side (Main) Primary Ejection Charge

$$G = Mass_{BP} = 0.006 \cdot (6in)^2 \cdot 9.25 \cdot 1.2 \approx 3 \; grams \; of \; black \; powder$$

Upper Recovery Section Side (Main) Redundant Ejection Charge

$$G = 3g + 1g = 4 \; grams \; of \; black \; powder$$

Lower Recovery Section Side (Drogue) Primary Ejection Charge

$$G = Mass_{BP} = 0.006 \cdot (6in)^2 \cdot 6.25 \cdot 1.2 \approx 2 \; grams \; of \; black \; powder$$

Lower Recovery Section Side (Drogue) Redundant Ejection Charge

$$G = 2g + 1g = 3 \; grams \; of \; black \; powder$$

3.2.1.6 Drawings and Schematics of Structural and Electrical Assembly

3.2.1.6.1 Avionics Bay Assembly and Sub-Assemblies (CAD)

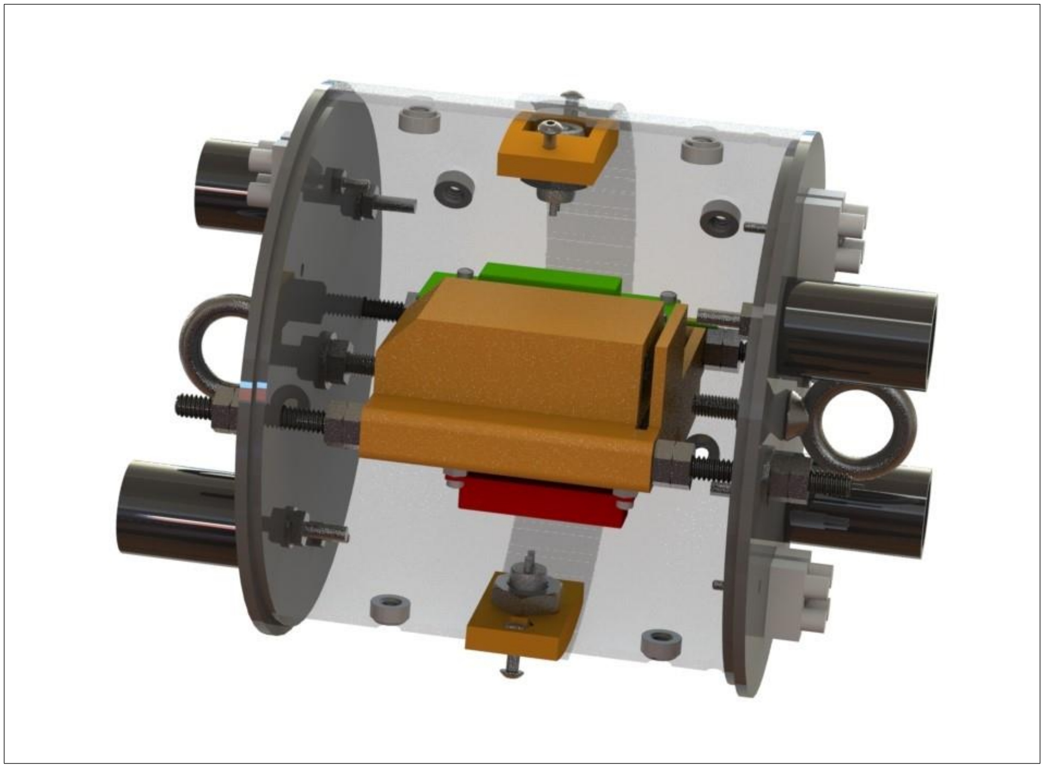

Figure 3.42: Section View of Avionics Bay Assembly

Figure 3.43: Avionics Coupler Sub-Assembly

Figure 3.44: Avionics Bulkhead Sub-Assembly

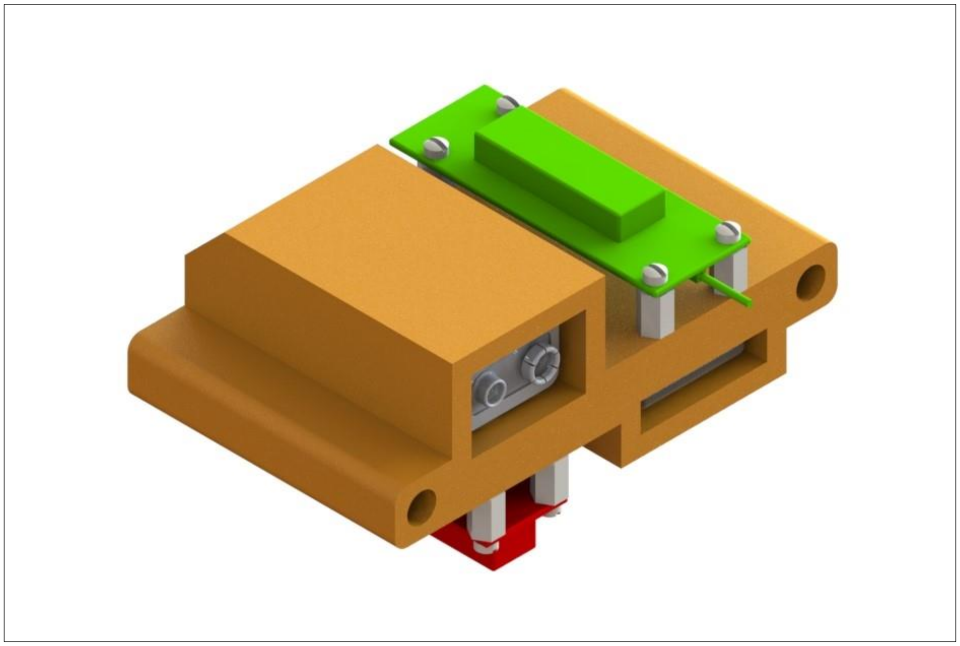

Figure 3.45: Altimeter Sled Sub-Assembly

3.2.1.6.2 Custom-Designed and 3D Printed Parts (Dimensional Drawings)

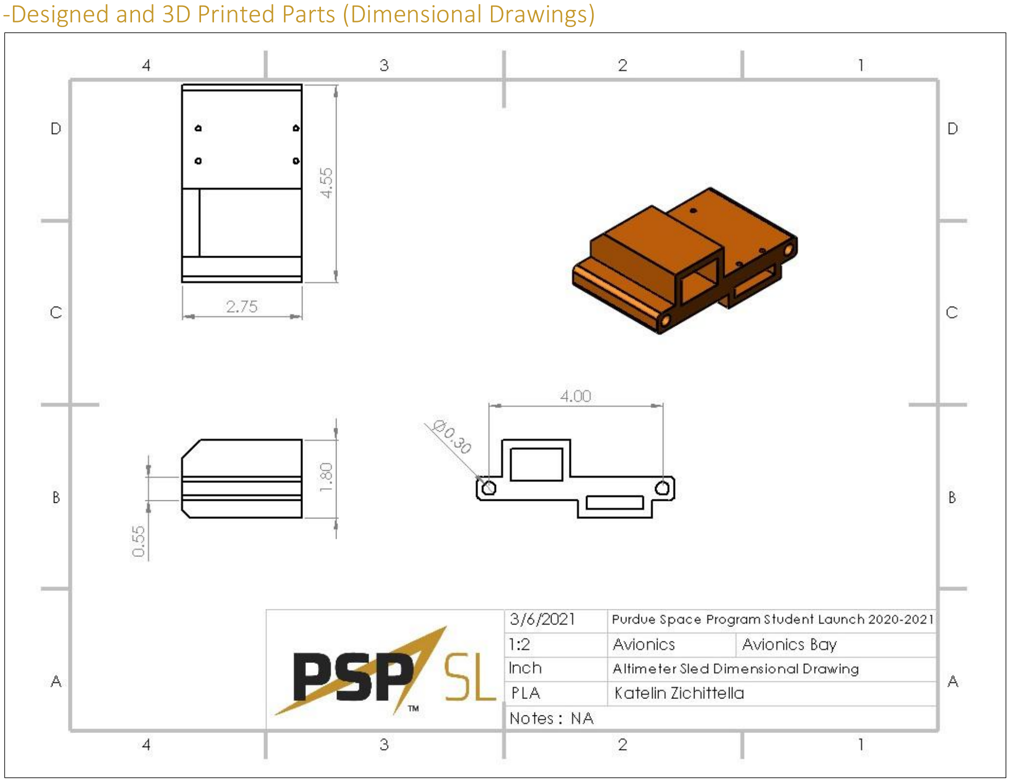

Figure 3.46: Altimeter Sled Dimensional Drawing

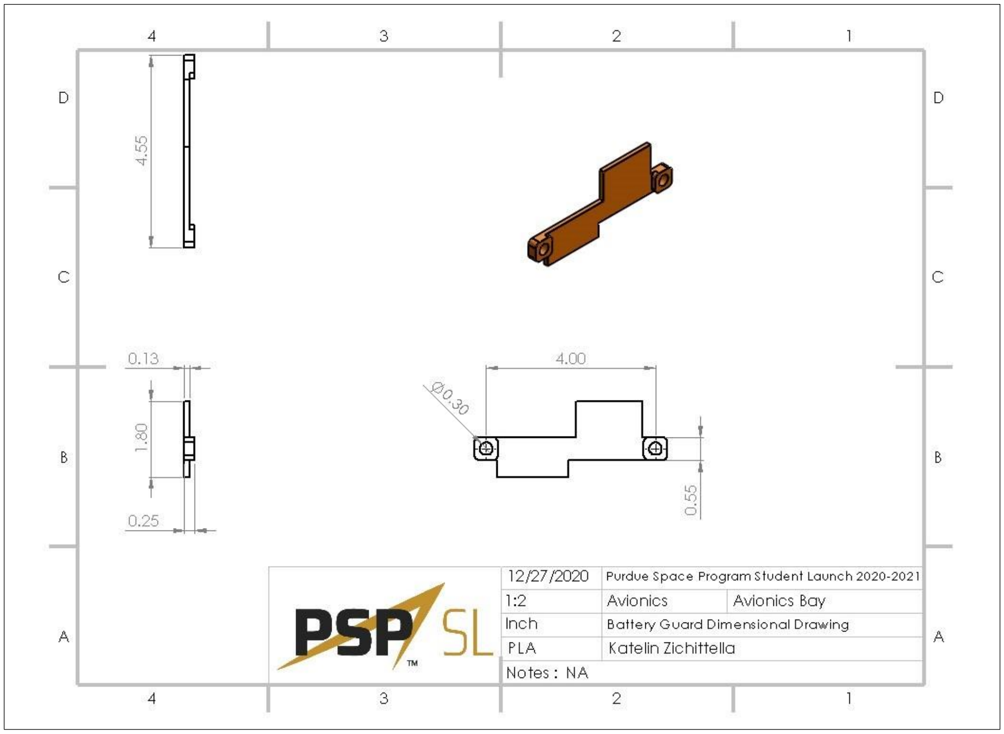

Figure 3.47: Battery Guard Dimensional Drawing

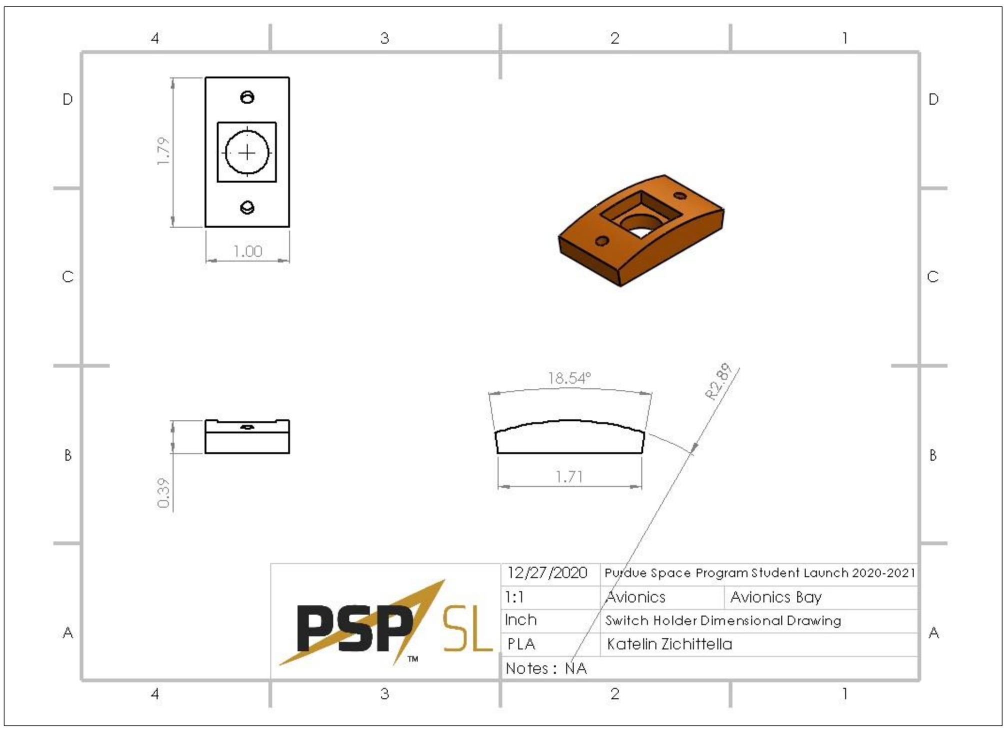

Figure 3.48: Switch Holder Dimensional Drawing

3.2.1.6.3 Wiring Diagram

The primary and redundant avionics system wiring diagrams are seen in the schematic below. These circuits are completely independent, preserving redundancy for the entire subsystem. In the primary recovery system, a key switch connects to the primary battery source and its altimeter, which in turn connects to main and drogue parachute ejection charges via lighters. The redundant recovery system follows the same approach in an independent system. The schematic labels these components as well as the power and signal connections.

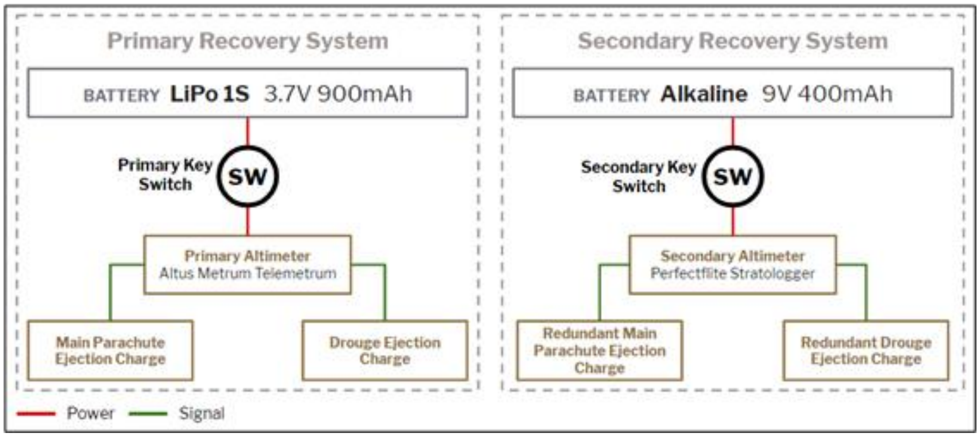

Figure 3.49: Avionics Wiring Diagram

3.2.1.7 Rocket-Locating Transmitters

The launch vehicle's primary tracking device is the TeleMetrum altimeter, which contains a 70 cm ham-band transceiver for telemetry downlink and an onboard, integrated GPS receiver. The RF transceiver's output power is 40 mW, and the specific frequency used by the team is 434.55 MHz. From past experience, it is known that the transmitter on the TeleMetrum has a range of at least one mile and is very reliable in establishing and maintaining a connection to the ground station during flight. This connection (to a standard laptop) is made using a TeleDongle and Yagi Arrow 3 Element antenna.

All major vehicle sections (tethered or otherwise) are also equipped with active GPS tracker/transmitters. These provide constant position information for the entire vehicle during flight, easing recovery in the event of an accident. In the previous year's project, the team temporarily lost a section of the launch vehicle due to lower-than-expected cloud cover and shock cord failure. While the section was recovered a month later, the team has decided that to avoid any risk of section loss, COTS GPS tracking modules should be added to each independent vehicle section (in this case, this meant adding trackers to the payload and booster sections). The team has selected the EggTimer Rocketry EggFinder system, as it provides long-range tracking, is low in weight, and is low in power consumption. The team has created a 3D-printed housing that contains the GPS module, battery, and a key switch. The selected battery can provide enough power for more than 4 hours of tracking, enough for 2 hours of pad time and 2 hours of vehicle location time. There are two of these modules in the vehicle, one in each of the breakpoint couplers, where they do not interfere with the other vehicle systems. One of the assembled tracking modules can be seen below in figure 3.38.

Figure 3.50: Complete GPS Tracking Module

3.2.2 **Sensitivity of the Recovery System**

Avionics and recovery components that could possibly be sensitive to onboard devices that generate electromagnetic fields (such as transmitters) include the lighters and altimeters that initiate parachute ejection. However, in several years of participating in the competition, the team has never experienced a lighter or altimeter malfunctioning due to an electromagnetic field. In fact, the TeleMetrum altimeter itself contains a transmitter that relays altitude and GPS telemetry to the ground station during flight and is designed to not negatively disrupt the lighters it is connected to as well as other altimeters and lighters in the vicinity. As for the other transmitters in the vehicle, including the XBee in the lander and the EggFinder trackers in the payload and booster couplers, they are shielded from interfering with the avionics and recovery system by a metallic case and large amounts of vehicle hardware, respectively.

3.3 Mission Performance Predictions

3.3.1 Flight Profile Simulations

3.3.1.1 Altitude Predictions with Simulated Vehicle Data

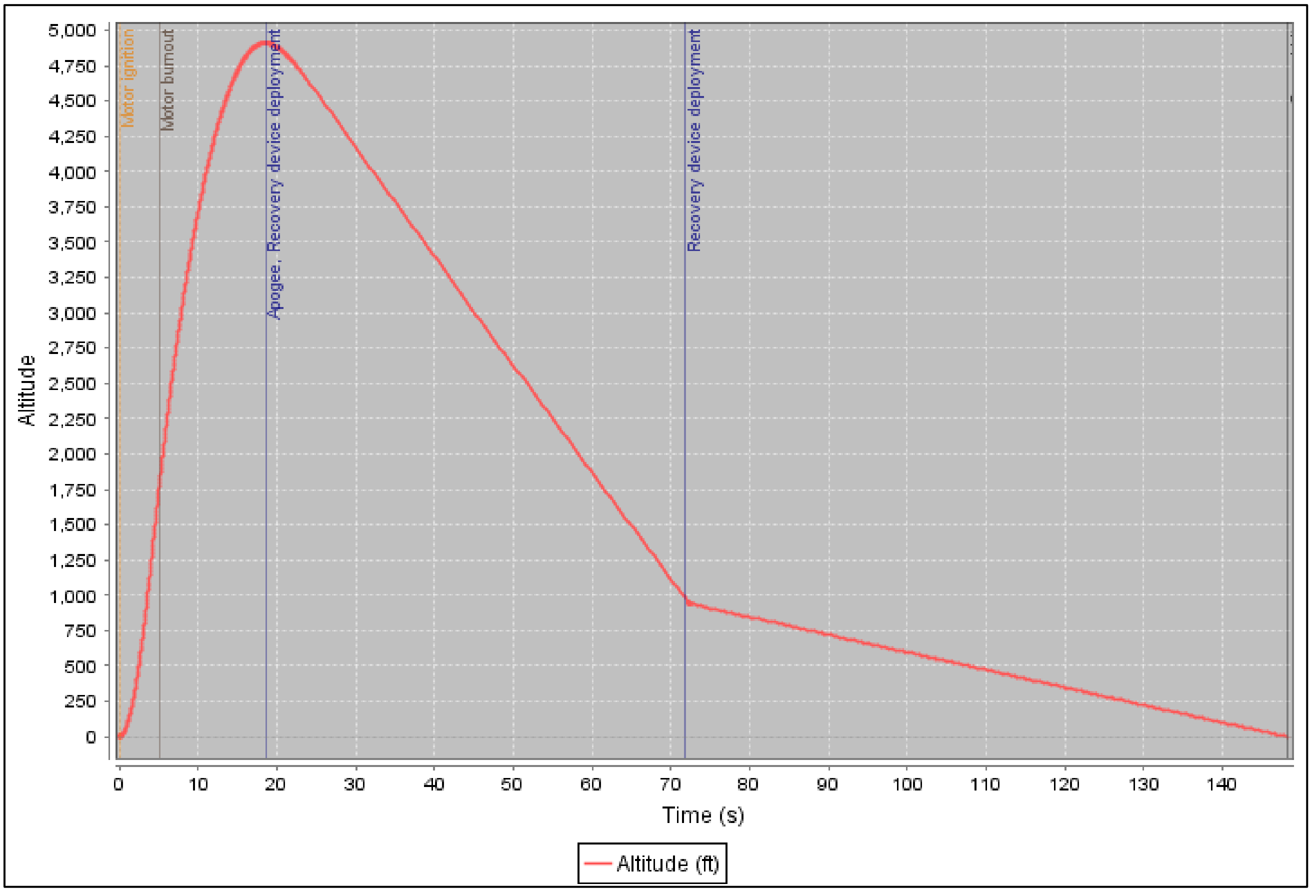

Figure 3.51: OpenRocket Altitude vs. Time Simulation of *Ideal Case at Purdue Dairy*

As shown in the graph above, the launch vehicle is simulated to reach a maximum altitude of around 5232' above ground level. This is well over the target altitude of 4100ft. However, the team will be adding nose ballast to help combat this issue. Furthermore, while the altitude results from the full-scale launch can be attributed to the airbrakes' issue, the team will be ensuring the correct functioning of the airbrakes for the final launch in April. This should further bring down the altitude reached – thus meeting the NASA requirement of 4100ft. Nonetheless, the additional ballast is a necessary addition to the final model. The 0 mph, 0-degree, ideal case is very unlikely to occur on launch day at Purdue Dairy as the current prediction of launch day winds is around 10mph.

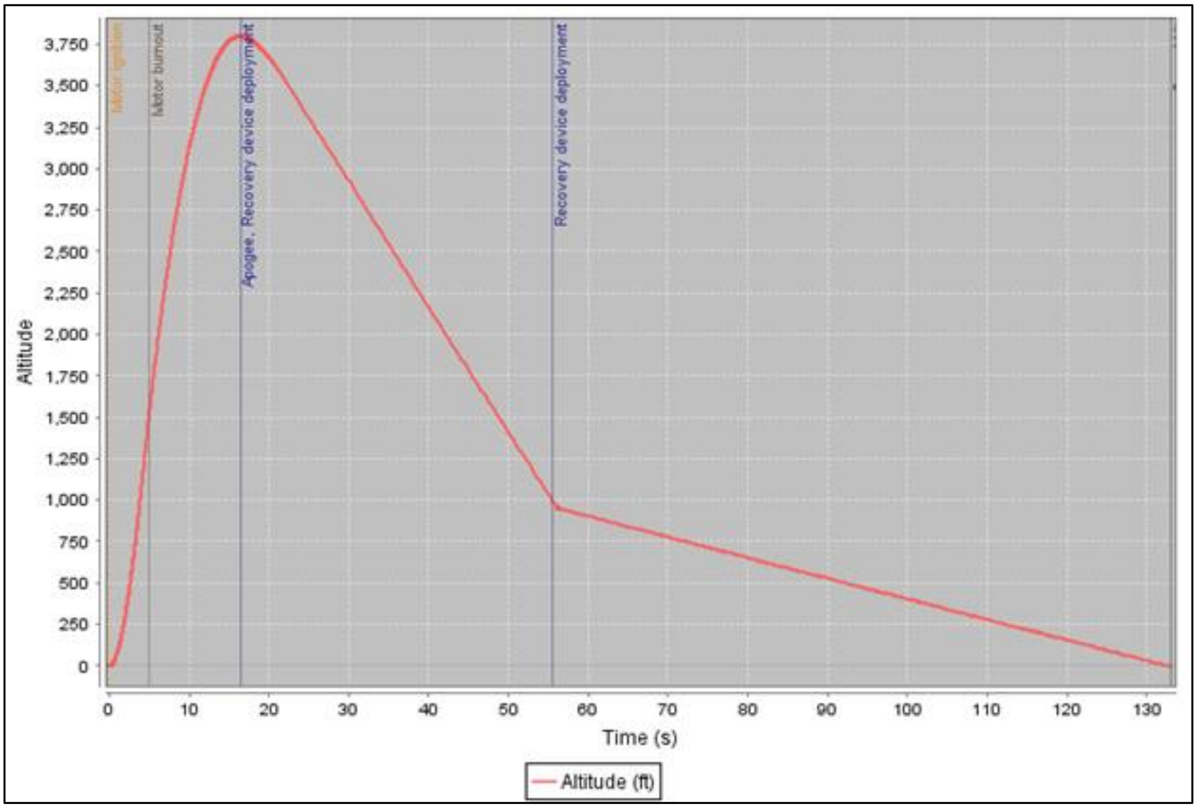

Figure 3.52: OpenRocket Altitude vs. Time Simulation of the 20mph, 15 deg incline case at Purdue Dairy

The case of 15-degree inclination and 20mph winds was chosen to be the worst-case scenario that the team simulated. As can be seen in the graph above, the launch vehicle would reach a maximum altitude of around 3798', which is considerably lower than the 4100' target altitude. Additionally, this would be the altitude without airbrakes, which means that the maximum altitude will be lower than the one simulated. However, as mentioned, the case was only simulated to assess the vehicle's worst possible performance. The case is very unlikely to occur given the launch day predictions of around 10mph.

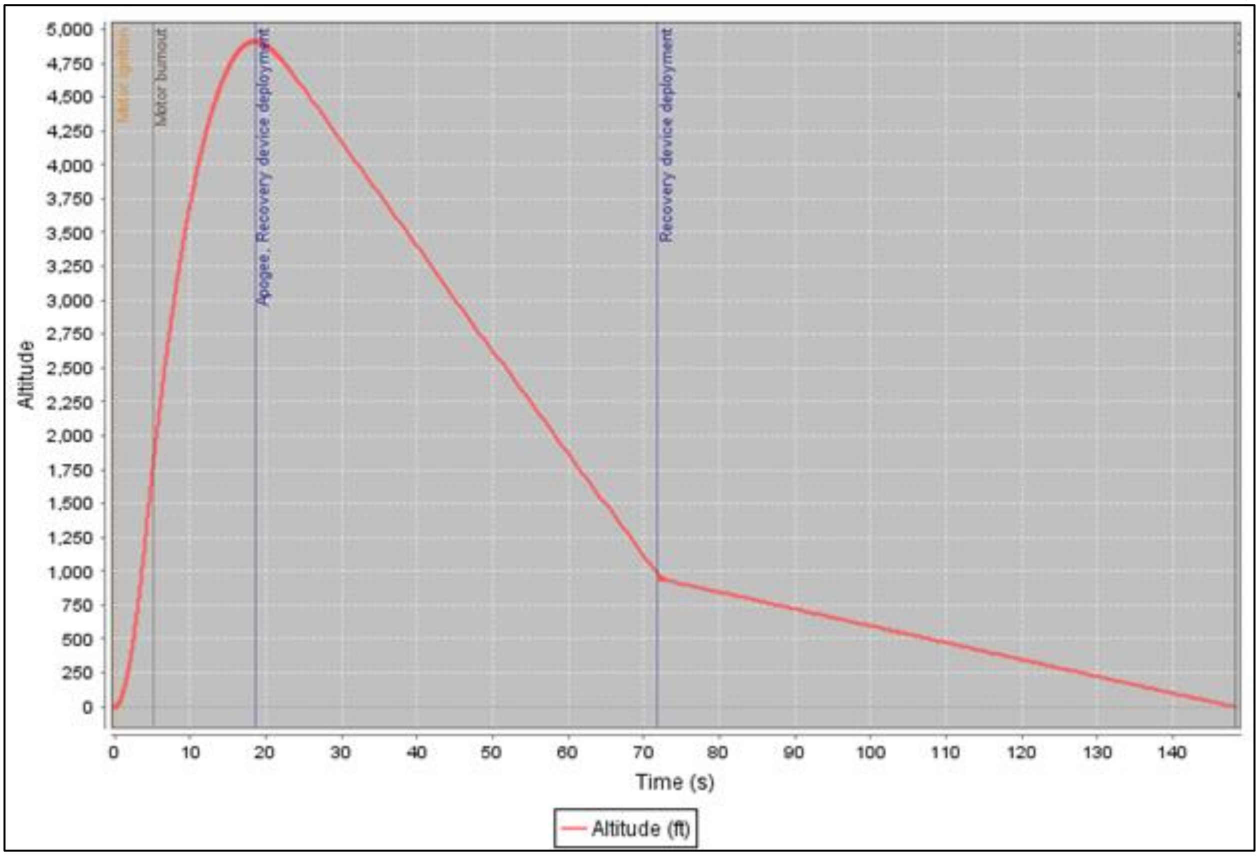

Figure 3.53: OpenRocket Altitude vs. Time Simulation of the 10mph, 5 deg incline case at Purdue Dairy

The case of 5-degree inclination and 10mph winds is a case that is a much more realistic and comparable simulation of the launch day in April. As shown by the graph above, the launch vehicle would reach a maximum altitude of around 4910'. While this is still significantly higher than the target altitude of 4100', with the additional ballast and the airbrakes' correct functioning, the team believes that the launch vehicle will be closer to the 4100' altitude target. This case is the most likely to occur out of the 3 cases discussed because of current weather predictions in April and launch inclination decisions.

3.3.1.2 Component Weights

Component	**Weight (lbm)**
Nose Cone	1.2
Payload	9
Booster	22
Recovery	12
Motor	5
Total without Ballast:	**49.2**
Nose-cone Ballast	3
Total with Ballast:	**52.2**

Table 3.4: Component Weights

Due to the added complexity of the launch vehicle this year, components were kept to large sections, encompassing the weight of small parts such as fasteners and wiring. The total weight of the launch vehicle is 49.2lbm, as seen above. This new weight comes out below the estimate of 52.2lbm by about 3lbm. This discrepancy is expected as paint still needs to be applied, which could add another 1-1.5lbm, and the team will add ballast to the nosecone to round out any remaining differences.

This additional nose ballast will be necessary as our Vehicle Demonstration Flight reached an altitude far above the target altitude. While most of this can be attributed to airbrakes, reducing the altitude from 5100ft to 4100ft additional ballast will likely be necessary.

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3.3.1.3 Simulated Motor Thrust Curve

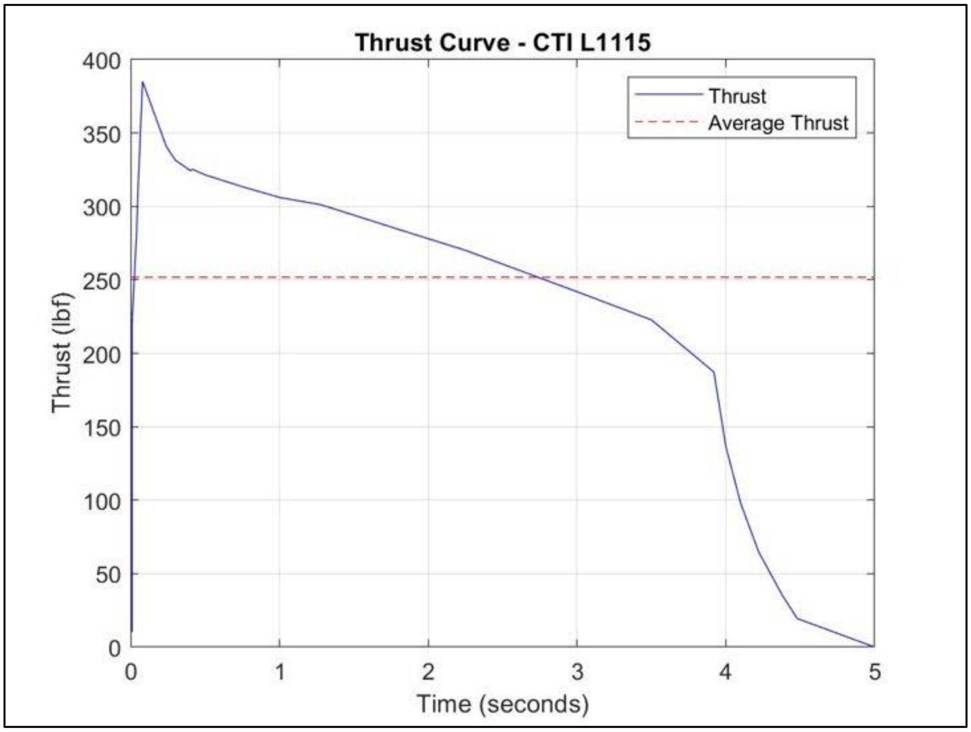

Figure 3.54: Thrust Curve Plot

The thrust cure above was created using a MATLAB script and depicts the launch vehicle's thrust throughout the flight. The first and most extreme section of the thrust curve comes from firing the motor and peaks once the motor has burned out. The drogue and main parachutes then provide some thrust towards the end of the flight. Finally, the thrust returns to zero once the launch vehicle lands back on the ground.

3.3.2 **Stability Margin and Center of Pressure (CP)/ Center of Gravity (CG) Relationship and Locations**

The launch vehicle model now has updated Center of Gravity (CG) and Center of Pressure (CP) values based on some changes made during the physical construction phase. The new CG from the tip of the nose cone is 44.543," and the new CP from the tip of the nose cone is 63.301". The vehicle's outer diameter is 6.17", which means that the stability margin of the launch vehicle at launch is (63.301 – 44.543) / 6.17 or 3.04cal. This is above the NASA requirement of having a stability of 2cal off the launch rail. These values are a little bit higher than previously predicted in the Critical Design Review of the model. Additionally, these changes result in a better, more stable performance from the vehicle.

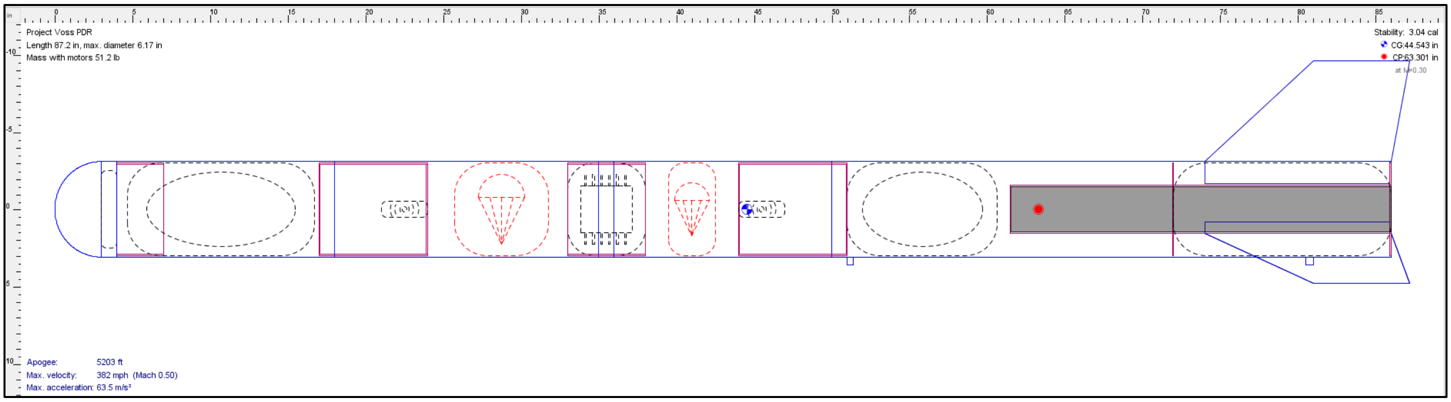

Figure 3.55: The schematic of the launch vehicle in OR with CG, CP and Stability Margin values

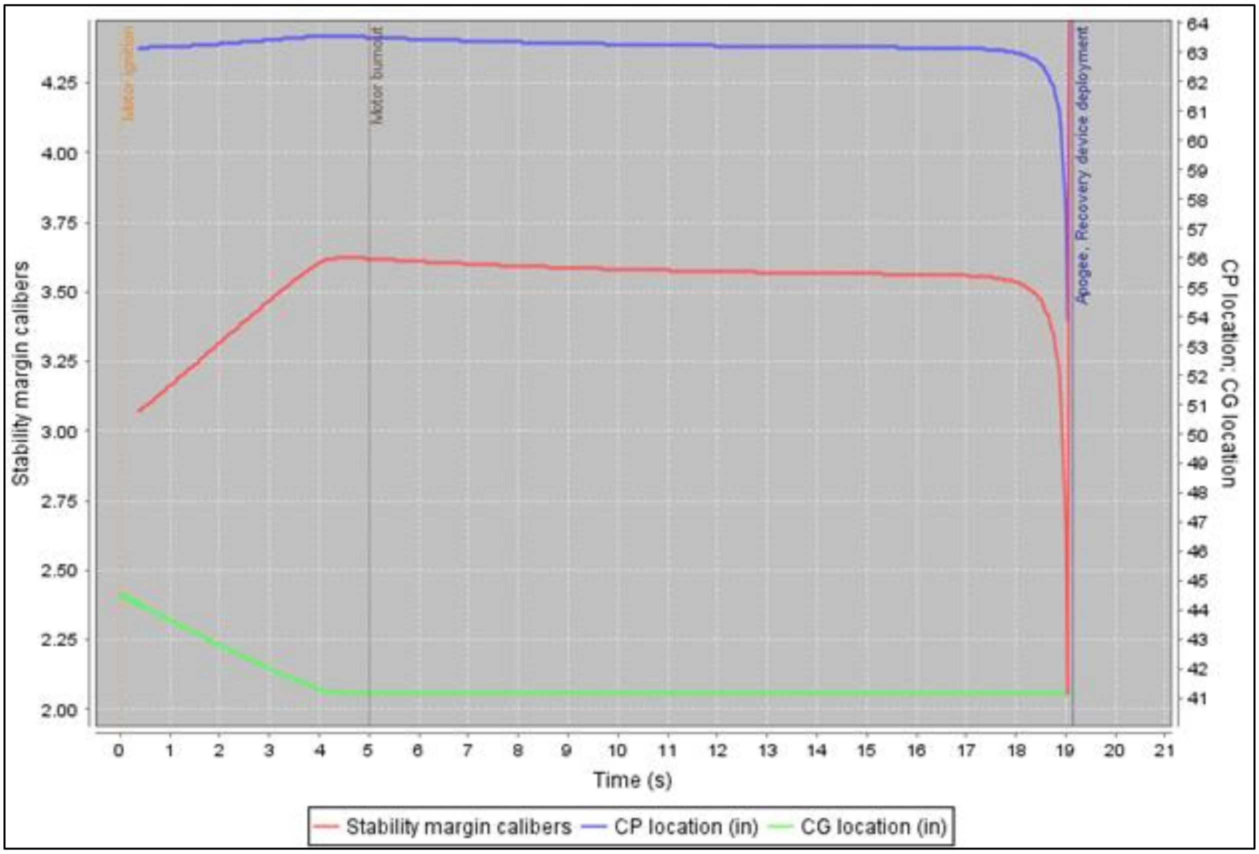

Figure 3.56: OpenRocket Stability vs. Time Simulation of Ideal Case at Purdue Dairy (0mph, 0 deg incline)

As can be seen by the graph above, the launch vehicle exits the 96" launch rail at Huntsville, Alabama, with a stability margin of 3.04 – meeting the NASA requirement of a minimum 2cal off the launch rail. During the ascent phase, the launch vehicle does not experience a significant drop in its stability. This changes when it reaches a low enough velocity near its apogee, causing the fins to no longer maintain aerodynamic stability. This occurs because the vehicle changes its plane of motion at apogee and is no longer upright. After apogee, the launch vehicle's stability is not as significant because it is under the effects of the recovery system. Despite this, the vehicle comfortably maintains a stability of over 3.25cal for nearly all the boost and coast phases.

The center of pressure, or the point where the total sum of all pressures acts on a vehicle, starts at a distance of 63.167" from the tip of the nose cone. The center of gravity, or the average location of the weight of a body, starts at a distance of 44.543" from the tip of the nose cone. During the motor's burn time, the center of gravity moves towards the tip of the nosecone at a constant rate due to the constant burn rate of the solid propellant. Here, the total shift is observed to be around 3.36cal, which is over half a caliber.

3.3.3 Kinetic Energy for Each Section

Vehicle Section	Landing Kinetic Energy (ft-lbf)
Upper Section	52.6
Middle Section	32.7
Lower Section (Dry)	74.3
Total Launch Vehicle (Dry)	159.6
Lander	13.7

Table 2.5: Simulink Landing Kinetic Energies

The most important value to note from these tables is the landing kinetic energy of the heaviest section of the vehicle (the lower section), which the Simulink simulation predicts to be 74.3 ft-lbf. This value (as well as the landing kinetic energies of the other independent sections) is under the maximum requirement of 75 ft-lbf.

3.3.4 Expected Descent Time for Rocket and Untethered Sections

3.3.4.1 Vehicle

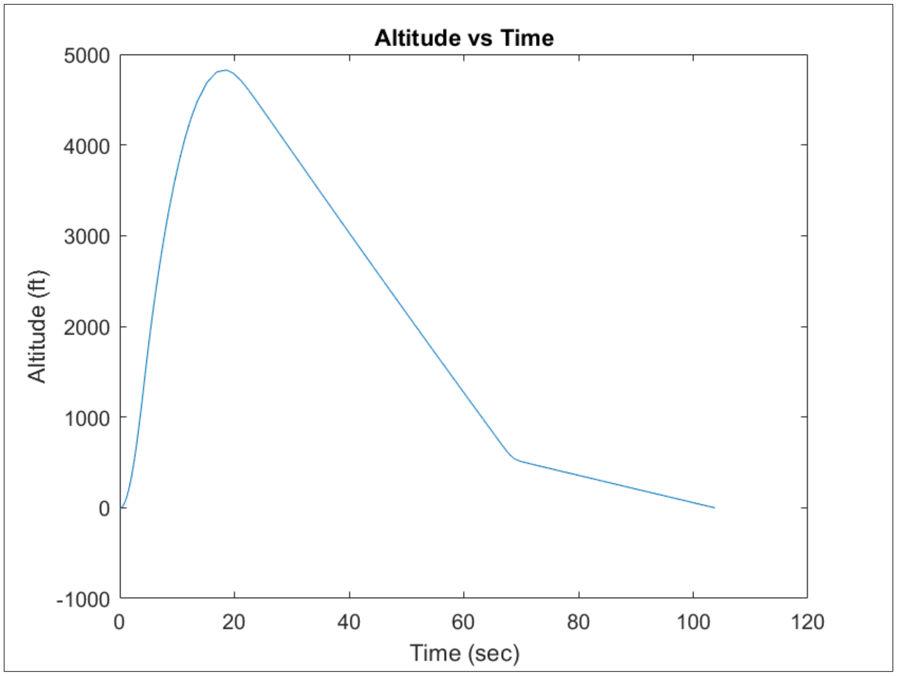

Figure 3.57: Simulink Altitude vs Time Plot

The Simulink simulation predicts an 85.1s descent time from apogee to landing, which is under the maximum requirement of 90s. One interesting thing to note is that a few of the parachute parameters were adjusted based on empirical observations from last year. The coefficient of drag of the drogue parachute was increased from the supplier's reported value, the coefficient of drag of the main parachute was decreased from the supplier's reported value, the main parachute deploys slightly lower than the set altitude, and the main parachute opens a little less than fully.

3.3.4.2 Lander

Using the provided tool from Fruity Chutes, the Payload team's manufacturer, the team determined that with its expected weight between 2 and 3 lbf, the Lander would travel at around 21.55 fps at terminal velocity. This value will be assumed to be constant for the purposes of calculation.

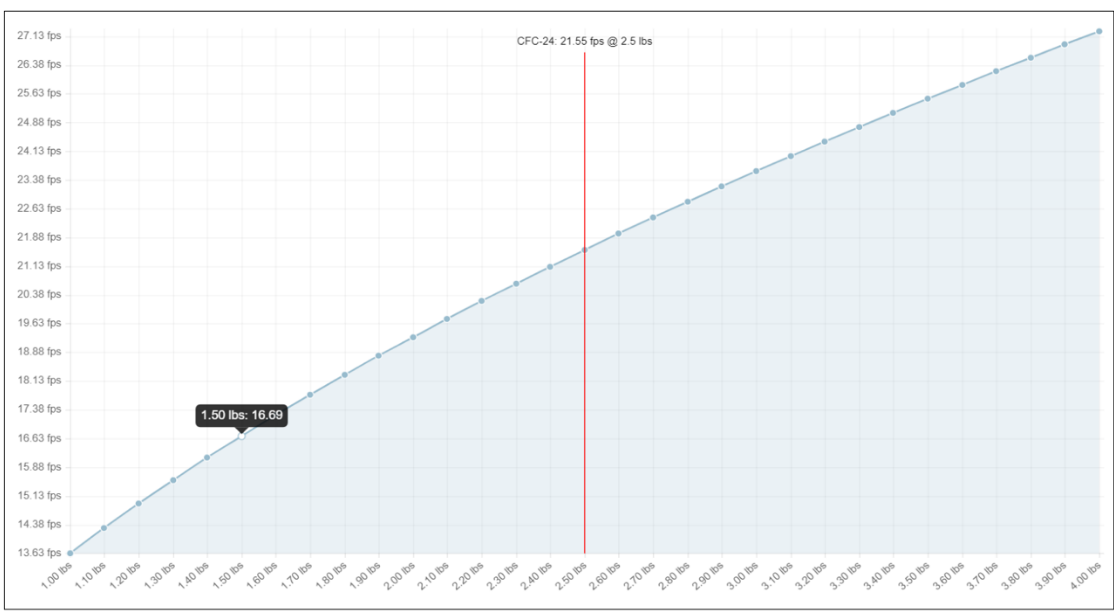

Figure 3.58: Fruity Chutes Descent Speed Plot

At a deployment height of anywhere between 500 and 700 feet, the Lander will have an ideal descent time between 23.202 and 32.483 seconds. Given acceleration time from the vehicle's downward velocity under main to terminal velocity of the Lander, these descent times may underestimate the true descent time by about a second.

3.3.5 Drift for Each Independent Section

The team decided to simulate the drift distance of the launch vehicle in OpenRocket under various weather conditions. These weather conditions were mostly related to wind speed as that team thought that the wind speed would be a crucial deciding factor on whether launch should be conducted or not. The following sections below show the vehicle's altitude and horizontal position with respect to the launch site. The only factors that were changed were wind speed.

3.3.5.1 No wind

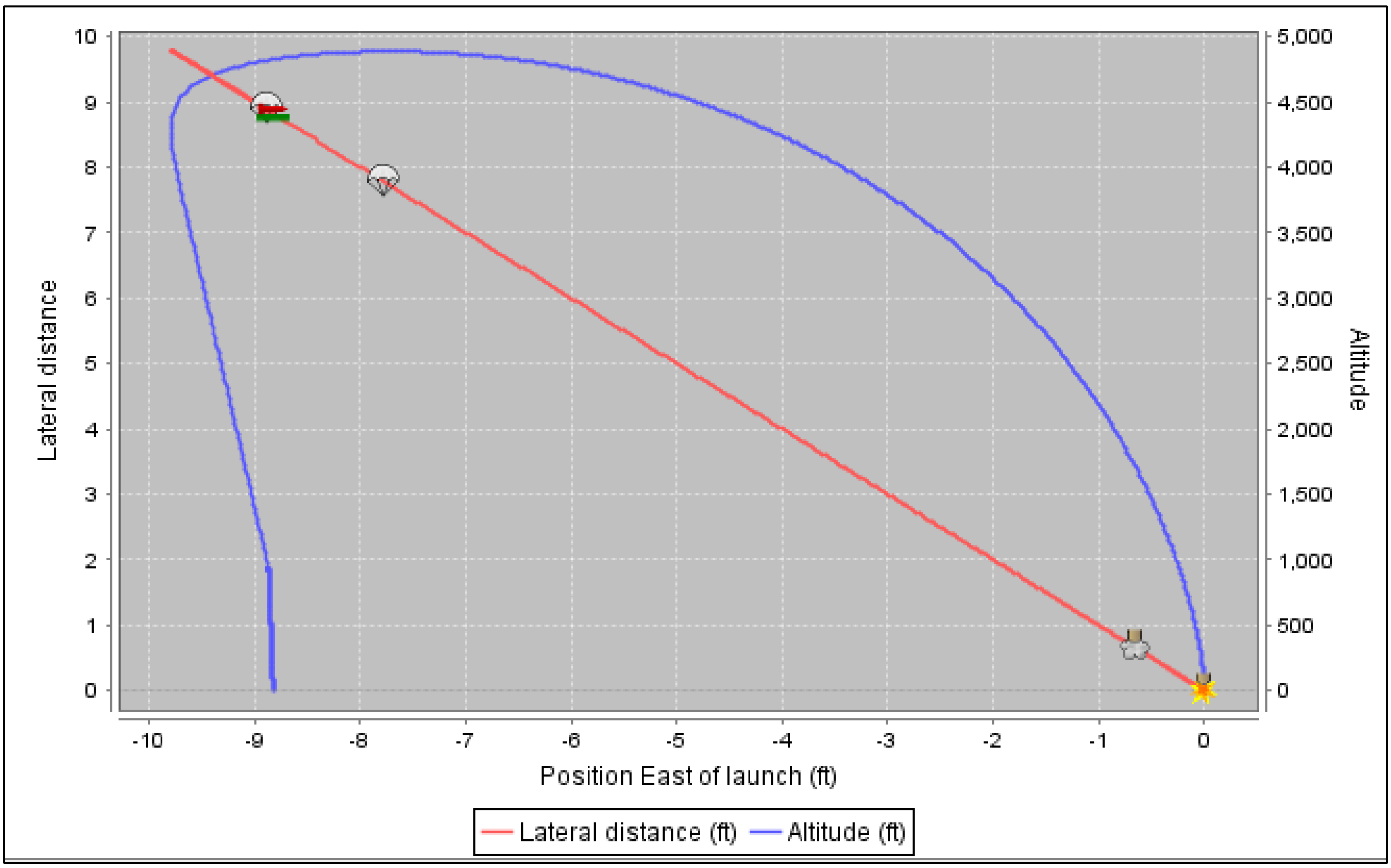

Figure 3.59: OpenRocket Simulation with Ideal Drift (No Wind) and 0 Inclination

The graph above describes the launch vehicle's trajectory when launched with a wind speed of 0 mph and a standard deviation of 0.5 mph. The turbulence intensity is 10%. In these conditions, the vehicle drifts a maximum of around 9.75 ft west and ends up landing just under 9 ft west.

3.3.5.2 5-mph wind

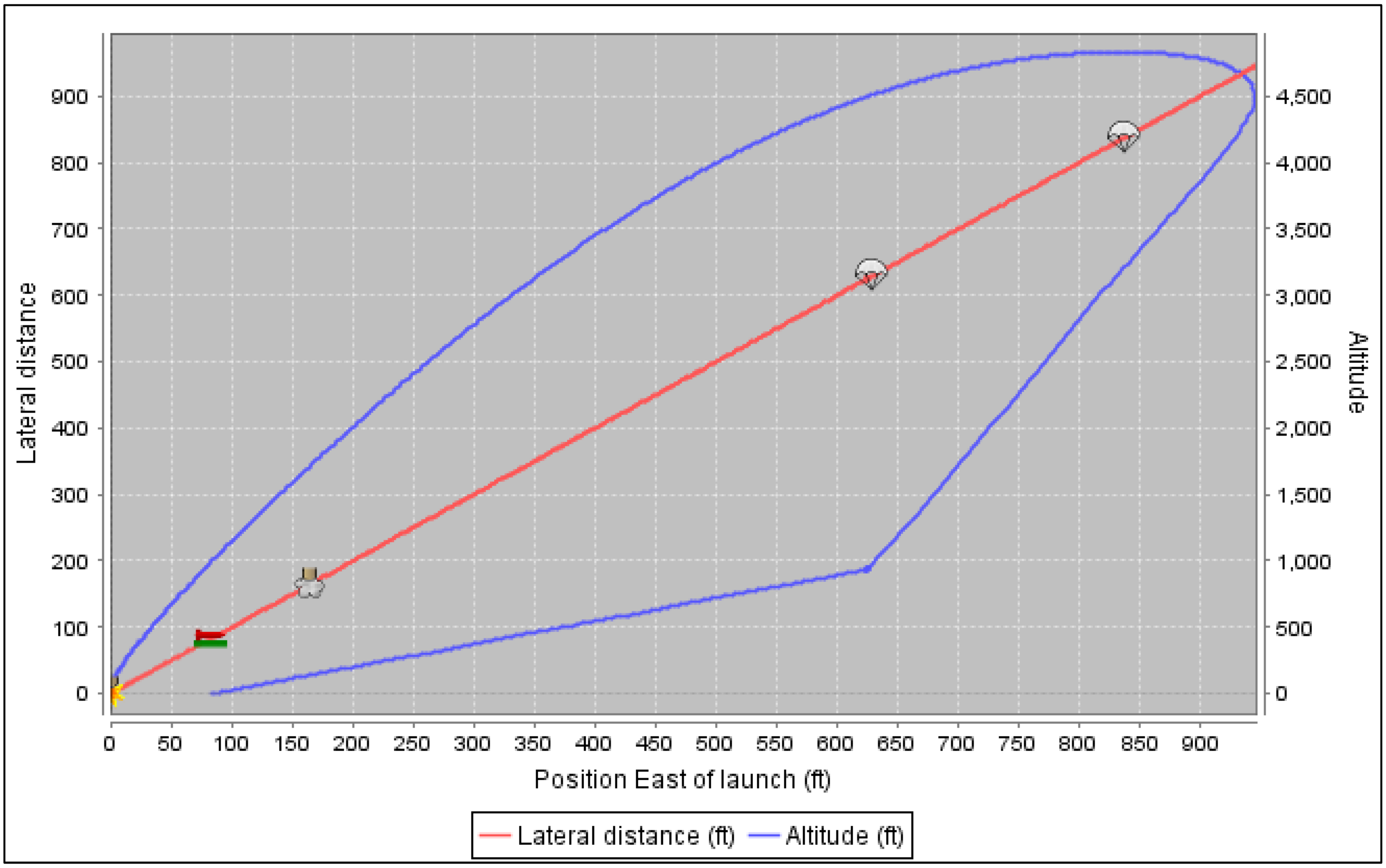

Figure 3.60: OpenRocket Drift Simulation with 5mph Wind and 0 Inclination

The above figure shows the drift trajectory of the launch vehicle with a 5-mph wind speed. Turbulence intensity and the standard deviation are held constant from the last simulation. In these conditions, the vehicle will drift up to a maximum of 1000 feet east. Once the recovery systems are deployed and the vehicle lands, it will be slightly under 100 feet east from the launch location.

3.3.5.3 10-mph wind

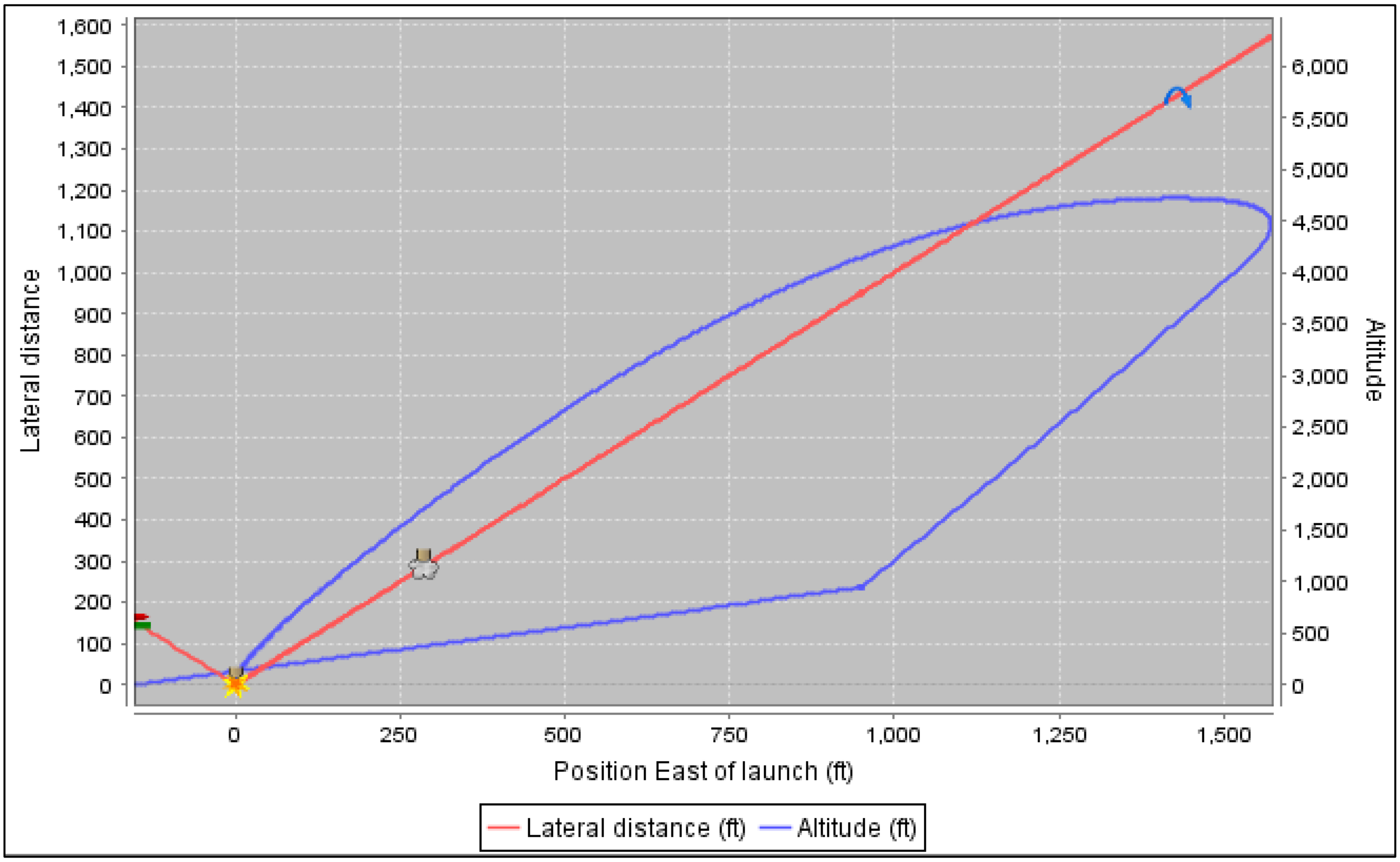

Figure 3.61: OpenRocket Drift Simulation with 10mph Wind and 0 Inclination

The figure above shows the drift trajectory for the launch vehicle when the wind speed is 10 mph. The launch vehicle will drift a maximum of about 1,600 feet east before the recovery system deploys. Once that happens, the vehicle will drift towards the west and land approximately 200 feet west from the launch location. Turbulence intensity and standard deviation are held constant between simulations like before.

3.3.5.4 15-mph wind

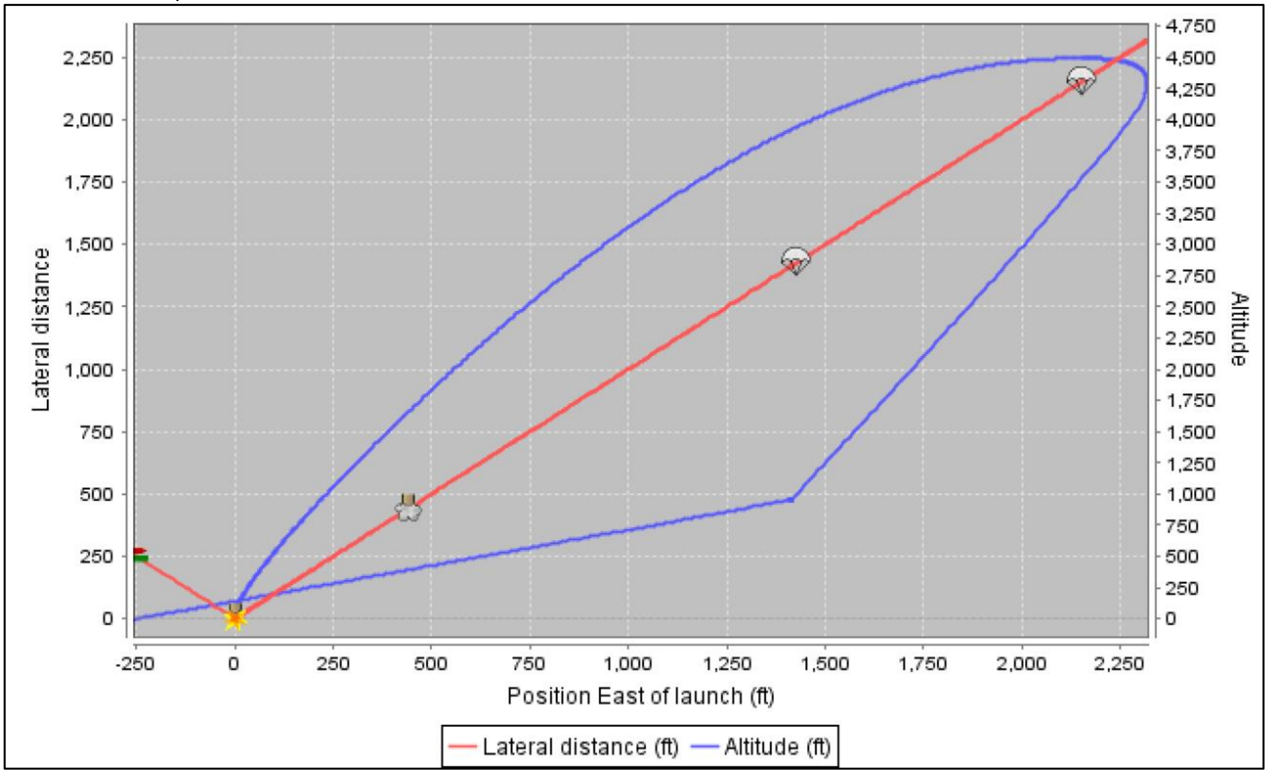

Figure 3.62: OpenRocket Drift Simulation with 15mph Wind and 0 Inclination

The figure above shows the drift trajectory for the launch vehicle when the wind speed is 15 mph. The launch vehicle will drift a maximum of about 2,300 feet east before the recovery system deploys. Once that happens, the launch vehicle will drift towards the west and land approximately 300 feet west from the launch location. Turbulence intensity and standard deviation are held constant between simulations like before.

3.3.5.5 20-mph wind

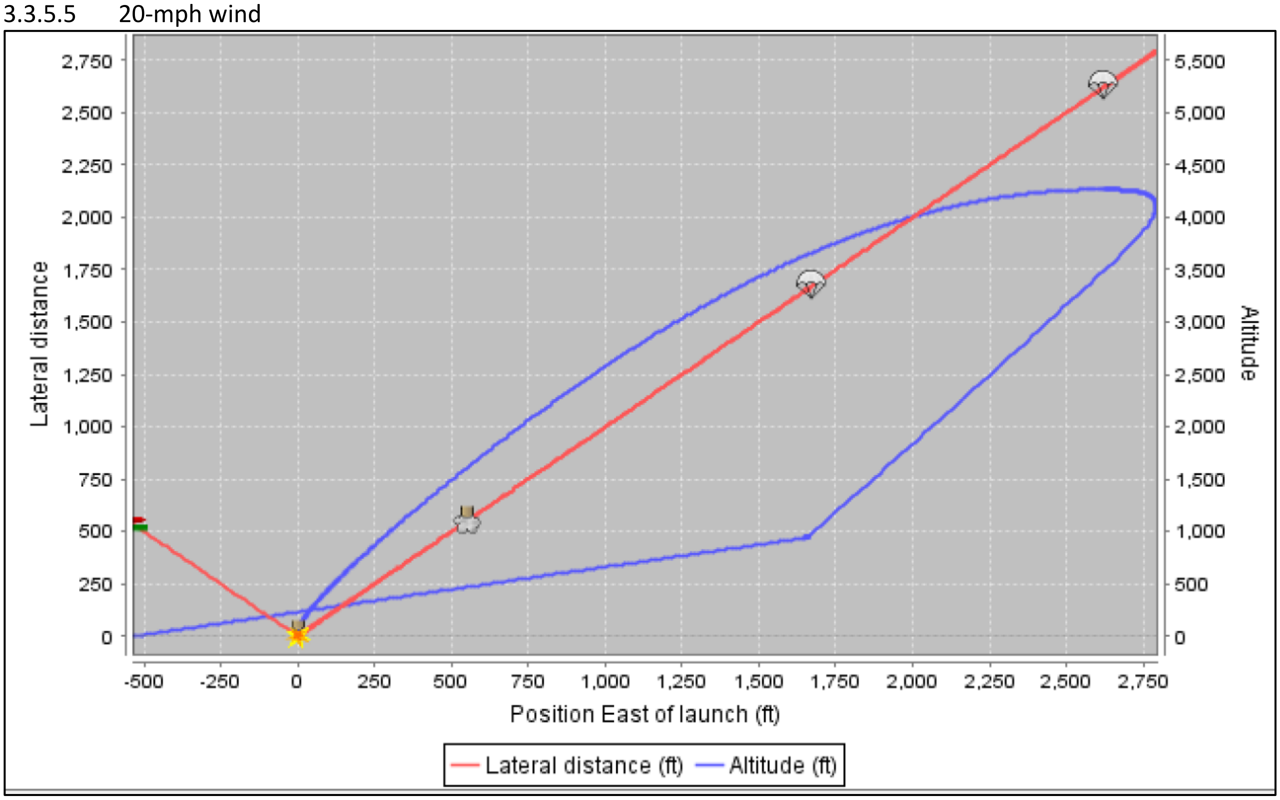

Figure 3.63: OpenRocket Drift Simulation with 20mph Wind and 0 Inclination

The figure above shows the drift trajectory for the launch vehicle when the wind speed is 20 mph. The launch vehicle will drift a maximum of about 2,750 feet east before the recovery system deploys. Once that happens, the launch vehicle will drift towards the west and land approximately 550 feet west from the launch location. Turbulence intensity and standard deviation are held constant between simulations like before.

3.3.6 Different Calculation Method to Verify Original Results (Simulink)

The team has developed a two degrees-of-freedom custom vehicle trajectory simulation in Simulink format to understand how different possible vehicle configurations affect flight and inform the new main parachute selection. Developing a custom simulation parallel to OpenRocket and RAS Aero II offers a greater range of control of different parameters to achieve as much accuracy as possible, acts as verification of the OpenRocket and RAS Aero II simulations, and increases the team's knowledge of and experience with flight dynamics.

The simulation includes a multitude of useful features. Various vehicle and vehicle component characteristics such as mass, size, drag coefficient, and motor thrust and environmental characteristics such as launch rail angle and wind speed can be input and modified via a MATLAB script. The Simulink model itself utilizes these parameters and established motion equations to simulate the powered ascent, coast, descent under the drogue parachute, and descent under the main parachute phases of flight. Altitude, drift distance, vertical velocity, and horizontal velocity over the flight time are then returned to MATLAB to be plotted and analyzed.

This simulation verifies the four critical requirements: descent time, drift distance, rail exit velocity, and landing kinetic energy of the heaviest section of the vehicle. These values are calculated from the simulation results and compared to the numerical requirements. Pass/fail results are returned to the user to provide a very quick and simple verification.

For all the Simulink sections, the simulation was run with a launch rail angle inclined at 8° from vertical, the horizontal wind speed set at 6mph, and no additional mass. The vehicle was launched with the wind.

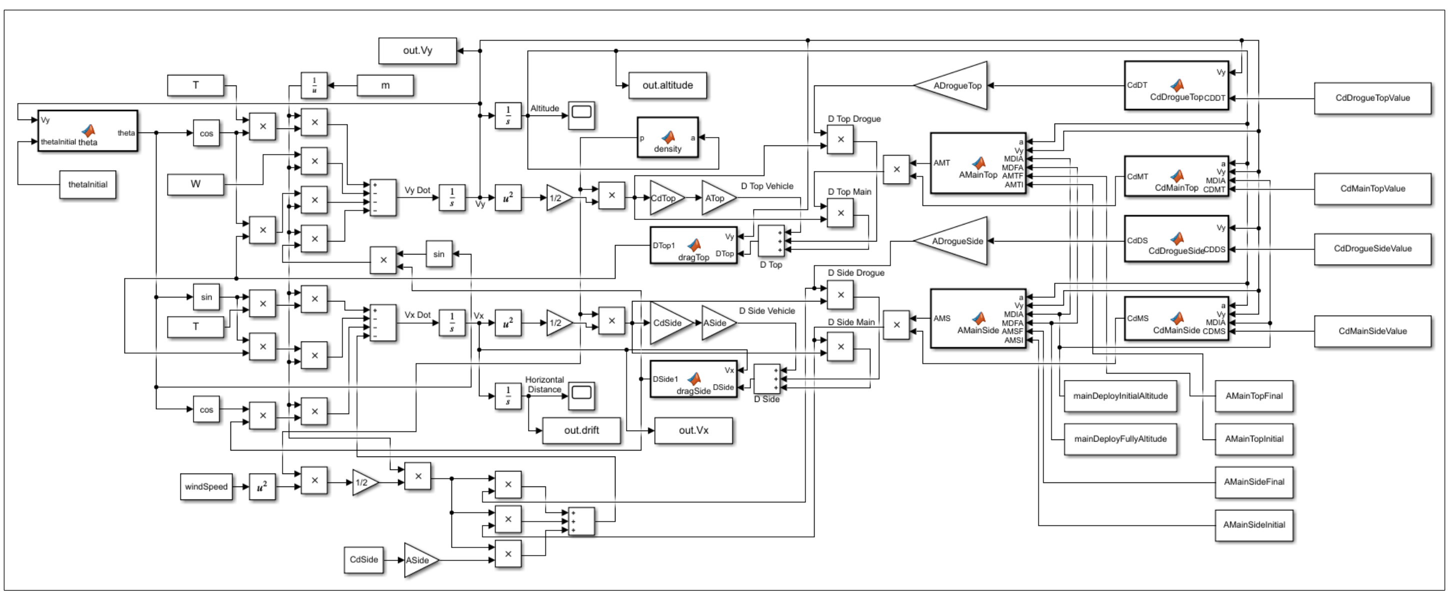

Figure 3.64: Simulink Model

The figure above shows the visual Simulink model.

4 Payload System

4.1 Payload Criteria

4.1.1 Mission Statement

4.1.1.1 Planetary Landing System

The Planetary Landing System (PLS) mission is to capture a level, 360° panoramic photograph of the landing site of the launch vehicle after being safely deployed from the vehicle during main parachute descent. The Lander Subsystem will be actively retained by the Retention and Deployment subsystem (R&D) during flight and after deployment of the vehicle's main parachute. The operation of the PLS will be designed to prevent interference with the launch vehicle after deployment. To ensure the safety of personnel on the ground, the descent design of the Lander must be optimized for reliability.

4.1.1.2 Aerobraking Control System

The AeroBraking Control System (ABCS) mission is to improve the team's apogee accuracy by increasing the altitude precision and accuracy of the launch vehicle towards the desired altitude. The ABCS will employ an autonomous control system designed to predict the vehicle's current apogee error during coast and adjust the vehicle's drag state to reduce this error. This system will require operation in a high-speed compressible aerodynamic regime, requiring utmost care for mechanical design, material usage, and assurance of stability; the ABCS will be designed with fail-safes to ensure proper deactivation given the possibility of loss of control authority by the vehicle's fins.

4.1.2 **Mission Success Criteria**

4.1.2.1 Planetary Landing System

This mission is divided into seven essential phases, each with a defining event leading into the action of the next. The system's mission will be considered complete if its status proceeds to the final phase without failure. In the case of a critical failure, additional contingency plans have been considered. The phases of the PLS mission are shown as follows:

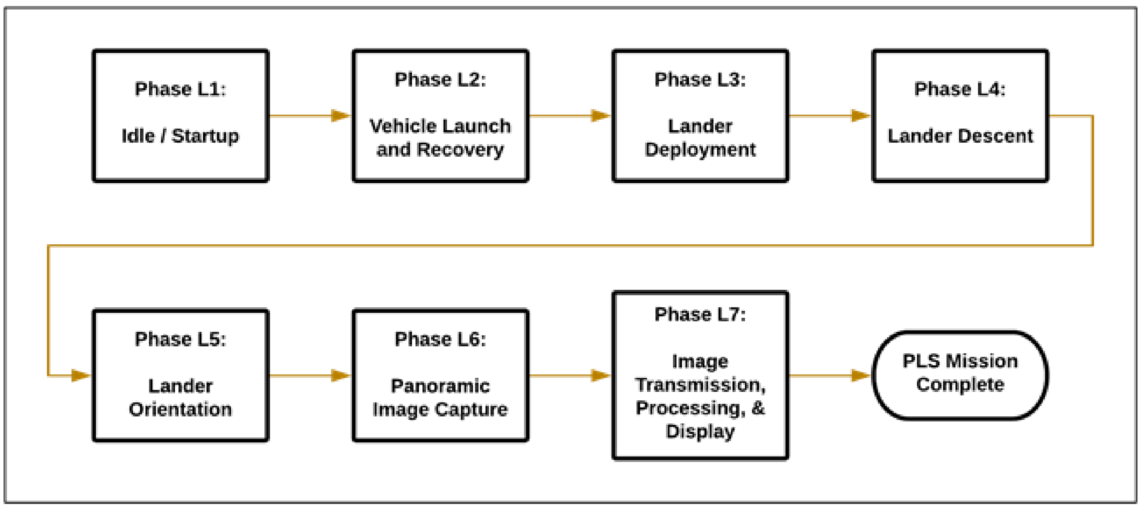

Figure 4.1: Planetary Landing System Mission Overview

L1: Idle / Startup:

The first phase of the mission includes the time between launch vehicle activation and the time of launch. During this time, the R&D will be in an idle but active state in preparation for launch. The Lander will also be in a state of sleep, awaiting indication from R&D to awaken and activate. Given that the vehicle is ready to launch, the mission may proceed to Phase L2.

L2: Vehicle Launch and Recovery

While the vehicle is in its ascent phase, the R&D will be ensuring that flight loads are transferred around the body of the Lander contained inside. The Lander will not be able to exit the vehicle during this stage due to a mechanical lock, which will not unlock without action from the onboard R&D controller. When the vehicle begins its descent, the load state of the R&D will tend to flip, but the system will still be designed to handle the required loads. The R&D will be capable of withstanding jerk from both the drogue parachute and the main parachute before continuing to Phase L3.

L3: Lander Deployment

After the completed deployment of the vehicle's main parachute by approximately 700' AGL, the R&D will begin to deploy the Lander. The R&D will begin to separate the lock vertically, constraining the Payload Bay's nosecone section, allowing the Lander to slide downwards with gravity. Once fully released, the nose cone section will slide downward before hitting stops. The Lander will then be unconstrained in one lateral dimension, allowing it to fall to the side and begin descent. During this time, the Lander's electronic systems will be awoken by the R&D, allowing it to proceed to Phase L4. If the R&D is unable to deploy the Lander for any reason, the Lander will remain sleeping and must be able to be deactivated on the ground with the permission of an RSO. With the Lander having exited the vehicle, the R&D system will remain in an open configuration until touchdown, retaining the nose cone of the vehicle.

L4: Lander Descent

The Lander should be clear of the launch vehicle by 500' AGL, by which time a parachute delay method will have disconnected itself from the Lander, allowing the Lander's parachute to open. It should be noted that even if the Lander does not properly awaken, the parachute will still be designed to deploy, ensuring the safety of the Lander and personnel on the ground. The parachute will bring the Lander's terminal velocity to a speed greater than the speed of the launch vehicle (20 fps) to ensure no interference occurs. The Lander will then reach the ground, landing in any orientation. If the awoken Lander detects a successful return to Earth, it will detach its parachute via nichrome wire wrapped tightly around the parachute connecting cable and begin Phase L5.

L5: Lander Orientation

Now grounded, but with no certainty of landing orientation, the Lander will begin to self-upright by using a motorized Self Orientation Subsystem (SOS). By increasing the Lander's effective support area, the Lander can be assured to bring itself into a stable upright configuration slowly. The SOS will attempt to adjust its final state to ensure that the onboard sensors confirm orientation within 5° of the local gravitational acceleration vector. Once the control system has completed this task, the Lander will proceed to Phase L6. If the Lander cannot complete this phase after a predetermined amount of time, it will deactivate itself to prevent injury to the ground team.

L6: Panoramic Image Capture

Leveled within the desired tolerance, the Lander should now be clear of debris and should have an elevated view of the launch field. The onboard Panoramic Image Capture Subsystem (PICS) cameras will activate and proceed to capture an image of the field. The image will be stored locally until it is ready to be sent to the team's Ground Control Station (GCS), moving the PLS to the final Phase L7.

L7: Image Transmission, Processing, & Display

Once a communication channel is secured between the GCS and the Lander, the PICS will begin to transfer the image data to the GCS via a radio transmitter. Once received, the GCS will store the image data. The Lander Subsystem has now completed its purpose and may be recovered. The GCS will then proceed to process the received image data and convert it into a viewable format. If the PICS utilizes a multi-image capture system, the GCS will need to stitch them together to view at one time. Once converted, the image will be displayed on the GCS's display screen for confirmation by the team, an RSO, and other NASA personnel. Having produced an image, the PLS has completed its mission and may be shut down for recovery by the ground team.

PLS Mission Completion

By the end of its mission, the PLS should have produced an unobscured image of the launch vehicle landing site. The system must overcome the challenge of being jettisoned from a high-power rocket during descent and master the elaborate dance of up-righting upon unknown terrain. At the same time, the system must satisfy every functional requirement set forth by the team to be considered ready to fly. If the system can produce these results without succumbing to material failure, inadvertent deployment, or a blocked camera subsystem, then the team will consider the mission a complete success.

4.1.2.2 Aerobraking Control System

This mission is divided into five essential phases, each with a defining event leading into the action of the next. The system's mission will be considered complete if its status proceeds to the final phase without failure. In the case of a critical failure, additional contingency plans have been considered. The phases of the ABCS mission are shown as follows:

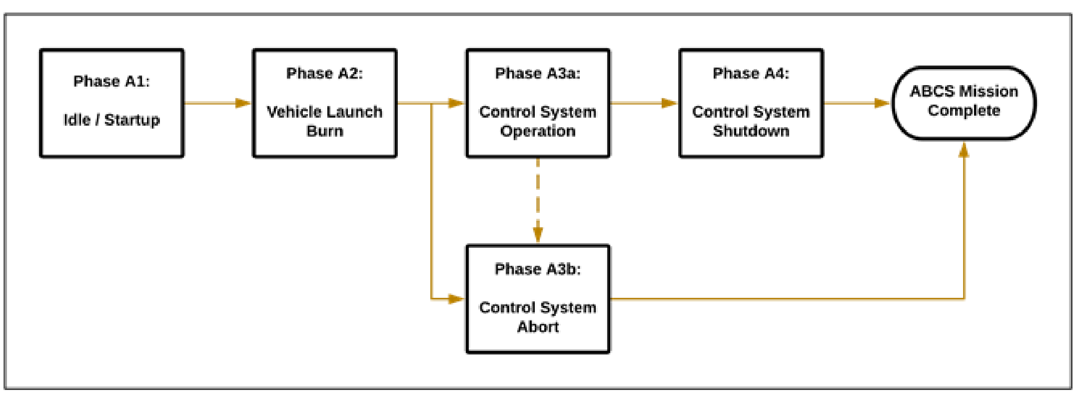

Figure 4.2: AeroBraking Control System Mission Overview

A1: Idle / Startup

The first phase of the mission includes the time between system power-on until the time of launch. During this time, the ABCS is in an idle state waiting for the detection of launch. Once ABCS accelerometers detect the launch burn, the ABCS will transition into phase A2.

A2: Vehicle Launch Burn

The ABCS control system will need to detect the launch vehicle's acceleration state at the start of its burn before it begins its operational stage. The ABCS mechanical system will not be allowed to actuate until the system detects that the launch vehicle's burn has been completed, and the vehicle has reached sufficient altitude, confirming a successful burn. With the ABCS remaining inactive during the boost phase, the vehicle's passive stabilizing fins can operate properly without possible loss of control authority. Once the criteria are met, the ABCS main drag control system loop may be activated, leading to Phase A3a. If the launch burn is not detected to have been completed properly, then the control system will proceed to Phase A3b.

A3a: Control System Operation

Given that the flight conditions are acceptable for the operation of the Airbrakes, the ABCS drag control system loop will begin operation. This control system will employ a suite of sensors to detect the vehicle's current state. Important inputs include the vehicle's linear and angular velocity, acceleration, air pressure, and altitude. A constant set by the team will be the desired final apogee of the launch vehicle. The control system will first predict the vehicle's current apogee error relative to the desired apogee and then determine how much drag would be required to achieve this final apogee. The ABCS will accordingly actuate its Airbrakes, producing this additional drag. An important initial condition of this phase is that the launch vehicle will, without intervention, achieve a final apogee greater than the desired altitude. Without this condition, the ABCS would be unequipped to provide any additional required velocity—it can only act to remove mechanical energy from the system. If at any time during the active phase the control system detects that the launch vehicle has exceeded attitude state or acceleration bounds determined by the team to be within an acceptable range, the control system will immediately switch to Phase A3b to avoid possible loss of stability. If the ABCS continues operation up until apogee, it will transition to Phase A4.

A3b: Control System Abort

The ABCS will be designed to cease its functionality if it detects that it could cause the launch vehicle's instability during ascent. If the ABCS reaches Phase A3b at any time from the beginning to the end of its designated operation time, it will follow a shutdown sequence to ensure that the system does not incur additional change in attitude or velocity. This shutdown sequence will immediately end the apogee optimization drag control system loop and completely retract the Airbrakes Subsystem's drag plates. This contingency plan is essential to allow the launch vehicle's stabilizing fins to return the vehicle's attitude to an acceptable state, avoiding an induced tumble. With all external surfaces now inactive, the ABCS control system will remain inactive for the remainder of descent and touchdown. While the control system could not fully optimize and complete its final calculations and adjustments, the team will still consider this contingency plan as successful as the overall vehicle will still complete its mission.

A4: Control System Shutdown

When the vehicle reaches apogee according to flight sensors, the ABCS will begin a deactivation sequence to reduce the possibility of damage to components. This deactivation sequence will immediately end the apogee optimization drag control system loop and completely retract the Airbrakes Subsystem's drag plates. With all external surfaces now inactive, the ABCS control system's mission will be considered complete and will deactivate for the remainder of descent and touchdown.

ABCS Mission Completion

By the end of its mission, the ABCS will hopefully reduce the error between the vehicle's actual apogee and the desired apogee relative to previous years' vehicles. The system must overcome the challenge of compressible regime aerodynamic loads while also deftly making complex trajectory calculations and executing upon them. Simultaneously, the system must satisfy every functional requirement set forth by the team to be considered ready to fly. If the system can produce these results without succumbing to material failure, having an uncontrolled deployment, or exasperate a hazardous vehicle tumble, then the team will consider the mission a complete success.

53

4.2 Planetary Landing System

4.2.1 System Overview

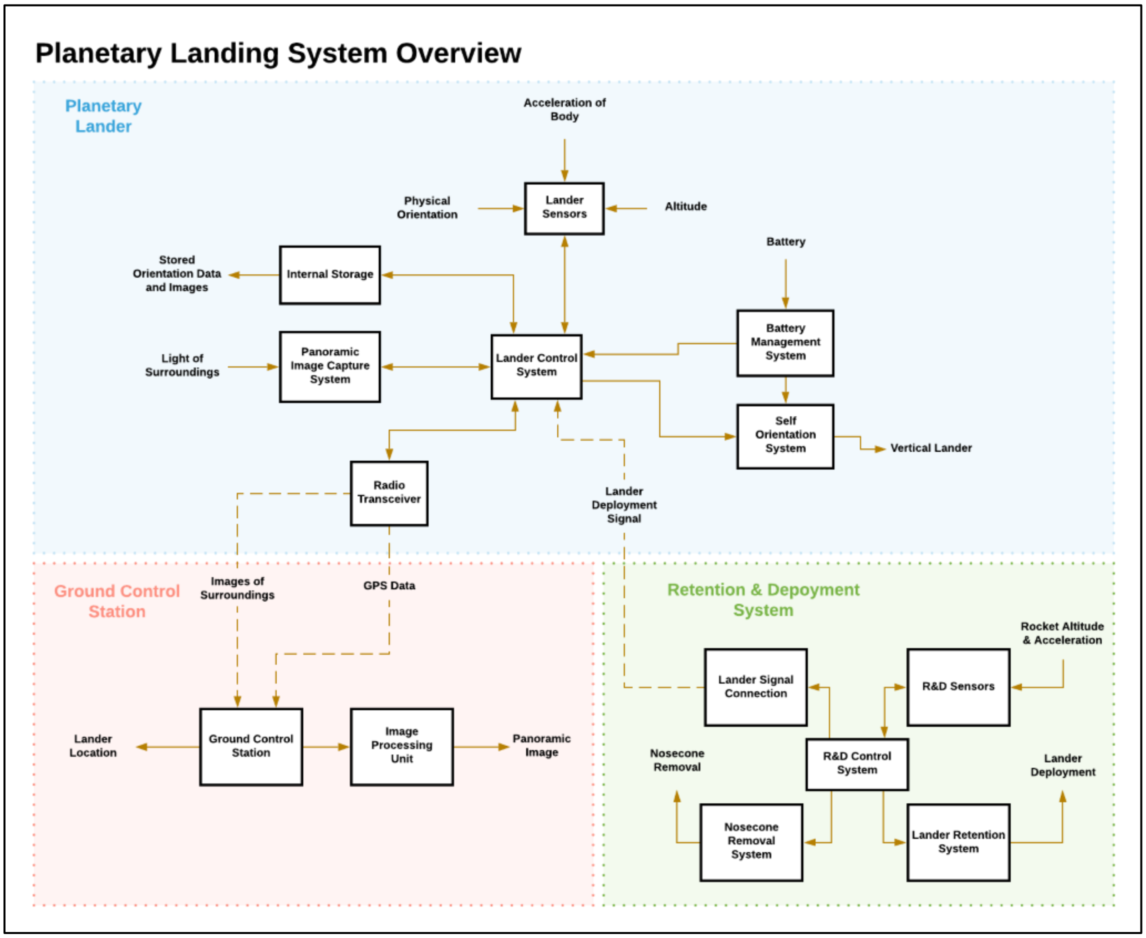

Figure 4.3: Planetary Landing System Functional Block Diagram

The Planetary Landing System (PLS) includes the Lander and its associated Retention and Deployment Subsystem (R&D). The Lander itself can be further broken down into the Self Orientation Subsystem (SOS), the Panoramic Image Capture Subsystem (PICS), the Lander Control Subsystem (LCS), and the in-flight Descent and Landing Subsystem (D&L). Once the launch vehicle has deployed its main parachute and its altitude has dropped below 800' AGL, the R&D system will release the Lander from the launch vehicle's nose section. The Lander will then deploy its own parachute after falling a sufficient distance from the launch vehicle, ensured by the D&L. The Lander will strike the ground at a sufficiently low speed deemed by the design team to be acceptable for the continued operation of the Lander's subsystems. Once the Lander detects that it has stopped moving, the SOS will begin to orient the Lander within 5 degrees of vertical. Once the SOS has completed self-orientation, the PICS will photograph the surrounding area from each of its 3 static cameras. The photos will then be stored in the Lander's digital storage to await radio transfer to the GCS. Once a stable connection has been established, the photos will be transferred to the GCS. An image processing unit in the GCS will then combine all three images into one panoramic image. The full panoramic image will then be displayed on screen for inspection.

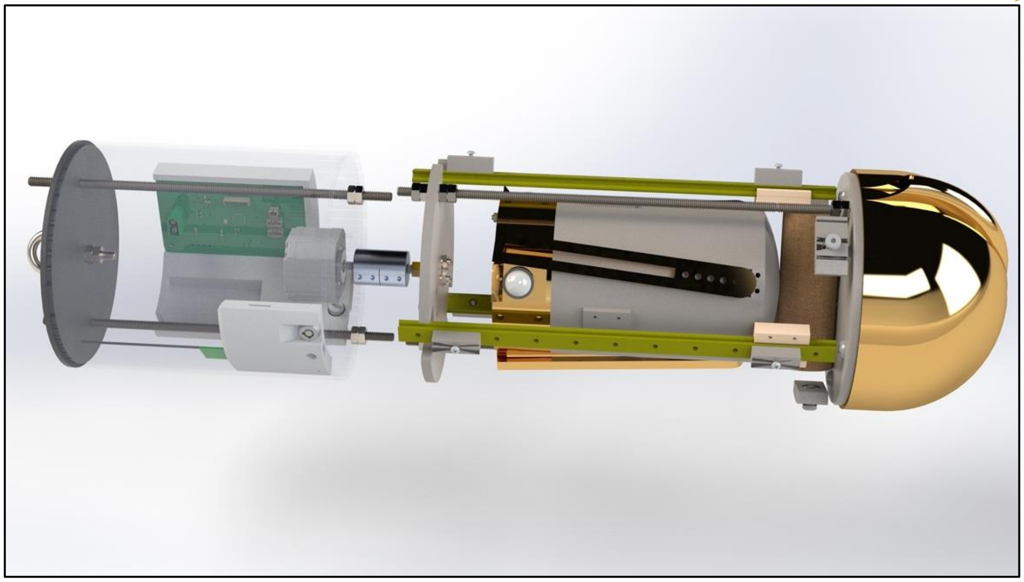

Figure 4.4: Overall Planetary Landing System Render (Closed Configuration, Airframe Transparent)

Since CDR, the team has only fully constructed the R&D, the most flight-essential system of the PLS. While the Lander itself—with the Mission Critical sections of the D&L—has also been physically constructed, resource shortages and delays have prolonged the assembly and code development process of the PLS as a whole. With the Payload Demonstration Flight upcoming, the team will be strongly focusing on the Lander's production and testing and its associated subsystems. This includes the SOS, LCS, PICS, and GCS.

The PLS design has remained almost the same since CDR, however, physical construction of the PLS has enabled the team to understand the true behavior of the apparatus and its boons and shortcomings. As seen above, the design of the R&D has been updated to reflect changes from expected behavior from CAD; most easily of note is the relocation of the Lander's parachute to be beneath the Lander itself during descent. This change and more follow the team's desire to ensure the proper functionality and reliability of the PLS system. The following excerpts will aim to provide an in-depth discussion of the current design state now that many components have been constructed in our workshop. Afterward, the team will provide a thorough report of the physical and digital manufacturing and assembly methods used to make this system a reality. Finally, the discussion will culminate in a brief report of the system's performance during the Vehicle Demonstration Flight. For additional information regarding Mission Critical Requirements and Verification Testing, please see the report's Project Plan section.

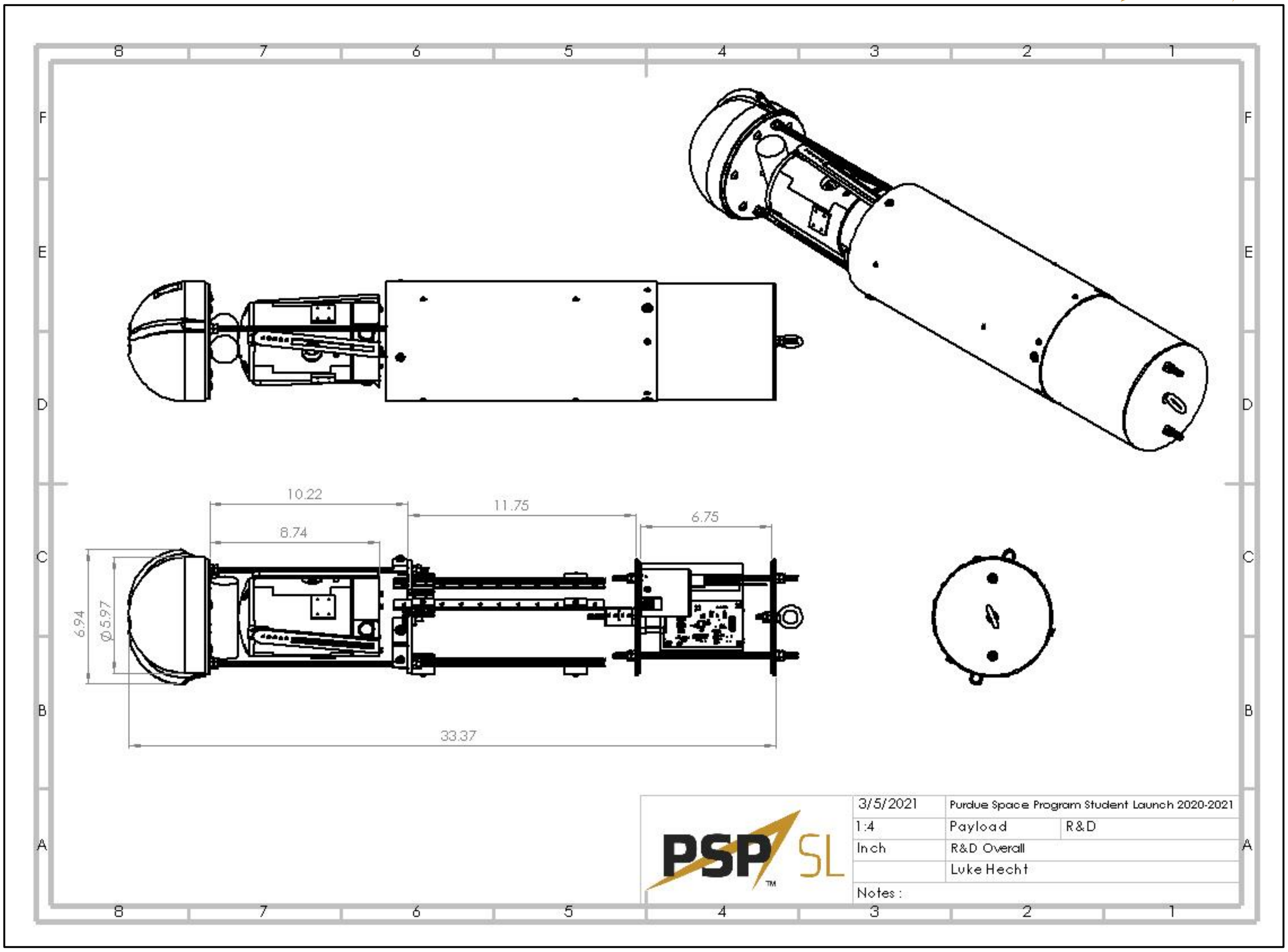

Figure 4.5: Overall R&D Payload Bay Drawing

4.2.2 As-Built Design Overview and Changes Made

4.2.2.1 Retention and Deployment Subsystem

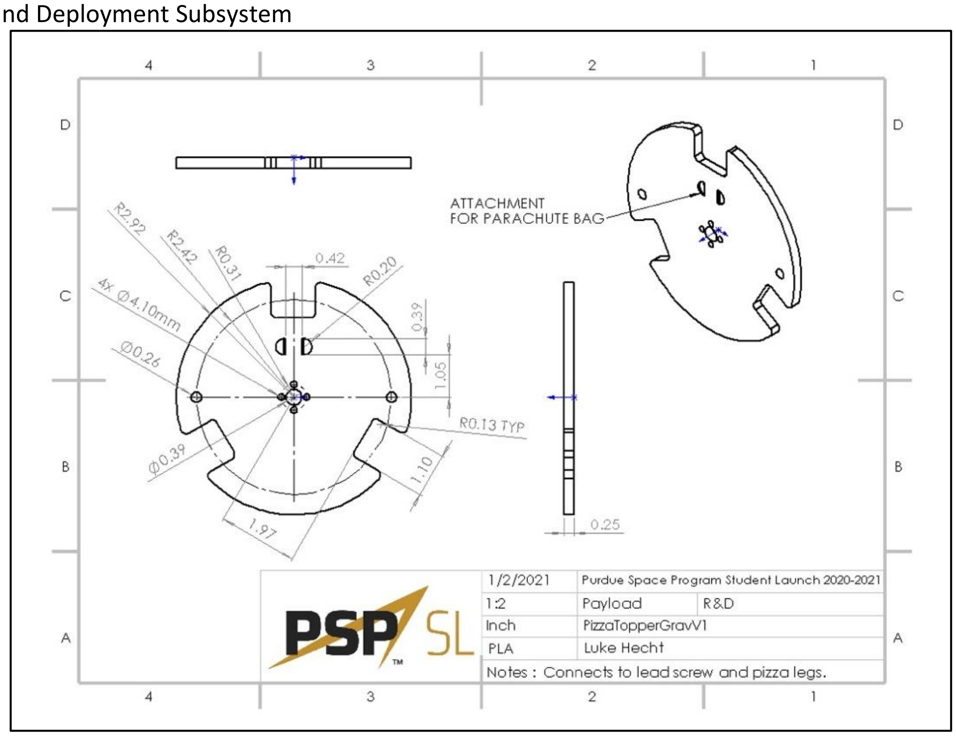

Figure 4.6: Pizza Table Plate Drawing

The R&D system uses a rail-secured sled referred to as the "Pizza Table" to open the nose cone, secure the Lander, and to transport the Lander so that it can be deployed. The Pizza Table consists of a thin plate with two, foot long ¼-20 threaded rods protruding from the top side. A pizza saver inspired this shape, a plastic device often found within pizza boxes to protect pizza from getting crushed. The Pizza Table's legs wrap around the Lander and terminate at the vehicle's nose cone. Since these two rods directly connect the Pizza Table to the nose cone, the apparatus allows for the nose cone's securement during flight and for ease of actuation when it comes time for deployment.

Additionally, the Pizza Table has three slots cut out of it to be centered within the Payload Bay by three rails. These three linear motion guide rails are mounted radially to the Payload Bay wall and serve to secure and guide both the Lander and the Pizza Table as mentioned. Finally, the Pizza Table has a lead screw nut mounted on its bottom side. This lead screw nut threads into the central lead screw of the Payload Bay which is attached to the stepper motor housed within the coupler between the Payload Bay and the recovery section. This serves to allow the stepper motor to hold the Pizza Table in place and push it towards the opening of the launch vehicle left by the actuated nose cone during the appropriate time.

Figure 4.7: R&D Battery

The R&D subsystem underwent a modification in the physical construction of the electrical system. Due to unforeseen issues with shipping delays involving the PCB, the PCB was not able to be implemented in time. To overcome this, a perfboard with the same components that will be used on the PCB was created. When possible, the same components as used on the PCB were chosen to ensure consistency in both function of the board, and so that the software needed for the project would not have to be changed between the two boards. Additionally, due to long shipping times, the R&D battery was replaced with a different battery. The new one has a capacity of 1300mAh and the old one had 1500mAh. Both are 7.4V, so no modifications were needed to the electrical systems. After passing the battery drain tests, the team alleviated any concerns about the slightly smaller capacity.

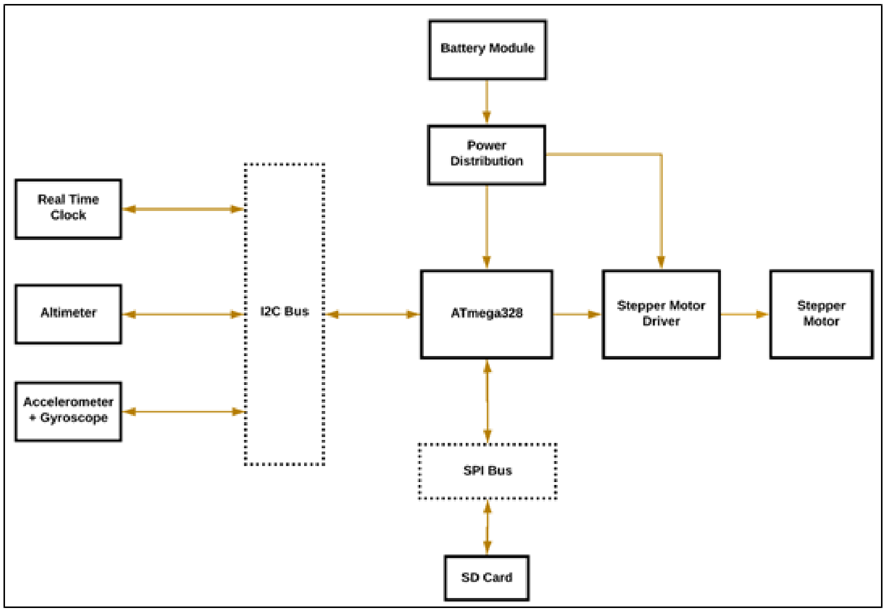

Figure 4.8: R&D Electrical System Overview

The R&D electronics have not changed in their over-arching electrical design. The Real Time Clock (RTC), Altimeter, and IMU all communicate with the ATmega328 via the I2C bus. The RTC chosen was the PCF8563 because of its simple design and availability. The Altimeter has changed due to demand. Originally, the team was planning on using the BMP280. After that went out of stock, the BMP388 was selected. This is what was used on the R&D perfboard. Due to shortages of the BMP388 chip itself, the drop-in replacement, BMP390, will be used for the PCB. The stepper motor is driven by the A4988 motor driver, which hasn't changed since CDR. The IMU hasn't changed from the LSM6DS33 originally chosen by the team. Additionally, the R&D key switch will still be connected in series between the positive lead of the battery, and the positive input of the board.

The team discovered that the Lander would often get stuck in the deployment phase due to the Lander and parachute bag being too tall. The two's combined height was causing the Lander to get stuck as the parachute bunched up in the opening, preventing the vehicle from being able to tilt out of the vehicle. During the construction process, a temporary solution was found by placing the Lander parachute bag underneath the lander allowing the Lander's weight to compress the bag during deployment. The team also experimented with folding the parachute bag in an uneven, ramp-like fashion to facilitate deployment. This helped the lander's top to clear the top of the R&D bay and fully deploy during testing. To alleviate this issue for future launches, the two threaded rods that connect the nosecone plate to the plate that accepts the lead screw will be replaced with longer versions. The longer rods will add the extra space needed for a full deployment of the Lander.

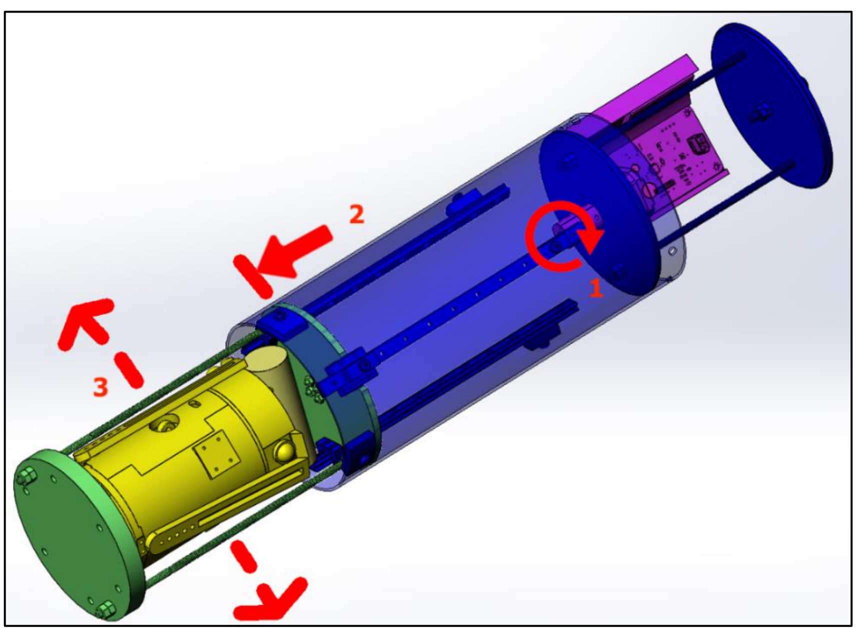

Figure 4.9: Legacy R&D Deployment Concept Render

The R&D subsystem underwent a modification in the physical construction of the electrical system. Due to unforeseen issues with shipping delays involving the PCB, the PCB could not be implemented in time. To overcome this, a perfboard with the same components that will be used on the PCB was created. When possible, the same components as used on the PCB were chosen to ensure consistency in both function of the board, and so that the software needed for the project would not have to be changed between the two boards. Additionally, due to long shipping times, the R&D battery was replaced with a different battery. The new one has a capacity of 1300mAh and the old one had 1500mAh. Both are 7.4V, so no modifications were needed to the electrical systems. After passing the battery drain tests, the team alleviated any concerns about the slightly smaller capacity.

During the Vehicle Demonstration Flight, the R&D system utilized the perfboard. However, with the possibility of getting the planned R&D PCB working before the Payload Demonstration Flight, the team may switch to that instead of the perfboard. The purpose of this would be to help reduce noise along data lines and get the board to fit into the electronics holder as planned, instead of only using 2 bolts. The team will only make this exchange if the PCB is tested thoroughly and verified to work the same as the perfboard. Otherwise, the perfboard will continue to be used.

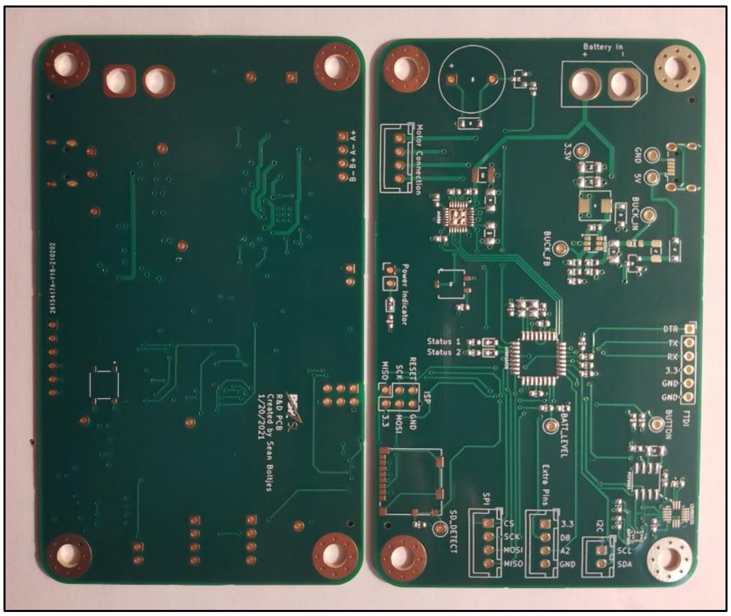

Figure 4.10: R&D PCB

The following page shows the schematic for the perfboard utilized in the R&D system. The only changes from the PCB design are the use of the modules. The pre-built modules include the Arduino Pro Mini, BMP388 altimeter, LSM6DS33 IMU, PCF8523 Real Time Clock, A4988 motor driver, and SD card module. Other than the change to pre-built modules for the sensors and microcontroller, the rest of the board is designed the same as it will be on the PCB.

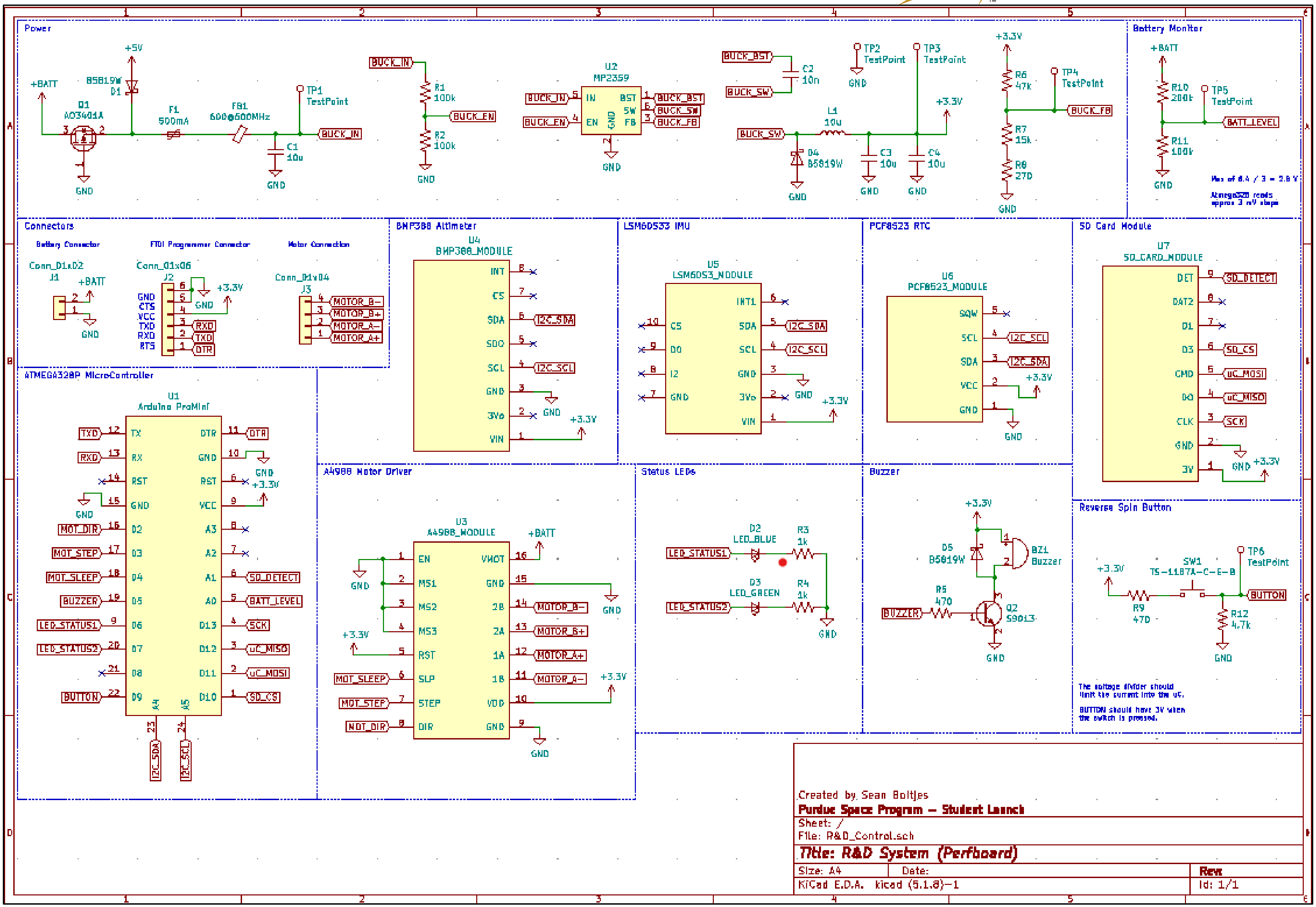

Figure 4.11: R&D Perfboard Schematic

4.2.2.2 Descent and Landing Subsystem

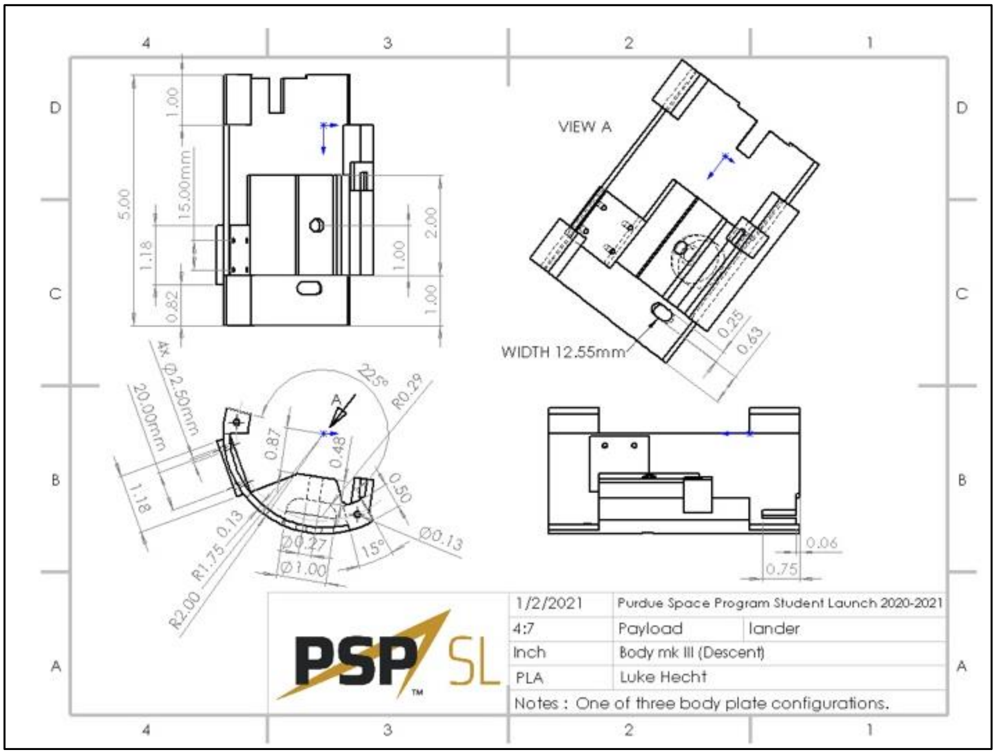

Figure 4.12: Lander Descent Body Plate Drawing

The Lander is tied via two Bowline knots to a 24-inch Fruity Chutes parachute. This parachute is folded flat and lightly wadded alongside the connecting nylon cable into a Rocketman parachute deployment bag. This bag is then tied via two more Bowline knots to the interior of the payload bay with 10 feet of nylon rope.

The descent system has changed from CDR mainly in the way the parachute is packed into the deployment bag. In the past, the parachute would merely be wadded without folding to prevent complications when removing the parachute from the bag. This was changed because the parachute deployed just as easily under this new method, with the added benefit that the folded parachute fit better into the payload bay.

Figure 4.13: Post-VDF Lander with Parachute Attached

In the future, the payload team will continue to work on integrating its system for detaching the payload from its parachute. This will be done by wrapping nichrome wire tightly around the nylon connecting the payload and parachute. This nichrome will be connected to copper wire and then to the Primary LCS Board. The LCS will trigger parachute release mechanism when it has detected touchdown. When triggered the LCS will close a relay and send current through the nichrome heating it up and severing the rope. The payload team tested the time taken to sever the selected nylon for varying currents at a constant resistance. The following is the tabulated results for severance time.

Current (A)	Time (s)
0.6	82.37
0.7	30.29
0.8	20.21

Table 4.1: Results and Conclusions

From this, the team decided to use 800 milliamps for the current on the lander's final design, as well as 7 wraps of nichrome around the nylon rope.

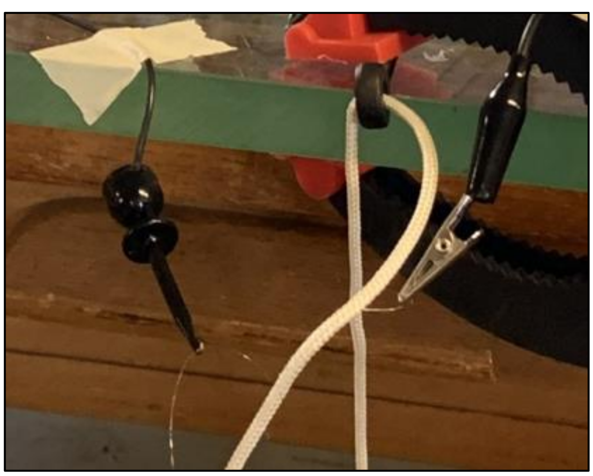

Figure 4.14: Nichrome Wrapping Method

4.2.2.3 Self-Orientation Subsystem

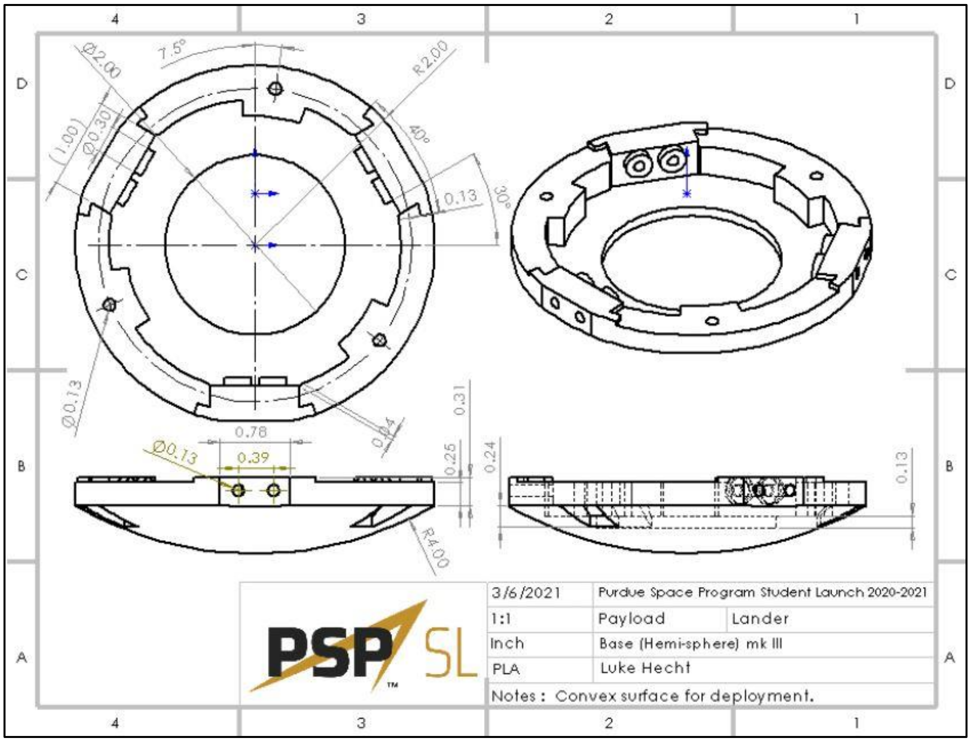

Figure 4.15: Lander Base Plate Drawing

The main change to the Self Orientation System is the modification of the Lander base plate. Most modifications made were minor changes to the geometry of the plate, which team believed would assist in assembling the lander. Examples include a rounded inner wall and deeper depression allowing for more free room during assembly. The other significant change to the base plate includes a geometry modification which increases the gap between the legs and the base of the lander. The team observed the prototype's legs being partially obstructed by the base in some instances, so decided to allow for a greater gap between the components. No changes were made to the legs themselves.

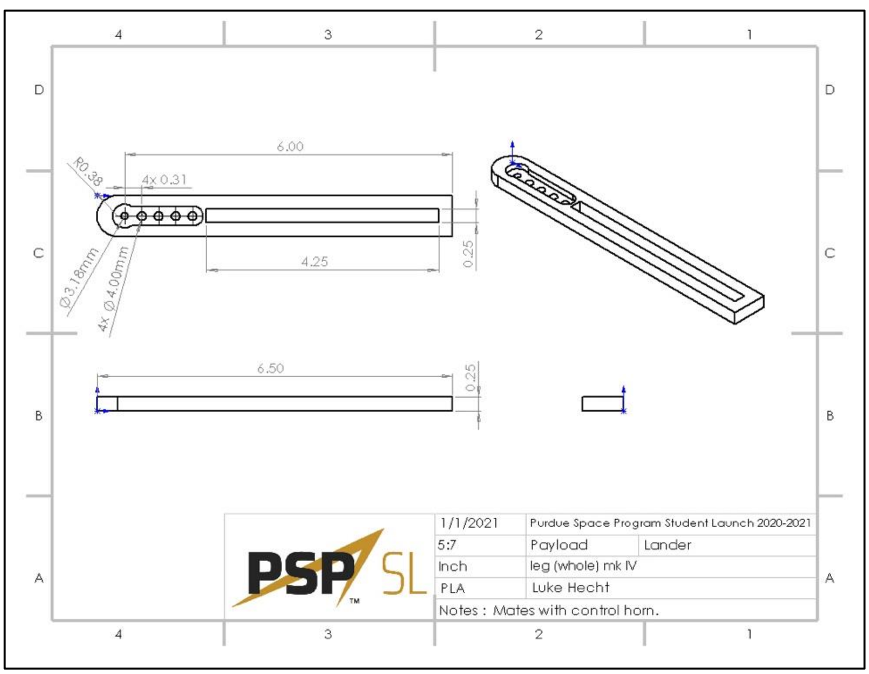

Figure 4.16: Lander SOS Leg Drawing

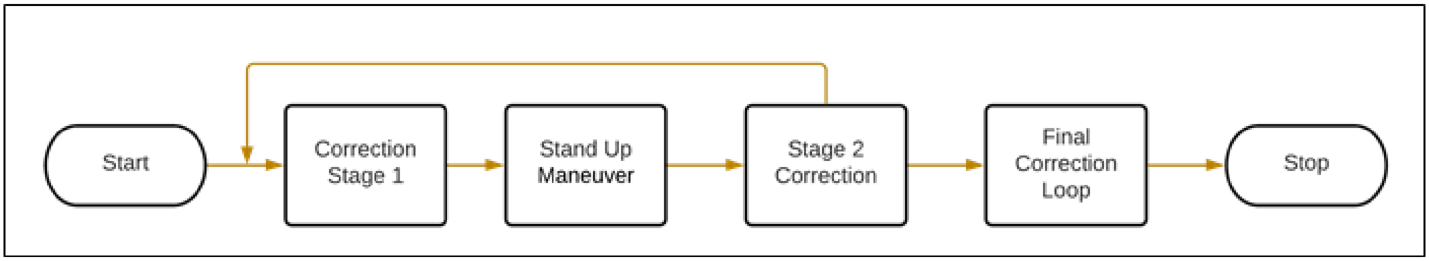

Figure 4.17: SOS Software Overview

The SOS software will be implemented on the LCS. The software will control the process of moving the Lander from the ground to standing within 5 degrees of vertical.

The first step of orientation is Stage 1 correction. The purpose of Stage 1 correction is to determine if the Lander is in a position where it can successfully orient itself before even attempting any maneuvers. This check will prevent the Lander from attempting to stand in terrain that may cause damage to the leg and jeopardize the success of the mission. In a situation like this, the Lander would perform a corrective maneuver, quickly moving a leg to attempt to roll the lander to a better position. Once the Lander moves, the new position is detected, and the detection process is repeated. Once the Lander passes Stage 1 Correction, it will move on to the Stand-up maneuver.

The purpose of the stand-up maneuver is to get the Lander from laying on its side to an upright position. Once upright the Lander will move onto Stage to Correction. The purpose of Stage 2 Correction is similar to Stage 1. Now that the Lander is upright, the Lander will detect if the orientation target, within 5 degrees of vertical, is within the range of motion of the servos. The Stage 2 check is to prevent the LCS from entering an endless final correction loop. If the Lander does not pass Stage 2, then the Lander will retract the legs, perform a corrective maneuver, and then return to Stage 1 Correction. If the Lander passes Stage 2, it will move into the Final Correction Maneuver.

4.2.2.4 Panoramic Image Capture Subsystem

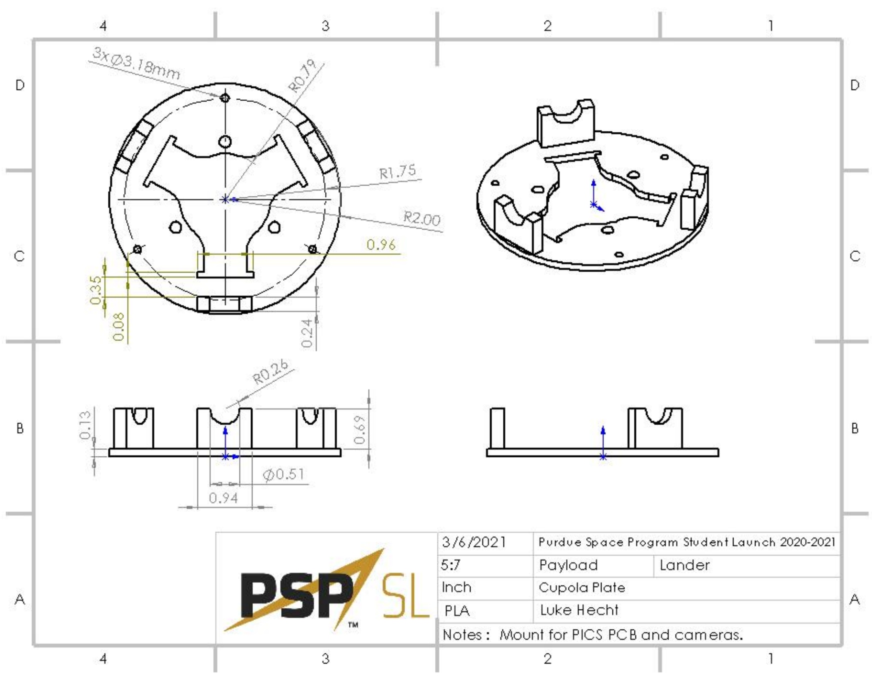

Figure 4.18: Lander PICS Cupola Plate Drawing

The PICS apparatus is located at the opposite end of the Lander to the SOS base—in a location named the "Cupola" after the viewing deck of the International Space Station. This cupola is positioned in such a way to provide an adequate viewing altitude for the PICS system. After orientation, this section will be located higher than any other system in the Lander. Additionally, the high location of the cupola allows for the centrally positioned GPS to operate with increased efficiency. This part requires placement far away from the electrically noisy main bay. Additionally, the materials used to produce the Cupola plates will be of non-RF-blocking nature. Since most of the lander will be utilizing the structural strength of superior Carbon Fiber reinforced 3D printing material, this will be a decently significant decrease in structural toughness in order to facilitate proper Lander operation.

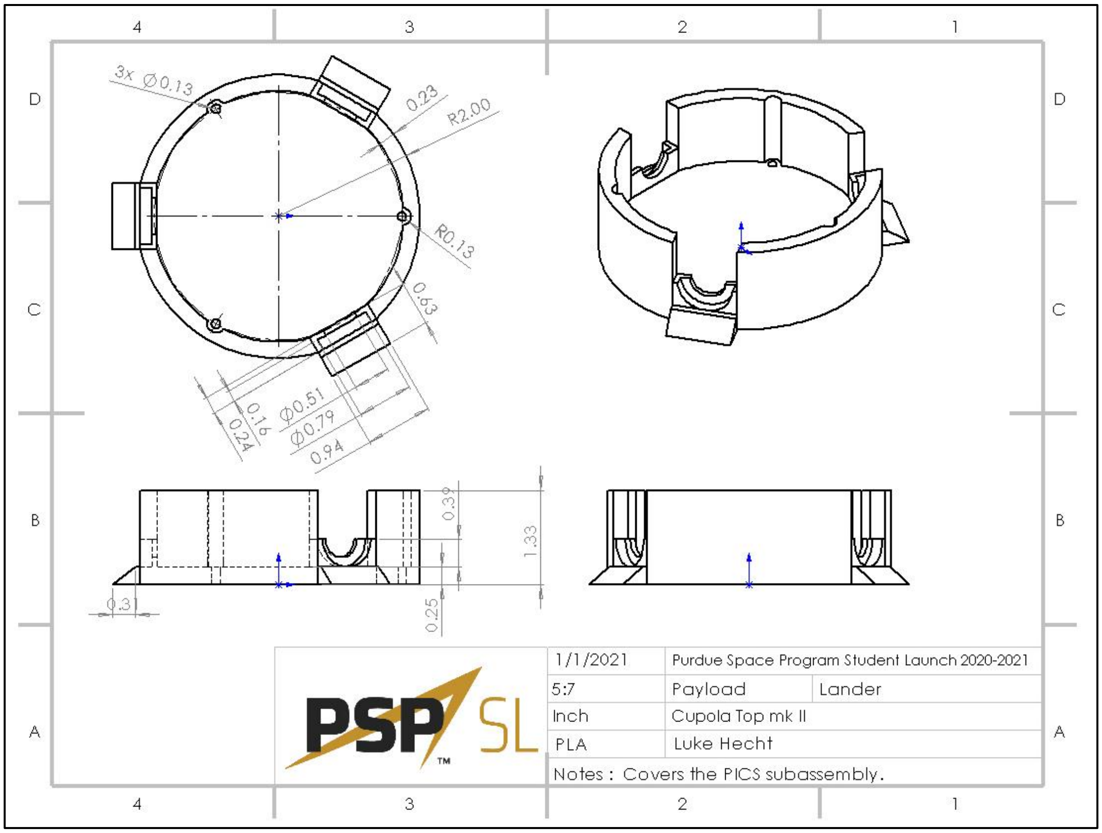

Figure 4.19: Lander PICS Cupola Top Plate Drawing

The top Cupola plate is intended to encapsulate the PICS system, which follows a different form factor to the rest of the Lander. With thicker walls and jutting protrusions to protect the camera lenses, the Cupola should provide adequate protection to the electronics within. In the foreseeable future, one final modification will likely occur to the lower Cupola plate. The chosen antenna for communication with the GCS is subject to change, and while there is a decent amount of vertical space within the Lander body, the chosen antenna is still likely to either not fit properly or not communicate sufficiently if not extended into the Cupola section. The final verdict on space accommodation changes will come from testing of the LCS.

Figure 4.20: Arducam 2MP Plus OV2640 SPI Camera

The PICS will use the Arducam 2MP Plus OV2640 SPI Camera Modules. The module includes an OV2640 image sensor to take the photos and an onboard microcontroller and digital storage unit that handle the configuration and capturing the photo from the image sensor. The camera sensor can be configured via I2C and the image data is transferred via SPI. This module was selected because it was simple to interface with the LCS. So far, the camera modules have performed to the team's expectations and no changes have been necessary.

The camera lens that is included with the camera module does not have a high enough horizontal FOV to create a panoramic photo with three cameras. To replace the stock lens, the team selected a fisheye lens with a horizontal FOV of 185 degrees. This gives the PICS more than enough coverage to take three images that can be combined into a panoramic photo. Fisheye lenses have distortion at the edges of the photo, but since the combined FOV of all three cameras is greater than 360 degrees the distorted parts of the images will be cut out when the panoramic photo is created.

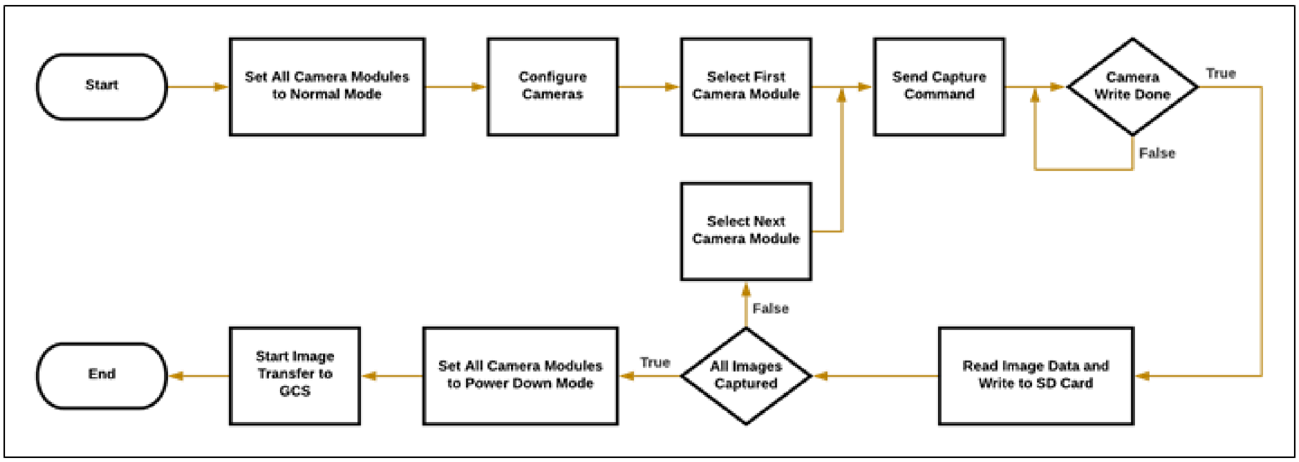

Figure 4.21: PICS Image Acquisition Process

The PICS process will start once the SOS has completed self-orientation. At this point, all camera modules will have been set to power down mode during system initialization when the LCS is powered on. The first step is to set all the camera modules to normal mode. Setting the camera modules to normal mode turns on the image sensor and allows images to be captured. Once all camera modules are set to normal mode, all the image sensors are configured to output a JPEG compressed image with a resolution of 320x240. All three image sensors are configured simultaneously via I2C.

After the image sensors are configured, the LCS will select the first module and send a capture command via SPI. The LCS will then transfer the capture image to the SD card via the SPI interface. This process will repeat until all three images have been captured and transferred to the SD card. The end result will be three separate image files stored on the SD card. Once all the files are transferred the PICS process is complete.

4.2.2.5 Lander Control Subsystem

The Lander Control Subsystem (LCS) controls all the functions of the Lander and interfaces with both the Panoramic Image Capture Subsystem (PICS) and the Self Orientation Subsystem (SOS) to execute their primary functions. The LCS includes the Lander's microcontroller, altitude sensor, IMU, and battery. Using one microcontroller to control all the subsystems of the Lander reduces the complexity of the software and electrical design while still keeping the subsystems modular. All the Lander's subsystems are connected internally with wires and connectors. The LCS executes and manages all the Lander's functions so that they are executed at the correct time.

The basic structural design of the LCS involves two complex, 3D printed plates which will integrate with other modular physical systems to form the PLS Lander. The physical design of this system has not been modified significantly since CDR, but the locations of some components have changed position slightly to enable better access for the LCS activation process. For instance, the reed switch holder has been moved to the opposite side of the battery holder in order to allow better access for the magnetic activator on the outside of the Lander within the R&D.

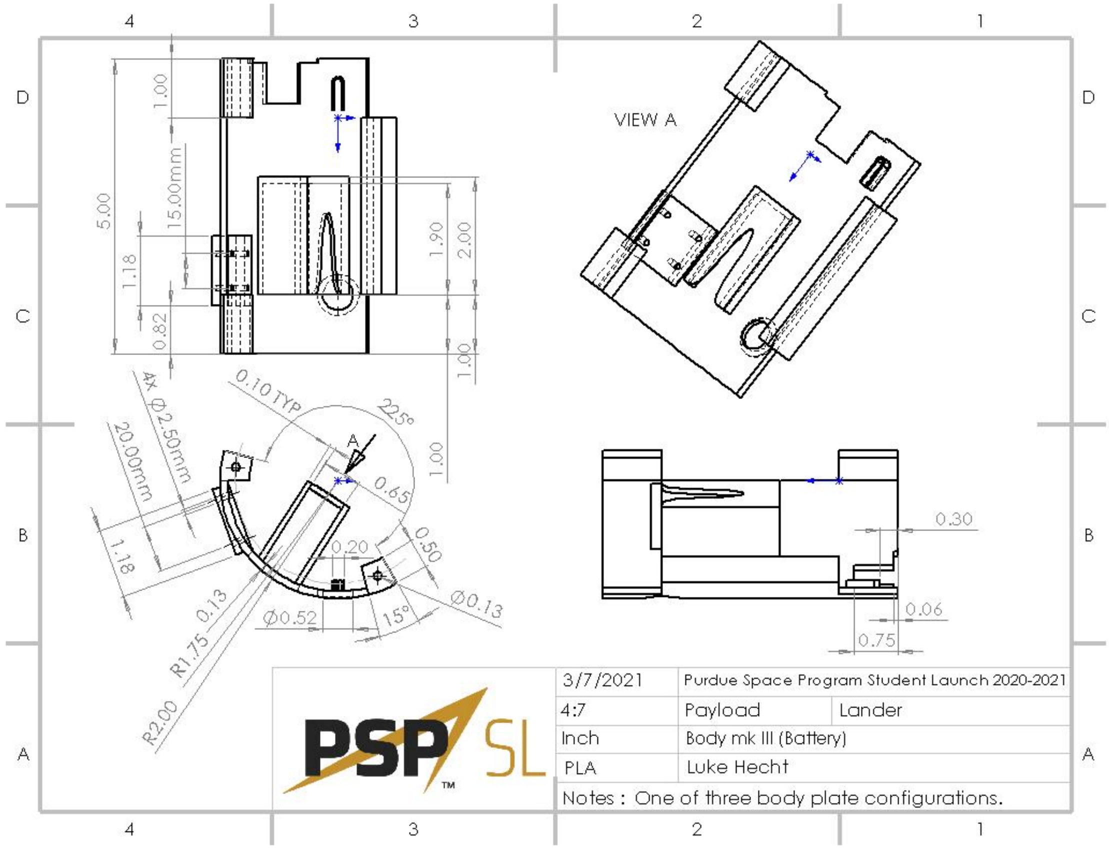

Figure 4.22: Lander Battery Body Plate Drawing

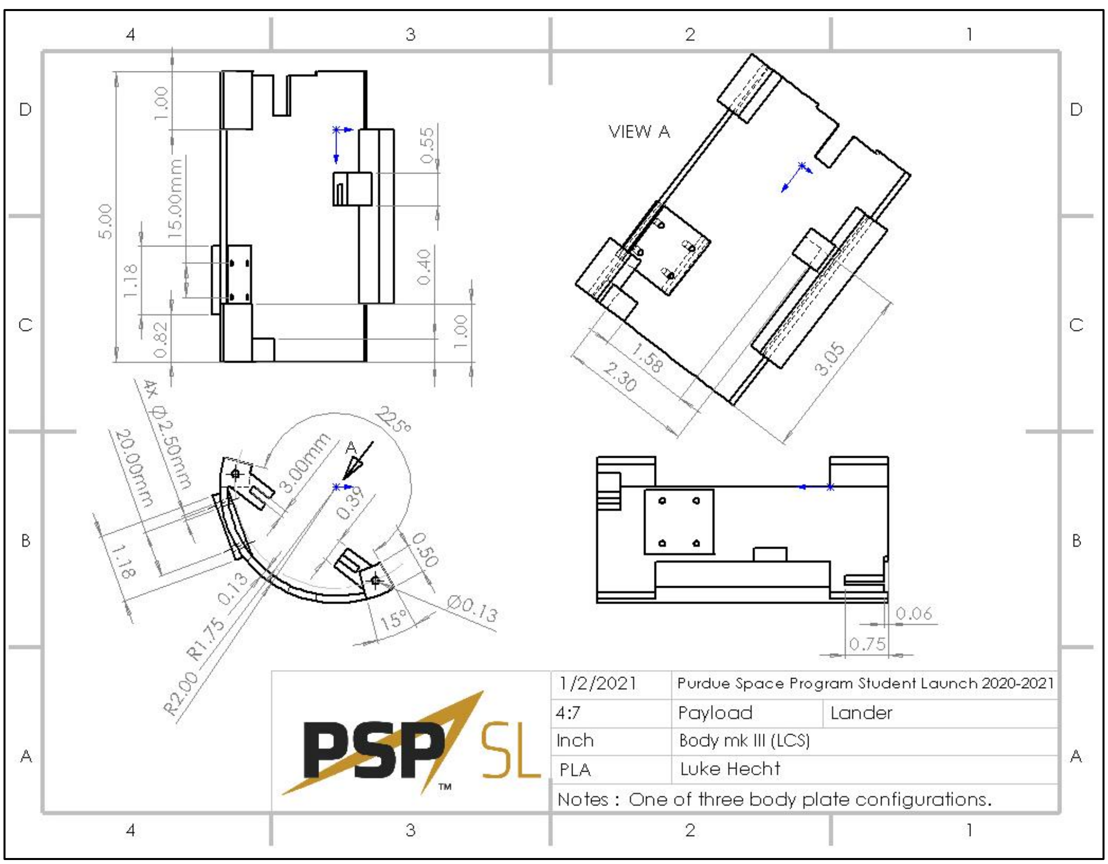

Figure 4.23: Lander LCS Body Plate Drawing

Due to issues with manufacturing, the team was not able to assemble and test the LCS in time for the VDF. The Lander that flew in the VDF did not contain any of the electronics elements of the LCS. The section paragraphs below will provide an overview of the current LCS design and highlight some design changes that were made. Since assembly, integration, and testing of the LCS has not been completed the team may be required to make changes to this design to accommodate any problems that arise. These problems and the changes made to solve them will be documented in the FRR addendum.

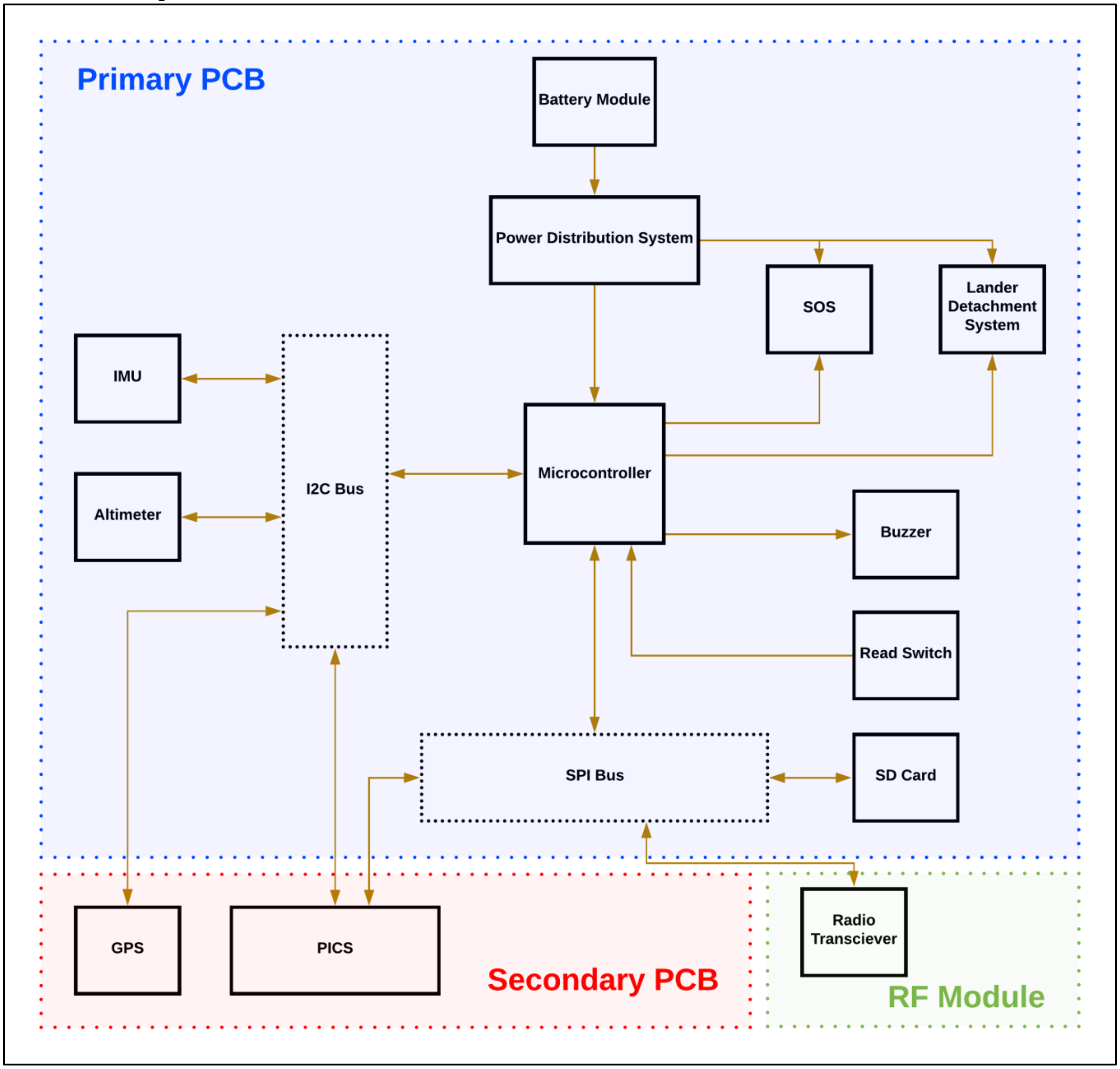

Figure 4.24: LCS Functional Diagram

The diagram above shows the major components of the LCS and how they interface with each other. The LCS is divided over two PCBs, the primary and secondary, as well as an external RF module. The original LCS design had the XBee RF module mounting directly to the Secondary board. It was determined that the XBee would not be able to fit into the small Secondary board along with the other components, the Primary board also did not have enough space. Therefore, the team decided that the XBee would be mounted separately in the Lander and would be wired to the Primary board.

The microcontroller in the LCS is the STM32F405RG. This microcontroller was selected because of its versatility and flexibility. The microcontroller has a larger number of pins that can be configured into many different communication protocols or used as GPIO pins. In addition, the STM32F405RG is a powerful yet efficient chip that meets all the teams processing needs while using minimal power. The team has not experienced any trouble with implementing this microcontroller and will be continuing to use it in this design.

Figure 4.25 Battery and Key Switch

The battery module contains the battery itself and a key switch to control the power. The battery selected was the Venom Fly 30C 1300mAh 7.4v LiPo battery. This battery was large enough to meet the power needs of the LCS while still being light enough to meet weight requirements. The team has had no issue with this battery, and it was flown as the R&D battery in the VDF flight.

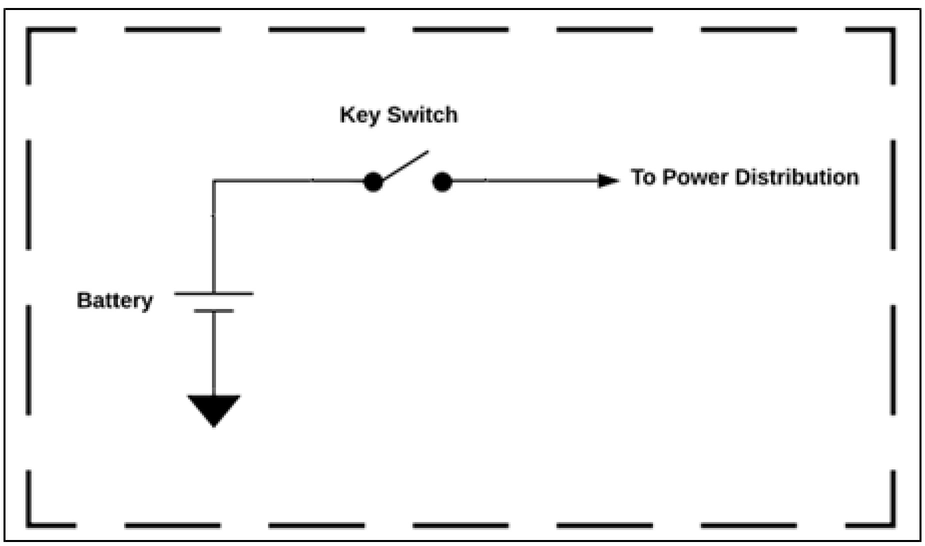

Figure 4.26: Battery Module

The key switch will be used to control the power to the Lander. The key switch will be in series with the positive lead of the battery to ensure that when the switch is turned of there is no voltage applied to any components in the system, therefore minimizing the risk of shock when handling the LCS. The battery connector in the Primary board has changed from a XT-60 to a smaller XT-30 connector to make the board smaller. To allow the selected battery to work without modification, the team will install an XT-60 connector on the battery side of the key switch and an XT-30 on the Primary side.

69

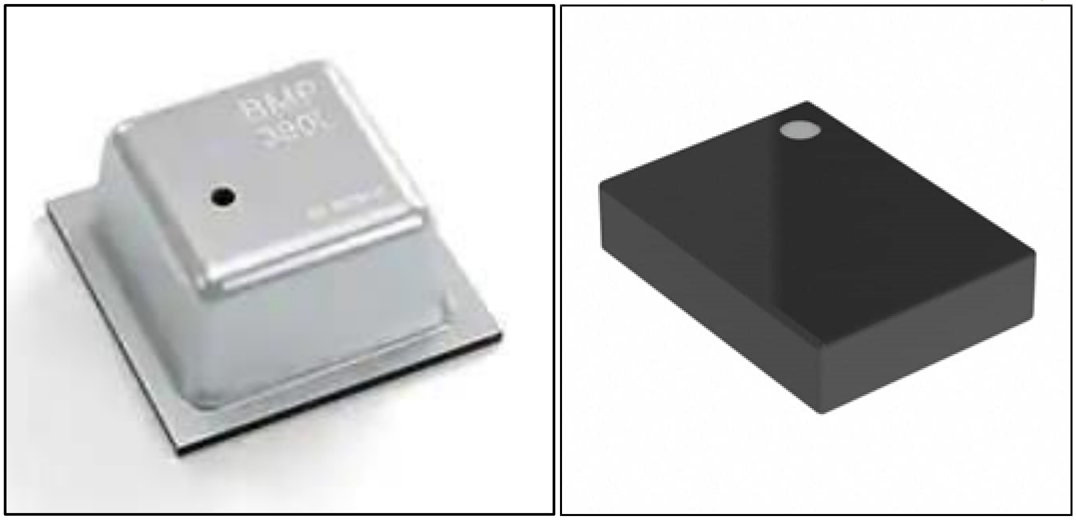

Figure 4.27: BMP390L and BNO085

The main sensors of the LCS system are the BNO085 IMU and the BMP390L barometric pressure sensor. The BNO085 IMU was selected because it was the lowest cost for a sensor that can output absolute orientation. The team has experienced not issues with this sensor so far and will continue to use it in the LCS design. The BMP390L is a change from the CDR. Initially the team planed on using the BMP280 but the due to supply shortages as a result of the Covid-19 pandemic, the team could not acquire the BMP280 for this design. The BMP390L was chosen as the replacement because it was the closest alternative that was still in stock. The BMP390L is more accurate than the BMP280, which was already determined to be accurate enough for the team's design. The downside is that the BMP390L was more expensive, but it still was withing budget.

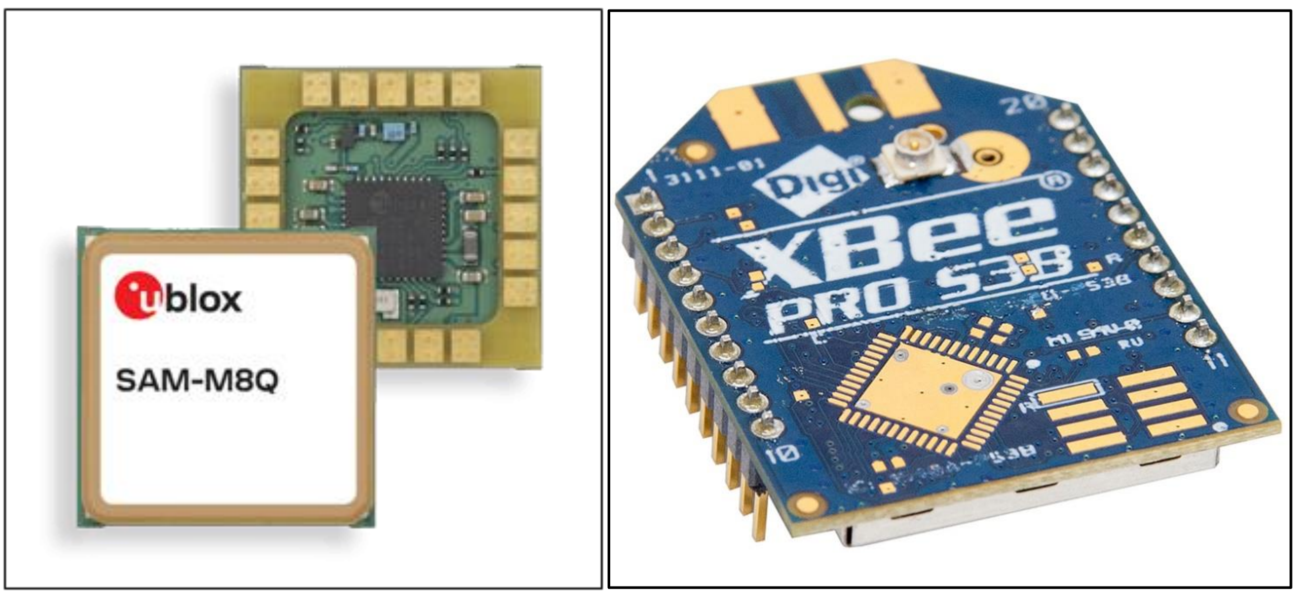

Figure 4.28: GPS and RF Modules

The LCS will continue to use the XBee module with some modifications from the previous design. As previously mentioned, the Secondary PCB was not large enough to accommodate the XBee module nor was the Primary Board. To solve this the team has decided to mount the Xbee elsewhere in the Lander and wire it to the Primary board. In addition, the teams original design planned on using Xbee-PRO 900HPs with a wire antenna. It was determined through preliminary testing that the wire antenna would not be sufficient to meet the range requirement of one mile described in requirement S.P.1.15. Through research the team determined that switching to a larger dipole antenna will be the simplest solution. The new antenna solution will be tested in early March and details of the antenna’s implementation along with any subsequent changes will be documented in the FRR addendum.

The Xbee PRO 900HP will use Digi’s proprietary protocol that is already programmed onto the Xbee. This protocol includes features for interference immunity and error detection. The main microcontroller will communicate with the Xbee using SPI communication.

The current GPS selection is the SAM-M8Q module. This module is an all-in-on GPS system that has a simple communications protocol. The Secondary PCB will be used as a ground plane to shield the GPS from the other electronics. The Secondary PCBs placement will give the GPS a clear view of the sky. The SAM-M8Q is the still the selected module, the team has not been able to acquire this module due to supply shortages. The team is currently using a breakout board with this module on it for software development and may have to incorporate this board into the design if the module cannot be acquired in time. The final design will be included in the FRR addendum.

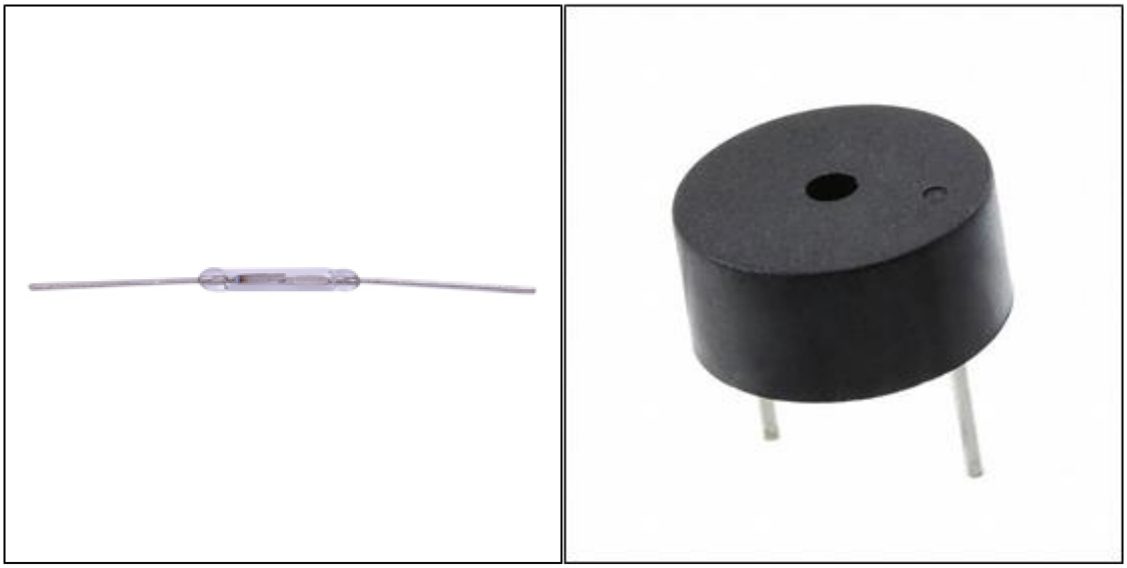

Figure 4.29: Reed Switch and Buzzer

The reed switch and the buzzer are important pieces of the LCS. The buzzer will be the Lander's only way of communicating with team members when the RF is disabled or not functioning. The buzzer will use different patterns of beeps to indicate a change in status or an error. The Reed switch will be used to determine when the Lander has left the Payload Bay. When the Lander is loaded into the Payload Bay, a small neodymium located on the inside wall of the Launch Vehicle will trigger the reed switch to close. When the Lander leaves the Payload Bay, the reed switch will open, and an interrupt attached to the microcontroller's GPIO pin will cause the microcontroller to exit sleep mode. The implementation of the reed switch and the buzzer is still ongoing, and more details will be included in the FRR addendum.

Another small design change the team will be implementing is the switch from JST-XH to JST-PH for most of the LCS connectors. The PH version is slightly smaller and was necessary to meet the size constraints on the PCBs. The PCBs are still in the process of being assembled and final images will be shown in the FRR addendum, the pictures below show the LCS PCBs with no components attached along with their updated schematics. The Primary PCB uses ENIG finish while the Secondary uses Lead Free HASL, the switch from ENIG for the Secondary was to save some money and speed up the manufacturing process. Unfortunately, the Lead free HASL finish did not turn out as clean as the ENIG but the team does not expect to have any issues with it.

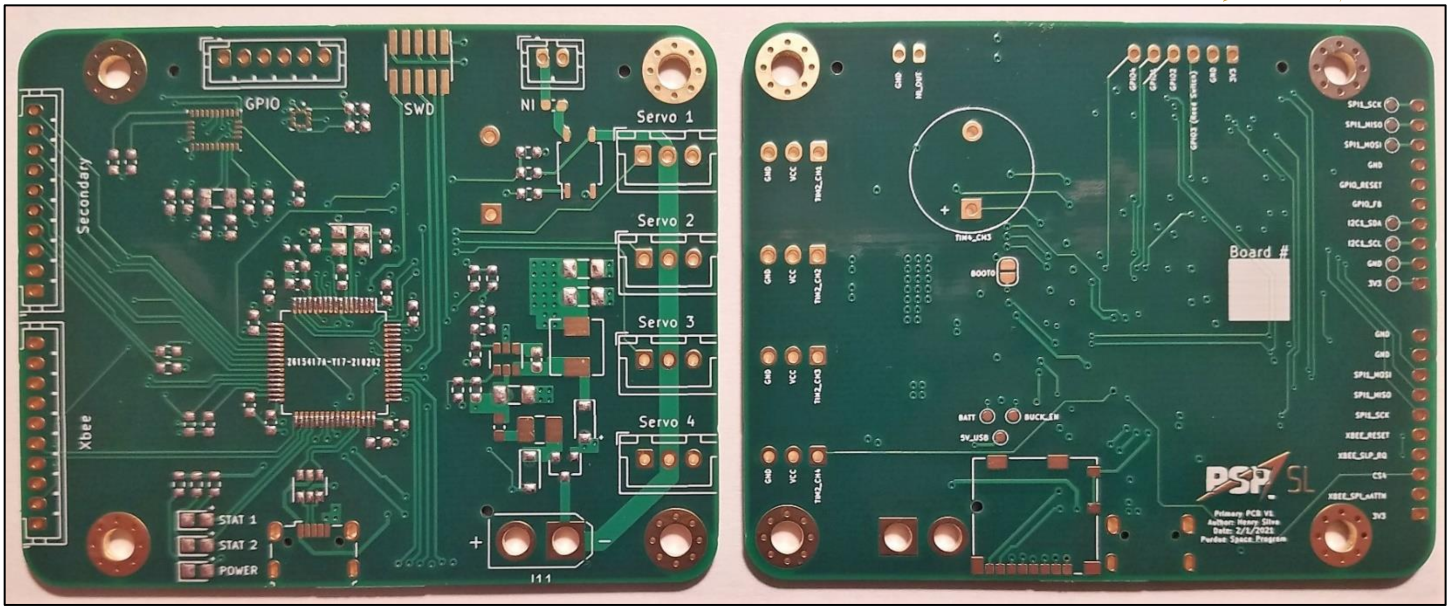

Figure 4.30: Primary PCB

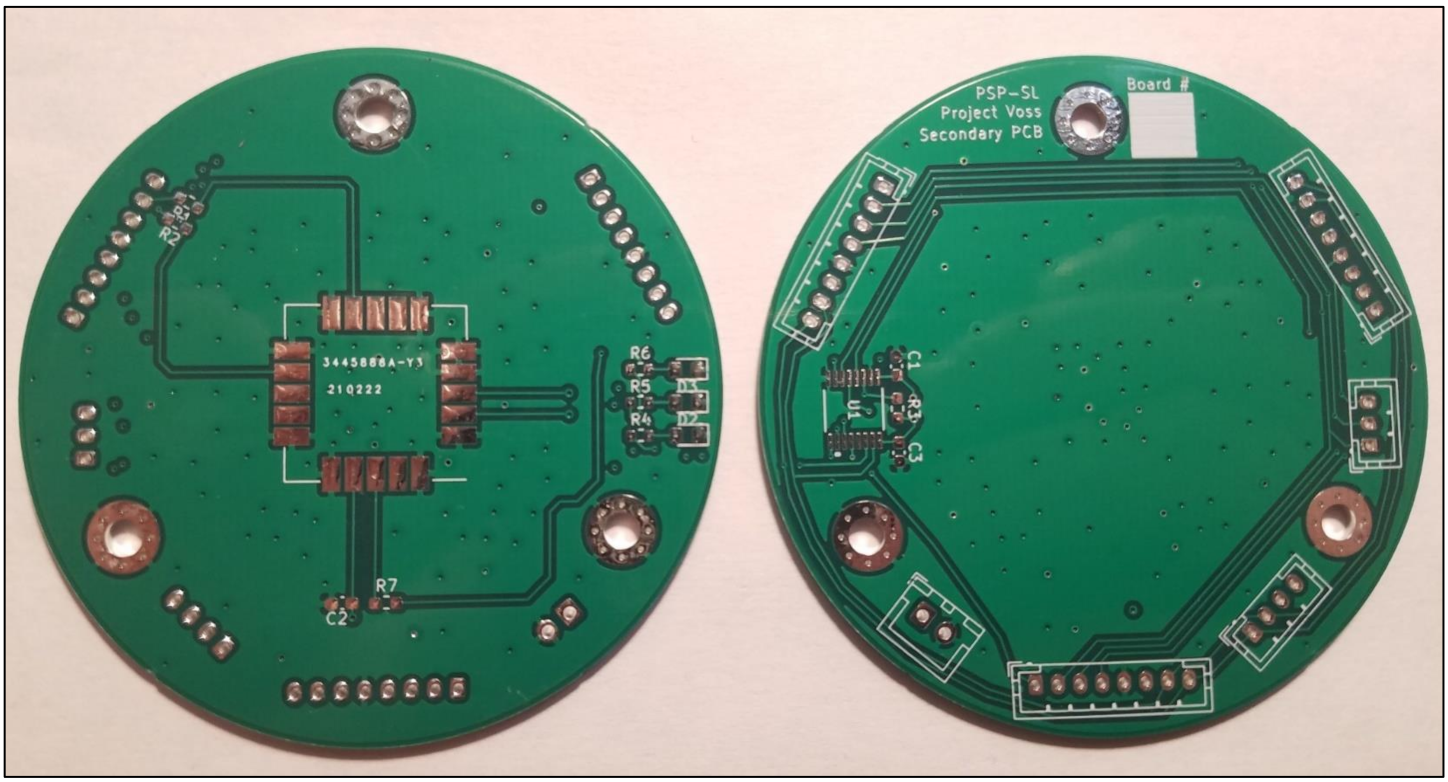

Figure 4.31: Secondary PCB

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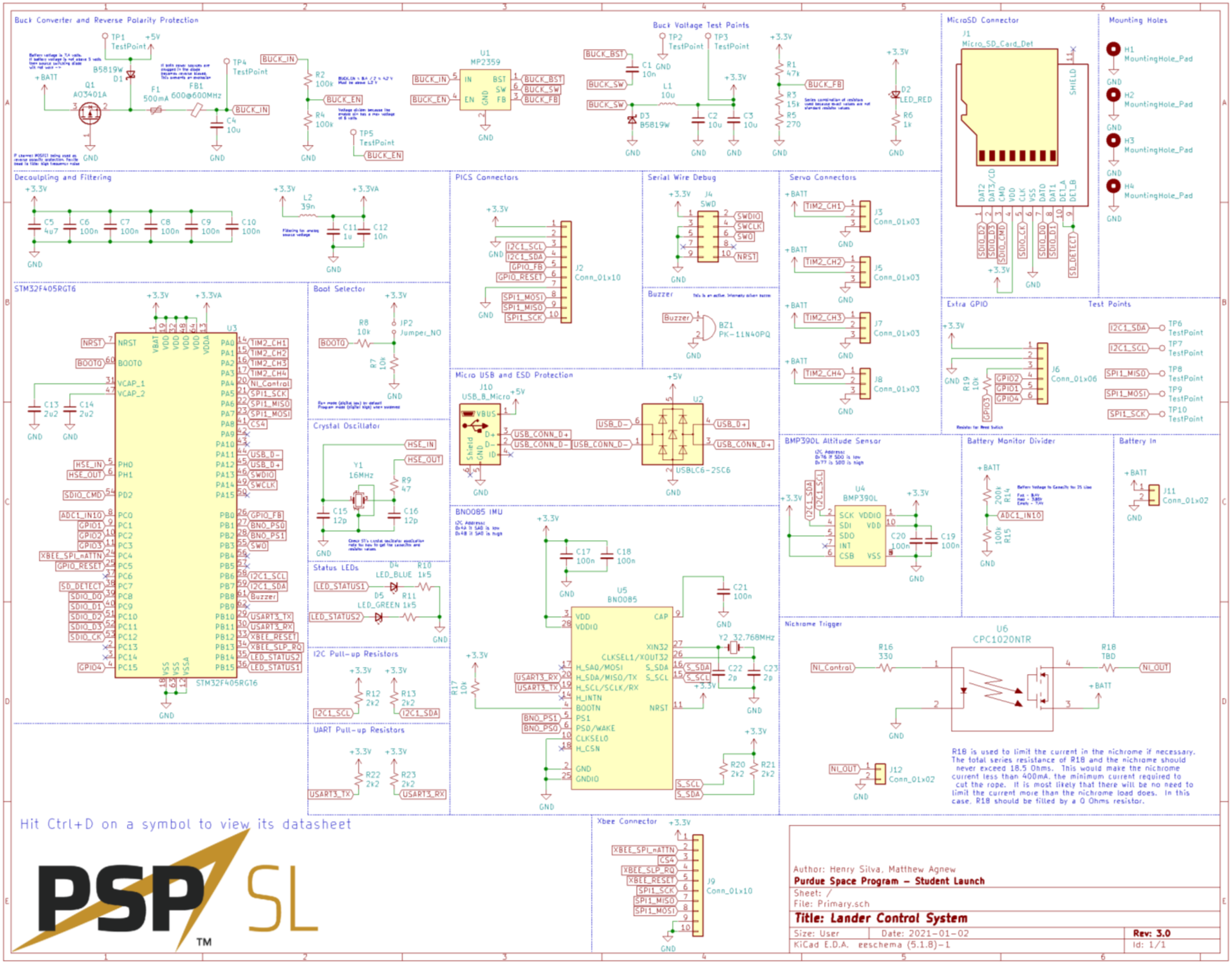

Figure 4.32: Primary PCB Schematic

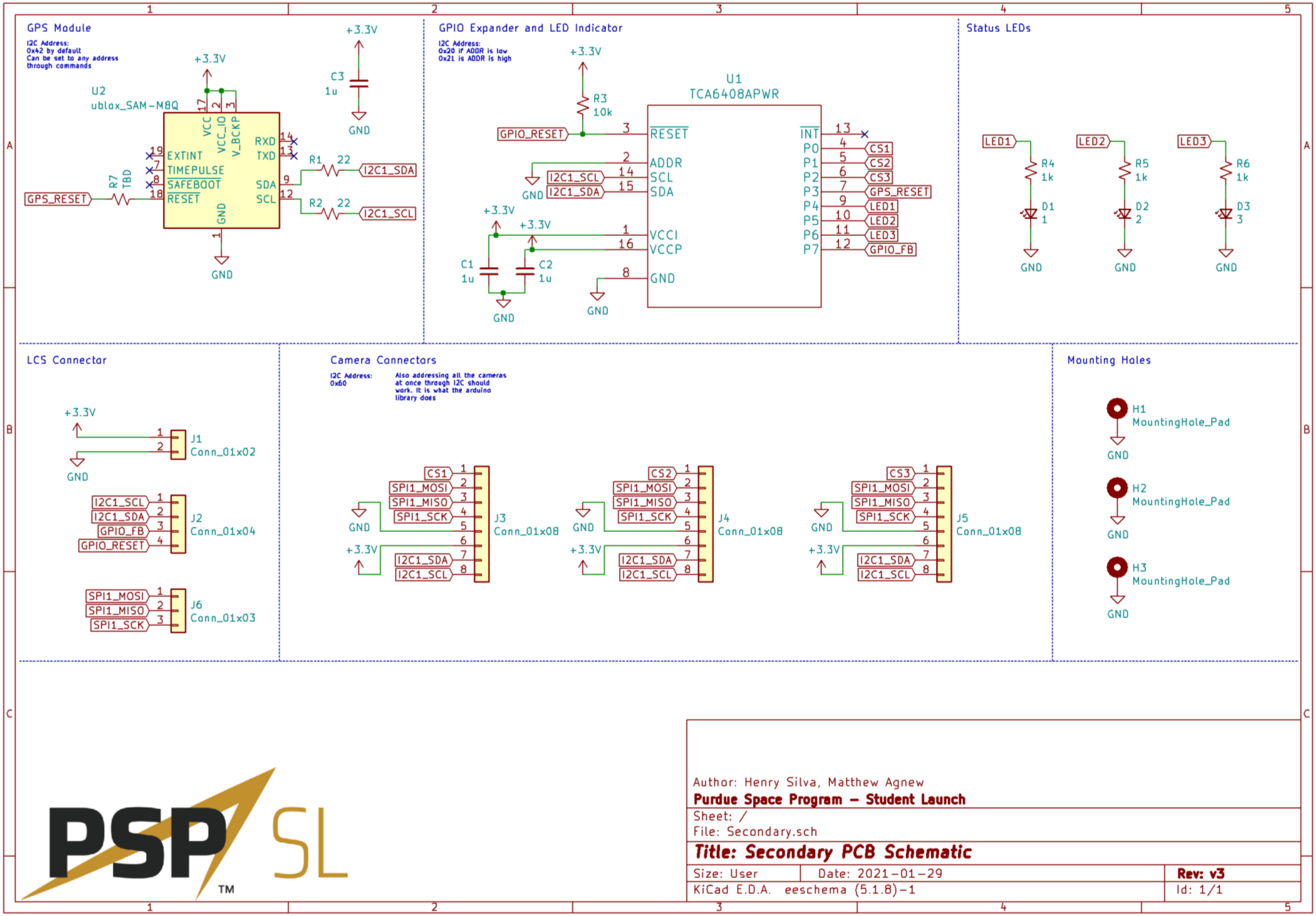

Figure 4.33: Secondary PCB Schematic

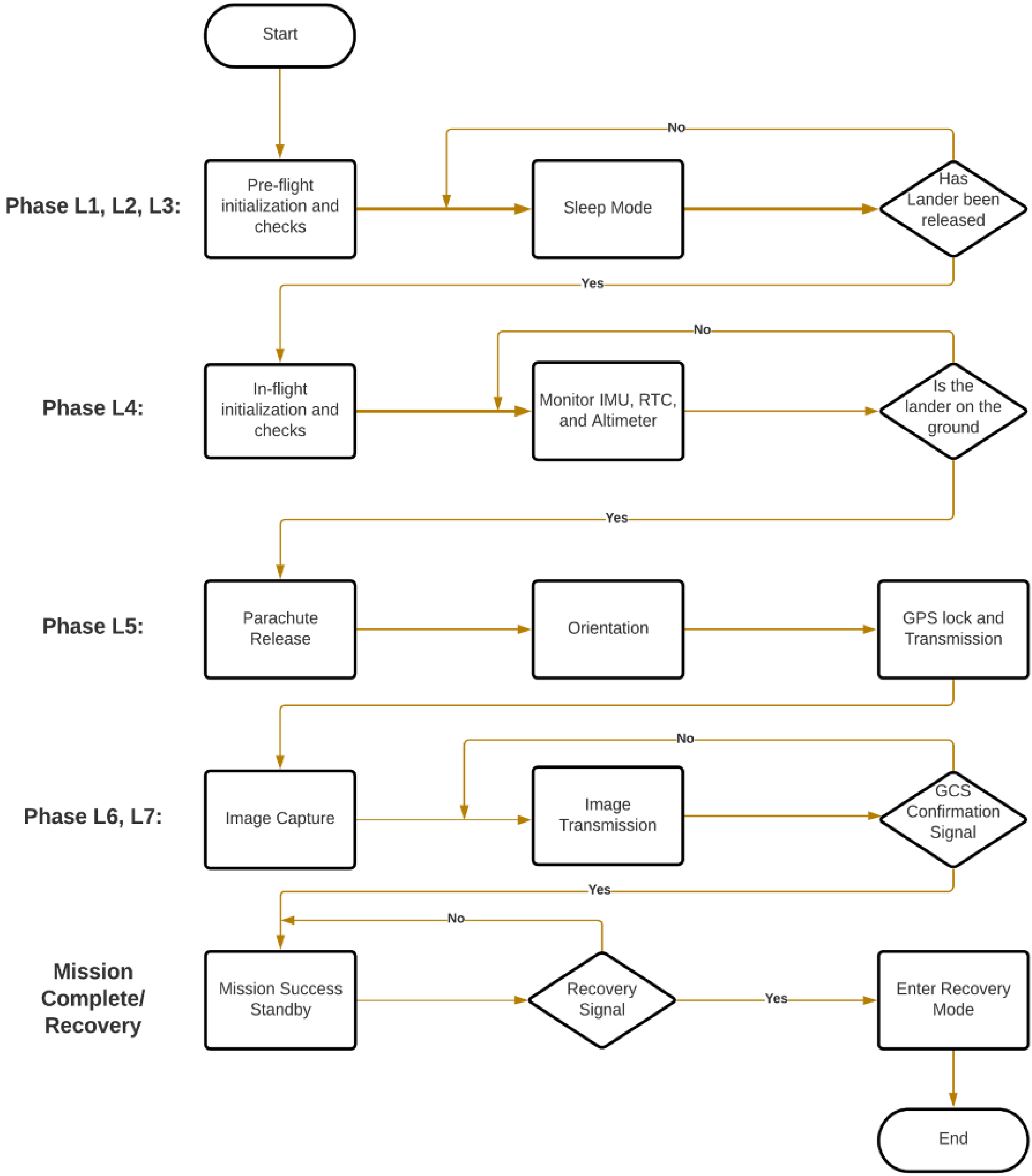

Figure 4.34 LCS Software Overview

After the Lander has been turned on, the LCS will begin the initialization phase. The initialization phase will test every system in a simulated mission except for the parachute release system. Any errors detected in this phase will be communicated to the team using the RF transmitter or the buzzer. Once the team is satisfied that the Lander is ready for launch, a command from the GCS will instruct the lander to prepare for launch. The lander will return the legs to the starting position and set all peripheral devices, except for the Xbee, into their respective sleep modes. Once the Lander is loaded into the bay, it will detect the magnet with the reed switch and will send a confirmation message to the GCS. Then, both the XBee and the microcontroller will be put into sleep mode. The Lander will remain in this state until the reed switch detects that the lander had left the payload bay.

Once the Lander has left the payload bay, the reed switch will open and trigger an interrupt on the microcontroller. The microcontroller will come out of sleep mode and begin the in-flight initialization. The microcontroller will begin start the real time clock (RTC) and instruct the Xbee and GPS modules to begin acquiring signals. The microcontroller will also begin to monitor altimeter and IMU data, as well as transmitting data back the GCS for the team to monitor. The Lander will use the RTC, IMU, and Altimeter data to determine if the Lander has landed. If the Lander does not detect landing after a period significant period of time, then there must be an error somewhere in the system. In this failure mode, the LCS will not proceed until it receives confirmation from the GCS that it is safe. If the Xbee has a connection to the GCS, the LCS will capture images using the PICS system as well as all relevant data and transmit it all to the GCS. The system will then wait for a command from the GCS, which will either instruct the Lander to abort the mission and enter recovery mode or to continue with the mission as planned.

If everything functions correctly, the LCS will detect a successful landing and trigger the parachute release mechanism. After the parachute has been released, the LCS will begin the orientation phase. Details of this phase were covered in the SOS software section. Since the GPS will most likely not be able to get a good position fix while the lander is on its side, the LCS will again poll the GPS after orientation and begin the PICS process. After the PICS process is complete the LCS will transmit the images to the GCS. After the GPS and image data are transferred to the GCS there will be an automatic confirmation reply. After the LCS receives confirmation of a successful transfer, the LCS will have completed its mission and will go into standby mode. The LCS will remain in standby mode until instructed by the GCS to transition to recovery mode. In recovery mode the Lander will return the legs to the starting position and will remain in this state until the Lander is turned off by the recovery team.

4.2.2.6 Ground Control Station

Being that the Lander was not in an active state during this flight, the GCS was not needed. It is currently not finished, and the team has adjusted the plan to create the GCS to make it easier to implement. The GCS computer designed and utilized last year was designed with a different challenge in mind, and the team has decided that too much refurbishment would be required to make it operational for the time being. The team has instead decided to use a common laptop as the GCS. This will allow for quick development and it will still be able to perform all the necessary tasks. The GCS will utilize a Python script in order to merge the images sent from the Lander and display the concatenated image on the laptop’s screen.

4.2.3 PLS Construction

4.2.3.1 R&D Construction

4.2.3.1.1 Component Fabrication

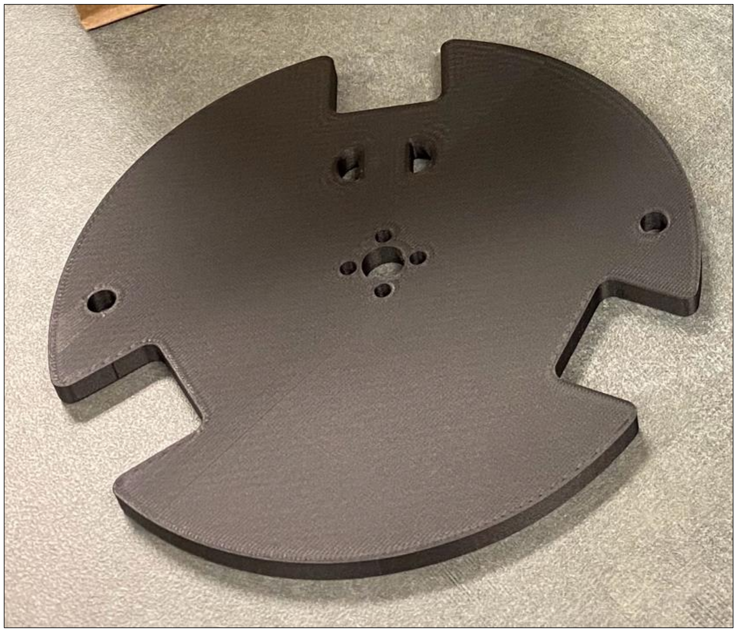

Figure 4.35: R&D Pizza Table Plate Manufactured

For the vast majority of non-hardware parts of the R&D, components were custom 3D printed. As stated in CDR, particular components will be handling flight loads while others will remain mostly static throughout the PLS mission. The materials chosen during CDR have remained to the final assembly iteration. The team decided that out of any subsystem to prioritize, the R&D's sound construction would be paramount to the launch vehicle's integrity, whether or not the PLS mission is attempted.

For the R&D's main sliding plates, the material used was Onyx Carbon Fiber Reinforced Nylon, available only at Purdue's Bechtel Innovation and Design Center (BIDC). Above can be seen the most complex plate, the R&D "Pizza Table," a plate which must interface with the R&D electronics lead screw as well as the Pizza Table legs. On the other end of the legs is the Pizza Table's counterpart plate, the Nosecone Attachment Plate, pictured in its assembled from below. Since the BIDC is busy this time of year and their scheduling system is being strained by the COVID-19 situation, the team had to prioritize some parts over others, but all R&D components which were essential to be made from this material were successfully manufactured.

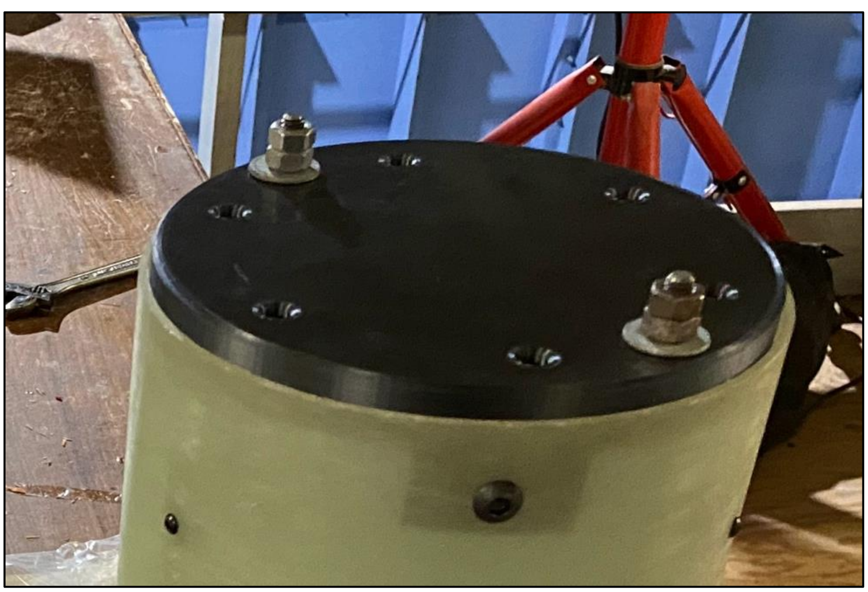

Figure 4.36: Nosecone Attachment Plate Assembled into R&D

For remaining components such as the offset blocks—used to bring the Lander's sliding rails towards the center axis of the Payload Bay—and the stoppers—designed to catch the deployed Pizza Table—these parts were 3D printed at PSP-SL's own manufacturing studio on one of two Creality CR-10 printers. The filament material chosen for these components was Polyethylene Terephthalate Glycol (PETG); while Polylactic Acid (PLA) has been a material very familiar to the team, some personal research performed by team members suggested that PETG would perform better in tensile and compressive strength, as well as overall toughness. While members have needed to perform additional print testing to ensure proper print quality, the result has been quite high-quality prints which have held up against all applied loads.

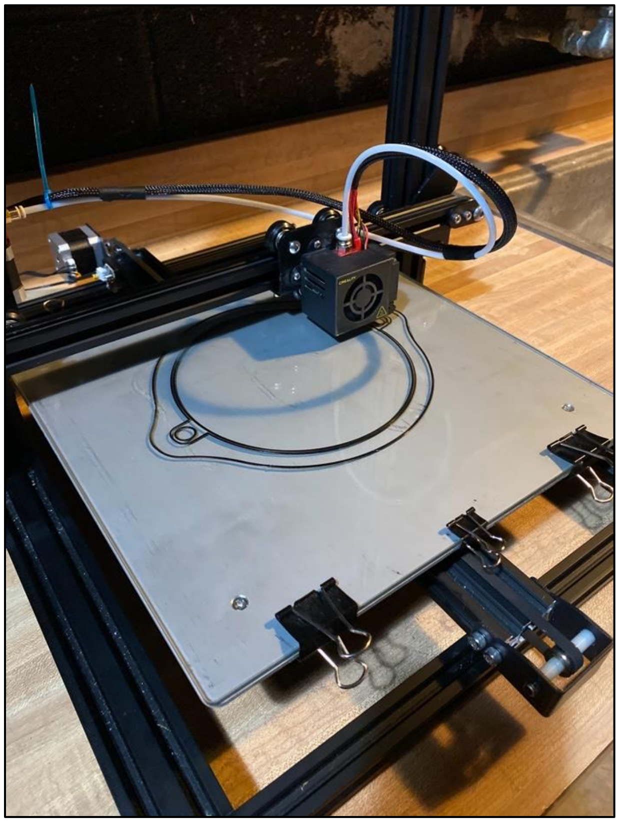

Figure 4.37: R&D Drilling Jig 3D Printing

While PETG was used for many flight components, the actual R&D airframe manufacturing process required extraneous printed jigs to help align drill holes. Thanks to the high precision of 3D printers (whose code accounts for acceleration and its derivative, jerk) the R&D jigs consistently produced accurate hole guides. The benefit of this jig design system will be discussed below, but the overall verdict is that 3D printed jigs allow for extremely low tolerance design to be *quickly* brought into reality despite any equipment or manufacturing inexperience any members may have.

4.2.3.1.2 Assembly

1. The first goal of properly manufacturing the R&D bay involved acquiring a rotational locking constraint. This can be done by first drilling the ring of holes required to attach the fiberglass R&D airframe and coupler. In order to do so, the first jig was installed and secured onto the end of the R&D airframe-coupler bay. This was done with masking tape to roughly prevent slipping during manipulation. A standard power drill, 3/16" drill bit, ¼" drill bit, and 0.5" drill bit was utilized to make the desired holes. Nearby members were advised to wear N-95 type facial coverings to prevent inhalation of fiberglass dust; this dust must be cleaned immediately after drilling has been completed.

Figure 4.38: R&D Initial Airframe-Coupler Hole Drilling

2. Once the initial holes were drilled, a second drilling jig (seen in gray) was installed onto the opposite end of the R&D bay and made flush with the nosecone-side rim. Since the original holes have been drilled, their respective bolts may be semi-loosely threaded through the first jig and into the airframe; this will rotationally and axially constrain the first jig. Using long, straight guide rods, the holes of the first and second jigs can be aligned, ensuring a rotational lock of the second jig. Once constrained, the stopper holes on the second drilling jig are able to be drilled.
3. Additional jigs were assembled to provide support for more accurately drilled holes. Once properly secured to the fiberglass airframe, additional holes for the R&D rails and R&D electronics plate access port may be drilled. Note that the alignment of the jigs is crucial to payload deployment, so this step must be executed with much caution. Seen below, in order to constrain the holes for the R&D rails as best as possible, a long "ruler" jig was produced with an exact holt-to-hole clearance of 200mm. In short, the third (seen in black) jig allowed for rotational constraint thanks to the first two jigs but relies on this ruler jig in order to be constrained just right axially. After drilling the rail holes, the team felt that this manufacturing method produced highly reliable and low-tolerance holes.

Figure 4.39: Jig attachments used to drill the R&D Bay

4. Each of the three rails is then screwed into place longways within the bay, supported from underneath by a rail offset block at each of the two bolts.
5. The next step is to assemble the Pizza Table. A threaded attachment to connect to the stepper motor lead screw is bolted to the bottom plate.
6. Threaded rods are threaded through the top Pizza Table plate and are secured with two nuts and a washer for each side of each threaded rod on each plate. The standard Jam Nut method is used to offload bolt pretension from the printed plate and direct most forces to between each set of nuts; executed correctly, this method helps prevent nuts' loosening through vibration. The outermost two nuts used are nylon lock nuts to prevent the effects of vibration further.
    a. To outline this process, first partially load a nut on either side of the plate against each other (approximately to 40% final intended torque).
    b. Afterwards, thread a second nut adjacent to each of the middle nuts.
    c. Tighten the nuts on a particular side of the plate to each other to full intended torque.
    d. Repeat for the nuts on the other side of the plate.
7. This above process is repeated on the opposite end of the threaded rods at the Nosecone Attachment Plate.
8. The Pizza Table is placed into the R&D fiberglass tube, where three radially equidistant stoppers are then screwed at the top opening of the airframe to prevent the bottom plate from sliding entirely out of the bay. If the stoppers are installed before this point, then neither the Pizza Table nor Nosecone Attachment plate will be able to be loaded into the bay.

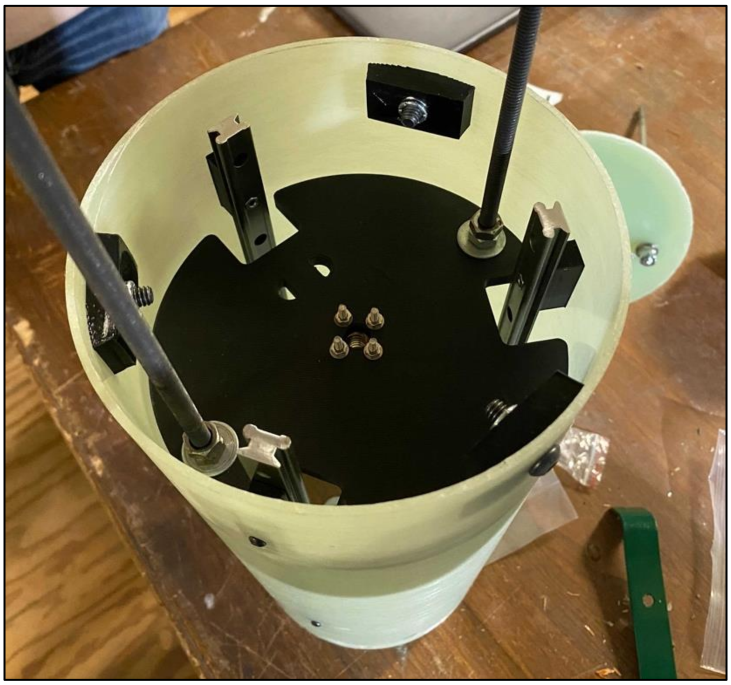

Figure 4.40: Rails, stoppers, and pizza table secured into R&D bay

9. To assemble the R&D coupler, a jig is first used to drill holes into the upper bulkhead. The largest of these holes (1/4”) is used to allow the stepper motor shaft to reach the lead screw coupler in the R&D bay. The other holes (3mm) provide bolting points to secure the stepper motor to the bulkhead. By this point, the Construction team had already prepared two additional ¼” coupler threaded rod holes on either bulkhead.
10. While the stepper motor is fastened to the upper bulkhead, the R&D perfboard and egg finder can be placed into their 3D printed mounts and temporarily secured to the coupler inside wall with hot glue. Later, when the coupler is fully integrated with the R&D bay, each mount will be fastened with a bolt placed through the airframe's body.

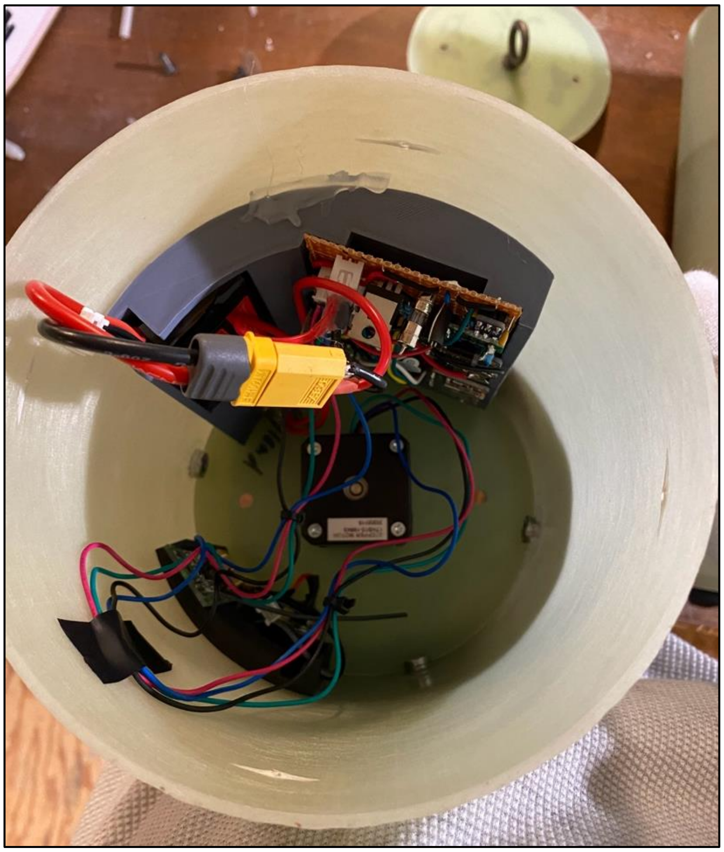

Figure 4.41: R&D Electronics Coupler Bay

11. When the R&D perfboard has been connected to the stepper motor and battery, threaded rods are used to fasten the bottom bulkhead with the stepper motor to the top bulkhead, sealing both ends of the R&D coupler. The Jam Nut method is again used to secure each threaded rod.
12. With the R&D coupler and bay fully constructed as separate components, the coupler can slide into place at the bottom of the R&D bay and be fastened into place with bolts.
13. The nosecone is fastened to the top plate with bolts.
14. To retract the R&D bay now, the stepper motor must be turned on and threaded into the top plate of the R&D bay, in which case it will continue to retract until a seal is made between the nosecone and the fiberglass airframe.

4.2.3.1.3 Integration

The rail system of the R&D used to deploy the lander has undergone a change. During testing, the Lander would not slide along the deployment rails easily. To remedy this, one of the carriages that was mounted on the lander was removed. The rail is currently still attached to the vehicle, the only thing that was removed was the carriage mounted on the lander. That means only 2 of the 3 rails are currently being used by the system, yet all 3 are still mounted in the vehicle. After performing tests, the rails have begun to shift into a better position and are sliding more easily than they did at the start. Due to this development, the team may re-implement the third rail if it no longer hinders the Lander's sliding.

The physical integration of the perfboard was different than the team originally planned. Due to the usage of the perfboard instead of the PCB, the electrical system's dimensions were changed. A slight modification had to be made when integrating the perfboard into the mechanical structure of the system. Originally, the team planned to use 4 bolts to secure the perfboard. Due to the perfboard being slightly longer than the PCB, this had to be cut down to just 2 bolts at the top of the attachment plate, allowing the bottom to hang off the plate. Although the attachment points were fewer, the board did not come loose or cause any issues when the team performed testing on the system.

Another electrical integration challenge that was discovered was the XT60 connector not fitting through the key switch hole. Due to this discovery, the key switch had to be mounted on the electrical attachment plate, and then soldered to the XT60 connector. While this was a relatively simple procedure, it is notable because the key switch and XT60 connector cannot be removed from the launch vehicle without removing the electrical attachment plate.

4.2.3.2 Lander Construction

4.2.3.2.1 Component Fabrication

ITEM NO.	PART ID	QTY.
1	Base (Hemi-sphere) mk III	1
2	Body mk III (Descent)	1
3	Body mk III (LCS)	1
4	Body mk III (Battery)	1
5	leg (whole) mk IV	3
6	Threaded rod (stand-in)	3
7	servo GoBuilda 25-2	3
8	Cupola Plate	1
9	3798K35	1
10	95462A029	1
11	90107A029	2
12	KO131A102 Keylock Switch	1
13	LanderControlSystem	1
14	Battery Stand-In	1
15	Cupola Top mk II	1
16	OV2640_Cam	3
17	1900-0025-0104	3
18	90725A020	6
19	SecondaryPCB_Stand-In	1

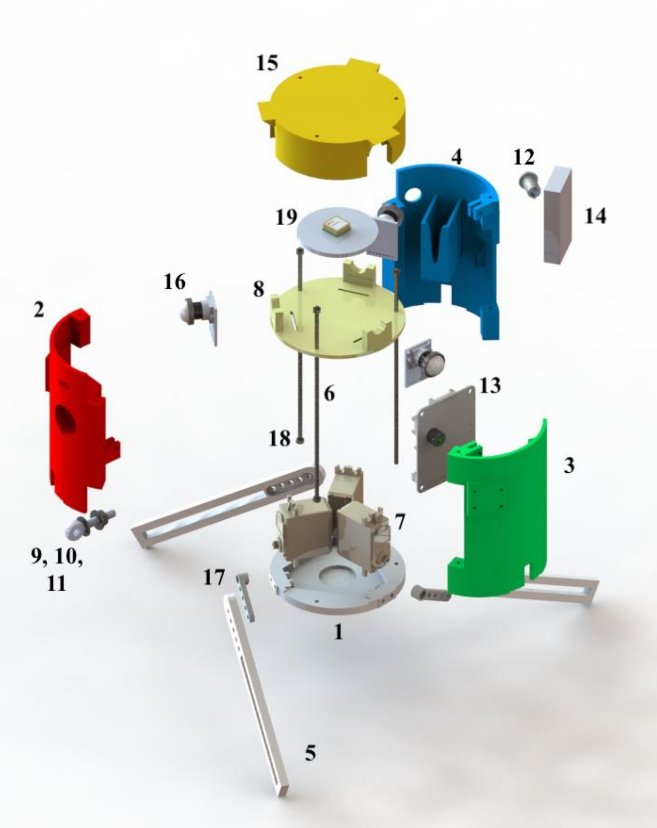

Figure 4.42: Lander BOM Render & Assembly Reference

For the purposes of VDF, only the Lander's structural components were required of the Payload team to get assembled. Therefore, aside from ordering the standard hardware required to produce the Lander, a suite of plates were manufactured to form the inactive Lander stand-in.

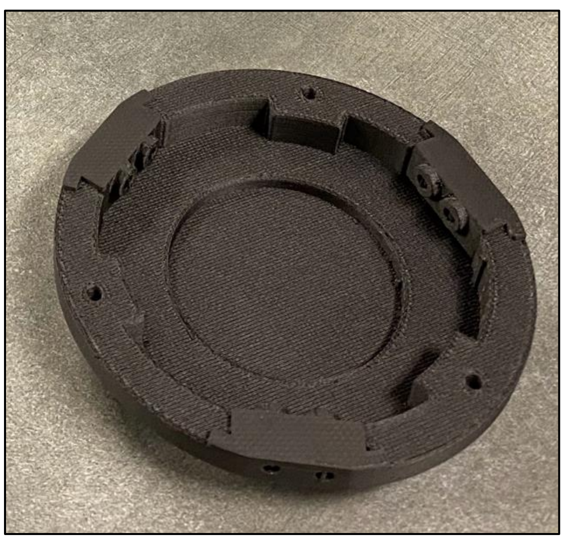

Figure 4.43: Lander Base Plate Manufactured

As described in the R&D construction section, the best material available to make such complex parts was Onyx Carbon Fiber Reinforced Nylon, available at the BIDC. Following the team's original design principles, the parts requiring the most stress will need to be manufactured with this material. Due to time restraints, however, the team needed to pick and choose which parts would be able to be fully manufactured from the desired material. In the Lander case, this was the Lander's base plate and its D&L body plate. These parts take the full brunt of parachute loading and landing damage, so they were prioritized and completed for VDF.

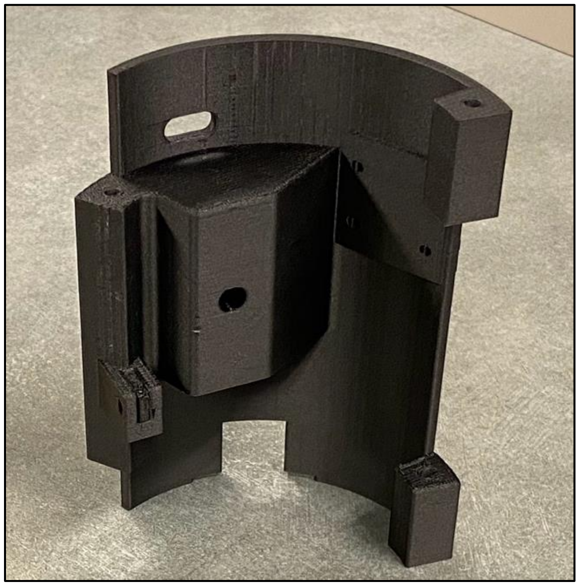

Figure 4.44: Lander Descent Body Plate Manufactured

For components that were unable to be printed out of Onyx, they were printed using the same material used by other Lander parts, PETG. For the purposes of the Lander stand-in, this material would serve just fine; if any of the other components were to fail, the remainder of the Lander should remain safely intact. In fact, both Cupola plates intended for the PICS system have and will require manufacturing out of PETG in order to better facilitate RF communications.

4.2.3.2.2 Assembly

1. Three servo motors are fastened with screws to the bottom plate, and the lander legs are fastened to the servos.
2. Rail carriages are fastened to the side of each plate. Spacers in the form of small washers are used to extend the carriages further outwards.
3. From there, each of the three plates interlock and are placed on top of the base plate. They are secured with three threaded rods, which holds each plate as if they were hinges, and extends through the base plate.
4. Ballast is placed inside the lander to replace the weight of electronics, which were not implemented for this launch.
5. The cupola plate is placed on top of the plates and slides onto the threaded rods, followed by the cupola.
6. Two nuts are placed on both sides of each threaded rod, and the Jam Nut method is used again to offload bolt pretension from the 3D printed components.

Figure 4.45. Lander assembly without electrical components or cupola plate

7. The threaded rods are cut to size with a Dremel. This is only done on one side in order to allow additional or replacement nuts to be added to the threaded rod at a future date; the team found it better to leave the Lander-bottom-side ends uncut.

4.2.3.2.3 Integration

Integrating the Lander into the R&D system changed since the initial design. As previously mentioned, the Lander was originally planned to be slotted onto the three rails of R&D system and have the parachute placed above it. Due to the rails' tight tolerances, this has proved to be hindrance to Lander deployment and as such, the team has moved to only slotting into two of the rails. Also, the team has found placing the parachute bag below the Lander to be a more reliable method for facilitating ejection. When the parachute bag is on top it tends to bunch up and obstruct the opening during deployment. By placing the bag beneath the Lander, it stays compressed and is therefore less of an obstruction risk. With these changes in mind, the current integration process for the Lander is as follows.

1. Payload parachute is folded and packed neatly into the parachute bag. It is important that the parachute packaging be flat but not take up too much surface area. If bunched up too much, the parachute bag will be difficult to fold up as described in step 3.
2. Slot the two carriages on the Lander onto the two appropriate rails within the Payload Bay.
3. Then Pizza Table is pushed slightly further into the Payload Bay and the parachute bag is folded, unevenly such that half of the bag runs along the side of the Lander and the other half sits underneath the Lander. All parachute shock chords are tucked under the Lander so as to not catch on anything during deployment.
4. Finally, while the Lander, parachute bag and Pizza Table are held securely the R&D stepper motor is reversed until the Pizza Table properly threads onto the threaded rod. It is important to not reverse the motor for too long and completely seal the bay until a visual inspection ensures no material from the parachute bag will get caught between the nosecone and payload bay fuselage. After this is ensured the stepper motor can reversed until the nosecone is snug with the payload bay fuselage.

4.2.4 PLS Software Production

4.2.4.1 R&D Code

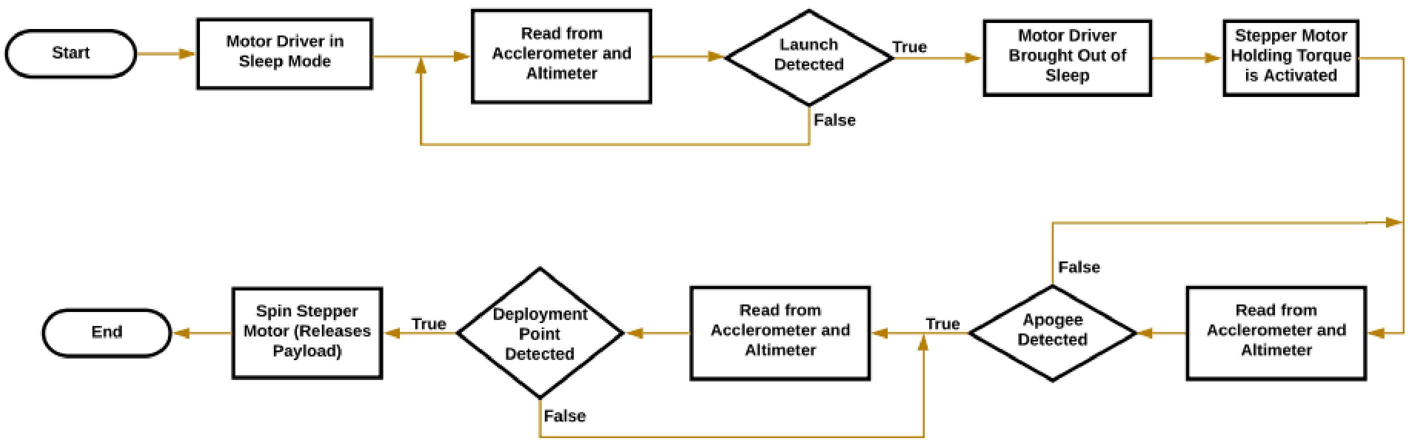

Figure 4.46: R&D Software Diagram

The goal of the R&D software is to wait until the appropriate time and then release the payload.

Before launch, the software keeps the R&D system in a state of readiness and power conservation. To do this, it puts the motor driver into sleep mode. All other components are kept out of sleep mode and in normal operation. The R&D's ability to accept the Lander into the vehicle has changed since CDR. While waiting for launch, the system can accept two different inputs from the button mounted on the electronics. If the button is pressed and held down, the motor driver is momentarily brought out of sleep mode and the stepper motor will spin so that the Lander will be accepted into the vehicle. A quick tap of the button results in the stepper spinning such that the Lander is ejected from the vehicle. This serves to set up the system prior to launch. While looking for launch, if the system reads that there is a rapid increase in magnitude of acceleration and a rapid increase in altitude, the system will be able to identify the occurrence of launch. This is important because the software can now pull the motor driver out of sleep mode and activate the stepper motor's holding torque so that the payload does not prematurely deploy.

During launch, the software monitors for key points and maintains the holding torque of the stepper motor. The software will monitor the altimeter and wait until an altitude of 800 feet is reached during descent. This is different from the original goal of 700 feet. This was changed so that the stepper motor will start to spin at 800 feet, but the payload will release around 700 feet. Once the altitude of 800 feet is reached, the software will signal the stepper motor to spin, causing the payload to deploy. As a backup signal, the accelerometer will detect both the drogue and main parachute deployments. It will ignore the drogue parachute deployment, as that occurs too high to deploy. If, for whatever reason, the software fails to identify the altitude from the altimeter, the accelerometer will detect main parachute deployment, which occurs at 900 feet. This is near the payload deployment range of 500-700 feet. Therefore, the system can use the accelerometer and the real time clock to determine the system's approximate altitude, basing off the main parachute deployment altitude of 900 feet. After the payload is deployed the R&D software has served its purpose and completed its task.

4.2.4.2 Lander Code

Due to time constraints, the team has had to push back development of the LCS software. Since the software is in early development, an in-depth discussion of the software would not be appropriate. This section will be a brief description of the software development plan before the Payload Demonstration Flight.

The team's first priority is to develop the parachute release code. This code will take the highest priority and will completed as soon as possible to allow for extensive testing. The PICS and SOS code are split amongst several team members and will be developed concurrently. For SOS development, the priority will be to develop the code for the stand-up maneuver as a starting point then the more complex correction algorithms will be continuously developed during testing. Once the stand-up maneuver is developed, the team can begin integration testing as the PICS, GPS, and XBee should work once the Lander is able to stand up.

Given the short time frame the team will be implementing agile development strategies. The software will be developed in short sprints with each sprint finishing with software that is safe to fly. Using this method, the team will be able to fly PDF even if non-critical software features are not implemented. The team is optimistic that most—if not all—of the software features will be developed prior to the PDF. However, time constraints may force the team to push non-critical software elements and the fine tuning of algorithms into the "Launch and Operational" phase of the development cycle.

4.2.5 Designed Flight Reliability Confidence

As will be described as required criteria for VDF, to be able to fly, the PLS must be in a state that will not cause any danger to the vehicle or any launch day crew. In order to produce this result, the systems of the PLS were tested for structural integrity. The primary concerns include whether the R&D will open or actuate during the vehicle's ascent stage and whether the Lander's parachute connections are satisfactory so as to not allow some or all of the Lander to plummet to the ground at unaided terminal velocity.

After construction, these systems were tested repeatedly in a static manner in a few different ways in order to ensure that the most essential structural components can hold up to flight loads as required by G.2.4.1 TD. The tests performed by the Lander team include VT.P.1.2 and VT.P.1.10. In both cases, the systems met and exceeded the required factors of safety, meaning that the R&D and Lander are structurally ready to be flown in an inactive Lander configuration.

Additional required testing included the proper functioning of R&D flight batteries through VT.P.1.4. The ability of the R&D to maintain full structural rigidity depends on the R&D's stepper motor being active. Since the batteries were deemed flight ready, the ability for the R&D to maintain its functional status has been more confidently assured.

Having satisfied these "Mission Critical" requirements, the PLS was given permission to fly during VDF.

The PLS was not without its risks during VDF, however. There were a number of flight safety risks which the team understood were within the realm of possibility. For the most part, these flight risks would need to manifest as corner cases of multiple failures. The primary concerns were structural and electrical in nature. In the inactive Lander case, this concern primarily regarded the possibility of the parachute not properly unfurling during descent. While the team is using a standard drogue-chute sized parachute, there always remains the possibility that the parachute becomes knotted, posing a kinetic risk to all launch day crew. On the side of the R&D, while many flight loads have been simulated in a basic manner during design—informing the materials and thickness of components used—there could be numerous unexpected loads applied upon the R&D Bay during flight near Mach 0.5. While highly unlikely, the team anticipated the possibility of the R&D system being ripped apart by high turbulence or vehicle tumble. These types of hazards are omnipresent, but the team had been/will be briefed on the capabilities and behavior of the PLS before launch.

4.3 Aerobraking Control System

4.3.1 System Overview

The ABCS main design impetus is to assist in achieving the predicted apogee which has been calculated through OpenRocket at 4100 ft. Through a control system, the ABCS will determine the trajectory of the launch vehicle and compute the necessary adjustments to a set of three aeroplates. The physical system in the lower airframe and is comprised of two main structures: the airbrake pad structure and the electronics bay.

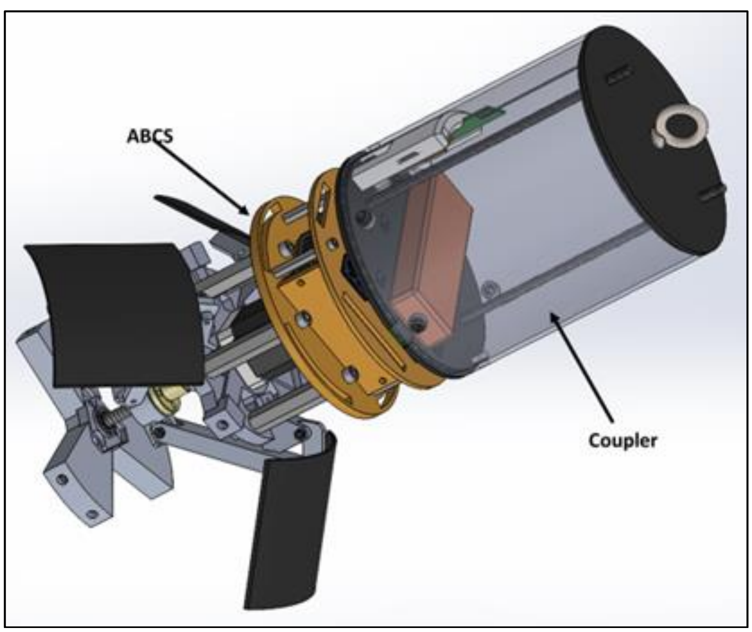

Figure 4.47: ABCS with Coupler

4.3.2 As-Built Design Overview and Changes Made

4.3.2.1 Mechanical System

The ABCS main design impetus is to assist in achieving the predicted apogee which has been calculated through OpenRocket at 4100 ft. Through a control system, the ABCS will determine the launch vehicle's trajectory and compute the necessary adjustments to a set of three Aeroplates. The physical system in the lower airframe and is comprised of two main structures: the airbrake pad structure and the electronics bay. The electronics bay rests atop the airbrake system as shown below.

Figure 4.48: ABCS Actuated

Figure 4.49: ABCS Actuated Top View

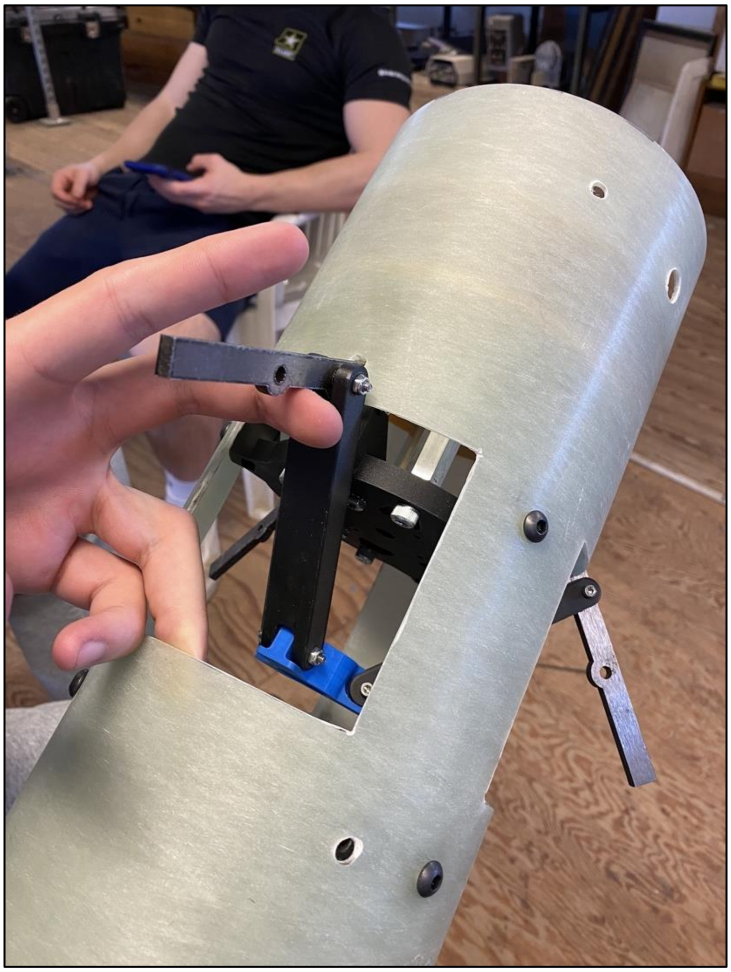

Figure 4.50: ABCS Structure

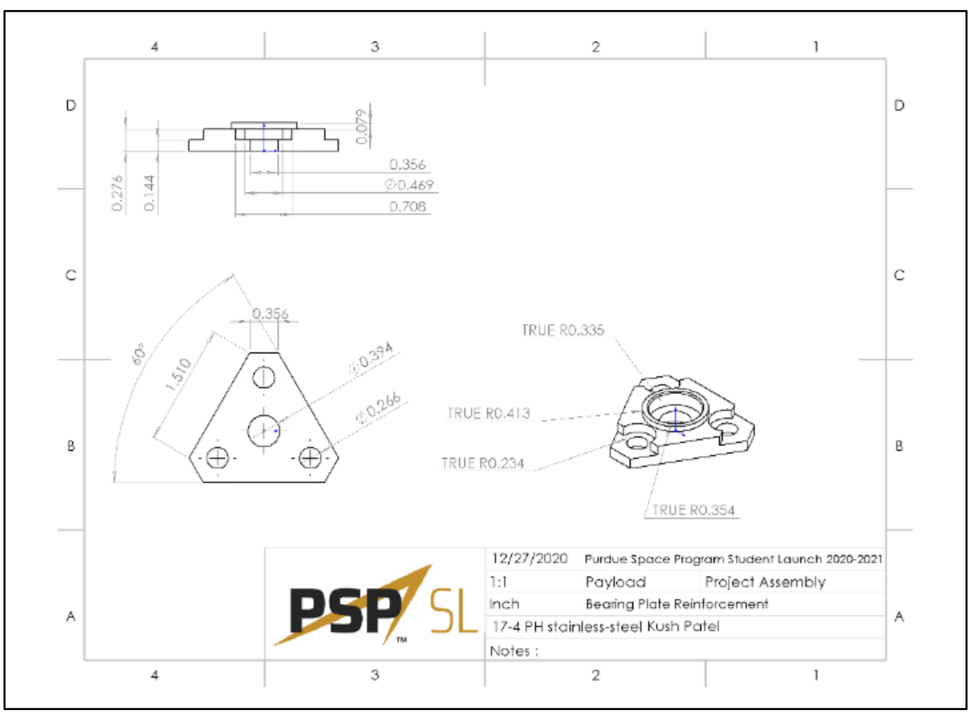

Figure 4.51: Bearing Plate Reinforcement Dimensional Drawing

The component shown above will be manufactured by 3D printing out of Markforge 17-4 PH Stainless-Steel rather than Markforge Onyx Carbon Fiber. This is because the Bearing Plate, shown below, is a component that is seen to be load-bearing, and the team wanted to ensure that it can withstand all forces applied to it by the system. The location of the Reinforcement Plate is centered on the Bearing Plate. The Reinforcement Plate was designed so a more robust material (17-4 PH Stainless-Steel) can entail all extreme force before it is distributed throughout the Bearing Plate, hence its central location.

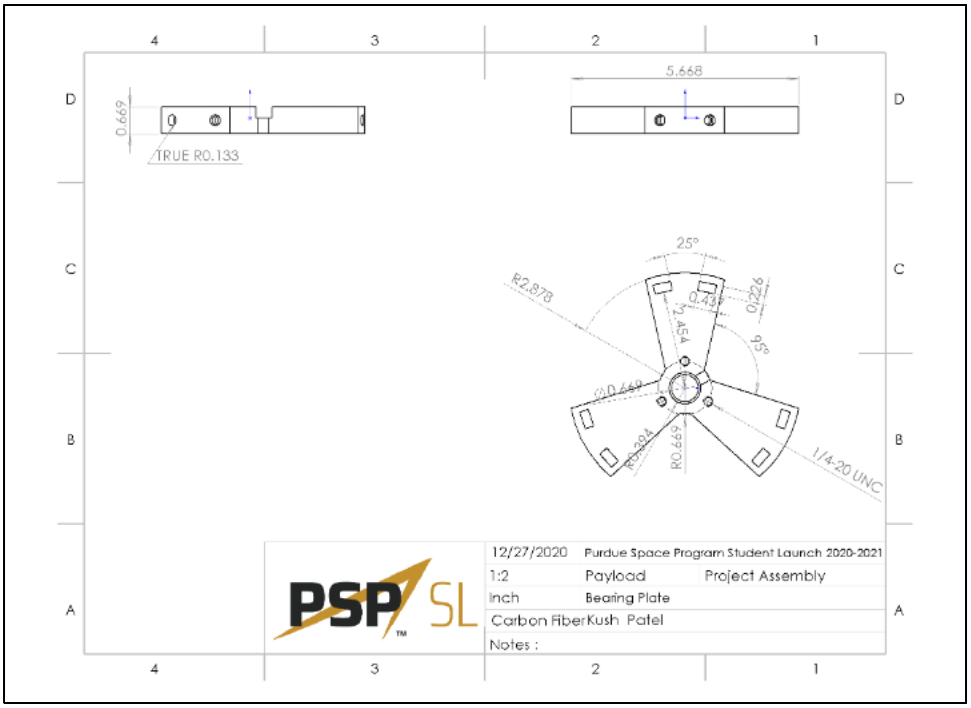

Figure 4.52: Bearing Plate Dimensional Drawing

The Bearing Plate shown above is the base of the system. Though it is load-bearing, it was printed out of Markforge Onyx Carbon Fiber. The Reinforcement Plate mentioned above will account for the applied load on the Bearing Plate by the system. The end of the lead screw will be attached to this plate, along with the Bearing Reinforcement Plate, a bearing, and locknut. It is also one of the two points of attachment to the Airbrake Coupler and Airframe.

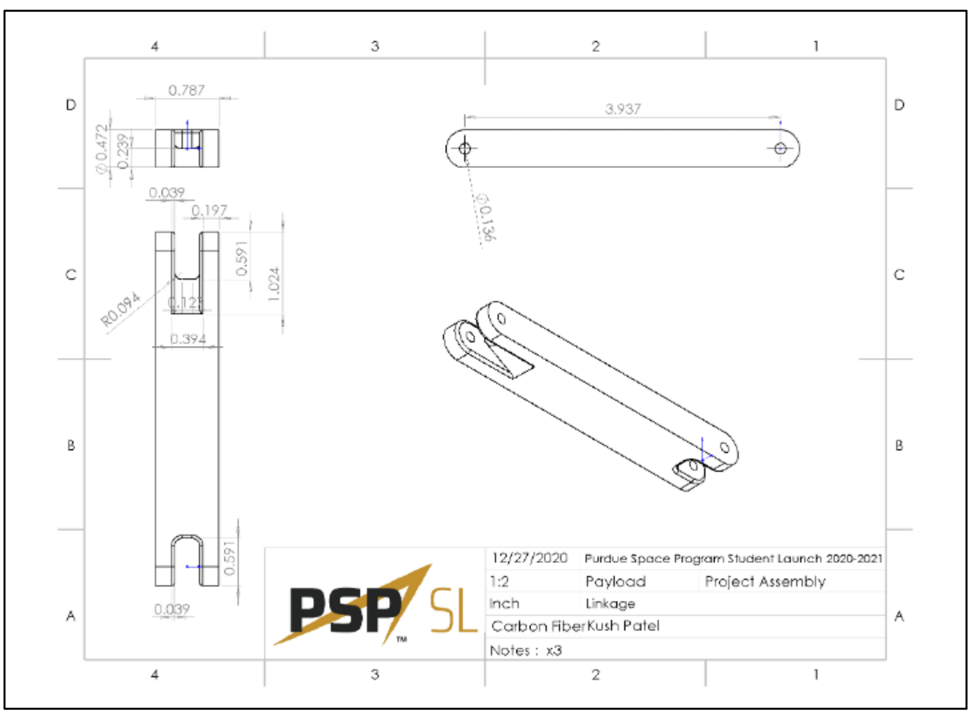

Figure 4.53: Linkage Dimensional Drawing

The linkages shown above attach to the Slide Plate, Motor Plate, and Paddle Struts and are used to help actuate the system. This system has three linkages because it will be actuating three Aeroplates simultaneously. Three attachment points were created on the Slide Plate and Motor Plate for the linkages. The linkages are not load-bearing and will be 3D printed out of Markforge Onyx Carbon Fiber.

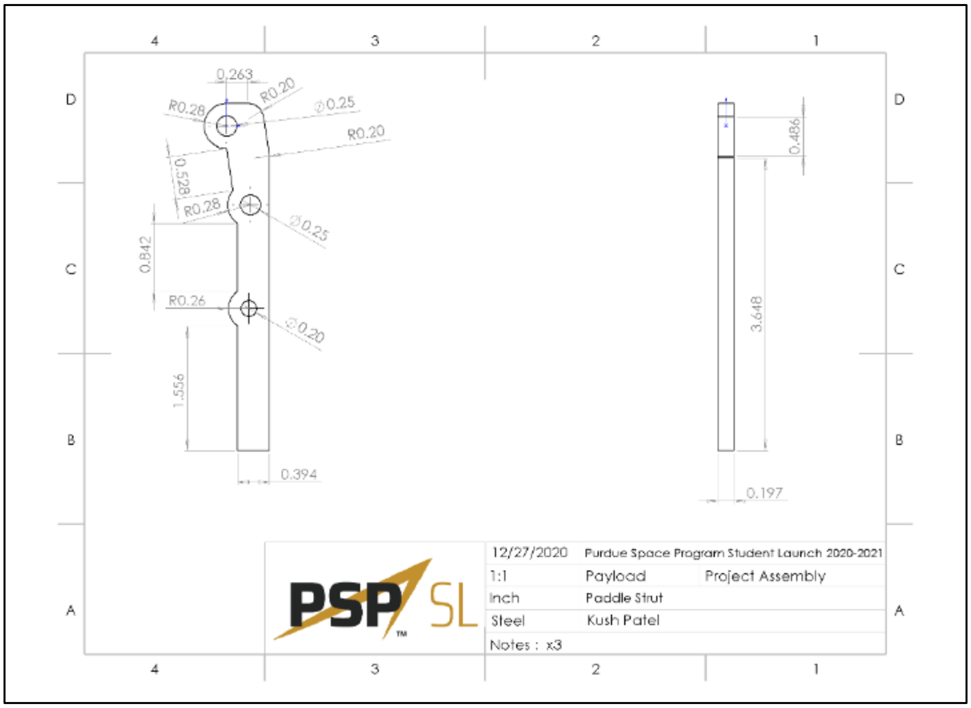

Figure 4.54: Paddle Strut Dimensional Drawing

The Paddle Struts shown above attach to the Slide Plate, Motor Plate, and Linkages and are used to help actuate the system. The Paddle Struts are also the base for the Aeroplates, which will be later epoxied onto the flat most surface shown to the right above. The Paddle Struts are the most load-bearing component of the system since they will encounter all of the force pushed on the Aeroplates first. Since they are the most load-bearing, they will be laser cut out of steel. The team will not be 3D printing this component out of Markforge 17-4 PH stainless-steel.

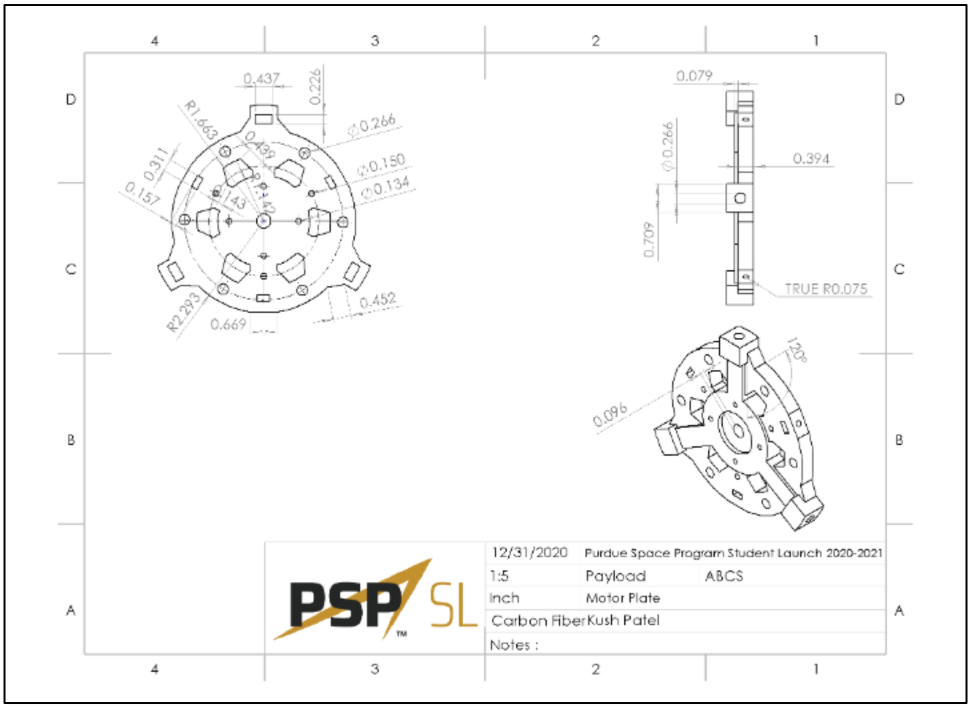

Figure 4.55: Motor Plate Dimensional Drawing

The Motor Plate shown above is the central component of the ABCS system; it is the attachment point of the paddle struts, electronics bay, and motor. The Motor Plate will be 3D printed out of Markforge Onyx Carbon Fiber since the component is not load-bearing.

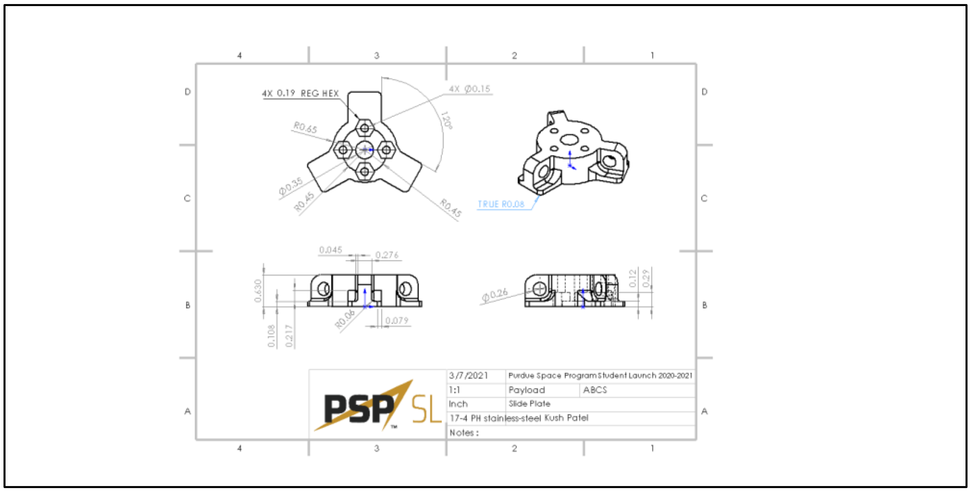

Figure 4.56: Updated Slide Plate Drawing

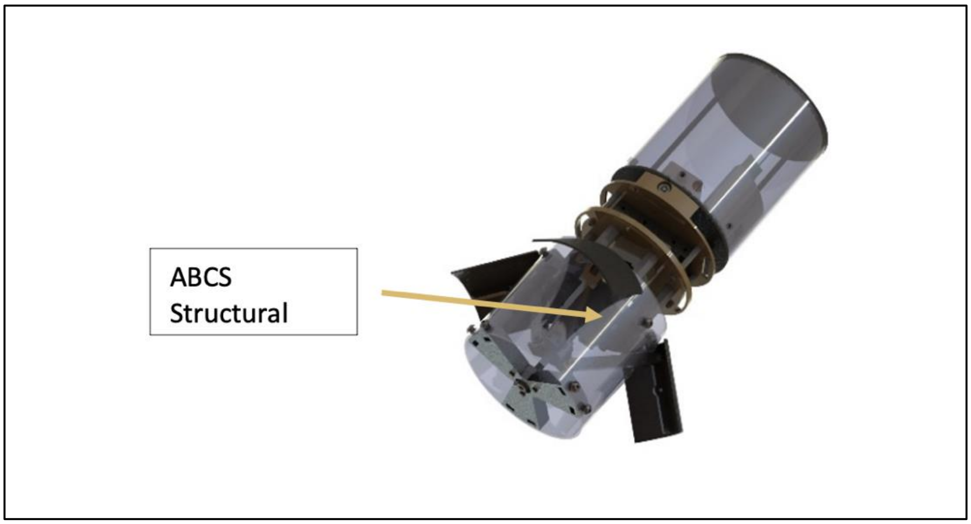

Figure 4.57: ABCS Coupler Attachment

4.3.2.2 Control System

Software for the ABCS consists of a continuous closed-loop control system that actuates the brake plates in order to provide the necessary amount of drag for the launch vehicle to reach its correct apogee. This control system uses an altimeter to read altitude and velocity and an accelerometer to read angular and linear accelerations. The accelerometer could have been used to read velocity, but the required discrete integration would not have been as accurate as the derivative of altitude readings from the altimeter.

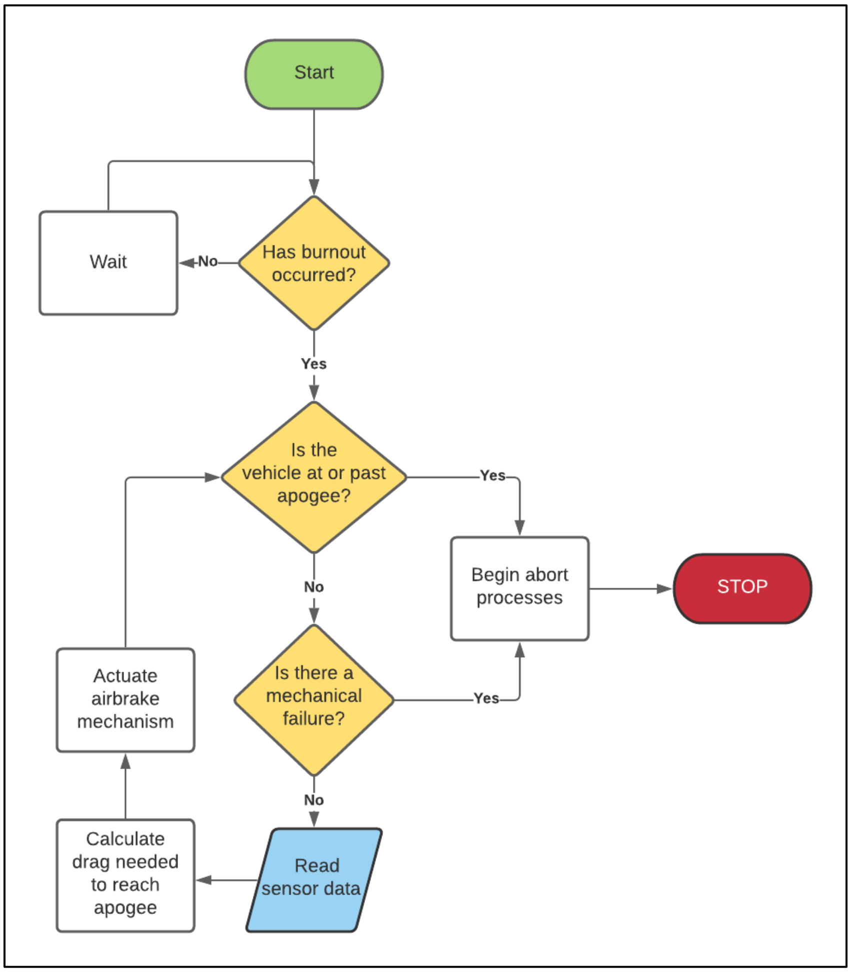

Figure 4.58: Control system

This flowchart outlines the logical flow for the ABCS during flight. First, the system will wait until it detects that the motor has burnt out through the accelerometer on the IMU. Then, it will repeatedly check if the launch vehicle is at apogee or if it has started to rotate unexpectedly. If so, the ABCS will begin aborting all of its subroutines, return the airbrakes to the closed position, and remain that way until the flight is over. Otherwise, it will calculate the drag needed to reach apogee and actuate the airbrakes accordingly.

4.3.3 **ABCS Construction**

4.3.3.1 Mechanical System Construction

4.3.3.1.1 Component Fabrication

The ABCS was constructed using 3D printed PLA, Markforged Onyx Carbon Fiber, Markforged 17-4 PH stainless-steel, and hand-cut fiberglass. The electronics bay was printed entirely out of PLA. Initially, there was some confusion about the key switch porthole's radial positioning, which was encountered during manufacturing. There was misalignment of the electronics bay switch hole and the cut the team had made for the switch hole on the booster section. A few new prints of the second tier of the electronics bay had to be made to achieve the key switch location's correct radial position. The brake plates were cut by hand using a Dremel from the main airframe of the launch vehicle. A 3D printed jig was used to outline the brake pads' exact dimensions, mounting holes, static portholes, and key switch porthole. The bearing plate, linkages, motor plate, and paddle struts were all printed out of Markforged Onyx Carbon Fiber. The slide plate and bearing plate reinforcement were printed out of Markforged 17-4 PH stainless-steel. The paddle struts were laser-cut steel. The original slide plate was printed with tapped holes which could not be adjusted to fit the bolts. As soon as the team figured the part was unusable, it was redesigned and reprinted– a problem with the sintering process also occurred, which delayed the delivery of the part, so a decision was made to carry out the ABCS structural test with a PLA replacement piece temporarily. The Markforged 17-4 PH stainless-steel replacement part did end up being delivered the day before the launch. The system was disassembled and reassembled to replace the PLA part with the stainless steel one.

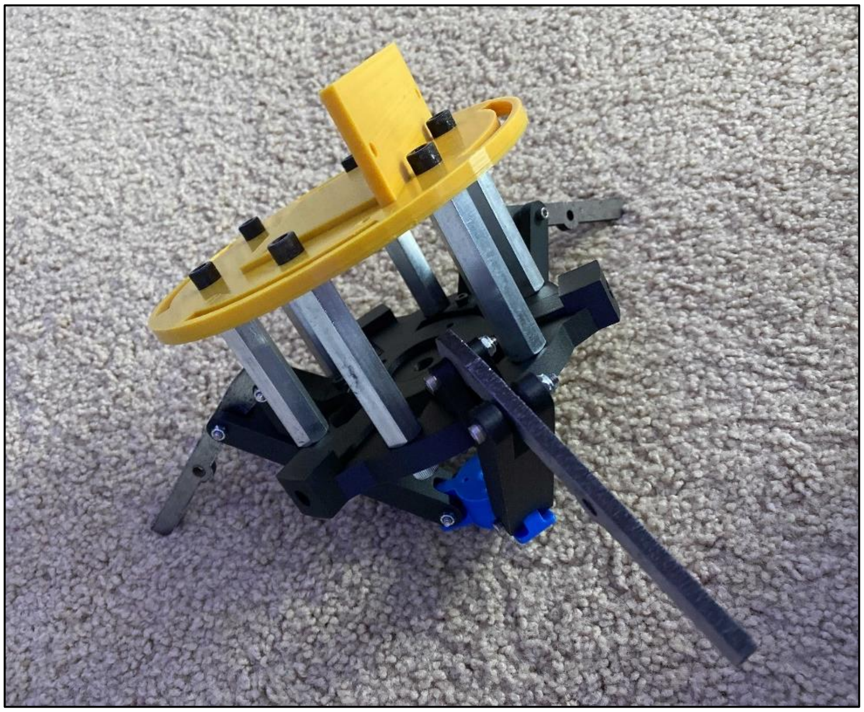

Figure 4.59: ABCS Mechanism Skeleton

Figure 4.60: ABCS Lower Airframe Cuts

4.3.3.1.2 Assembly

The assembly of ABCS is as follows:

1. Attach bearing plate reinforcement to bearing plate.
2. Attach bearing to bearing plate reinforcement.
3. Align Airbrakes coupler inside main airframe, flush with fastener holes
4. Mount stepper motor on to the motor plate using M3 screws

5. Bolt motor plate through coupler and main airframe with three ¼-20" screws. Fasten into embedded nuts within motor plate.
6. Attach flex coupler to stepper motor shaft, tighten flex coupler fasteners onto the stepper motor shaft.
7. Mount slide plate to the copper nut screw.
8. Lead the lead screw through the copper nut screw.
9. Attach lead screw to the other end of the flex coupler, tighten flex coupler fasteners onto the lead screw.
10. Attach paddle struts onto motor plate paddle strut fixtures.
11. Attach paddle struts to linkages.
12. Attach linkages to slide plate.
13. Attach brake pads to motor plate.
14. Feed lead end of lead screw through bearing plate.
15. Attach bearing plate through coupler and main airframe with six ¼-20" screws. Fasten into embedded nuts within bearing plate.
16. Flip booster section over to the thrust exit section.
17. Add free bearing to the lead end of the lead screw under the bearing plate.
18. Screw lock nut around the base of the lead screw and free bearing.
19. Attach standoffs for the second tier of the electronics bay to first tier of the electronics bay
20. Fix electronics bay standoffs to motor plate while booster is flipped over.
21. Attach motor driver down to first tier of the electronics bay.
22. Feed wires from stepper motor into motor driver
23. Fasten first tier of the electronics bay to the motor plate standoffs.
24. Mount PCB to second tier of the electronics bay using velcro straps and hot glue.
25. Insert key switch through the second tier port hole
26. Feed wires from motor driver to PCB
27. Hot glue velcro straps to the bulkhead, which the battery will sit on within the airbrakes coupler.
28. Place battery inside upper coupler.
29. Velcro battery onto the bulkhead.
30. Feed battery connector to PCB.
31. Mount Airbrakes coupler to the booster with ¼-20" screws.

Figure 4.61: ABCS Well-Aligned In Airframe

4.3.3.1.3 Integration

Aerobraking Control System was physically integrated with the booster section of the vehicle. That portion of the airframe was cut to produce the brake plates to size. A shock coupler was installed above the Aerobraking System that also enclosed the system's battery; the shock coupler attachment is also how the booster section attaches to the rest of the vehicle. The ABCS coupler was whittled after being cut to allow the linkages in the booster section to smoothly clear the edges. One of the main design flaws in the system was the access to the bottom of the ABCS. One had to reach through the entire booster section to tighten bolts and lock nuts which was challenging even for team members who had long arms. Due to the Aerobraking System's tight location within the booster section, a problem occurred during the motor casing installation; the team devised a solution by increasing the thrust structure's length to account for the extra length needed for the motor casing to fit.

4.3.4 ABCS Software Production

The ABCS software code was designed and written concurrently with the mechanical system so that changes to the hardware could be reflected immediately in changes to software. Once testing began, the entire system and all sensors were wired together onto a prototyping board, and the altimeter was tested in a vacuum chamber. A Python program was written to obtain and output altimeter data from the microcontroller as well as the motor command that would be issued given the altimeter readings. This vacuum test allowed the team to be confident that the ABCS software was working as intended and could function with sensor inputs during an actual flight. The IMU was also tested to confirm that the ABCS would abort if the launch vehicle began rotating in an unexpected manner. The sensor was rotated at various speeds around all three axes, and if the angular velocity was deemed too high, the microcontroller would abort all processes immediately. These safeguards ensure that the ABCS minimizes its risk during flight to both the launch vehicle and all other systems. A pseudo-flight simulation will be conducted using test flight data collected from the Avionics systems in addition to the vacuum test. This data will be streamed real time to the ABCS as a test to see how it would react in a nominal flight. Once the data reaches the coasting phase, the real flight data will turn into simulated data to simulate the drag induced by the ABCS. This will ensure that the system will perform well during the final flight.

4.3.5 Designed Flight Reliability Confidence

The design went through rigorous testing after assembly, also to note that all testing was conducted while the Aerobraking System was within the booster section. As previously mentioned, the slide plate was the most tedious component in terms of manufacturing. When the slide plate was redesigned and reprinted, a problem with the sintering process occurred, which delayed the part's delivery. A decision was made to carry out the ABCS structural test with a PLA replacement piece temporarily. The test was a complete success and accounted for 100 lbs of simulated drag force, even though the most load-bearing component was 3D printed out of PLA. When the part was 3D printed, it was printed with 70% infill capacity, making it nearly solid. This attempted to account for the PLA material's limitations when printed at a low infill density. Due to the sheer success with the structural test, the team was confident of performing an Aerobraking test during our Full-Scale launch. Furthermore, the day before launch, the new Markforged 17-4 PH stainless-steel replacement part had been delivered. This made it so the team could use the original design with confidence because it should handle similar stresses as the structural test. After all, the slide plate material was significantly upgraded from PLA to stainless-steel.

4.4 Vehicle Demonstration Flight Performance

4.4.1 Success Criteria

Since the Vehicle Demonstration Flight is not considered to be the Payload team's official Payload Demonstration Flight, the criteria for success during this launch were of a purely mission critical nature. To this end, only the requirements most essential to the integrity of the launch vehicle and safety of the launch day crew have been required to be tested and satisfied. For example, while the structural integrity of the physical R&D may determine the ability of the launch vehicle to safely fly, the inability of the Lander to properly take a panoramic picture will in no way cause any danger to the vehicle or any launch day crew. The nominal requirement identifier utilized by the team has therefore been "Mission Critical." In the context of Mission Critical requirements, all essential requirements for flight have already been satisfied for VDF. Given that all launch day procedures were diligently followed, this VDF has been a success on the Payload team's behalf.

On the other hand, the team has utilized the VDF to ascertain points of failure within the Payload's systems. While the VDF is not the Payload's official launch, the team will utilize any acquired data to make modifications to structure, code, and procedures.

In the case of the PLS system, additional desired observations and criteria include:

- Proper deployment of the Lander, ensuring that no cables or wires become tangled.
- The proper opening of the Lander's parachute.
- Low drift distance during Lander descent.
- Lander descent time within bounds.
- Low structural damage upon Lander touchdown.
- Whether the Lander is affected by wind.

In the case of the ABCS system, additional desired observations and criteria include:

- Actuation of the aeroplates.
- Maintained stability of the launch vehicle, whether or not the aeroplates are deployed.
- Effects of aeroplate drag on launch vehicle apogee.
- Proper deactivation of the ABCS under failure modes or after apogee.

4.4.2 **Results of VDF**

4.4.2.1 Analysis of Payload Retention System Performance

The Payload retention system succeeded in its task of keeping the Lander inside the vehicle and attempting to eject the Lander at the appropriate time. The system failed in its actual task to eject the Lander. This was due to the Lander getting stuck when the system was in its deployed state. Additionally, the system failed in its goal of protecting the Lander. There was damage to the Lander's top plate where the screws of the R&D plate pushed into the top of the Lander. There was also damage to the flex coupler that attaches the lead screw to the stepper motor. To fix this problem, the team is considering replacing the coupler with a non-flexible type that will not be bent out of shape easily.

Analyzing the data logged by the R&D electronics, the team confirmed that the R&D electronics and software succeeded in their tasks. It was able to monitor and identify the stages of flight successfully. The system logged the detection of launch, the detection of apogee, and the Lander's release point. These occurred as expected, so no change is necessary to the electronics and software of the system.

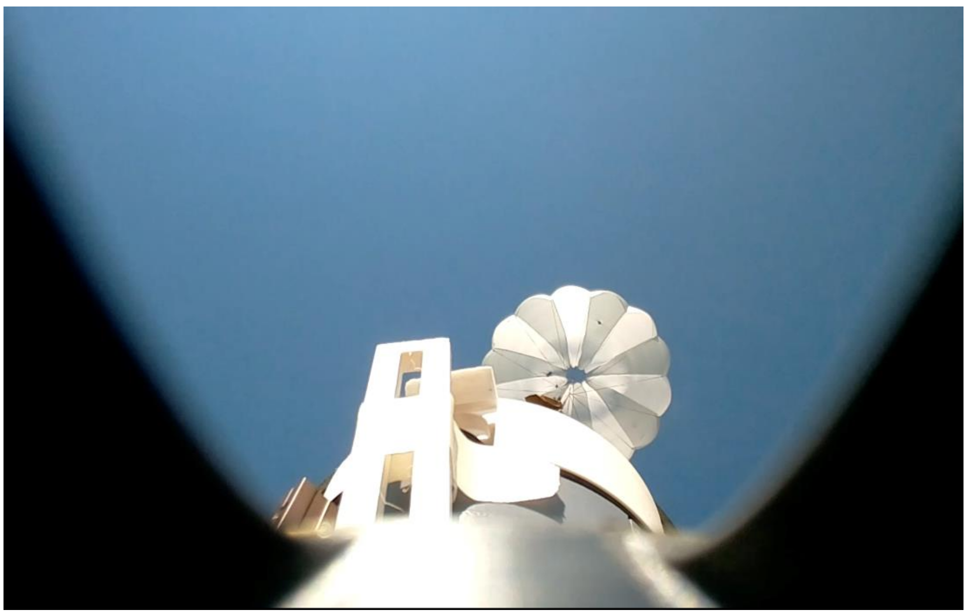

Figure 4.62: The Lander, Deployed but Stuck (Rear-Facing Nosecone Camera)

After inspecting the video recorded by the rear-facing camera mounted in the nosecone, the team was able to verify that the Lander bay was pushed out of the vehicle after the deployment of the main parachute. However, it is not inherently clear if the stepper motor controlled by the R&D electronics released the Lander bay or the force of the main parachute deployment that caused the motor to back drive and release the system. To clarify, the Lander bay was pushed out of the vehicle, but the Lander itself was not ejected from the Lander bay, meaning it did not fully deploy from the vehicle. As for why the Lander did not fully deploy from the payload bay, it appears to a combination of two factors: 1st the cord for the parachute bag appeared to have tangled around one of the threaded rods obstructing the exit, and 2nd the tight tolerance for the exit. The R&D electronics started pushing the Lander bay out of the vehicle at 745 feet, giving time to push the bay out fully and allow the Lander to jettison close to the goal of 700 feet. Being the main parachute deploys at 900 ft, this would still satisfy project requirement P.4.3.1, ejecting the Lander between 500 and 1000 ft, no matter which method made it deploy. If the main parachute caused deployment, it falls outside the range of team requirement S.P.1.6, ejecting the Lander between 500 and 700 ft. Due to the main parachute deployment altitude being within the requirement P.4.3.1, the team is considering modifying the S.P.1.6 requirement to encompass the range of 500 to 900 feet, therefore making the main parachute an acceptable deployment method.

Figure 4.63: The Lander and R&D subsystem after launch (Left: Nosecone Side, Right: R&D Bay Included)

Figure 4.64: The R&D with lead screw coupler damage

4.4.2.2 Analysis of ABCS Performance

Throughout the launch, the ABCS did not function, though it was in an active state at the start of the launch. After the vehicle's booster section was recovered, the team noticed that the ABCS battery was detached from the Perf Board within the upper ABCS coupler. The likely cause of this was the sudden jolt due to the vehicle's acceleration, which unglued the Velcro straps holding the battery in place. Moving forward, the team has designed a new bracket that will house the battery, fastened with bolts to the upper ABCS coupler. The team has also devised actuation test plans, which include feeding the control system the altitude vs. velocity data from this launch. This way, the ABCS should function when it hits its parameters for deployment, After the system was recovered, it remained fully intact.

Figure 4.65: Launch Vehicle Nearing Apogee (Rear-Facing Nosecone Camera)

4.4.3 Planned Payload Demonstration Flight

All mission-critical PLS and ABCS requirements were successfully verified before VDF. With the results of the VDF analyzed by the Payload Team, the team feels that it will be able to pursue a Payload Demonstration Launch between March 19th and 21st of 2021. Before then, all fatigued and fractured Payload components will need to be cleaned and replaced. Any modifications made to the system will require full re-testing to be flight-worthy once again. Ideally, within the provided time frame, the Payload Systems will be ready to satisfy their requirements fully.

5 Demonstration Flights

5.1 Flight Information

The flight conducted was to satisfy the requirements of the VDF, while the Payload Demonstration Flight is scheduled for a later date. The flight took place on the 27th of February 2021 at Purdue Dairy Farms. The weather was favorable, with 6mph winds to the southwest, a temperature of 45 degrees Fahrenheit, and a pressure of 30 inHg. The motor flown was the CTI L1115, which will also be used for the upcoming flights. No ballast was used for this flight, but the team expects to use around 3lbs for the upcoming launches, to be around 52.0lbs on the pad. The team is targeting for an altitude of 4100' for the competition launch. Utilizing the launch conditions and an unballasted launch vehicle of 49.2lbs, the simulated apogee is 5134', while the recorded in-flight data had the apogee at 5187'. Adding 3lbs of ballast to the payload section and simulating with the launch conditions, the anticipated apogee is 4738', which will be greatly reduced with the use of the ABCS. The MFSS functioned above and beyond the expectations of the team. From the on-flight recording, the MFSS mitigated basically all chance of fin flutter, and the motor was successfully retained both during and after the flight ceased. The nose cone also performed to the highest standards. Not only did the hemispherical design not have any major impact from skin drag, but the team retrieved high quality flight recording from each of the three cameras.

5.2 Analysis of Vehicle Demonstration Flight

The demonstration flight was a large milestone to verify the launch vehicle design, aside from simulation-based verifications. This was purely an attempt to fulfill the VDF project requirement, so a successful payload demonstration was not anticipated. A successful VDF would be deemed from the satisfaction of the following criteria:

1. The launch vehicle would be launched with all necessary systems in an active state. Data from these systems would be recorded and be made available to the team for future analysis.
2. The vehicle recovery systems would initiate at predetermined altitudes and allow for a safe retrieval of the vehicle and its subsystems.

Based off of the following criteria, the team concluded that the VDF was successful in its goals.

Vehicle Demonstration Flight	Conducted, Success
Payload Demonstration Flight	Not Conducted
Launch Day Criteria	February 27th, 2021 Purdue Dairy Farm Partly Cloudy

	48°F Wind 6mph SW
ABCS State	Active
Motor Flown	CTI L1115 4-grain
Target Altitude	4100’
Predicted Altitude	5136’
Actual Altitude	5187’

Table 5.1: Demonstration Flight Analysis

5.3 Simulation with Launch Day Conditions (Simulink)

Parameter	Value	Pass/Fail
Apogee	4826’	N/A
Ascent Time	18.7s	N/A
Drogue Descent Velocity	89.9ft/s	N/A
Landing Velocity	15.0ft/s	N/A
Lander Landing Velocity	21.6ft/s	N/A
Descent Time	85.1s	Pass
Drift Distance	1361’	Pass
Rail Exit Velocity	59.8ft/s	Pass
Landing Kinetic Energy of the Heaviest Section	74.3ft-lbf	Pass

Table 5.2: Simulink Important Returned Parameter Values

In the table above are some important returned parameter values from the Simulink simulation generated under the actual launch day conditions from the vehicle demonstration flight. The most significant values to note are the four critical requirements: descent time, drift distance, rail exit velocity, and landing kinetic energy of the heaviest section. These are highlighted in gold in the table above. As can be seen, all four critical requirements are passed.

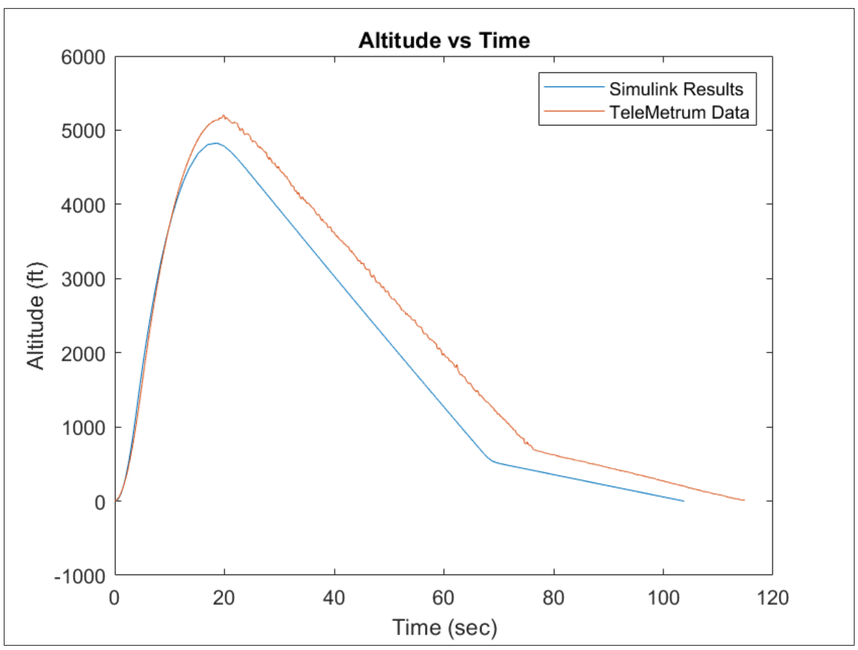

Figure 5.1: Comparison Between Simulink Results and TeleMetrum Data

The above plot shows a comparison between the Simulink results under launch day conditions and the TeleMetrum data from the actual vehicle demonstration flight.

5.4 Comparison to Subscale Flight

Subscale Apogee (ft)		Full Scale Apogee (ft)	
Predicted	Actual	Predicted	Actual

625	620	5094	5186

Table 5.3 Subscale and Fullscale flight comparison

The above table displays the apogee recordings for both the subscale and full scale launches. The table contains the predicted apogee from OpenRocket and the actual data recorded from the altimeters on board. The small differences between the predicted and actual data verifies the use of OpenRocket and the consistency in its data. The two launches in tandem verified the current vehicle design, and the data from OpenRocket help reach this final iteration.

5.5 Hardware Damaged and Plan of Action

During the flight, the drogue parachute acquired one burn hole from the ejection charges, and the main parachute acquired several burn holes. The team believes that, even though the parachutes were wrapped very carefully with the Nomex blankets, some of the hot gases could still sneak around the edges and singe the parachutes. This may be a consequence of the "canon" method of parachute deployment, as there is a lot of pressure in the recovery airframe sections and nowhere for the hot gases to go except toward the parachutes. Though this method is ideal for absolutely ensuring the parachutes are ejected (hence why the team chose to incorporate it into the vehicle design), it is more likely to damage the parachutes. The team has already repaired the burn holes with tape and plans to explore other methods of packing and sizes of ejection charges, conducting another black powder ejection test before the payload demonstration flight as verification.

5.6 Lessons Learned from the Flight

In terms of avionics and recovery, there were two other minor issues during the vehicle demonstration flight besides the burn holes in the parachutes. The StratoLoggerCF altimeter experienced some brownout at main parachute deployment and total power loss at landing. Though it could not report the apogee in beeps immediately following the landing, the flight data was able to be totally recovered using the laptop interface some time afterward. The team believes a loose battery connection could have caused this issue. The team will ensure the battery connector fits snugly onto the battery for the StratoLoggerCF altimeter in future flights. One of the EggFinder trackers (specifically the one located in the booster section) was also unable to acquire a GPS lock after waiting for some time, so the launch proceeded with just the other EggFinder tracker and the TeleMetrum GPS used as vehicle locators. The team believes that the ABCS electronics near this tracker could have interfered with the GPS signal. In future flights, additional shielding will be implemented to prevent this issue.

5.7 Planned Future Demonstration Flights

To satisfy the Payload Demonstration Flight requirement, the team plans to launch once more before the competition flight. The flight is scheduled for March 19th, 2021 with a fall-back launch date of March 21st, 2021 in case of unexpected weather delays.

6 Safety and Procedures

6.1 Hazard Analysis:

Two criteria evaluate the seriousness of a risk: the likelihood of an event to occur and the severity of the event should it happen or fail to be prevented. The breakdown of the methods used in the team's risk analysis and the assessment of personnel, vehicle failure mode, environmental, and project risks are discussed in the following sections:

6.1.1 Likelihood of Event

Category	Value	Gauge
Remote	1	Extremely unlikely to occur
Unlikely	2	Unlikely to occur
Possible	3	Average odds to occur
Likely	4	Above-average likelihood to occur
Very Likely	5	Very likely to occur/has occurred previously

Table 6.1: Event Likelihood Scale

6.1.2 Severity of Event

Category	Value	Health and Personal Safety	Equipment	Environment	Flight Readiness
Negligible	A	Negligible injury. No first aid required. No recovery time needed.	Minimal and negligible damage to equipment or facility. No required correction.	Negligible damage. No repair or recovery needed.	No flight readiness disruption.
Minor	B	Minor injury. Requires band-aid or less to treat. 5-10	Minor damage. Consumable	Minor environmental impact. Damage is focused on a small	Flight proceeds with caution.

		minutes of recovery time required.	equipment element requires repair.	area. Little to no repair or recovery needed. Outside assistance not required.	
Moderate	C	Moderate injury. Gauze or wrapping required. Recovery time up to one day.	Reversible equipment failure. Non-consumable element requires repair. Outside assistance not required.	Reversible environmental damage. Personal injuries unlikely. Outside assistance recommended. Able to be contained within team.	Flight delayed until effects are reversed.
Major	D	Serious injury. Hospital visit required. No permanent loss of function to any body part.	Total machine failure. Outside assistance required to repair.	Serious but reversible environmental damage. Outside assistance required. Personal injuries possible.	Flight on hold until system is removed.
Disastrous	F	Life-threatening or debilitating injury. Immediate hospital visit required. Permanent deformation or loss of bodily function.	Irreversible failure. Total machine loss. New equipment required.	Serious irreversible environmental damage. Personal injuries likely. Immediate outside assistance required. Area must be vacated. Needs to be reported to a relevant environmental agency.	Flight scrubbed or completely destroyed.

Table 6.2: Event Likelihood Scale

6.1.3 Risk Analysis

By cross examining the likelihood of an event with the impact it would have if it occurred, a total risk can be determined, and is detailed in the table below. The color code displayed is as follows:

- Green: Minimal risk
- Yellow: Low risk
- Orange: Medium risk
- Light red: High risk
- Dark red: Very high risk

		Severity				
		Negligible (A)	**Minor (B)**	**Moderate (C)**	**Major (D)**	**Disastrous (F)**
Likelihood	**Remote (1)**	A1	B1	C1	D1	F1
	Unlikely (2)	A2	B2	C2	D2	F2
	Possible (3)	A3	B3	C3	D3	F3
	Likely (4)	A4	B4	C4	D4	F4
	Very Likely (5)	A5	B5	C5	D5	F5

Table 6.3: Total Risk Scale

Before a plan for risk mitigation, many of the events listed in the following sections fall outside of the acceptable tolerance of Medium risk. Listed alongside these events are the team's risk mitigation plans and verification metrics to ensure team compliance. Post-mitigation risk is also listed, ensuring all project risks are acceptable after mitigation.

6.1.4 Personnel Hazard Analysis

Hazard	Likelihood (Cause)	Severity (Effect)	Risk	Mitigation	Verification	Post Mitigation Risk
Burns from Motor or Motor Casing	2 (Improper proximity to launch pad, touching engine too soon after landing)	C (Mild to moderate burns)	C2, Low	Maintain minimum safe launch distance from vehicle according to NAR standards. Wait an appropriate amount of time after launch to retrieve vehicle. Do not launch if personnel are within the minimum safe distance.	The Safety Team lead will ensure the minimum safe distance region is marked and communicated to team members at the launch.[1]	C1, Low
Contact with Airborne Chemical Debris	3 (Airborne particulate debris generated from construction or testing operations making direct contact with the body)	B (Minor burns, abrasions)	B3, Low	Install / use proper guard on machinery to prevent contact with debris if possible. Always wear appropriate PPE such as gloves, lab coats and breath masks.	Safety Team or relevant Team Lead will verify that each participating member is wearing appropriate PPE during construction and testing operations.	B1, Minimal
Direct Contact with Hazardous Chemicals (epoxy, etc.)	3 (Improper use or storage of chemicals leading to unintended contact with the body)	C (Moderate burns, abrasions)	C3, Medium	Minimize or eliminate the need for hazardous chemicals (for example, the MFSS in this vehicle). Always wear appropriate PPE, such as gloves or lab coats, when working with chemicals.	Safety Team or relevant Team Lead will verify that each participating member is wearing appropriate PPE during construction and testing operations.	C1, Low
Dust or Chemical Inhalation	3 (Breathing in airborne particulate debris from construction or testing operations)	C (Short to long-term respiratory damage)	C3, Medium	Work in a well-ventilated area if possible. Always wear appropriate PPE for materials being worked with, such as a respirator. Team members will not be allowed to work with hazardous materials without proper PPE.	Safety Team or relevant Team Lead will verify that each participating member is wearing appropriate PPE during construction and testing operations.	C1, Low
Dehydration	2 (Failure to drink adequate amounts of water)	D (Exhaustion and possible hospitalization)	D2, Medium	Ensure all members have access to water at all team activities, including launch, testing, and construction operations.	Team members will be instructed to bring water to team activities, and team leads will ensure all members are properly hydrated by encouraging members to drink water when not working.	C1, Low
Heatstroke	2 (Extended exposure to high temperatures during team operations)	D (Exhaustion and possible hospitalization)	D2, Medium	Wear clothing appropriate to the weather, and ensure all members have access to water at team operations.	Safety Team or relevant Team Lead will monitor team members for appropriate dress and presence of water at team operations, including launch. If this is not the case, the team member will be sent to remedy their situation in whatever way the relevant Team Lead deems fit.	D1, Medium
First Degree Burns (Sunburn)	4 (Extended exposure to the sun during launch or general outside operations)	B (Discomfort of affected area)	B4, Medium	Team members must be appropriately dressed for being outside. If one feels that additional sun protection is needed (sunscreen, etc.), then apply that protection.	Safety Team or relevant Team Lead will monitor team members for appropriate dress. If this is not the case, the team member will be sent to remedy their situation in whatever way the relevant Team Lead deems fit.	A1, Minimal
Sleep Deprivation	5 (Staying awake for extended periods of time / not getting enough sleep before launch or	F (Lapses in judgement may cause disastrous machining accidents or	F5, Very High	All personnel attending machining, construction, or launch operations must be properly rested. While scheduling is tight with University COVID-19 restrictions and the accelerated timeline of Project Voss, the vehicle must be ready to be	Team Leads must ensure that their team members are mentally present when participating in team operations. Project Management and the Team Leads must ensure that the vehicle is ready to launch well in advance of launch day.	F1, Medium

	construction operations)	forgetting a critical step in preparing for launch, causing a potential loss of life and / or loss or destruction of the vehicle and its systems)		integrated and launched well before launch day. Team members must not stay awake for extended periods of time completing the vehicle in close proximity to the time of launch.		
Hypothermia	3 (Extended exposure to cold temperatures during team operations)	D (Sickness and possible hospitalization)	D3, Medium	Wear clothing appropriate to the weather, and ensure all members have access to a warm area to rest at launch, such as a heated car or inside of a building.	Safety Team or relevant Team Lead will monitor team members for appropriate dress. If this is not the case, the team member will be sent to remedy their situation in whatever way the relevant Team Lead deems fit.	D1, Medium
Electrocution	2 (Unintended contact with electrical systems that are faulty or improperly used or stored)	D (Potentially dangerous levels of electricity being passed through a team member, potential hospitalization)	D2, Medium	Give labels to all high voltage equipment warning of their danger and ground oneself when working with high-voltage equipment.	Members working with high voltage equipment must guarantee no open electrical components by inspection. Team Leads must allow only one member to work on electrical components at a time with proper PPE and student supervising.	D1, Medium
Entanglement with Construction Machines	3 (Unintended contact of loose hair, clothing, or jewelry with machines utilizing spinning or binding parts)	F (Severe injury, death)	F3, High	Secure loose hair, clothing and remove jewelry before operation machinery. Always wear appropriate PPE for the machine being worked with.	All use of construction machines will be done under the supervision of a person / people also trained on that specific machine. This is fulfilled by student supervisors at the locations where construction machines are found.	F1, Medium
Epoxy Contact	3 (Bodily contact with resin spill through improper use or storage of resin)	C (Mild skin irritation, possible allergic reaction, redness and rashes on skin)	C3, Medium	Minimize the need for hazardous chemicals (for example, the MFSS in this vehicle). Always wear appropriate PPE, such as gloves or lab coats when working with resin.	Team Leads must ensure all members working with hazardous chemicals are wearing proper PPE and are working in a safe environment.	C1, Low
Eye Irritation	3 (Airborne particulate debris entering unprotected eye, dry air / low humidity)	B (Temporary eye irritation)	B3, Low	Install / use proper guard on machinery to prevent contact with debris if possible. Always wear appropriate PPE such as face shields and safety glasses.	Team Leads must ensure all engineering controls available have been implemented and that proper PPE is always worn during team operations.	B1, Minimal
Hearing Damage	4 (Close proximity to loud noises)	D (Long term hearing loss)	D4, High	Seek alternative machines / methods to fabricate the desired part if possible. Always wear appropriate PPE such as earplugs when using power tools and larger machines.	Team Leads must ensure all engineering controls available have been implemented and that proper PPE is always worn during team operations.	D1, Medium
Kinetic Damage to Personnel	2 (Forceful detonation of combustible or explosive materials	D (Possible severe kinetic damage to personnel)	D2, Medium	Eliminate need for excitable materials if possible. Ensure team members are aware of excitable materials in the workspace and how to properly store and use them. Packaged	The Student Mentor is the only one allowed (per Purdue University regulations) to store black powder and other energetics and must only allow	D1, Medium

103

	near team members due to reckless actions or improper storage of materials)			energetics (black powder inside charge wells, motor inside its casing, etc.) must not be stored for extended periods of time before ethe launch. This means that the installation of energetics must be done as late as possible into the launch procedures. Black powder will be installed the morning of the launch, and the motor will be inserted into the vehicle immediately prior to the vehicle's installation on the launch pad.	the Team to access them when they are fully ready to install them into the vehicle.	
Launch Pad Fire	2 (Completion of fire triangle on launch pad)	D (Moderate burns, irreversible damage to the vehicle and its systems)	D2, Medium	Prevent excess heat from occurring on the launch pad, as the fuel (vehicle motor) and oxygen (air) cannot be removed from the system. Have fire suppression systems nearby and use a protective ground tarp. A fire extinguisher will be borrowed from the Purdue Fire Department for the day of the launch.	The Safety Team Lead is responsible for maintaining proper fire suppression equipment and for bringing it to all launch activities.[1]	C1, Medium
Injury from Falling Vehicle	3 (Vehicle striking team members due to a recovery system failure (ballistic trajectory) or a lack of awareness of vehicle descent under parachutes)	F (Severe injury, death)	F3, High	Keep all eyes on the launch vehicle during flight. Call "heads up" if vehicle is approaching team members under parachutes. Call "scatter" if vehicle is under ballistic descent.	Team will be briefed on launch day procedures before the launch occurs by the Safety or Systems Team Lead, emphasizing the importance of keeping eyes on the launch vehicle during flight.[1]	F1, Medium
Injury from Falling Components (including the payload lander)	3 (Failure to keep all components securely attached to the launch vehicle, result of improper staging constraints, part failure, or excessive vibration during flight, lack of awareness of the payload lander descending)	F (Severe injury, death (from more massive vehicle components))	F3, High	Keep eyes on the launch vehicle during flight. Call "heads up" if unintended components separate from the vehicle during flight.	Team will be briefed on launch day procedures before the launch occurs by the Safety or Systems Team Lead, emphasizing the importance of keeping eyes on the launch vehicle during flight.[1]	F1, Medium
Injury from Navigating Terrain	2 (Tripping over uneven ground, contact with poisonous plants, falling into fast-moving water)	F (Broken bones, infections, drowning)	F2, High	Do not attempt to recover the launch vehicle from dangerous areas. Seek professional aid to recover vehicle if it cannot be done by team members.	The Safety Team Lead will set boundaries to not cross at the launch location before the launch occurs and communicate that to the rest of the team.[1]	F1, Medium
Injury from Projectiles Launched by Vehicle Jet blast	2 (Debris striking team members because of a failure to properly clear	C (Moderate injury to personnel)	C2, Low	Clean the launchpad before use. Ensure all team members are an appropriate distance from the launch vehicle when launching. Do not launch if	The Construction and Safety Team Leads will verify that the launch pad is clean and clear of debris before launch occurs. [2]	C1, Low

104

	launchpad, or failure to stand an appropriate distance from the launch vehicle during launch)			personnel are within the minimum safe distance.		
Physical Contact with Hot Sources	3 (Contact with launch vehicle parts which were recently machined, improper use of soldering iron or other construction equipment)	C (Moderate to severe burns)	C3, Medium	Turn off all construction tools when not in use. Team members must be aware of potential hot surfaces created during machining. Always wear appropriate PPE.	Team Leads must brief team members on the dangers of the materials prior to their use.	C1, Low
Physical Contact with Falling Construction Tools or Materials	3 (Materials which were not returned to a safe location after use striking a team member)	D (Bruising, cuts, lacerations, possible severe physical injury)	D3, High	Brief personnel on proper clean-up procedures for working with tools and materials. Wear appropriate clothing and shoes for machine work.	Team Leads and / or relevant supervisors must ensure team members are aware of proper procedures for cleaning up the current workplace.	D1, Medium
Premature Ignition	2 (Short circuit, improper installation of motor and / or ignitors)	C (Mild burns)	C2, Low	Prepare energetic devices only immediately prior to flight. Ensure ignitor leads are shorted before attachment to the motor.	The Safety and Systems Lead must ensure that the proper personnel prepare the ignition system for flight.[3]	C1, Low
Downed Power Lines	2 (Launch vehicle becomes entangled in power lines, knocking them within range of personnel)	F (Fatal electrocution)	F2, High	Ensure power lines are at least the minimum safe distance from the launch pad (300 feet for an L class motor); do not angle the launch rail towards power lines. If vehicle entanglement occurs, call the power company, and stand clear until proper personnel arrive.	Any team member must alert all team members of the hazard if spotted. The Safety Team Lead must ensure all members are stood clear of the area until certified personal clean up the area and verify it is safe.	F1, Medium
Power Tool Cuts, Lacerations, and Injuries	3 (Carelessness or improper use of power tools, power tool malfunction or failure)	D (Possible hospitalization from damages)	D3, Medium	Ensure loose hair and clothing is tied back and jewelry is removed before operating power tools.	Team Leads must brief team members on the dangers of the current workplace prior to its use. For machining and construction operations, student supervisors at the Team's manufacturing locations will either ensure the team member is operating the equipment safely, or the supervisor will do it themselves.	D1, Medium
Tripping Hazards	3 (Improper storage of materials and equipment, unsecured cables overhead and along the ground)	C (Bruising, abrasions, possible severe harm if tripping into construction equipment)	C3, Medium	Brief personnel on proper clean-up procedures for working with tools and materials. Wear appropriate clothing and shoes for machine work. Tape loose cords or wires to the ground if they must cross a path which is used by personnel. Follow rules and guidelines of the Team's manufacturing locations.	Team Leads must brief team members on the dangers of the current workplace prior to its use.	C1, Low
Unintended Black Powder Ignition	3 (Accidental black powder exposure to flame or enough	F (Possible severe hearing damage or other personal injury)	F3, High	Label containers storing black powder, ensure black powder is only handled by those with relevant safety training. Per Purdue University regulations, the Student Mentor is the only one	Project Management and the Team Leads must verify that the handling of black powder is only done and supervised by team members qualified to handle it.	F1, Medium

	electric charge near black powder)			allowed to store the black powder. They will supervise the Team's use of any energetic.		
Workplace Fire	2 (Unplanned ignition of flammable substance, overheated workplace, improper use or supervision of heating elements, or improper wiring)	F (Severe burns, loss of workspace, irreversible damage to project)	F2, High	Have fire suppression systems nearby, prohibit open flames, and store energetic devices in Type 4 magazines as stated in the CFR, Title 27. Any machining or construction location has fire suppression capabilities.	Team Leads must brief team members on the dangers of the current workplace prior to its use and ensure all materials are being properly stored. The Safety Team Lead must ensure that fire suppression systems are available and acknowledged by the team members when the team is in a workplace.	F1, Medium

Table 6.4: Personnel Hazards

For verification of certain mitigation plans, see the following footnotes:

1. *6.2 The Day Of*
2. *6.2 The Day Of, "Installing the Vehicle on the Launch Rail"*
3. *6.2 The Day Of, "Installing Ignitor"*

6.1.5 Vehicle Failure Modes and Effects Analysis

Hazard	Likelihood (Cause)	Severity (Effect)	Risk	Mitigation	Verification	Post Mitigation Risk
Airframe Failure	1 (Buckling or shearing of the airframe from poor construction or use of improper materials, faulty stress modeling)	F (Partial or total destruction of vehicle, ballistic trajectory)	F1, Medium	Use appropriate materials according to industry standards and previous flight experiences of the airframe, bulkheads, fasteners, and shear pins. Make use of reliable building techniques, confirm analyses with test launches.	Construction Team will ensure proper materials are being used. The airframe withstood the forces of all previous nominal flights, including the VDF discussed in this document.	F1, Medium
Failure to Ignite Motor	2 (Lack of ignitor continuity)	A (Recycle launch pad)	A2, Minimal	Check for continuity prior to attempted launch.	Ignitor continuity shall be checked prior to launch. [6]	A1, Minimal
Motor Detonation	1 (Motor defect, assembly error)	F (Partial or total destruction of vehicle)	F1, Medium	Inspect motor prior to assembly and closely follow assembly instructions.	Motor shall only be assembled, operated, and installed by the Student Mentor. Motor inspection shall be performed by Student Mentor prior to launch.[7]	F1, Medium
Instability	1 (Stability margin of less than 1.00)	F (Potentially dangerous flight path, loss of vehicle)	F1, Medium	Measure physical center of gravity and compare to calculated center of pressure.	Have measured physical center of gravity documented and marked prior to arriving at the launch site. Verify this with computer models of the vehicle.	F1, Medium
Motor Expulsion	2 (Improper retention methods)	F (Risk of recovery failure, low apogee, falling debris)	F2, High	Use positive retention method to secure motor.	Motor retainment inspection shall be performed by Student Mentor prior to launch. FEA of the MFSS and the VDF discussed in this document verifies that, so long as the MFSS is installed properly, the motor will be retained during flight.7	F1, Medium
Premature Ejection	2 (Altimeter programming, poor venting)	F (Zippering, potential loss of vehicle components)	F2, High	Check altimeter settings prior to flight and use appropriate port holes. Test altimeter in similar conditions to those to be experienced at launch.	Altimeter settings shall be checked prior to launch. The altimeters have been tested prior to launch, and the primary altimeter functioned properly during the Team's VDF. [8]	F1, Medium

Loss or Damage of Fins	2 (Poor construction or improper materials used)	F (Partial or total destruction of vehicle)	F2, High	Ensure proper analysis has been completed on the thrust structure.	Fin slots in the thrust structure must be designed to properly contain the fins. The MFSS performed as expected for the Team's VDF and are expected to perform as well on subsequent flights.	F1, Medium
Damaged / Destroyed Nose Cone	2 (Poor construction or improper materials used, damage from previous flights, poor storage, or transportation)	F (Partial or total destruction of vehicle)	F2, High	Use materials and building techniques appropriate to high-power rocketry.	Check for nose cone damage prior to flight and ensure that nose cone is secured to vehicle for test flights. No significant damage was suffered to the nose cone for the VDF, verifying its structural integrity under expected launch conditions.[4]	F1, Medium
Ejection Charge Failure	3 (Not enough power from improper charge sizing, electrical failure)	F (Ballistic trajectory, destruction of vehicle)	F3, High	Perform ground test to ensure ejection charges sufficiently separate vehicle sections.	Black powder ejection charges have been verified to properly eject the recovery system in testing and during the VDF. Ensuring that the altimeters are programmed and initialized properly will detonate the ejection charges for future launches. [8]	F1, Medium
Altimeter Failure	3 (Loss of connection or improper programming)	F (Ballistic trajectory, destruction of vehicle)	F3, High	Perform altimeter settings and continuity check prior to launch.	The altimeters have been proven to function properly during the VDF. The Team must program and initialize them properly in future launches.[8]	F1, Medium
Payload Failure	3 (Electrical failure, program errors, dead battery)	D (Disqualified, objectives not met)	D3, Medium	Test payload prior to flight, check batteries and connections. Assemble payload with care to prevent errors.	Full payload testing will occur after the FRR deadline.	D1, Medium
Heat Damage to Recovery System	2 (Insufficient protection from ejection charges)	F (Parachute damage, excessive landing velocity, potentially ballistic trajectory)	F2, High	Use appropriate protection methods, such as Nomex blankets.	Check that proper recovery system protection methods are installed before launch.[9] Minor damage to the parachutes occurred during the VDF, and measures will be taken by the Avionics Team Lead and Student Mentor to ensure the recovery system will be properly protected for future launches.	F1, Medium
Broken Fastener	1 (Excessive force from launch or descent)	F (Ballistic trajectory)	F1, Medium	Ensure proper fasteners are purchased and used based on the seller's reputation and the products past use in flight.	Inspect fasteners before launch to ensure they are not damaged.[9]	F1, Medium
Motor and Fin Support Structure Failure	2 (Excessive force from motor, poor construction)	F (Partial or total destruction of vehicle, ballistic trajectory)	F2, High	Design thrust structure according to analysis of material strength and performance under stress, make use of reliable building techniques, confirm analyses with test launches.	The MFSS successfully retained the motor and fins in the VDF. Examination for and repairs of small damages of the MFSS will occur before future launches.	F1, Medium
Battery Overcharge / Leakage/ Ignition	3 (Unsupervised/undocumented charge, battery puncture)	F (Destruction of battery, potential ballistic trajectory of vehicle)	F3, High	Ensure batteries are documented and supervised if charging. Place charging batteries in an appropriate fire-proof bag to minimize the spread of fire if one occurs. Properly house and place batteries in launch vehicle.	Reminders will be set by testing personnel to track battery charging tests.	F1, Medium

107

Premature Black Powder Ignition	2 (Accidental exposure to flame or sufficient electric charge)	F (Partial destruction of vehicle, premature stage separation)	F2, High	Ensure design has sufficient distance/ protection from outside, and motor, charges, and batteries.	Ensure by design and testing that black powder wells secure from other systems. Ground testing of ejection charges and the recovery section's performance during the VDF have been deemed successful. The Team must ensure that launch day procedures are followed for future launches.	F1, Medium
Destruction of Bulkheads	2 (Poor construction or improper bulkheads chosen which cannot withstand launch forces)	F (Partial or total destruction of vehicle, ballistic trajectory)	F2, High	Use appropriate materials according to analysis of materials and previous flight data, make use of reliable building techniques, confirm analyses with test launches.	Bulkheads will be visually inspected for damage prior to launch.[9]	F1, Medium
Motor Angled Incorrectly	2 (Poor construction, damage from previous flights, poor storage or transportation)	D (Lower launch vehicle stability, launch vehicle does not follow desired flight path)	D2, Medium	Ensure proper measurements and alignments are made during construction, ensure there is no rush to attach the motor tube. Implement checklists to ensure proper constraint and alignment of the motor within the thrust structure	Inspect motor and motor retainer prior to launch to ensure proper installation. [7]	D1, Low
Premature Stage Separation	3 (Premature ejection, shear pin or fastener failure)	F (Possible recovery failure and damage to or loss of vehicle, ballistic trajectory)	F3, High	Check altimeter settings prior to flight, use appropriate vent holes, choose shear pins and fasteners suitable for flight.	Redundant altimeter will be used by design. Shear pins and fasteners will be inspected for proper installation.	F1, Medium
Forgotten or Lost Components	3 (Carelessness with launch vehicle components, failure to take note of inventory before attempting to launch)	D (Launch vehicle does not launch at the desired launch time)	D3, Medium	Ensure all launch vehicle components are accounted for prior to departure to launch field. Bring backup parts to launch field as necessary.	Team Leads are responsible for assigning the transportation of their section of the vehicle to the launch field. For the VDF, a pickup truck was borrowed from Zucrow Laboratories to transport the launch pad to the launch field.	D1, Medium
Launch Vehicle Disconnects from Launch Rail	2 (High wind speeds, failure to properly use the rail buttons, faulty rail buttons)	F (Partial or total destruction of vehicle, ballistic trajectory which endangers personnel, onlookers, and property on the ground)	F2, High	Use physical analysis to ensure the rail buttons are properly aligned and working as planned, double check the rail buttons are properly attaching the launch vehicle to the launch pad before launch, test rail buttons with subscale flights.	Rail buttons will be inspected prior to launch for cracks, misalignment, or other inaccuracies.[9]	F1, Medium
Flight Path Interference	2 (Wildlife in the air, unforeseen obstacles such as a loose balloon)	F (Minor to severe change in the vehicle's flightpath, possible ballistic trajectory)	F2, High	Ensure there are clear skies above before launching, ensure an FAA waiver has been obtained for the designated launch area. Hold launch until flight path is clear.	Visually inspect the surrounding launch area to make sure no incoming wildlife or loose objects appear.[11]	F1, Medium
High Launch Rail Friction	3 (Faulty installation of rail buttons, faulty setup of launch rail, faulty installation of	B (Launch vehicle does not follow the designated	B3, Low	Set up the rail using instructions which come with the product, use lubrication on the rail as needed according to weather	Launch rails will be tested by tactile inspection to ensure proper lubrication.[5]	B1, Minimal

	launch vehicle on launch rail, failure to properly lubricate launch rail as needed, weather conditions cause excess friction)	flight path well, lower maximum height, failure to leave pad)		and rail type, ensure the launch vehicle is properly installed on the launch rail.		
Failure to Ignite Propellant	2 (Faulty motor preparation, poor quality of propellant, faulty igniter, faulty igniter power source, damage to motor)	F (Launch vehicle does not immediately launch and is a considerable hazard until it is confirmed that it will not launch, changes to igniters or launch vehicle required)	F2, High	Purchase motor and ignitors only from reliable sources, Team Mentor must install motor and ignitors, determine if the igniters chosen work well during subscale testing.	Team Mentor is the only one allowed to install motor and ignitors.[6,7]	F1, Medium
Propellant Fails to Burn for Desired Duration	2 (Faulty motor preparation, poor quality of propellant, damage to motor)	C (Launch vehicle does not follow the designated flight path well, lower maximum height, if drastic change in maximum height the ejection charges for recovery may not deploy)	C2, Low	Purchase motor and ignitors only from reliable sources, check the motor for damage prior to launching, Team Mentor must install motor and ignitors.	Team Mentor is the only one allowed to install motor and ignitors.[6,7] Inspect motor prior to launch to ensure proper installation.	C1, Low
Propellant Explosion	1 (Faulty motor preparation, poor quality of propellant, damage to motor)	F (Ballistic trajectory, catastrophic destruction of vehicle, possible harm to bystanders)	F1, Medium	Purchase motor and ignitors only from reliable sources, check the motor for damage prior to launching, Team Mentor must install motor and ignitors.	Team Mentor is the only one allowed to install motor and ignitors.[6,7] Inspect motor prior to launch to ensure proper installation.	F1, Medium
Payload Computer Failure	3 (Electrical failure, program error, poor setup of wiring causes a connection to come undone, forgotten connection, battery failure)	F (Disqualified, objectives not met, loss of electronic control, improper payload deployment)	F3, High	Test payload prior to flight, check batteries and connections before flight.	Ground test payload in flight like conditions, inspect software before use, monitor payload during PDF. Payload testing will be done after the FRR deadline.	F1, Medium
Power Loss to Avionics Bay and/or Payload	3 (Faulty wiring, battery failure, poor setup of wiring causes a connection to come undone, forgotten connection)	F (Disqualified, objectives not met, failure to correctly trigger ejection charges)	F3, High	Test the reliability of the wiring and batteries through subscale flights, check batteries and connections before flight.	Perform continuity checks for altimeters prior to launch, visible wires will be inspected for nicks or damage prior to launch.[8]	F1, Medium

109

Arming System Failure	3 (Faulty arming system, faulty wiring, battery failure, poor setup of wiring causes a connection to come undone, forgotten connection)	F (Disqualified, objectives not met, failure to correctly trigger ejection charges)	F3, High	Ensure the avionics bay is successfully communicating with the team prior to flight, test arming system through test launches.	Ensure communication between avionics bay and the team is established and reliable right before launch.[10]	F1, Medium
Stages Fail to Separate	3 (Faulty ejection charge, excessive strength is used to hold stages together, altimeter failure)	F (Launch vehicle does not follow desired flight path, possible ballistic trajectory, lower maximum height, damage to the launch vehicle)	F3, High	Examine ejection charges for damage before launch, ensure proper functionality of the altimeters, ejection charges, and interstage joints, have a secondary ejection charge for each stage separation.	Ejection charge testing and the VDF have verified that the charges can separate stages. Dual altimeters are employed to provide redundancy. The Avionics Lead must follow the proper procedures to successfully program, initialize, and install the recovery section.	F1, Medium
Main Parachute Fails to Deploy	2 (Poor design of where parachute is in launch vehicle, poor sealing of parachute chamber, poor loading of parachute, faulty parachute or ejection charge, altimeter failure)	F (Main parachute does not slow down the launch vehicle, recovery failure, ballistic trajectory)	F2, High	Any team member who seals or packs the parachute chamber must be supervised by at least one other team member, examine parachute and ejection charges for damage before launch, have a secondary ejection charge in case of emergency which is larger than the first.	Ejection charge testing has ensured the ejection charge effectively deploys the main parachute. The Avionics Lead must follow the proper procedures to successfully program, initialize, and install the recovery section.	F1, Medium
Drogue Parachute Fails to Deploy	2 (Poor design of where parachute is in launch vehicle, poor sealing of parachute chamber, poor loading of parachute, faulty parachute or ejection charge, altimeter failure)	F (Drogue parachute does not slow down the launch vehicle, recovery failure, ballistic trajectory)	F2, High	Any team member who seals or packs the parachute chamber must be supervised by at least one other team member, examine parachute and ejection charges for damage before launch, have a secondary ejection charge in case of emergency which is larger than the first.	Ejection charge testing has ensured the ejection charge effectively deploys the drogue parachute. The Avionics Lead must follow the proper procedures to successfully program, initialize, and install the recovery section.	F1, Medium
Parachute Shroud Lines Break	1 (Poor shroud line materials, improper ejection of recovery system, damage from previous flights or transportation)	F (Possible recovery failure, ballistic trajectory)	F1, Medium	Only buy parachutes from reliable sources, remove threats to parachute integrity from the parachute housing, check the recovery system for damage before launch.	Examination of the shroud lines and parachutes must occur before packing into the main vehicle.[9]	F1, Medium
Shock Cord Breaks or Disconnects	1 (Faulty shock cord, damage to shock cord, poor connection to the launch vehicle)	F (Parachute disconnect from the launch vehicle, recovery failure, ballistic trajectory)	F1, Medium	Any team member who connects the shock cord to the launch vehicle must be supervised by at least one other team member, check the shock cord for damage before and after flight, only buy shock cords from reliable sources, analyze the shock cord with test flights.	Orange tape must be placed over the fasteners connecting different vehicle components together.[9]	F1, Medium
Tangled Parachute or Shock Cord	2 (Faulty or damaged shock cord or parachute, poor packing of shock cord and/or parachutes, poor sizing of parachutes or shock cord, unstable or ballistic flight)	F (Shock cord or parachutes may not fully extend or inflate, possible ballistic trajectory, possible failed recovery)	F2, High	Only buy parachutes and shock cords from reliable sources, any team member who seals or packs the parachute chamber must be supervised by at least one other team member, examine parachutes and shock cord for damage before launch, check performance of parachutes and	Ensure parachute packing is observed by at least one other team member with knowledge of the recovery system.[9]	F1, Medium

				shock cord in test flights, appropriately follow recommended sizing for shock cord and parachutes.		
Parachute Comes Loose from Launch Vehicle	2 (Failure of recovery system mount on the launch vehicle body, poor shroud line materials, improper ejection of recovery system, damage from previous flights or transportation)	F (Recovery failure, ballistic trajectory)	F2, High	Only buy parachutes from reliable sources, check the recovery system for damage before launch, double check that the recovery system is properly mounted before launch.	Ensure parachute packing is observed by at least one other team member with knowledge of the recovery system.[9]	F1, Medium
Parachute or Shock Cord Catch Fire	2 (Not enough space given between ejection charge and parachute, poor insulation of parachute, poor parachute packing, faulty or poorly chosen ejection charge)	F (Shock cord or parachutes do not fully achieve their goal, possible ballistic trajectory, possible failed recovery, damage to internal launch vehicle components)	F2, High	Any team member who packs the parachute or ejection charges must be supervised by at least one other team member, use recommended sizing methods for ejection charges, confirm proper placement and packing methods of ejection charges and parachutes with test flights.	Ensure parachute packing is observed by at least one other team member with knowledge of the recovery system.[9]	F1, Medium
ABCS Failure to Deploy	3 (Software error, mechanical failure)	B (Improper final vehicle altitude)	B3, Low	Design software and mechanics according to expected flight conditions.	Monitor ABCS performance during VDF and PDF.	B2, Low
Erratic Vehicle Path from ABCS Failure	3 (Software error, mechanical failure)	F (Partial or complete destruction of vehicle, possible ballistic trajectory)	F3, High	Design software and mechanism according to expected flight conditions. Ensure system enters low drag state during all failure modes.	Perform ground testing of various failure modes to ensure ABCS disengages if erratic movement is detected. Monitor ABCS performance during VDF and PDF.	F1, Medium
Payload R&D Activates During Ascent	2 (Software error, sensor failure)	C (Potential vehicle instability, PLS deploys at apogee, well above the required altitude window, potential entanglement with drogue parachute)	C3, Medium	The R&D system must be able to detect altitude and have enough power and torque to deploy the PLS.	The R&D system successfully deployed during the VDF, verifying that it is capable of deploying the PLS through either the R&D system itself, or backspin from main parachute deployment. See footnote for discussion of R&D performance during the VDF.[12]	C1, Low
Insufficient Payload R&D Power to Deploy PLS	2 (Incorrect assumptions of stepper motor capabilities, faulty power supply to R&D, incorrect calculation of force needed to move the PLS and R&D systems)	A (R&D will still deploy the PLS through the stepper motor being back spun by the force of the main parachute deploying)	A2, Minimal	The R&D system must be tested to have enough force to properly extend and deploy the PLS.	The R&D system successfully deployed during the VDF, verifying that it is capable of deploying the PLS through either the R&D system itself, or backspin from main parachute deployment. See footnote for discussion of R&D performance during the VDF.[12]	A1, Minimal

Payload R&D Power Loss During Flight	2 (Launch forces disconnect battery from R&D, insufficient charge on R&D batteries)	D (PLS deploys at main parachute deployment, potential entanglement with main parachute.	D2, Medium	The R&D battery must be properly connected before flight.	The R&D system successfully deployed during the VDF, verifying that it is capable of deploying the PLS through either the R&D system itself, or backspin from main parachute deployment. See footnote for discussion of R&D performance during the VDF.[12]	D1, Medium
PLS Fails to Deploy	4 (R&D failure, PLS becomes stuck in R&D, PLS parachute chords become entangled with R&D)	B (Payload mission failure, repairable damage to PLS and R&D)	B4, Medium	The PLS must have enough clearance to slide out of the R&D system and must not be impeded by it in any way.	Ensure the PLS can cleanly slide out of the R&D system by testing prior to the PDF.	B2, Low
Mechanical Damage to Payload R&D Upon Landing	4 (Impact with ground)	B (Repairable damage to PLS or R&D)	B4, Medium	Purchase extra materials and electrical components for the PLS and R&D systems.	Extra mechanical and electrical components have been purchased.	B2, Low
GPS Lock Failure	2 (Interference or dead battery)	F (Loss of vehicle)	F2, High	Ensure proper GPS lock and battery charge before flight.	Ensure GPS signal is established before flight.[16]	F1, Medium
Insufficient Landing Speed	3 (Improper load, higher coefficient of drag for the parachutes than needed, higher surface area of the parachutes than needed)	B (Unexpected changes in flightpath and landing area, increased potential for drift)	B3, Low	Use subscale flights to determine if the subscale parachutes were accurately sized, use recommended and proven-to-work parachute sizing techniques for full scale vehicle.	Avionics Lead must ensure the proper parachute is purchased and used.	B1, Minimal
Excessive Landing Speed	3 (Parachute damage or entanglement, improper load, improperly sized parachute)	F (Partial or total destruction of vehicle)	F3, High	Properly size, pack, and protect parachute.	Avionics Lead must ensure the proper parachute is purchased and used. Parachute packing must be observed by at least one other team member with knowledge of the recovery system.[9]	F1, Medium

Table 6.5: Vehicle Failure Modes and Effects Analysis

For verification of certain mitigation plans, see the following footnotes:

1. *6.2 The Day Of*
2. *6.2 The Day Of, "Installing the Vehicle on the Launch Rail"*
3. *6.2 The Day Of, "Installing Ignitor"*
4. *6.2 The Day Of, "Installing the Motor"*
5. *6.2 The Day Of, "On the Pad"*
6. *6.2 The Day Before, "Vehicle Interfacing"*
7. *6.2 The Day Of, "Setting Up the TeleDongle at the Launch Viewing Area"*
8. *6.2 The Day Of, "Countdown to Launch"*
9. *4.4.2.1 Analysis of Payload Retention System Performance*

6.1.6 Environmental Hazard Analysis

Hazards to Environment						
Hazard	**Likelihood (Cause)**	**Severity (Effect)**	**Risk**	**Mitigation**	**Verification**	**Post Mitigation Risk**

112

Pollution from Exhaust	5 (Combustion of APCP motors)	A (Small amounts of greenhouse gasses emitted)	A5, Medium	Use only launch vehicle motors approved for use by the National Association of Rocketry, Canadian Association of Rocketry, or Tripoli Rocketry Association.	Launch vehicle motors in consideration will be purchased and installed by the team's Student Mentor to ensure compliance.	A5, Medium
Pollution from Vehicle Itself	3 (Loss of components from vehicle in surroundings)	C (Materials degrade extremely slowly, possible harm to wildlife or water contamination)	C3, Medium	Ensure all parts are attached to each component of the vehicle and that the components of the vehicle are properly attached. Scavenge for fallen parts after launch is completed.	As the vehicle is in flight, all monitoring its path must call out if an unintended piece of the vehicle has separated. That piece will then be tracked to its landing location and collected. Orange tape must be placed over the fasteners connecting different vehicle components together.[10]	C1, Low
Pollution from Team Members	2 (Failed disposal of litter, improper cleanup procedures, members walk through important plant life, farming fields, sod, etc.)	D (Litter may degrade extremely slowly, wildlife may consume harmful litter, destruction of crops)	D2, Medium	Brief team members on proper cleanup procedures, foster a mindset of leaving no trace at launch sites, only the minimum number of required team members should retrieve the launch vehicle.	Follow societal standards and leave site cleaner than was found, make sure disposable equipment is kept track of and guaranteed to remain at designated locations. This will occur in the Safety briefing upon team arrival to the launch field.[11]	D1, Medium
Pollution from Machining / Construction	5 (Propelling fine debris into the air, into ventilation systems, and/or onto objects)	F (Lung damage to people, property damage to buildings and workplaces)	F5, Very High	Machining and construction operations may only occur in locations that have the proper controls in place to collect / divert emissions from the Team's activities. If it is not automatic, the Team must clean up any mess that is made.	All team members are responsible for checking if the workplace is clean, and all team members know that if the Team repeatedly does not clean up the workplace, access to that location will be revoked, and the project will not be able to be completed.	F1, Medium
Vehicle collisions with Man-made Structures or with Humans	2 (Failure to properly predict trajectory, failure to choose an appropriate launch area)	F (Damage to public property or private property not owned by the team, damage to team equipment, serious damage to team personnel or passerby)	F2, High	Do not launch under adverse conditions which may affect the course of the launch vehicle, run simulations which analyze the launch vehicle's trajectory mathematically and physically, choose a launch area which is not close to civilization, follow launch procedures closely.	Simulate results for vehicle trajectory.[12] Project Management and the Avionics Team Lead must ensure that the actual launch is ran in a similar way to that which was simulated. Safety Team Lead will monitor weather conditions prior to launch.	F1, Medium
Battery Leakage	3 (Absence of or damage to battery casing causing puncture to battery)	C (Possible toxic acid leak, heavy metal contamination, degradation and harm to plant and animal life)	C3, Medium	Batteries will be individually enclosed in plastic casing, parachutes will be selected to reduce landing kinetic energy below levels that will damage the casing.	Examine the battery casing for damages prior to launch.[13] It is assumed that if the kinetic energy of the vehicle landing is less than the maximum outlined in the Handbook, the battery casing will not be damaged to the point of battery puncture. Fulfillment of the kinetic energy upon landing requirement is calculated.	C1, Low
Fire to Surroundings	3 (Exhaust caused by launch vehicle engine)	F (Possible spread of wildfire, damage to wildlife or landscape)	F3, High	Prevent excess heat from occurring on the launch pad, as the fuel (vehicle motor) and oxygen (air) cannot be removed from the system. Have fire suppression systems nearby and use a protective ground tarp. A fire extinguisher will be borrowed from the Purdue Fire Department for the day of the launch.	Safety Team Lead will ensure compliance with NAR safety standard on minimum clear area.[11] Safety Team Lead is responsible for bringing fire suppression equipment to the launch field.	F1, Medium

Kinetic Damage to Buildings	2 (Launch vehicle veers off trajectory causing landing in occupied area)	D (Repairable destruction to building)	D2, Medium	Choose launch site that is remote enough to make this risk negligible.	Safety Team Lead must ensure minimum distance from building exceeds minimum building distance as established by NAR safety standard.[11]	D1, Medium
Kinetic Damage to Terrain	4 (Launch vehicle has excessive landing speed)	A (Creation of small ground divots, mild inconvenience to wildlife and flora)	A4, Medium	Parachute selection must ensure that vehicle does not land with an excess of kinetic energy.	Avionics Team has verified proper vehicle landing kinetic energy.	A1, Minimal

Table 6.6: Hazards to Environment

For verification of certain mitigation plans, see the following footnotes:

10. *6.2 The Day Before, "Vehicle Interfacing"*
11. *6.2 The Day Of*
12. *3.3.1.1 Altitude Predictions with Simulated Vehicle Data*
13. *6.2 The Day Before, "Assembling the Avionics Bay"*

Hazards from Environment						
Hazard	**Likelihood (Cause)**	**Severity (Effect)**	**Risk**	**Mitigation**	**Verification**	**Post Mitigation Risk**
Landscape	3 (Vehicle contact with trees, brush, water, power lines, wildlife)	F (Inability to recover launch vehicle, damage or destruction of vehicle or vehicle components)	F3, High	Angle launch vehicle into wind as necessary to reduce drift. Choose a launch area that is flat and clear of large flora.	Safety Team Lead, Project Management and the Student Mentor shall pick a launch area that is free from obstructions.[14]	F1, Medium
Obscured Launch Field (snow, hills, etc.)	3 (Weather / precipitation, nature of launch field)	F (Entire vehicle is lost, some vehicle components are lost)	F3, High	The Team must have a way to locate any section of the vehicle in the event that one or more components unintentionally detach from the rest of the vehicle.	EggFinder GPS systems have been installed into every major component of the vehicle. The PLS also has a GPS installed. In the event of unintended component separation, the GPS signals will be tracked.	F1, Medium
Heavy Precipitation	2 (Climate, poor forecast)	C (Inability to launch on that day, new launch date must be found, damage to electronics, degradation of some materials)	C2, Low	Do not launch if the air around the launch field is obscured. Store vehicle in warm dry place until it is ready to launch. Ensure all electronics are functioning properly before launch.	Project Management must pick a launch day and time that is favorable to launch. The Safety Team Lead will monitor weather conditions prior to launch. Electronics are initialized either right before the vehicle is placed on the launch rail, or right before launch, ensuring that the Team knows they are functioning properly prior to launch.[15]	C1, Low
High Humidity	2 (Climate, poor forecast, improper storage of launch vehicle when not in use)	D (Rust on metallic components, failure of electronics components)	D2, Medium	Use as little ferrous metal as possible in vehicle design, store vehicle indoors when not in use. Choose launch dates with a forecast fit for launch.	Team Leads should be aware of this hazard throughout the design process of the vehicle and its components.	D1, Medium
Low Humidity	2 (Climate, poor forecast, improper storage of launch vehicle when not in use)	D (Static buildup on or around vehicle causing shorts to electronics)	D2, Medium	Design redundancies in critical systems. Choose launch dates with a forecast fit for launch. Store vehicle in a more humid place when not in use.	Dual altimeters are being used to ensure proper parachute deployment, and multiple redundancies are being implemented in the Payload R&D system to ensure proper PLS deployment. Project Management will select a launch date with favorable weather, and the Safety	D1, Medium

					Team Lead will monitor weather conditions on the launch field.	
Winds	3 (Poor forecast)	D (Inability to launch, excessive drift)	D3, Medium	Angle into wind as necessary, abort launch if wind exceeds 20 mph (NAR High Power Rocketry Code, point 9)	Safety Team Lead will monitor weather conditions prior to launch.	D1, Medium
High Temperature	3 (Poor forecast)	C (Heat related injury or damage to vehicle components)	C3, Medium	Ensure team is wearing appropriate clothing for extended periods of time in hot environments. Keep launch vehicle in shaded area until before launch.	Safety Team Lead or Project Management must notify the team of weather on day of launch or manufacturing to wear proper clothing, Safety Team Lead must ensure mitigation is strictly followed due to weather conditions.	C1, Low
Low Temperatures	3 (Poor forecast)	F (Cold-related personnel injuries, frost on ground, ice on vehicle, clogging of vehicle ventilation, change in launch vehicle rigidity and mass, higher drag force on launch vehicle, electronics failure leading to a greater system failure)	F3, High	Ensure team is wearing appropriate clothing for extended periods of time in cold environments. Keep the launch vehicle at room temperature or bundled in materials which hold in heat, if ice appears anywhere on the launch vehicle, do not launch, and return it to a warm location. Ensure all electronics have continuity and are working properly immediately prior to launch.	Safety Team Lead or Project Management must notify the team of weather on day of launch or manufacturing to wear proper clothing, Safety Team Lead must ensure mitigation is strictly followed due to weather conditions. Electronics are initialized either right before the vehicle is placed on the launch rail, or right before launch, ensuring that the Team knows they are functioning properly prior to launch.[15]	F1, Medium
Wildlife Contact with Launch Vehicle	1 (Failure to accurately predict trajectory, unexpected appearance of wildlife, poor choice of launch area)	D (Damage to vehicle components, damage to wildlife, unexpected trajectory close to the ground)	D1, Medium	Launch in an open area with high visibility, be aware of the surroundings when choosing a launch area and launching.	Safety Team Lead, Project Management and the Student Mentor shall pick a launch area that is free from obstructions and places where wildlife could be found.[14]	D1, Medium
Wildlife Contact with Launch Pad	1 (Failure to monitor the launch pad, poor choice of launch area)	D (Possible inability to launch the launch vehicle, unpredictable launch behavior or trajectory)	D1, Medium	Launch in an open area with high visibility, be aware of the surroundings when choosing a launch area and launching, if animals tamper with the launchpad, do not launch.	Safety Team Lead, Project Management and the Student Mentor shall pick a launch area that is free from obstructions and places where wildlife could be found.[14]	D1, Medium

Table 6.7: Hazards from Environment

For verification of certain mitigation plans, see the following footnotes:

14. *6.2 The Day Of*
15. *6.2 The Day Of, "On the Pad"*

6.1.7 Project Hazards

Hazard	Likelihood (Cause)	Severity (Effect)	Risk	Mitigation	Verification	Post Mitigation Risk
Insufficient Funding	4 (Lack of revenue, parties unwilling /	F (Inability to purchase parts and	F4, Very High	Create and execute a detailed funding plan properly, minimize excessive spending by	Each subteam must verify purchases with Project Management and the Business Team Lead to ensure the	F1, Medium

	unable to contribute due to COVID-19 complications)	construct the vehicle)		having multiple members check the necessity of purchases.	team is still within their given budget. Program's Treasurer and Business Lead will work to create a uniform document for member purchases.	
Failure to Receive Parts	2 (Shipping delays, out of stock orders)	F (Cannot construct and fly vehicle)	F2, High	Order parts while in stock well in advance of needed date. Seek other vendors if product is out of stock.	Team Leads must ensure parts are ordered at least a month before the parts are scheduled to be used by referencing the GANTT chart. A month was chosen to give ample time for shipping, especially during holidays and in the pandemic. [16]	F1, Medium
Damage to or Loss of Parts	2 (Failure during testing, improper part care during construction, transportation, or launch)	F (Cannot construct or fly vehicle without spare parts)	F2, High	Order extra parts in case some need to be replaced. Take care in handling parts for transportation, launch, and construction operations.	Team Leads must confirm a minimum number of parts needed so the team can obtain duplicates for needed items. They must also assign responsibility for more important and expensive parts as they see fit.	F1, Medium
Rushed Work	3 (Rapidly approaching deadlines, unreasonable schedule expectations)	D (Threats of failure during testing or the final launch due to a lower quality of construction and less attention paid to test data)	D3, Medium	Set deadlines which both keep the project moving at a reasonable pace and leave room for unforeseen circumstances.	Team Leads shall verify that projects are being completed before the deadline arrives as denoted by the GANTT chart.[16]	D1, Medium
Major Testing Failure	2 (Improper construction of the launch vehicle, insufficient data used before creating the launch vehicle's design)	F (Damage to vehicle parts, possible disqualification from the project due to a lack of flight data, an increase in budget for buying new materials, delay in project completion)	F2, High	Ensure parts used fall within specifications of required use. Take care to perform tests correctly.	Team Leads / team members who write testing procedures must ensure that proper parts and methods are being used in tests.	F1, Medium
Unavailable Test Launch Area	2 (Failure to locate a proper area to launch vehicle, failure to receive an FAA waiver for any launch)	F (Disqualification from the project due to a lack of flight data)	F2, High	Secure a reliable test launch area and FAA waiver well in advance of the dates on which test launch data is required.	Project Management must work with the Student Mentor of the team to ensure the launch site is able to be used. The Safety Team Lead must ensure that the Student Mentor of the team has submitted the proper FAA waiver and that it is approved.	F1, Medium
Loss or Unavailability of Work Area	4 (Construction, building hazards, loss of lab privileges, COVID restrictions imposed by Purdue University)	D (Temporary inability to construct vehicle)	D4, High	Follow work area regulations and have secondary spaces available.	Inform members of proper work area etiquette to prevent loss of lab privileges. Project Management and Team Leads must regularly confirm that the team has access to secondary locations if the need arises.	D1, Medium
Failure in Construction Equipment	1 (Improper long-term maintenance of construction	C (Possible long-term delay in construction)	C1, Low	Ensure proper maintenance and use of construction equipment and have backup	Team members involved in the construction of the vehicle must inspect equipment before and after use to confirm it is functioning properly, consulting the	C1, Low

	equipment, improper use or storage of equipment)			equipment which can be used in case of an equipment breakdown.	supervisors of the area in which work is being done if any doubts arise.	
Insufficient Transportation	3 (Insufficient funding or space available to bring all project members to launch sites or workplace)	C (Loss of labor force, team members lose knowledge of what is happening with the project, low attendance to the final launch)	C3, Medium	Organize and budget for transportation early, keep track of dates on which large amounts of transportation are needed.	Project Management and Team Leads must organize transportation at least two weeks prior to major activities to make sure either enough drivers are secured, or buses are rented.	C1, Low
Inactivity / Low Availability of Personnel	3 (Members are unable or unwilling to work due to an increase in classwork, COVID-19 restrictions, or other mandatory activities)	F (Low attendance, loss of team members, labor shortages, inability to construct vehicle)	F3, High	Ensure all team members have an important role in the design process, shift extra personnel resources to needed areas.	Team Leads and Project Management will ensure the GANTT chart is followed and all members are engaged with the design process. [16]	F1, Medium
Damage by Non-Team Members	2 (Accidental damage caused by other workspace users)	F (Extensive repairs necessary, delay in construction)	F2, Medium	Separate all of the team's components from other areas of the workspace as necessary.	All team members must ensure only team members can have access to vehicle components by using the storage mechanisms allotted to the team in Purdue's ASL, including cabinets and shelves.	F1, Medium
Vehicle Damage During Transit	2 (Mishandling during transportation)	F (Inability to fly launch vehicle)	F2, High	Protect all launch vehicle components during transit.	Personnel transporting vehicle components must ensure the vehicle is secured with padding and bracing.	F1, Medium
Weather Delays	3 (Poor weather conditions during tests or launches such as high wind speeds, ice and frost, or storms)	F (Possible disqualification from the project due to a lack of flight data)	F3, High	Have multiple dates available on which test launches can be conducted in case of adverse weather conditions.	Project Management must set adequate launch and backup launch dates on the GANTT chart.[16]	F1, Medium

Table 6.8: Project Risks Analysis

For verification of certain mitigation plans, see the following footnotes:

16. The Team's GANTT Chart can be found in previous reports.

Acknowledging the successful Vehicle Demonstration Flight discussed in this report and the upcoming Payload and Competition Flights, concerns about the success of the project warrant acknowledgement. Due to COVID-19, Purdue University has imposed restrictions on all their student organizations limiting when and how they can meet and the flexibility of events such as a launch. While it is occasionally frustrating, the Team is following every process that is required by Purdue to secure times and locations to build, test, and launch the project this year. The Team has already secured approval from Purdue to hold both of the team's remaining launches and the times and locations to perform construction and vehicle integration operations. The only remaining factor that could determine if a launch his happening or not is the weather, and the Team will work with Purdue to ensure a launch field and launch date are secured, without compromising the safety or function of the project as a whole.

Even as Purdue has eased some of their event restrictions, for example, the total number of people that can be at an in-person event, the Team is still maintaining a strict policy to limit the team members' exposure to one another. Project Management has formed a plan for the repercussions of breaking these rules, and there is a clear understanding amongst the Team of what these policies entail. Moving into the final stages of the competition, the Team has complete confidence that the project will be completed and be of the quality expected by NASA-SL and the Purdue Team.

6.2 Launch Operations Procedures

In order to have successful Vehicle, Payload, and Competition Flights, a clear flow of events must be present to take the vehicle from a state of being fully built to a Launch Ready. The vehicle integration, system preparation, vehicle initialization, and launch procedures utilized for the Vehicle Demonstration Flight are presented here. That is to say, these procedures are what is to be done after the machining and construction of each component of the vehicle is complete, but not yet all put together. Events are organized to be generally chronological, with events prior to vehicle integration occurring without a need for sequential order and some initialization steps occurring simultaneously either before or after arriving at the designated launch location.

In Advance

Preparing the Payload Electronics

- Charge the Lander, R&D, and ABCS LiPo batteries.
- Remove and clear the memory storage drives (SD cards) of all data logging devices. This includes the Lander and ABCS.
- Final software needs to be uploaded to the GCS and Lander.
- Reinsert all memory storage drives into their respective logging devices.
- Calibrate the inertial measurement units on the Lander and ABCS.
- Calibrate the altimeters on the Lander and ABCS.

Programming the TeleMetrum Altimeter

(Note: the LiPo battery can be charged by plugging it into the TeleMetrum and then plugging the TeleMetrum into a laptop with a micro-USB cable. The red light will turn green when the battery is fully charged. A switch does not need to be connected.)

1. Connect the LiPo battery and a switch to the TeleMetrum, then plug it into a laptop with AltOS installed (https://altusmetrum.org/AltOS/) using a micro-USB cable.
2. Choose Configure Altimeter and then turn on the TeleMetrum using the switch while the TeleMetrum is lying flat. It should appear as a device to select. Select the TeleMetrum device and continue to the settings window. The TeleMetrum should halt beeping altogether as a connection indicator.
3. Configure settings as desired. In this case, the main deploy altitude should be set to 900' and the apogee delay should be set to 0 seconds. Also ensure the following:
    a. Frequency: 434.550 MHz Channel 0
    b. Telemetry/RDF/APRS Enable: Enabled
    c. Telemetry Baud Rate: 9600 baud
    d. APRS Interval(s): 5
    e. Callsign: KD2IKO
    f. Maximum Flight Log Size (kB): 8192 (1 flight)
    g. Igniter Firing Mode: Dual Deploy
    h. Pad Orientation: Antenna Up
4. Choose Save to save the new settings to the TeleMetrum. If desired, the accelerometer can be calibrated by choosing Calibrate Accelerometer and the TeleMetrum rebooted by choosing Reboot.
5. Before any flight, choose Save Flight Data and delete all previous flights to ensure no actual flight logs are lost.

Programming the StratoLoggerCF Altimeter

1. Connect the DT4Ux cable to the USB-B → USB-A cable, then connect the DT4Ux cable to the data port of the StratoLoggerCF altimeter and the USB-B → USB-A cable to laptop with PerfectFlite DataCap installed (http://www.perfectflite.com/Download.html). Also connect a 9V battery and a switch to the StratoLoggerCF.
2. Turn on the switch and open the DataCap software. While the StratoLoggerCF is performing its initialization beeps, ensure the correct comm port (COM6) is selected by choosing Altimeter, then CommPort. Also choose Altimeter, then Setup to ensure the connection to the altimeter was successful. If it was, the serial number and current settings should appear, and the altimeter should halt its initialization beeps and begin beeping once every few seconds as a connection indicator.
3. If the above process does not work, try connecting to the altimeter by choosing Data, then Acquire first.
4. Configure settings as desired. In this case, Preset 4 should be chosen, which sets the main deploy altitude to 700' and the apogee delay to 2 seconds. Also ensure the Siren Delay is set to 0 seconds. Choose Update Alt to save the settings to the StratoLoggerCF.
5. If desired, self-tests can be performed by choosing Altimeter, then Test.
6. There is no way to delete previous flights from the StratoLoggerCF. After 16 flights, the oldest will be automatically deleted.

Setting Up the EggFinder Trackers

1. Use a key to turn on the keylock switch of one EggFinder TX.
2. Plug the corresponding EggFinder RX into a laptop. The red LED should immediately come on, indicating the board has power. After one or two seconds, the green LED should then begin blinking, indicating that it is receiving data from the EggFinder TX.
3. On the Prolific serial driver webpage (https://prolificusa.com/product/pl2303hx-rev-d-usb-serial-uart-bridge-controller/), the correct driver to download is the "Windows Driver Installer Setup Program" at the bottom of the list. After downloading, extract the zip file and run the application "PL2303-WHQLDriver_Setup_v1230_20190815.exe", following the instructions to install the driver.
4. Download and run MapSphere (http://www.mapsphere.com/download/mapsphere). You will need to create a MapSphere account first before use.
5. Repeat steps 1 and 2 with the other EggFinder TX and RX on another laptop.

The Day Before

Assembling the Avionics Bay

- Cut the fingertips off four fingers of a nitrile glove. Measure out 2g, 3g, 3g, and 4g quantities of FFFFG black powder using a gram scale and funnel one of each into a glove fingertip. Insert a lighter cut to size into the fingertip and seal shut using two small zip ties.
- Insert the 2g and 3g black powder charges into the corresponding black powder canisters on the drogue bulkhead and the 3g and 4g black powder charges into the corresponding black powder canisters on the main bulkhead. Pack tightly with fireproof cellulose insulation and seal with masking tape. Screw the lighters into their corresponding terminal blocks.
- Screw each set of switch connection wires into the switch terminals of each altimeter. Also, screw a set of both drogue and main lighter connection wires into each altimeter's corresponding terminals.
- Attach the TeleMetrum and StratoLoggerCF altimeters to their corresponding sets of mounting posts on the altimeter sled using nylon altimeter mounting screws.
- Inspect all batteries for damage. Insert the (fully charged) 3.7V LiPo and 9V batteries into their corresponding compartments in the altimeter sled and connect the 3.7V LiPo battery to the TeleMetrum. Also, attach a 9V battery connector to the 9V battery and screw the connector into the battery terminals on the StratoLoggerCF.
- On each threaded rod, screw on two hex nuts so that there is about 0.8" between the top of the second hex nut and the threaded rod's bottom. Place a washer on each threaded rod.
- Slide the drogue bulkhead facing down onto the threaded rods.
- On each threaded rod, screw on two more hex nuts so that there is about 0.5" between the bottom of the first hex nut and the bulkhead.
- Slide on the altimeter sled with the battery compartment facing up to touch the hex nuts just placed on the threaded rods. Feed the drogue lighter connection wires from each altimeter though the corresponding holes in the drogue bulkhead.
- Slide on the battery guard, then add two more hex nuts onto each threaded rod to touch the battery guard.
- Slide the coupler over the components until it is touching the bulkhead.

- Connect the two sets of switch-to-altimeter JST connections together, and also screw the drogue lighter connection wires into the other ends of their corresponding terminal blocks on the exterior of the bulkhead. Make sure the switches are OFF.
- Feed the main lighter connection wires from each altimeter through the corresponding holes in the main bulkhead, then slide the bulkhead onto the threaded rods to seal the coupler.
- Screw the main lighter connection wires into the other ends of their corresponding terminal blocks on the exterior of the bulkhead. Add a washer and two hex nuts to each threaded rod to secure everything together.

Vehicle Interfacing

QUALITY WITNESS NOTE: The Avionics Team Lead must be present to witness these events. They will be asked by the Project Manager later if this system is "Go" for launch. If the Team Lead cannot be present for this, a team member not involved in these events must witness the success of these steps and then report that this system is "Go" for launch to the Team Lead.

- As specified in the CAD model, attach one EggFinder tracker module to the booster coupler's interior (pointing up) and the other to the interior of the payload coupler (pointing down) using screws.
- Inspect all shock chord, rail buttons, and bulkheads for damage. In each shock cord, make three loops (one on each end and one 1/3 of the shock cord length from one end). For every 10' of shock cord, make one bundle of z-folds and tape it together with masking tape. Inspect all quick links for damage. Attach large quick links to every loop.
- Inspect main parachute for damage. Fold the main parachute on a tarp so that it is long and thin. Attach the drogue parachute and a Nomex blanket to the middle quick link of the 30' shock cord and the main parachute and another Nomex blanket to the middle quick link of the 60' shock cord. Flag each quick link with orange tape to signify it has been closed.
- Attach the shorter end of the drogue shock cord to the eyebolt on the bulkhead of the avionics bay's drogue side and the longer end to the eyebolt on the bulkhead of the booster section through the lower recovery section. Flag each quick link with orange tape to signify it has been closed. Reconnect the lower recovery section to the booster section using shear pins. A rubber mallet may be required.
- Inspect drogue parachute for damage. Insert the drogue parachute, then shock cord into the lower recovery section and make sure they are adequately covered on the top with the Nomex blanket to protect them from ejection charge gases. Reconnect the lower recovery section to the avionics bay using screws.
- Attach the longer end of the main shock cord to the eyebolt on the bulkhead of the main side of the avionics bay and the shorter end to the eyebolt on the bulkhead of the payload section through the upper recovery section. Flag each quick link with orange tape to signify it has been closed. Reconnect the upper recovery section to the payload section using shear pins. A rubber mallet may be required.
- Insert the folded main parachute, then shock cord into the upper recovery section and make sure they are adequately covered on the top with the Nomex blanket to protect them from ejection charge gases. The main parachute should be as loose as possible while still fitting in length into the upper recovery section. Reconnect the upper recovery section to the avionics bay using screws.
- Use a key to briefly turn on and off each keylock switch through the switch band and listen for initialization beeps from each altimeter to ensure all wiring is still intact.

Assemble the Payload Bays

QUALITY WITNESS NOTE: Inspect Payload Bay assembly for the following. If any are missing, damaged, or otherwise incorrect, halt launch procedures and direct attention to the Payload Team Lead, who will appropriately respond to the irregularity. Inspect for presence of:

- Proper installation of SOS system
- Proper installation of D&L system
- Proper installation of PICS system
- Proper installation of LCS system
- Proper installation of ABCS electronics bay
- ABCS integration into Lower Airframe / Booster Section
- Lander:
  - Construct the associated subsystem plates: SOS, D&L, PICS, and LCS
  - The D&L attachment and release mechanisms must be installed:
    - Prepare the parachute and attach to the D&L attachment mechanism.

    - Both the parachute ring and eyebolt should be fastened utilizing two standard Bowline knots each.
    - The nichrome winding should appear to wrap around the nylon cord connected to the parachute without any particular loop making contact with the next.
  - The LCS board should be connected to essential components and the battery.
  - The battery and reed switch are loaded into their slots.
  - Assemble the Lander by inserting the skeletal threaded rods into the main attachment points.
    - The LCS board will be fastened AFTER the LCS, Battery, and D&L plates are assembled.
    - The SOS's servos should be attached and wired prior to attachment.
    - The PICS cupola should be constructed in its entirety before being fastened to the top of the Lander.
- R&D:
  - Ensure that the R&D stepper is installed into the Payload Bay coupler.
  - Ensure that the R&D Pizza Table rail assembly has been installed into the Payload Section.
  - Assemble the Pizza Table and parachute bag apparatus. Set aside for vehicle integration with the Lander and nosecone.
  - Load R&D electronics into their holder. This includes the board, key switch, and battery.
  - The R&D electronics and holder will be installed into the Payload Bay coupler before it is installed into the launch vehicle.
  - The R&D electronics holder is fastened into the Payload bay coupler by a single airframe bolt. The key switch should align with its outer hole.
  - The Payload Bay rear bulkhead can now be attached to the forward bulkhead and installed, paying special attention to avoid rotation of the forward bulkhead.
  - When the nosecone is prepared, it should be installed onto the Pizza Table attachment plate with all six ¼-20 bolts. The nosecone cameras should remain off.
- ABCS:
  - Ensure that the aeroplates are properly installed onto the airbrakes mechanism.
  - Assemble the ABCS electronics bay.
    - Insert the battery into its coupler slot and connect to electronics bay.
    - Ensure that the battery is solidly fastened in place within its slot.
  - Integrate the mechanism and electronics bay.
  - The ABCS and its couplers are now able to be assembled into the Lower Airframe.

The Day Of

Upon arrival to the launch field, the following events must occur:

- Briefing to team members by Safety or Systems Team Lead:
  - Timeline of events prior to, during, and after launch
  - Launch field etiquette
  - NAR minimum safe distance from launch vehicle
  - "Scatter" callout in case of ballistic trajectory
  - Identification of fire suppression and first aid equipment
  - Designate a "rapid response" person or persons to be the one(s) to perform duties such as administering first aid in the case of an emergency.
  - Designate spotters to keep track of the launch vehicle's descent and to point out its location as it falls.

Events marked with "*" may occur at the same time:

- *Selecting a launch area:
  - Student Mentor, Project Management, Construction Team Lead, and Safety Team Lead select a free launch area from wildlife intrusion and general obstructions.
  - Ensure a fire blanket has been placed under the pad if conditions at launch are dry enough to require it.
  - Safety Team Lead marks off NAR minimum safe distance for personnel and communicates it to the team.
- *Inspect all vehicle components for damage from travel.
  - If damage has occurred, Project Management must be notified to determine whether the launch may proceed.

- *Inspect motor, motor casing, and motor retainment system for damage.
    - If damage has occurred, Project Management must be notified to determine whether the launch may proceed.
- *Ensure two-way radios are functioning properly.

*Lander Initialization

QUALITY WITNESS NOTE: The Payload Team Lead must be present to witness these events. They will be asked by the Project Manager later if this system is "Go" for launch. If the Team Lead cannot be present for this, a team member not involved in these events must witness the success of these steps and then report that this system is "Go" for launch to the Team Lead.

- The team will determine an appropriate area to initialize the Lander. The area should be relatively flat and free of any obstacles that may obstruct the Lander. Ideally this location will be close to the team's viewing area so the GCS will not need to be moved.
- The GCS will be powered on and initialized.
- The Lander will be placed on the ground on its side and will be turned on using the key switch.
- The Lander will automatically enter its initialization sequence:
    - The Lander will establish a connection with the GCS.
        - If the Lander cannot establish a connection the buzzer will sound, and the team will need to troubleshoot the problem.
    - Once the Lander has established a connection to the GCS, the Lander will send codes for any errors that were detected during the initial checks. If there are no errors, then the Lander will send a signal confirming it is ready for the next initialization phase.
        - If errors are received, the team will need to troubleshoot and resolve them before moving onto the next step.
    - The member at the GCS will announce to nearby team members that the Lander is about to perform the orientation maneuver. This will be to ensure the safety of nearby team members and the safety of the Lander. This announcement will also alert non-payload team members so they can witness the glory of what the payload team has created.
    - While the Lander is orientating, team members will closely inspect the Lander for any defects or unexpected behavior. If something is noticed, project management will be notified and will decide if the issue needs to be corrected.
    - Once orientated, the lander will acquire a position fix, and run the PICS system. The Lander will send the GPS data as well as the images to the GCS. The Lander will also report any errors detected. Team members will review this data and resolve any errors before continuing.
    - Once satisfied the Lander is ready for launch, the team will send a command from the GCS to instruct the Lander to enter its Launch-Ready configuration. The team member entering the command must also notify nearby members that the Lander will be moving.
        - The Lander will return the legs to the starting position.
        - The LCS will place all peripheral devices, except the Xbee, into their sleep modes.
- The Lander will now be ready to be loaded into the Payload Bay.

Lander-Payload Initialization

- THE LANDER MUST BE INITIALIZED TO CONTINUE.
- The Lander's parachute should be packed into the Pizza Table's deployment bag and held on the bottom of the Lander cupola.
- The Lander and Pizza Table/Nosecone can be loaded together into the Payload Bay.
    - The Lander should fit within the Pizza Table's confines.
    - The Lander must be installed into the only correct rail orientation. Failure to do so will not trigger the Lander's reed switch via magnet.
- The payload should be carefully slid backwards to engage the R&D lead screw with its lead nut.
- When the Lander detects the magnet in the payload bay it will send a message to the GCS confirming that the payload has been loaded then both the Xbee and main microcontroller will be put to sleep. If the payload is inserted into the payload bay and confirmation is not received by the GCS, then team members will inspect the Lander and the payload bay for the cause of this error. If necessary, the Lander will be removed from the bay and the problem corrected. The GCS must receive

confirmation that the Lander is loaded before the team can move on to next steps. If the Lander is erroneously pulled out of sleep mode or detects an error after the Xbee is put to sleep, the buzzer will sound to notify team members.

- Utilizing on-board button on the R&D PCB, the Pizza Table should be installed onto the R&D electronics servo lead screw, avoiding over-tightening of the Pizza Table.
    - The R&D can be turned on utilizing its key switch.
    - The R&D will enter its initialization sequence, providing audible and/or visible feedback of flight-ready status.
    - The codes for audible feedback can be found here.
    - The R&D is now armed, but will remain inactive until altitude and acceleration criteria are met for activation.
    - The Payload Bay should be handled carefully; dropping the R&D at this point could potentially cause malfunction and activation of the Pizza Table mechanism.
    - By depressing and holding the R&D button through its external hole, the leadscrew will begin to retract.
    - If the lead nut is properly engaged with the lead screw, the payload should begin to retract into the Payload Bay.
    - Once the nose cone is flush with the rim of the airframe, continue depressing the R&D button briefly before letting go. This should preload the nosecone against the vehicle's airframe.
    - The R&D should be turned back off utilizing its key switch.
- The upper Payload Bay is now ready for vehicle integration with the central airframe.

Motor Installation

QUALITY WITNESS NOTE: The Construction Team Lead must be present to witness these events. They will be asked by the Project Manager later if this system is "Go" for launch. If the Team Lead cannot be present for this, a team member not involved in these events must witness the success of these steps and then report that this system is "Go" for launch to the Team Lead.

- Prep and install motor (PPE required: gloves and safety glasses). Note: The Student Mentor is the ONLY person allowed to install the motor and ignition system.
    - Grease motor tube forward and aft closure threads.
    - Bolt on forward closure (with eye bolt attached).
    - Place one grain in motor tube.
    - Insert RUBBER washer.
    - Repeat last two steps for all motor grains.
    - Apply lubricant as necessary to O-rings.
    - Bolt the aft closure / nozzle onto the motor tube.

Note: Igniter and nozzle cap will be added once the launch vehicle is on the launch pad. Under no circumstances are they to be inserted prior to being on launch pad.

- Install motor into lower airframe using the MFSS.

Installing the Vehicle on the Launch Rail

- Check that the weather conditions remain favorable for launch
- Move launch vehicle to launch rail
    - NOTE: Only launch essential personnel and those carrying the launch vehicle are allowed to accompany the launch vehicle to the launch pad
    - Ensure launch rail is at least the minimum safe distance from spectators based upon the NAR minimum distance table
    - Ensure the launch controller is disarmed prior to installing the launch vehicle onto the pad
    - Ensure the launch pad is stable and is an adequate size for the launch vehicle being used.
    - Inspect the launch pad, vehicle rail buttons, launch rail for damage. If any is present, halt launch proceedings to fix the issue.
- Tilt launch rail and slide launch vehicle onto rail along rail buttons
- Ensure the launch vehicle slides smoothly along the launch rail.
    - If this is not the case, halt launch proceedings to lubricate the launch rail and check the rail buttons for proper alignment.

On the Pad

QUALITY WITNESS NOTE: The Avionics Team Lead must be present to witness these events. They will be asked by the Project Manager later if this system is "Go" for launch. If the Team Lead cannot be present for this, a team member not involved in these events must witness the success of these steps and then report that this system is "Go" for launch to the Team Lead.

Ensure **bolded** events occur:

- Use a key to turn on both keylock switches for the altimeters through the switch band.
- The StratoLoggerCF should emit the following sets of beeps. One lower-pitched beep precedes each set.
  - 4 beeps (indicating **Preset 4** was set).
  - 7 beeps, then 10 beeps, then 10 beeps (indicating a main deploy altitude of **700'** was set).
  - One very long beep (indicating an apogee delay of **2 seconds** was set).
  - Beeps corresponding to the apogee recorded in the previous flight in feet.
  - Beeps corresponding to the battery voltage in volts (ones place, then tenths place). Count to ensure the voltage is at least **above 8.0V**.
  - **3 continuity beeps** every 0.8s.
    - If only 2 continuity beeps – Indicates continuity on only main lighter
    - If only 1 continuity beep – Indicates continuity on only drogue lighter
    - If 0 continuity beeps – Indicates continuity on neither drogue nor main lighters
- The TeleMetrum should emit the following sets of beeps. Here *dits, dahs,* and other specific beeps are specified. Ensure **bolded** events occur.
  - Beeps corresponding to the battery voltage in volts (ones place, then tenths place). Count to ensure the voltage is at least **above 3.3V**.
  - *Dit*, *dah*, *dah*, *dit* (indicating the TeleMetrum is in **Pad Mode** and waiting for launch).
    - If only *dit*, *dit* – Indicates the TeleMetrum is in Idle Mode; ensure it is in the correct orientation (pointing up)
  - **3 continuity *dits*** every 5s.
    - If only 2 continuity *dits* – Indicates continuity on only main lighter
    - If only 1 continuity *dit* – Indicates continuity on only drogue lighter
    - If *brap* – Indicates continuity on neither drogue nor main lighters
    - If *warble* – Indicates storage is full; need to delete extraneous flights
- Use a key to turn on both keylock switches for the trackers. This can be done at the same time as R&D and ABCS initialization.
- Ensure all static port holes are clear of debris.

<u>R&D Initialization</u>

- Before the launch vehicle is installed onto the launch rail, the R&D must be turned on. If it is not done before being installed, then no members will be able to reach its key switch.
- The R&D can be turned on utilizing its key switch.
- The R&D will enter its initialization sequence, providing audible and/or visible feedback of flight-ready status.
  - This consists of 1 long beep and 4 short beeps.
  - Any other combination of beeps is cause for alarm; bring R&D personnel to the pad to investigate.
  - The codes for audible feedback can be in internal documentation, "R&DBuzzerCodes.docx".
- The R&D is now armed, but will remain inactive until altitude and acceleration criteria are met for activation.
  - The Payload Bay should be handled carefully; dropping the R&D at this point could potentially cause malfunction and activation of the Pizza Table mechanism.
- The launch vehicle is now clear to be installed onto its launch rail.

<u>ABCS Initialization</u>

- The ABCS can be turned on utilizing its key switch.
- The ABCS will enter its initialization sequence, providing audible and/or visible feedback of flight-ready status.
- The ABCS is now armed, but will remain inactive until altitude and acceleration criteria are met for activation.
- The Lower Airframe should be handled carefully; dropping the ABCS at this point could potentially cause malfunction and activation of the drag plates.

<u>Installing Ignitor</u>

- Ensure ONLY the Student Mentor installs the ignitor.
- Ensure ignitor clips are clean and undamaged.
- Ground ignitor clips to ensure excess static charge has been dissipated.

- Install ignitor into the motor.
- Return to the viewing area.
- Ensure the ignition system has continuity.

Setting Up the TeleDongle at the Launch Viewing Area

QUALITY WITNESS NOTE: The Avionics Team Lead must be present to witness these events. They will be asked by the Project Manager later if this system is "Go" for launch. If the Team Lead cannot be present for this, a team member not involved in these events must witness the success of these steps and then report that this system is "Go" for launch to the Team Lead.

- Assemble the TeleMetrum antenna. The longest prongs go at the bottom and the shortest go at the top.
- Plug the antenna into the TeleDongle, then plug the TeleDongle into a laptop with AltOS installed.
- Open AltOS and choose Monitor Flight. The TeleDongle should appear as a device to select. Select the TeleDongle device and continue to the telemetry window.
- Set the frequency to 434.550 MHz Channel 0 and baud rate to 9600 baud. Live telemetry from the TeleMetrum should now be appearing on the screen.
- Ensure all lights are **green**.
    - Battery, apogee igniter, and main igniter voltages are all **above 3.3V**.
    - On-board Data Logging is **Ready to record**.
    - **At least 4** GPS satellites are in solution. This may take a few minutes.
    - GPS Ready is **Ready**.
- Also ensure Site Map tab is filled with launch area.

Setting Up the EggFinder Trackers at the Launch Viewing Area

QUALITY WITNESS NOTE: The Avionics Team Lead must be present to witness these events. They will be asked by the Project Manager later if this system is "Go" for launch. If the Team Lead cannot be present for this, a team member not involved in these events must witness the success of these steps and then report that this system is "Go" for launch to the Team Lead.

- Follow step 2 in the "Setting Up the EggFinder Trackers" section above.
- In MapSphere, choose GPS, then Configure. Choose the COM port the GPS is connected to, then OK.
- In the GPS Status tab to the lower right, GPS satellites should begin coming into view. **At least 3** GPS satellites must be in solution. This may take a few minutes.
- In the main map, **current location should now be shown** as an orange triangle and be tracking in real time.
- Repeat the above steps with the other EggFinder tracker. Although it may be the same one that the TeleDongle is plugged into, another laptop must be used.

Go / No Go Poll

- The Project Manager will now conduct a "Go / No Go" Poll for each of the following systems:
    - Payload Lander
    - Payload R&D
    - Avionics and Recovery
    - ABCS
    - MFSS
- If any system is "No Go" for launch, halt all proceedings until that system is "Go." If the "Go / No Go" Poll is halted at any time, restart the Poll once all personnel are ready.
- ***If all systems are "Go," the vehicle is now ready for launch.***

Countdown to Launch

- Ensure the launch and the flight are not angled towards any spectators or buildings.
- Check cloud ceiling and winds and make sure the skies around the launch area are clear.
- Ensure there are no obstructions or hazards in the launch area.
- Designate 2 rapid response persons to administer first aid and call for help, respectively.
- Designate 2 spotters to track launch vehicle's flight path.
    - Spotters must point to the launch vehicle at all times.
- Remind spectators of the appropriate reaction to a ballistic trajectory and "scatter" call
    - If a "scatter" is called, all personnel must turn away from the launch vehicle and run for at least 10 seconds.
- Shortly before the countdown, give a loud announcement that the launch vehicle will be launched; if applicable to the situation, use a PA system.

- **When launching, give a loud countdown of “5, 4, 3, 2, 1, LAUNCH!”**
- Spotters are to follow the launch vehicle's path and call any deviation or unusual behavior in the vehicle’s flight (unsteady flight, sudden course deviation, etc.).
- Ensure deployment of drogue parachute is evident at most 4 seconds after apogee.
- If no sign of drogue deployment is apparent, see Troubleshooting below.
- Call a loud “Heads up!” (If needed, sound an air horn) in the case of any launch vehicles approaching the prep area or spectators; all who see the incoming launch vehicle should point at it as it descends.
- Ensure that whoever is responsible for recovery is kept fully aware of the launch vehicle's status (failed to launch, nominal in-flight, midair failure, returning for recovery, etc.).
- Communicate launch progress effectively to NASA officials, if needed.

<u>At the Landed Vehicle</u>

- Ensure the main parachute is secured and not dragging the vehicle along the ground.
- Take numerous photos at various angles of the landed vehicle.
- The StratoLoggerCF should emit the following sets of beeps. One lower-pitched beep precedes each set.
    - Beeps corresponding to the apogee in feet.
    - Beeps corresponding to the maximum velocity in miles per hour.
- The TeleMetrum should emit the following sets of beeps.
    - Beeps corresponding to the apogee in meters.
- Once these three values are recorded, use a key to turn off both keylock switches for the altimeters through the switch band. Note: Failing to record altimeter data before turning them off might result in disqualification from competition.
- Gather the sections of the vehicle and carry back to the launch viewing area.

<u>Payload Ground Mission</u>

- Each launch will have a team member designated as the payload recovery lead (PRL). This team member will oversee locating the Lander and ensuring that all recovery tasks are performed.
- If necessary, the PRL will use GPS data to locate the Lander. If another team member reaches the Lander, they will wait so that the PRL will be the first to approach the Lander.
- If the wind is blowing the parachute away from the Lander, then the PRL will put another team member in charge of recovering the parachute.
- As the PRL approaches the Lander they will look for any visual damage to the Lander, paying close attention to damage that may present a danger to other team members such as sharp edges or battery damage.
- If the PRL determines there is an immediate safety threat with the Lander, the PRL will notify the safety lead via radio or send another team member. If a danger is present the PRL must stay near the Lander to warn other team members.
- If there is no immediate safety threat but a danger is observed, the PRL will clearly identify the dangers to nearby team members. The PRL will then make a decision if extra PPE, such as gloves or safety glasses will be needed to recover the Lander. If extra PPE is required, the PRL will instruct team members to acquire the necessary PPE.
    - Note: at this point the Lander is still in the upright position.
- The next step is to verify that the nichrome is at a safe temperature. The PRL will take the temperature of the nichrome using a non-contact thermometer.
    - If the nichrome is a safe temperature then the recovery can continue on its normal path.
    - If the nichrome is still hot then the PRL will warn nearby team members. The PRL will then take great care to avoid the nichrome as they use the key switch to disable the Lander. The PRL will then wait for the nichrome to cool before continuing with recovery.
- Now that recovery is safe to continue the PRL will ensure the following tasks are completed:
    - Pictures of Landing area and Lander are taken.
    - Any damage and irregularities are documented for future analysis.
    - If the parachute detached, pictures of the parachute and the approximate distance from the Lander.
- The PRL will now use a radio, or send a team member, to request that the Lander is put into its recovery state. A team member will use the GCS to send the recovery command to the Lander. The Lander will then slowly return the legs to the start position causing it to fall back on its side. The PRL will ensure that team members are clear of the Lander for this operation.
- Once in recovery mode, the Lander can be disabled and returned to the team's prep area. If the Lander was disabled in the upright configuration due to a nichrome error, then it will need to be recovered in the upright position.

- Team members will partially disassemble the Lander documenting any damage or irregularities found inside the Lander. The batter will be disconnected and stored safe place. The SD card will also be removed and stored for later analysis.

Downloading GPS Data from the EggFinder Trackers at the Launch Viewing Area

- In MapSphere on one laptop, choose GPS, then Save GPS-log to save the GPS log as a raw GPS data file.
- Repeat the above step for the other EggFinder tracker on the other laptop.
- Use a key to turn off both keylock switches for the trackers.

The Day After

Downloading Flight Data from the TeleMetrum Altimeter

1. Follow step 1 in the “Programming the TeleMetrum Altimeter” section above.
2. Choose Save Flight Data and then turn on the TeleMetrum using the switch. It should appear as a device to select. Select the TeleMetrum device and continue to the next window. The TeleMetrum should halt beeping altogether as a connection indicator.
3. Select the newest flight and save the raw TeleMetrum data file to the laptop.
4. To display a plot, statistics, and a map from the flight, choose Graph Data, then select the raw TeleMetrum data file just saved. The plot can be configured by choosing Configure Graph and selecting different options.
5. To convert the raw TeleMetrum data file to a CSV file, choose Export Data, then select the raw TeleMetrum data file just saved. Choose Save to save the CSV file to the laptop. Coordinate location information can also be saved by changing the Export File Type to Googleearth Data (.KML) and analyzed in the same way as the raw GPS data files from the EggFinder trackers two sections below.
6. The raw TeleDongle data file can also be saved and analyzed in a similar way when the TeleDongle is plugged into the laptop.

Downloading Flight Data from the StratoLoggerCF Altimeter

1. Follow steps 1 and 2 in the “Programming the StratoLoggerCF Altimeter” section above.
2. Choose Data, then Acquire. Select the newest flight and choose Start.
3. A plot and statistics from the flight should be displayed. Different plots can be displayed by selecting different options under Displayed.
4. To retrieve the numerical data, choose Data, then Inspect.
5. Choose Select All, then Copy. The data can then be pasted into an Excel document to be plotted and analyzed.
6. The raw StratoLoggerCF data file can also be saved by choosing File, then Save As. It may be opened later without a StratoLoggerCF interfaced to the laptop by choosing File, then Open, then the raw data file.

Converting Raw GPS Data Files from the EggFinder Trackers

1. On one laptop, select Choose File in GPSVisualizer (https://www.gpsvisualizer.com/) and choose the raw GPS data file that had been downloaded on launch day.
2. Choose JPEG map as the output format, select Map It, and download the image on the next page to save the map.
3. Go back to the first page, choose plain text table as the output format, select Convert It, and download the text file on the next page to save the coordinate location information. The coordinates can then be pasted into an Excel document and converted to a CSV file for further analysis.
4. Repeat the above steps for the other EggFinder tracker on the other laptop.

Additional Troubleshooting

In the case of a misfire:

- Wait a minimum of one minute before approaching launch pad.
- Disarm launch controller and avionics.
- Remove failed igniter and motor if needed.
- Determine if another attempt at launch is feasible.

In the case of unintended ballistic trajectory:

- If the launch vehicle is in freefall for longer than four seconds without any indication of parachute ejection (smoke from ejection charge, parachute deploying), those tasked with observing the trajectory will loudly announce “Scatter.”
- All spectators of the launch are to immediately turn away from the launch vehicle's direction and run for a minimum of 10 seconds.

In case of missing section of launch vehicle during descent:

- If any sections of the launch vehicle are present, inspect for signs indicating point of separation.

- If failure mode can be determined, keep in mind any dangers that may be associated with the missing sections of the launch vehicle.

- Taking into account last known launch trajectory and wind, on a map or map-analogue identify the most likely location of missing part.
- Assemble team at the edge of the nearest road or other linear landmark.
    - Spread the team out with between 30 and 50 feet between adjacent team members.
    - Instruct team members to keep their gaze between 40 and 50 feet in front of them, scanning the ground in 180-degree arcs, walking in a straight line.
        - If applicable, follow ruts in the dirt from plowing devices or planting
- Once the far end of the search area has been reached, move the search party such that the last person in the line now stands where the first person was before the move
    - Move back in the direction of the initial linear landmark, and repeat search.

7 Project Plan

7.1 Avionics Testing

7.1.1 Altimeter Ejection Vacuum Test - VT.A.5.3

Test Objective: Fulfill requirement S.A.5.1: Both altimeters need to be able to ignite both ejection charges at the appropriate times consistently.

Testing Variable: The testing variable is the number of times the lighters are ignited by the TeleMetrum and StratoLoggerCF altimeters.

Success Criteria: Both altimeters must ignite the drogue parachute lighters at apogee (or 1s after apogee) and the main parachute lighters at the correct altitude during descent.

- For the TeleMetrum altimeter, the magnitude of the difference between the apogee altitude and the altitude the drogue lighter ignites at must be less than 500’ for all three trials.
- For the TeleMetrum altimeter, the altitude the main lighter ignites at must be between 900 ± 50’ for all three trials.
- For the StratoLoggerCF altimeter, the drogue delay (the time between apogee and ignition of the drogue lighter) must be between 0.75 and 1.75s (as it is programmed to be 1s) for all three trials.
- For the StratoLoggerCF altimeter, the altitude the main lighter ignites at must be between 700 ± 50’ for all three trials.

Why it is Necessary: Both altimeters must be able to ignite both ejection charges at the correct times in flight in order to ensure the successful recovery of the vehicle and validate the choices of altimeters.

Methodology:

(Note: If desired, both altimeters can be tested at the same time for a total of only three rather than six trials)

1. One large hole was drilled into the sheet of plexiglass. The wine stopper was placed into this hole and a small ring of plumber’s putty was placed around it in order to prevent air from escaping.
2. A smaller hole was drilled to the larger side (this acted as a pressure release hole to simulate descent).
3. To test one altimeter, a lighter was connected to each the drogue and main outputs, and a battery and switch were also connected. This system (along with the AltimeterOne turned on and set to Real Time mode) was placed in the glass bowl, with the switch and the lighters hanging over the rim of the bowl to allow easy access to turn the altimeter on and off as well as to allow the lighters to ignite in a non-constrained environment. If the TeleMetrum was being tested, it was placed pointing up.
4. A larger ring of plumbers’ putty was placed around the rim of the bowl, over the lighters and switch wires. The prepared sheet of plexiglass was then placed over the bowl and pressed down until there was a uniform seal around the entire perimeter. Extra plumbers’ putty was placed around the exposed wires as needed.
5. A small piece of plumbers’ putty was used to seal the pressure release hole, then the altimeter was switched on and allowed to complete its initialization routine. It was important that these steps were completed in this order because if the chamber was sealed after the altimeter was switched on, it might have detected the small drop in pressure and started the launch.
6. The wine bottle air remover pump was then used to remove air through the stopper. Once the process of removing air was halted at the expected apogee altitude (the digital display of the AltimeterOne indicated when this was), the drogue lighter was expected to ignite (or one second after apogee for the StratoLoggerCF altimeter).
7. Finally, the small piece of plumbers’ putty was very slightly lifted away from the plexiglass to slowly allow air back inside it, causing the altitude to decrease according to the AltimeterOne. The main lighter was expected to ignite at pressures corresponding to an altitude of 900’ (or 700’ for the StratoLoggerCF altimeter).
8. The flight data was downloaded onto a laptop for analysis.
9. The procedure was repeated two more times for a total of three trials, then three more times with the other altimeter.

Impact of Results: If both altimeters pass this test, no action will be required to correct the performance of lighter ignition, and it can be expected that the altimeters will eject the parachutes with no issues during launch. If one or both altimeters fail this test, a complete retest will need to be conducted on the altimeter(s) that failed in order to determine and correct the issue, and new altimeters may be considered.

Results, Conclusions, and Lessons Learned:

This test was first conducted January 24th, 2021. After analyzing the data from that test, it was determined that the TeleMetrum altimeter **passes** and the StratoLoggerCF altimeter **fails**. For all three trials for the TeleMetrum, the magnitude of the difference between the apogee altitude and the altitude the drogue lighter ignited at was less than **500'**, and the altitude the main lighter ignited at was between **900 ± 50'**. For all three trials for the StratoLoggerCF, the altitude the main lighter ignited at was between **700 ± 50'**, but the time between apogee and ignition of the drogue lighter **was not between 0.75 and 1.75s**, rather closer to around 4 seconds. After some thought, the team decided that the time between the ignition of the drogue lighter by the TeleMetrum and the ignition of the drogue lighter by the StratoLoggerCF would be a better parameter to measure for this particular success criteria, because the conditions of the test setup delay both ignitions from apogee an anomalous amount compared to a real flight. However, for all three trials, the time between TeleMetrum and StratoLoggerCF drogue ignition **was still not between 0.75 and 1.75s**, rather closer to 0 seconds (simultaneous ignition).

Because of this failure of the StratoLoggerCF altimeter, a retest was conducted two weeks later on February 7th, 2021 with the drogue delay changed to **2 seconds** in an attempt to compensate for the tendency of the StratoLoggerCF to ignite the drogue lighter too close in time to that of the TeleMetrum. This new drogue delay setting is still within the relevant NASA requirement. In the retest, all of the success criteria that passed previously in the initial test still **pass**. Additionally, for all three trials, the time between TeleMetrum and StratoLoggerCF drogue ignition was between **0.75 and 1.75s**. Therefore, the StratoLoggerCF altimeter **passes** this test. There is no need to retest, and project requirement S.A.5.3 has been verified.

Picture:

Figure 7.1: One Trial of the Altimeter Ejection Vacuum Test

7.1.2 Black Powder Ejection Test - VT.A.2.1, VT.A.3

Test Objective: Fulfill requirements S.A.2.1: Parachutes will be completely protected with a Nomex blanket on the side of the ejection charges, and S.A.3: The black powder canisters will create appropriate separation between the airframe sections.

Testing Variable: The testing variable is the amount of separation on the ground between the correct airframe sections both the drogue and main side black powder canisters result in.

Success Criteria: Both black powder canisters must separate the correct airframe sections the appropriate amount on the ground, not damage any vehicle components, and fully eject the parachutes.

- Black powder canister on the upper recovery section side of the avionics bay: ignition must result in at least 6’ of separation between the upper recovery section and the payload section for at least one amount of black powder equal to or greater than 3g.
- Black powder canister on the lower recovery section side of the avionics bay: ignition must result in at least 6’ of separation between the lower recovery section and the booster section for at least one amount of black powder equal to or greater than 2g.

Why it is Necessary: Both black powder canisters must separate the correct airframe sections the appropriate amount on the ground, not damage any vehicle components, and fully eject the parachutes in order to ensure the successful recovery of the vehicle and validate the choices of all of these components.

Methodology:

1) The black powder canister on the upper recovery section side of the avionics bay was filled with 3g of black powder. Specifically, the black powder was measured out using the gram scale and poured into the cut tip of a finger of a disposable latex glove, which was then zip-tied shut with the end of a lighter also placed in there. This was then placed into the black powder canister, which was packed with fireproof cellulose insulation and covered with masking tape to prevent anything from falling out.
2) The other end of the lighter was connected to the terminal block on the avionics bay, and the 10’ extension wire was also connected to the other end of the terminal block.
3) The main parachute and a Nomex blanket were attached off-center to the 60’ shock cord via a loop and quick link. The longer end was attached to the eyebolt on the bulkhead of the upper recovery section side of the avionics bay, and the shorter end was attached to the eyebolt on the bulkhead of the payload section through the upper recovery section. The main parachute and Nomex blanket were packed in flight configuration in the upper recovery section, which was then reconnected to the avionics bay using screws. The upper recovery section was also reconnected to the payload section using shear pins (using a rubber mallet if necessary).
4) The extension wire had been threaded through one of the switch holes so it could be accessed from the outside of the vehicle. The remote detonator was connected to the extension wire.
5) The person conducting the test stood 40’ away from the system and set off the remote detonator. The ejection charges were then expected to ignite and result in the separation of the two sections connected by shear pins. If they did indeed separate, the distance between them was measured in feet using the tape measure.
6) If the below success criteria were not met, the procedure was repeated using increasing amounts of black powder (in 1g increments) until 6’ of separation was achieved. This last amount of black powder was then recorded as the ideal amount of black powder.
7) The procedure was also repeated for the black powder canister on the lower recovery section side of the avionics bay (with the drogue parachute inserted and attached on the other side to the booster section with the 30’ shock cord), with 2g of black powder.

Impact of Results: If both black powder canisters pass this test, no action will be required to correct the performance of airframe separation, and it can be expected that the black powder canisters will successfully separate the correct airframe sections and eject the parachutes with no issues during launch. If one or both black powder canisters fail this test, the following responses will be taken: if the upper recovery section and payload section separation is less than 6', black powder will be added in 1g increments from the initial 3g until 6' of separation is achieved. If the lower recovery section and booster section separation is less than 6', black powder will be added in 1g increments from the initial 2g until 6' of separation is achieved. These retests will be conducted until 6' of separation of the two airframe sections is achieved by both the drogue and main side black powder canisters. Then, these ideal amounts of black powder will be used in the new vehicle design.

Results, Conclusions, and Lessons Learned: This test was conducted on February 17th, 2021. The black powder canister on the drogue side of the avionics bay resulted in **9’ 7”** of separation of its two respective airframe sections with **2g** of black powder used, and the black powder canister on the main side of the avionics bay resulted in **29’** of separation of its two respective airframe sections with **3g** of black powder used. Both black powder ejection systems resulted in greater than **6’** of separation of their corresponding airframe sections, **did not damage** any vehicle components, and **fully ejected** their corresponding parachute with the calculated ideal amounts of black powder. Therefore, both systems **pass** this test, and the team determined that the current system is satisfactory. There is no need to retest, and project requirements S.A.2.1 and S.A.3 have been verified.

Picture:

Figure 7.2: One Main Parachute Trial of the Black Powder Ejection Test

7.1.3 Altimeter Continuity and Battery Drain Test – VT.A.5.1, VT.A.5.2, VT.A.6.1, VT.A.6.3

Test Objective: Fulfill requirements S.A.5.1: Altimeters will continue to function across all likely flight temperatures, S.A.5.2: Both altimeters will achieve and maintain continuity consistently throughout flight, S.A.6.1: Altimeter batteries will supply usable voltage and current for 1 hour longer than the given pad time of 2 hours, and S.A.6.3: Altimeter batteries will not fail to function at any flight temperature and will function properly at a variety of temperature extremes.

Testing Variables: The testing variables are the number of continuity beeps emitted by both the TeleMetrum and StratoLoggerCF altimeters and the voltages of both the 3.7V LiPo and 9V batteries.

Success Criteria: Both altimeters must maintain continuity and receive adequate power from their respective batteries for 3 hours powered on in both temperature extremes, and the voltages of both batteries must remain the same after 18 hours powered off in warm weather.

- Warm-weather test: Must be above 75°F.
- Cold-weather test: Must be below 35°F.
- Every continuity measurement of both the StratoLoggerCF and the TeleMetrum altimeters must be 3 beeps (full dual-deployment continuity).
- In the powered-on test, the voltage of the 9V battery must not drop below 8V.
- In the powered-on test, the voltage of the 3.7V LiPo battery must not drop below 3.3V.
- In the powered-off test, the voltage of each battery must remain exactly the same after 18 hours.

Why it is Necessary: Both altimeters must maintain continuity and receive adequate power from their respective batteries for 3 hours powered on in both temperature extremes, and the voltages of both batteries must remain the same after 18 hours powered off in warm weather in order to ensure the successful recovery of the vehicle and validate the choices of all of these components.

Methodology:

Powered-On Test (Warm and Cold Weather)

1) A note was made of the current temperature.
2) One new 9V battery was connected to the StratoLoggerCF altimeter using a 9V battery connector, and a switch was also connected. A lighter was connected to each of the drogue and main outputs as well.
3) The altimeter was powered on using the switch and allowed to complete its initialization routine. Then, the system was left for 3 hours.
4) Every 0.5 hours (including at 0 hours and 3 hours), the voltage of the battery was recorded using a multimeter, and the number of continuity beeps that were being emitted was also recorded.
5) The procedure was repeated with the 3.7V LiPo battery and the TeleMetrum altimeter. However, since a multimeter cannot be used to measure the voltage of a 3.7V LiPo battery, the voltage was measured by briefly flipping the switch off and then on again, restarting the TeleMetrum. The number of initialization beeps (which represent the current voltage level detected by the TeleMetrum) was then recorded as the voltage measured for that interval of time.
6) The entire test was conducted in both the early fall and in the winter in order to verify that full continuity and adequate voltage supplied to the altimeters can consistently be achieved in both warm and cold weather.

Powered-Off Test (Warm Weather Only)

1) In warm weather only with the same setup as in the powered-on test, but with the altimeters powered off, a voltage reading of each battery was taken before and after 18 hours of everything being wired together in flight configuration.

Impact of Results: If both altimeters and batteries pass this test, no action will be required to correct the continuity and power delivery performance, and it can be expected that the altimeters will eject the parachutes with no issues during launch. If one or both altimeters or batteries fail this test, a complete retest will need to be conducted on the altimeters or batteries that failed in order to determine and correct the issue, and new altimeters or batteries may be considered.

Results, Conclusions, and Lessons Learned: This test was conducted on both November 10, 2020 and December 15, 2020 to test the components in both warm and cold weather conditions. Both altimeters consistently **demonstrated continuity over the entire 3-hour period in both temperature extremes** with no issues. Therefore, it can be said that both altimeter systems **pass** the continuity test for warm and cold weather. Both batteries also remained **well above the safety margins for voltage in both temperature extremes** when powered on. When powered off and in warm weather, neither battery voltage measured as changing in the entire 18-hour period, but when powered on, the voltage measured decreased slightly over the 3-hour period. However, since this decrease is low and the batteries were able to remain **above their respective thresholds**, it can be said that both altimeter systems **pass** the battery drain test as well. No design changes need to be made, there is no need to retest, and project requirements S.A.5.1, S.A.5.2, S.A.6.1, and S.A.6.3 have been verified.

Picture:

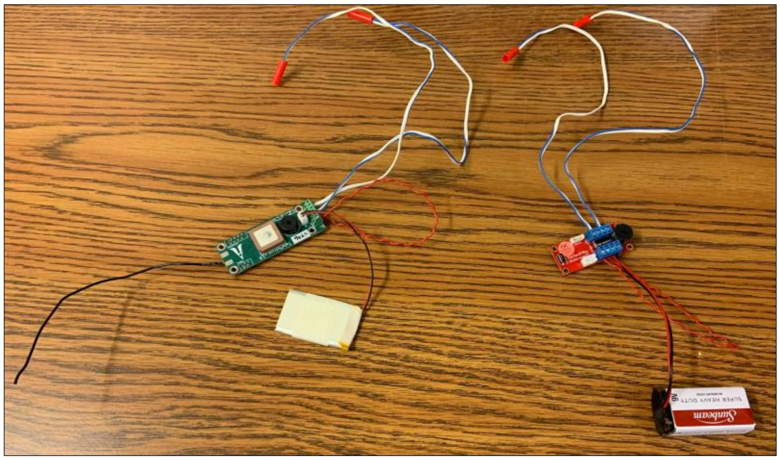

Figure 7.3: Altimeter Continuity and Battery Drain Test Setup

7.1.4 Parachute Drop Test - VT.A.2

Test Objective: Fulfill requirement S.A.2: Parachutes will open consistently within an appropriate distance range or time frame to allow for full deployment after ejection.

Testing Variables: The testing variables are the elapsed time between the weight being dropped and the drogue parachute fully opening and the final estimate for the total drop distance required for the main parachute to open fully, including shock cord extension.

Success Criteria: Both parachutes must fully deploy within their respective maximum parameter.

- The elapsed time between the weight being dropped and the drogue parachute fully opening must be below 1s for each trial.
- The final estimate for the total drop distance required for the main parachute to open fully, including shock cord extension, must be below 150'.

Why it is Necessary: Both parachutes must fully deploy within their respective maximum parameter in order to ensure the successful recovery of the vehicle and validate the choices of parachutes.

Methodology:

1) The 60' shock cord was marked with blue tape in 5' increments and draped over the top edge of the parking garage to serve as a vertical distance marker.
2) The drogue parachute was attached to the center of the 30' shock cord via a loop and quick link, and the ends of the shock cord were tied a few times around the 50lbm weight (simulating the weight of the launch vehicle) and secured with another quick link.
3) The drogue parachute was packed in the old upper airframe with the Nomex blanket wrapped around it (in flight configuration), which was then held over the top edge of the parking garage. With a running timer on one smartphone in view of another smartphone also video recording the drop, the weight was tossed over the top edge of the parking garage.
4) This procedure was repeated three times for a total of three drops of the drogue parachute.
5) This procedure was also repeated three times for a total of three drops of both the subscale and main parachutes. However, these were not timed.

6) When later analyzing the video recordings, the elapsed time between the weight being dropped and the drogue parachute fully opening was recorded for each trial. For the subscale parachute, the distance between the parachute leaving the airframe and fully opening was recorded for each trial. For the main parachute, the distance between the parachute leaving the airframe and hitting the ground was recorded for each trial, as well as the approximate percentage the parachute was open to just before hitting the ground.
7) The distance to open values (these not including the extension of the shock cord) of the drogue and subscale parachutes were plotted against parachute surface areas (hemispherical model). Linear and exponential models were then created from this data.
8) The percentage opened values of the main parachute were plotted against precise drop distance, and an exponential model was then created from this data. This model was used the estimate the total drop distance required for the main parachute to open fully (100%).
9) The surface area of the main parachute was input into both the linear and exponential distance to open models created from the drogue and subscale data to output two more estimates of the total drop distance required for the main parachute to open fully. The one that is closer to the estimate from the main parachute percentage data was then averaged with that estimate. Finally, 30' (the extension of the 60' shock cord that will be used with the main parachute in flight, when doubled up) was added to that number to produce the final estimate.

Impact of Results: If both parachutes pass this test, no action will be required to correct the deployment performance, and it can be expected that the parachutes will deploy with no issues during launch. If one or both parachutes fail this test, a complete retest will need to be conducted on the parachute(s) that failed in order to determine and correct the issue, and new parachutes or packing methods may be considered.

Results, Conclusions, and Lessons Learned: This test was conducted on November 14, 2020. After plotting the data for trials involving the full-scale main parachute, an extrapolated estimation of 82' is required for the parachute to fully open. The data from the full-scale drogue and subscale parachutes were then used to create linear and exponential models that show the relationship between distance dropped once fully open versus parachute surface area. The linear model showed a closer approximation to the extrapolated result with an estimation of 100' for the full-scale main parachute to open completely. This approximation was averaged with the extrapolated data point, and an estimation of 91' is required for the full-scale main parachute to completely open. Including the extension of the 60' shock cord that will be used with the parachute (30' when doubled-up), a final estimation of **121'** is required for the full-scale main parachute to completely open. This value is less than the **150'** maximum as per the project requirements, meaning the full-scale main parachute **passes** this test. All three trials for the full-scale drogue parachute saw it open fully **within the 1s** maximum time period set by the project requirements, including the extension of the 30' shock cord that will be used with the parachute (15' when doubled-up). The conclusion can therefore be made that the drogue parachute also **passes** this test. Seeing as both parachutes pass the testing requirements, there is no need to retest and project requirement S.A.2 has been verified. Also, no design changes need to be made.

Picture:

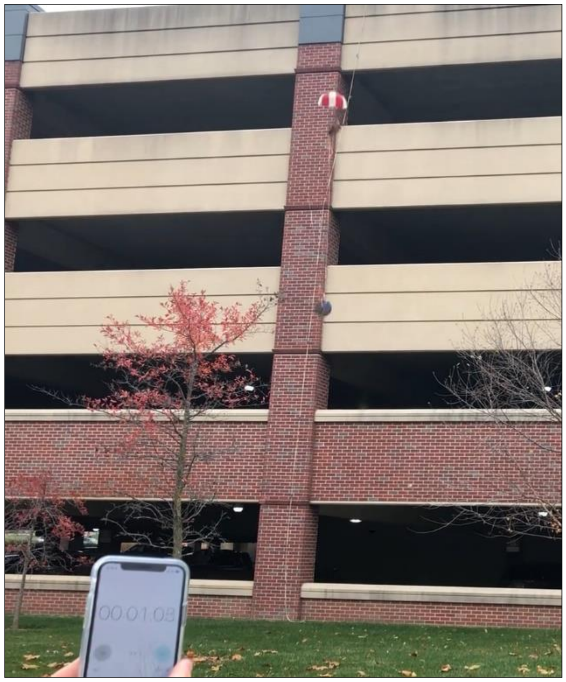

Figure 7.4: One Drogue Parachute Trial of the Parachute Drop Test

7.2 Payload Testing & Flight Reliability

The PLS has and will undergo numerous tests to ensure flight confidence. Below is a catalog of test ID's with their nominal designations:

General:

- VT.P.0.1, 2, 3, 4: Payload Weight Testing

PLS:

- VT.P.1.1: R&D Deployment Testing
- VT.P.1.2: R&D Retention Testing
- VT.P.1.3: PLS RF Transceiver Testing
- VT.P.1.4, 5, 6: PLS Battery Testing
- VT.P.1.7: PICS Image Testing
- VT.P.1.8: SOS Orientation Testing
- VT.P.1.9: D&L Wind Release Test
- VT.P.1.10: D&L Structural Testing
- VT.P.1.11: R&D Altimeter Test
- VT.P.1.12: R&D IMU Test
- VT.P.1.13: Lander Drop Test

ABCS:

- VT.P.2.1: ABCS Physical Testing
- VT.P.2.2: ABCS Battery Testing
- VT.P.2.3: ABCS IMU Testing
- VT.P.2.4: ABCS Activation Testing

7.2.1 Weight Testing – VT.P.0.1, VT.P.0.2, VT.P.0.3, VT.P.0.4

Test Objective: Fulfill requirements S.P.0: The overall mass of the payload systems shall not exceed 16lbm, S.P.0.1: The overall mass of the lander subsystem shall not exceed 3lbm, S.P.0.2: The overall mass of the retention and deployment subsystem shall not exceed 5lbm, and S.P.0.3: The overall mass of the ABCS shall not exceed 8lbm.

Testing Variables: The testing variables are the mass of each system of the Payload in pound-mass, determined through measuring pound-force.

Success Criteria: Mass of the Payload systems including Lander subsystem, Retention and Deployment subsystem, and ABCS properly fulfill set weight requirements.

Why it is Necessary: A smaller total weight is necessary to obtain the required minimum thrust-to-weight ratio of 5:1, as defined by S.V.9. Additionally, properly coordinated weight is essential to achieving the desired apogee.

Methodology:

1) Assemble individual components in flight configuration.
2) Measure the mass of each system with a scale.
    a) Measure the combined mass of the Payload.
    b) Measure the individual mass of the Lander Subsystem.
    c) Measure the individual mass of the Retention and Deployment Subsystem, subtracting the mass of the vehicle airframe.
    d) Measure the individual mass of the ABCS, its couplers, and attachment fasteners, subtracting the mass of the lower airframe (including all motor components).

Impact of Results: Should any system exceed weight requirements, further work would be required to optimize the materials used in construction of components, whether that be design changes or other relevant compromises. Should each system meet weight requirements, no further modifications would be necessary.

Results and Conclusions: This test has not been conducted and will be done before PDF.

7.2.2 PLS R&D Deployment Testing — VT.P.1.1

Test Objective: Determine whether requirements: S.P.1.4, S.P.1.18, S.P.1.19, and S.P.1.21 will be fulfilled or not.

Success criteria: The Lander analogue stays nearly immobile in the payload bay while it is suspended and while it is suspended and shaking/swaying. The team can switch the R&D electronics from pre-flight to flight ready without disassembling the payload bay during the test. Finally, the Lander Analogue deploys under 5 seconds during both the static test and the swaying test.

Why it is necessary: The test ensures the payload bay and R&D system protect and deploy the Lander as designed.

Methodology:

1) Fully assemble the payload bay and insert Lander Analogue into the bay. Visually inspect fit of Lander Analogue.
2) Close payload bay and attempt to switch R&D electronics from pre-flight status to flight ready status.
3) Suspend the payload bay from the test stand.
4) Induce both vibration and swaying of the payload bay to simulate flight conditions and inspect Lander Analogue for movement or damage.
5) Signal the R&D electronics to deploy the Lander Analogue and time the process from signal sent to full deployment.
6) Perform the previous step under various swaying condition, both different intensities and different direction of sway.

Impact of Results: If the payload bay assembly perform as expected no action is necessary. If significant movement or any damage of the Lander Analogue is observed during the test modification of the payload bay will be necessary to better secure the Lander. If the deployment time is observed to be over 5 seconds during any of the tests the team will determine whether it is feasible to start the deployment process earlier in the flight so that Lander ejection occur in the correct altitude range. Additionally, the times recorded will be used to determine how much earlier to begin the deployment. If the Lander Analogue fails to deploy in any of the test's significant modifications to the ejection method might be necessary. This is also true for if the R&D electronics prove impossible to switch from pre-flight to flight ready during the test.

Results and Conclusions: This test has not yet been conducted but will be done before PDF.

7.2.3 PLS R&D Altimeter Test – VT.P.1.11

Test Objective: Verify S.P.1.6: The Lander will detect ascent at 50’ AGL. The Lander will search for apogee after 2000’ AGL. The Lander must deploy under main parachute descent between an altitude of 700’ and 500’ AGL.

Success Criteria: The R&D light activation points must remain within ±50’ of the designated values for all three tests to pass the test. This is based off expected altimeter performance, altimeter refresh rate, and team Avionics standards. If the altimeter does not activate within the required bounds, it must be adjusted and calibrated.

Why it is necessary: This test is necessary to ensure the R&D altimeter is accurate enough to properly measure the altitude of the launch vehicle. These measurements are used to identify the current flight stage that the launch vehicle is in (launch, apogee, and payload release).

Methodology:

1) One large hole was drilled into the sheet of plexiglass. The wine stopper was placed into this hole and a small ring of plumber's putty was placed around it in order to prevent air from escaping.
2) A smaller hole was drilled to the side of the larger one (this acted as a pressure release hole to simulate descent).
3) To test the altimeter, the system will be turned on, allowed to zero and will be placed in the glass bowl; it will be accompanied by the reference AltimeterOne altimeter, turned on and set to Real Time mode.
4) A large ring of plumbers' putty is placed around the rim of the bowl, over the system. The prepared sheet of plexiglass was then placed over the bowl and pressed down until there was a uniform seal around the entire perimeter.
5) The wine bottle air remover pump is then used to remove air through the stopper. Once the first R&D indicator light alights, the process halts.
6) The R&D believes that it has achieved the first expected takeoff altitude of 50' AGL. Record the altitude displayed on the reference AltimeterOne altimeter.
7) The wine bottle air remover pump is once again used to remove air through the stopper. Once the second R&D indicator light alights, the process halts again.
8) The R&D believes that it has achieved the second expected apogee-seeking altitude of 2000' AGL. Record the altitude displayed on the reference AltimeterOne altimeter.
9) Finally, the small piece of plumbers' putty was very slightly lifted away from the plexiglass to slowly allow air back inside it, causing the altitude to decrease according to the AltimeterOne.
10) Record the altitude at which both of the R&D indicator lights turn on. The R&D believes that it has achieved the final deployment altitude of 700' AGL.
11) The procedure was repeated two more times for a total of three trials.

Impact of Results: This test will see how closely the R&D altimeter performs relative to the team's reference altimeter. The reference altimeter, the AltimeterOne, is assumed to be accurate. If the results are close to what is expected, then the altimeter is well adjusted.

Results and Conclusions: The altimeter performed relatively as expected. Throughout all tests, the takeoff altitude was less than the actual altitude. Due to this, the team will adjust the takeoff altitude to 100 ft so that the observed margin of error will not have as much of an effect while still performing the necessary task of detecting takeoff. The altimeter was fairly consistent at approximating the altitude at 2000 ft, but in one test was over 60 ft off the measured altitude of 2000 ft. Although this is outside the team's ±50 ft goal, being this measurement only serves to detect when the launch vehicle's flight is somewhere above 2000 ft, this is an acceptable error. The release altitude was decently inconsistent. Accounting for this may be the testing apparatus. The vacuum chamber would increase pressure very quickly after the team stopped pumping air out of it. That in combination with the low refresh rate of the AltimeterOne makes the results hard to verify. The team has also deemed that it may be necessary to start deploying the lander above the initial 700 ft mark, in order to fully deploy the Lander in time. With these considerations and changes, the team has decided to consider the requirement met.

7.2.4 PLS R&D IMU Test – VT.P.1.12

Test Objective: Verify R&D properties necessary to satisfy S.P.1.6 and S.P.1.18: The accelerometer of the R&D system will have accurate readings to ensure proper identification of important stages in the vehicle's trajectory.

Success Criteria: The IMU should read around 0 ft/s^2 for all axis, ensuring that the sensor is calibrated.

Why it is necessary: The accelerometer of the R&D system needs to be calibrated in order to properly measure the acceleration of the vehicle, allowing the acceleration of the vehicle to be used in flight stage identification.

Methodology:

1) Orient the board so that it is lying flat (+Z direction)
2) Read the acceleration in ft/s^2 using the Arduino Serial Plotter
3) Repeat steps 1-2 but with the board oriented first in the +X direction, then the +Y direction.

Impact of Results: The results of this test will verify that the accelerometer is calibrated and will be able to detect changes in acceleration during the flight. This allows the team to use it to identify the different stages of flight.

Results and Conclusions: The requirements were met, as the IMU measured approximately 1 ft/s^2 acceleration with an acceptable amount of noise in each direction.

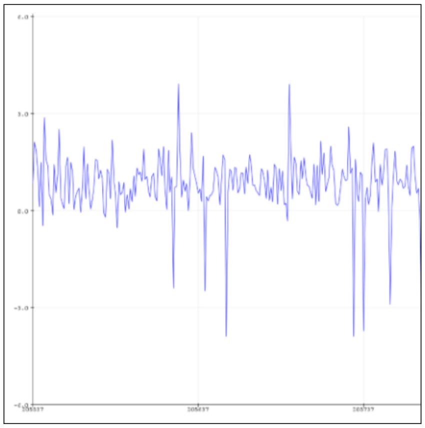

Figure 7.5 IMU z-direction (ft/s^2)

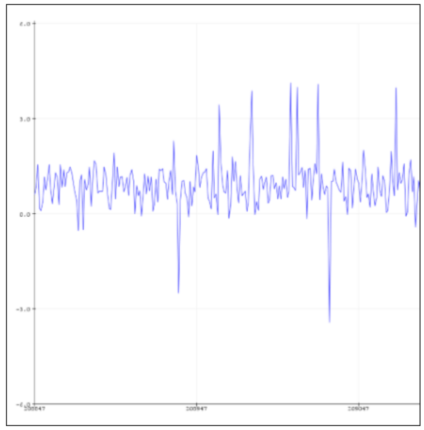

Figure 7.6: IMU x-direction (ft/s^2)

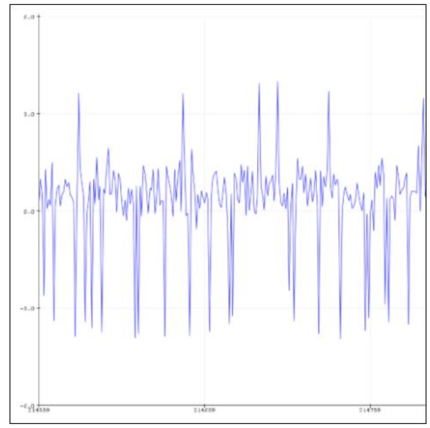

Figure 7.7 IMU y-direction (ft/s^2)

7.2.5 PLS R&D Retention Testing – VT.P.1.2

Test Objective: Ensure that the R&D complies with Subteam Requirement S.P.1.18 and Project Requirement G.2.4.1TD. These requirements demand that the Lander remains protected within the R&D under flight loads until the point of deployment with at least a 1.5 failure point factor of safety.

Success Criteria: The R&D is able to retain the Lander under a Payload Section deceleration force equivalent of at least 2g.

Why it is necessary: While the software design of R&D must activate within the required altitude bounds, there remains the possibility of the failure of R&D to retain the Lander before the desired time and location. Therefore, the R&D must be tested to ensure that it will operate correctly under worst-case flight loads. As discussed in the CDR mechanical testing theory section, while the deployment of the main parachute generates the most deceleration of about 2g, the team would be satisfied by the forced back-drive of the R&D system under such conditions, seeing as the R&D will be designed to release when this point of flight is detected. Meanwhile, the team is concerned about the deceleration caused during drogue descent; this quantity is much less—marginally greater than 1g. Therefore, to ensure a middle ground for safety design, the team has decided to implement a test plan to exceed the 1.5 FoS requirement with respect to the drogue descent stage. Ultimately, the team decided on elevating this virtual FoS to 2, planning to expose the R&D to typical deceleration experienced during main parachute deployment.

Methodology:

1) The execution of this test will be in the same style as a typical tensile test. However, for sake of testing, a particular testing rig must be produced.
2) The Lander, R&D Pizza Table, nosecone, and nosecone attachment plate should be weighed together.
3) The Payload Bay must be assembled to its completed state. For the purposes of this testing rig, the vehicle's nosecone will be removed.
4) The Lander should be loaded into the R&D and secured.
5) The R&D electronics' stepper should remain online and its motor driver activated to produce a holding torque.
6) The Payload Bay will be suspended by its eyebolt.
7) A weight equal to the Lander, R&D Pizza Table, and nosecone attachment plate PLUS twice the nosecone should be secured to the nosecone attachment plate. This will statically simulate 2g of deceleration.
8) The team should wait until oscillation of the Payload Bay has ceased or until the Pizza Table is back-driven out from the R&D. If the latter occurs, the R&D has failed the test.
9) Record the displacement distance of the nosecone attachment plate—if any—for future reference.
10) Remove the applied load.
11) Repeat steps 3 through 8 two more times to ensure short-term cyclic loading integrity.
12) The team should inspect the R&D for internal damage. If the R&D visibly back-drives at all during this test, the team should reconsider the safety of the design.

Impact of Results: The results of this test will inform whether the R&D retention design has enough strength and resistance to complete its descent task under the worst possible situations. If the design is shown to fail under these loading conditions, then the R&D must be redesigned to handle more load. If the R&D is shown to handle this level of loading without detectable damage, then the R&D will be ready for flight.

Results and Conclusions: The test was successful. The R&D system retained the Lander under the required deceleration of 2g. The team shook and jostled the R&D system under this load and decided to test under 3g, an effective FoS of 3. The system passed this test as well, further ensuring the systems compliance with the requirement.

7.2.6 PLS RF Transceiver Testing — VT.P.1.3

Test Objective: To verify the RF design can fulfill requirement S.P.1.15 which states that the Lander must be able to transfer image data to the ground control station within 1 mile.

Success Criteria: The Lander will be able to transfer image date to the GCS at a range of one mile.

Why is it necessary: The primary purpose of the Planetary Lander System is to capture a panoramic image and transmit the image back the team. Failure to transmit the image from the Lander to the GCS would result in an overall mission failure for the PLS. This test will ensure that the selected RF solution is capable transmitting image data from any location within the landing zone.

Methodology:

To fully verify the functionality of the RF solution would require the Lander to be completely assembled to ensure no other components are causing interference. To ensure that problems are identified as soon as possible the team will conduct a preliminary test and a final test. The preliminary test will not require the Lander to be fully assembled and can be conducted much earlier.

The preliminary test will take place in more ideal conditions and will not require the full Lander assembly. This test will identify any issues with the transceiver at the component level and verify the transceiver can transmit at the desired range in ideal conditions. The final test will be to test the integration of the transceiver with the entire Lander assembly and verify that the transceiver will function at a system level. Since this test includes the entire Lander assembly, it will verify that the Lander electronics and outer materials are interfering with the transceiver operation.

The preliminary test procedures are as follows:

1) The RF transceiver will be connected to a remote system that is cable of storing and transmitting an image. This system will simulate the Lander and can be a test assembly of the Lander Control System or another system capable of completing the test.
2) The “local” RF transceiver will be connected to a device capable of recording the RSSI and packet loss from the transceiver. This device will simulate the GCS and will remain stationary during the duration of the test. This device can be the GCS, but it is not required for this test.
3) The simulated GCS and Lander devices will be powered on and a connection will be established. The Lander device will transmit an image that will be displayed on the GCS. Once this initial check has been completed the Lander device will be powered down. The GCS device will remain powered on.
4) Utilizing a GPS enabled phone, or similar device, the Lander device will be walked .25 miles away from the GCS device.
5) The Lander device will be powered on and the time it takes to establish a connection will be measured.
6) Once a connection is established, the Lander device will transmit a sample image to the GCS device. At the GSC device, team members will verify the integrity of the image and record the RSSI and packet loss reported by the transceiver.
7) The Lander device will be powered down.
8) Steps 4-7 will be repeated at increments of .25 mile until the Lander device has been tested at 1 mile away from the GCS device

The final test procedures are as follows:

1) The RF transceiver will be installed on the fully assembled Lander. The Lander will have modified code specifically created for this test, as well as a preloaded sample image on the SD card. The lander must be in its final state for this test.
2) The other RF transceiver will be installed on the GCS. The GCS will not need to be in its final state for this test, however, it must have software capable of receiving and displaying an image. The GCS must also be capable of displaying the RSSI and

packet loss data from the transceiver. The GCS will also be placed on the table or stand so that it is in the same or a similar configuration to the on it will be in on launch day.

3) The GCS and Lander will be powered on. The Lander will transmit an image to the GCS. Once the team verifies that the Lander and GCS software are functioning as expected, the Lander will be powered off. The GCS will remain on.
4) Utilizing a GPS enabled phone, or similar device, the Lander will be walked .25 miles away from the GCS. Once there, the Lander will be placed on its side as if it had just landed.
5) The Lander will be powered on and the time it takes to establish a connection will be measured.
6) Once a connection is established, the Lander will transmit the sample image to the GCS. At the GCS device, team members will verify the integrity of the image and record the RSSI and packet loss reported by the transceiver.
7) The Lander will be powered down.
8) Steps 4-7 will be repeated at increments of .25 mile until the Lander has been tested at 1 mile from the GCS.

Impact of results: Successful completion of this test verifies that the selected transceiver can carry out the required image transfer at the maximum range it may be required too. If the selected Transceiver fails the preliminary test, then the team will need to search for a component level replacement. This means that the team will seek to replace the transceiver, antenna, or both. If the transceiver passes the preliminary test but fails the final test then the transceiver is not functioning at the system level. This most likely means that interference from other systems on the Lander is causing a failure. In this situation the team will need to take steps to mitigate interference by making design modification on other systems on the Lander. If it is not practical to make these modifications, then the team will have to replace will need to upgrade the transceiver or antenna.

Results and conclusions: Neither the preliminary nor the final test have been conducted. The final test will be completed as soon as the electronics for the Lander get completed. The preliminary test will occur in early March 2021.

7.2.7 PLS Battery Drain Testing — VT.P.1.4, VT.P.1.5, VT.P.1.6

Test Objective: To verify that the Planetary Lander System is compliant with S.P.1.11 and S.P.1.12. These requirements dictate that all PLS subsystems must have sufficient battery life to sustain their pre-flight state for 18 hours, and their launch-ready state for an additional 2 hours.

Success Criteria: The Planetary Lander System will contain enough battery to successfully perform it mission after staying in a pre-flight state.

Why it is necessary: If the battery were to drain too much during the pre-flight and launch-ready phases, then the battery may not contain enough charge for the system to carry out its tasks, resulting in a failed mission. To avoid this, the team will test the batteries to identify any faults before the design is finalized.

Methodology:

The Lander, R&D, and GCS can be tested separately or together using the following methodology.

Pre-flight drain test:

1) The battery is connected to its charger until it is fully charged.
2) The battery is disconnected from its charger and the starting voltage is measured using a multimeter.
3) The battery is then connected to the electronics it will be connected to on launch day. The electronics will remain off.
4) After 18 hours the battery will be disconnected from the electronics and the voltage will be measured again.

Launch-Ready test:

1) The battery is connected to its charger until it is fully charged.
2) The battery will be disconnected from the charger and connected to its respective control system.
3) The control system will be turned on and put into its launch-ready configuration.
4) The system will be left on for at 2 hours for R&D and 3 hours for the GCS and Lander.
5) The voltage of the battery will be measured every 0.5 hours (including 0 hours and 3 hours)

After the tests have been completed the test data will be analyzed to determine if the battery still contains sufficient charge and voltage to complete the mission.

Impact of Results: If the selected batteries cannot sustain the PLS subsystems for the required time then the team will need to make modifications and conduct more tests. These modifications could include changes to the electronics or software to reduce power consumption or changing to a bigger battery.

Results and Conclusions: Only the R&D battery drain test has currently been conducted. Due to the R&D battery losing only 10 mV of its voltage during the pre-flight test and 20 mV during the launch-ready test, the team has affirmed the R&D battery will have enough charge in order to satisfy the pre-flight and launch-ready state battery requirements.

Test	Time	R&D	Lander	GCS
Launch-Ready	0	8.39 V	-	-
	0:30	8.39 V	-	-
	1:00	8.38 V	-	-
	1:30	8.38 V	-	-
	2:00	8.37 V	-	-
Pre-Flight	0	8.39 V	-	-
	18:00	8.38 V	-	-

Table 7.1: Results and conclusions

7.2.8 PLS Panoramic Image Capture Test — VT.P.1.7

Test Objective: To verify that the Planetary Lander System, and more specifically the Panoramic Image Capture Subsystem (PICS), is compliant with requirements S.P.1.10, S.P.1.13, and S.P.1.14. These requirements ensure that the Lander can both capture and send the images necessary to create a panoramic photo in expected terrain conditions.

Success Criteria: The Planetary Lander System will successfully capture and transfer image data to the Ground Control Station (GCS) while also storing a local version of the image data on the LCS's SD card. The GCS will receive and process the image data into a panoramic image which will display on its monitor.

Why it is necessary: The capture and generation of a panoramic photo that displays the surroundings of the Lander is an essential part of its mission. If the team does not ensure that all systems involved with the photo's successful display on the GCS are fully functional then it is almost ensured that the systems will not work when they are expected to. This test will reveal any bugs or errors in the systems and narrow down the causes which will speed up the development process.

Methodology:

Test software will be loaded onto the LCS prior to testing to allow for manual control of the Lander's subsystems through a connection from the Lander's radio and the GCS. The GCS will also have an application created specifically for manual control of the Lander for testing purposes.

1) The Lander, completely assembled and powered on, will have all its legs in a standing position and placed upright in terrain simulating the expected conditions of the launch field.
2) The GCS will be in proximity of the Lander and turned on. The Lander will begin initialization and attempt to establish a connection with the GCS. Once connection has been established, the Lander will communicate if initialization of all system was successful.
3) If initialization is successful, the GCS be powered off and moved at least a quarter mile away from the Lander. The Lander will continue to try to establish a connection of the GCS.
4) The GCS will then be powered on and wait to connect to the Lander.
5) Once connection with the GCS has been established, a command will be sent to the Lander from the GCS to start its image capture protocol.
6) The Lander will send a notification to the GCS that all images have been captured and stored on the SD card. If the Lander is not able to capture and store the photos, an error message will be sent to the GCS.
7) If the image capture was successful, the GCS will send a command to the Lander to start the image transfer process.

8) Once the images are transferred, each photo will be inspected prior to image processing to confirm that the images were captured successfully and unobstructed by the terrain.
9) The GCS will then process the images into one panoramic photo. After processing is complete, the panoramic photo should automatically be shown on the GCS's display.
10) The panoramic photo is inspected to conclude if the image processing was successful.
11) The Lander is turned off and disassembled to allow access to the SD card.
12) The SD card is read to confirm that the images were saved successfully.

Impact of Results: The test is constructed in such a way that allows any failures that occur to be associated with a specific system within the Lander or GCS. If the entire test is successfully conducted, then the team can be sure that all systems and software for the Lander and GCS are functional and integrated correctly.

Results and Conclusions: This test is incomplete.

7.2.9 PLS SOS Orientation Testing — VT.P.1.8

Test Objective: To verify that the Planetary Lander System is compliant with P.4.3.3 which states that the Lander will self-level within 5 degrees of vertical.

Success Criteria: The Lander can self-level within 5 degrees of vertical.

Why it is necessary: The ability to self-level is critical to the Lander's mission. If the Lander is not able to self-level, the Lander's mission will be considered a failure. Conducting this test will allow the team to determine if changes must be made to the Self Orientation Subsystem, whether they be mechanical or software.

Methodology:

Test code will be uploaded to the Lander for this test. The GCS or another RF capable device will send commands to the Lander to control it remotely. The Lander will have to be in its final state and fully assembled for this test.

1) Place the Lander on its side in terrain simulating the area of the launch field. The GCS or RF capable device should be on and ready to connect to the Lander.
2) Turn on the Lander through its key switch and wait for it to connect to the GCS.
3) Measure the starting orientation of the Lander using a measuring tool.
4) Once connected, a command will be sent to the Lander to begin self-leveling.
5) The Lander will run through the stages of self-leveling and will send progress notifications to the GCS.
6) Once the Lander has completed self-orientation, measure the orientation of the Lander using a levelling device.
7) Verify that the external measurement and the orientation measurement sent by the Lander are within a reasonable margin of measure.

Impact of Results: This test will ensure total functionality of the Self Orientation System before any demonstration flights. Successful completion of this test will verify that the SOS system is capable of self-leveling. If the Lander fails the test, the team will need to modify software and/or the mechanical systems until the Lander meets the requirement. If successful, P.4.3.3 will still not be completely verified until a separate wind-release test—discussed below in the wind-release test procedure—has been completed. If this test has been completed but a failure to complete the wind-release test results in design changes, then this test will need to be completed again with the new changes.

Results and Conclusions: This test is incomplete.

7.2.10 PLS D&L Wind-Release Testing — VT.P.1.9

Test Objective: Ensure that the Lander can satisfy Subteam Requirement S.P.1.9, stating that the Lander is able to withstand 10 mph wind while grounded.

Success Criteria: The Lander is able to remove its connection with its parachute in order to sustain 10 mph winds. This must be assured to occur despite orientation.

Why it is necessary: In order to orient properly, the Lander must not be affected by any external loads, whether that be by the parachute or by ambient winds. The purpose of this test is to verify the efficacy of the D&L detachment mechanism in separating from the parachute. Without its parachute, the Lander should be able to sustain such winds while grounded without falling over.

Methodology:

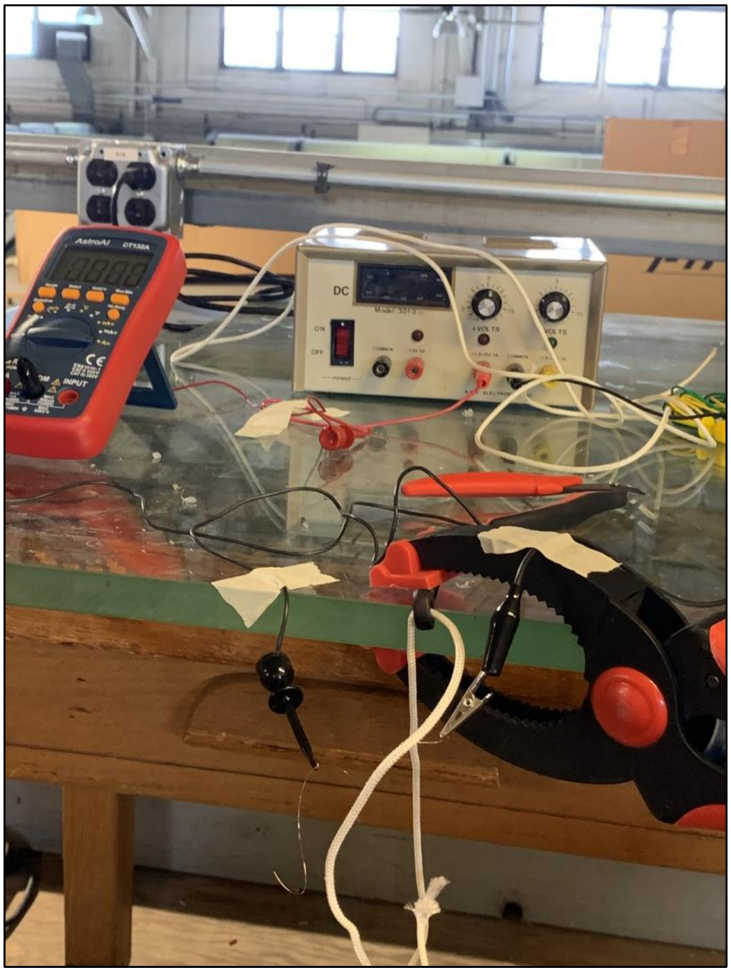

Figure 7.8 Preliminary Test Setup

1) This test involves the operation of the D&L under various conditions, proving that the D&L will be able to ensure the stability of the Lander in its upcoming orientation phase. This test is multi-part but should cover every foreseeable D&L worst-case scenario.
2) Assemble the Lander with its parachute attached.
3) Enable the D&L system remotely to avoid any heat hazard caused by the descent solution.
4) Bring the Lander outside, clear of personnel or buildings. For D&L mechanisms utilizing nichrome, seek a suitable non-flammable ground surface such as gravel.
5) Orient the Lander in one of these possible configurations:
6) Lander on its side, attachment cable sticking up.
7) Lander on its side, attachment cable sticking to the Lander's side.
8) Lander on its side, attachment cable pressed into the ground, but led to the side of the Lander. This is to ensure operation while crushed.
9) Enable the D&L release mechanism while clear of the Lander.
10) Wait for 5 minutes or until the D&L has visibly operated correctly. If the D&L does not operate or the Lander catches fire, disable the D&L immediately and utilize a fire extinguisher.
11) Observe whether the D&L has successfully disconnected the parachute attachment cable. Retrieve parachute if necessary.
12) Repeat testing process for all three main orientations.

Impact of Results: The successful operation of the D&L will determine its ability to be used during the vehicle flight. If the D&L is unable to operate reasonably well within 5 minutes, then the D&L design must be modified to work correctly. Additionally, if the design is deemed too dangerous for operation, consideration of other designs must be made.

Results and Conclusions: This test has not yet been conducted but will be done before PDF.

7.2.11 PLS D&L Structural Testing — VT.P.1.10

Test Objective: Verify the D&L's compliance with Project Requirement G.2.4.1TD, requiring that the PLS withstand all expected flight loads with a 1.5 failure point factor of safety. This test is mission critical for flight and operation of the PLS.

Success Criteria: All elements of the D&L will be able to withstand loading of at least 19lbf without discernable damage for at least 3 cycles.

Why it is necessary: In order to ensure that the Lander may safely descend under its parachute, all points of connection with the parachute to the Lander must be capable of sustaining worst-case descent loads. Considering that the D&L will attempt to sever the point of attachment with the parachute once grounded, it must be proven that this will not occur before the D&L/LCS system decides. Through static analysis, the drag experienced by the parachute is assumed to be equal to the tension in the attachment cord; calculation available in this report puts this load at 12.425 lbf. With a FoS of 1.5, this results in the success value of 19 lbf.

Methodology:

1) Testing the structural integrity of the D&L requires that the entire Lander assembly be physically present, ensuring that both the D&L itself and Lander body is cable of withstanding such loads. Therefore, this test will involve the static loading test of the entire Lander and D&L.
2) The Lander must be assembled to its full physical state, including its parachute but without the R&D deployment bag.
3) The Lander will be suspended by the parachute's metal attachment ring. All drag loads will be assumed to have been transferred to this ring during descent.
4) Beneath the Lander will be suspended an at least 19 lbf weight, producing an attachment cord tension of at least 19 lbf. This test will most likely round to 20 lbf to account for available weights. The weight should be wrapped around the Lander's central body to distribute the load internally.
5) The team will wait until suspension oscillation has ceased before removing the applied weight. If the Lander shows any visible or audible sign of yielding, the test has been failed.
6) The team will repeat steps 3 and 4 two more times to ensure short-term cyclic loading integrity.
7) The team should disassemble the Lander to inspect for internal damage. By the discretion of the testers, the team will report whether the D&L is ready for flight.

Impact of Results: The results of this test will inform whether the D&L structural design has enough strength and resilience to complete its descent task under the worst possible situations. If the design is shown to fail under these loading conditions, then the D&L must be redesigned to handle more load. If the Lander is shown to handle this level of loading without detectable damage, then the D&L will be ready for flight, whether or not the disconnection mechanism is utilized.

Results and Conclusions: This test has been partially completed for the purposes of VDF. Initial testing has been done to verify the strength of the D&L body plate, eyebolt, and the bowline knots used to affix the Lander to its parachute. Since the rest of the Lander will hang beneath these components, and since the D&L plate is manufactured from nylon rather than metal, these components were at most risk of failure. The nylon cord was tied via two bowline knots to a 20lbf weight and released such that the weight provided its full force on the knots. While in static equilibrium, members inspected the D&L body plate for yielding. The loading was repeated multiple times. Since the knots held and the structural components showed no sign of fatigue, the team concluded that these components could be used for launch.

Initial VDF Testing Results:

Trial	Applied Weight	Observed Damage	Test Status
1	18.5lbf	Only bending.	PASS
2	19.0lbf	Only bending. Required load achieved.	PASS
3	20lbf	Only bending. Required load succeeded.	PASS

Table 7.3: Initial VDF Testing

Figure 7.9: VDF D&L Structural Test

7.2.12 PLS Lander Drop Testing — VT.P.1.13

Test Objective: Fulfill requirement S.P.1.1: The Lander remains structurally in-tact for operation after descent.

Success Criteria: No elements of the Lander become separated during descent at about terminal velocity.

Why it is necessary: If the structural shell of the Lander retains its structural integrity after descent, then the remaining Lander systems will be able to operate properly.

Methodology:

1. The Lander will need to be built to its full structural state, excepting expensive internal electronics. The Lander should weigh within 0.25lbf of its design weight, using ballast. The D&L system is properly adhered to the Lander. For this test, only the Parachute and its associated nylon cord is required. The nylon nichrome release mechanism is not required to be present.
2. The Lander will be brought to a high gravitational potential location of at least 50’ AGL, such as a parking garage. At 32.2ft/s^2 local acceleration, the Lander should reach terminal velocity under parachute at this height.
3. Team members and bystanders will be told to clear the landing site.
4. The Lander will be held by a member in one hand, with its associated parachute lightly bundled in their other hand.
5. The Lander will be thrown outwards and allowed to fall to the ground.
6. The impact site will be inspected, and damage to the Lander will be assessed.

Impact of Results: The team will make modifications to the descent system based on its descent performance. If damage comes to the D&L itself, then the weight and adhesion methods of the Lander will need to be reworked. If the Lander reaches the ground with significant damage, then the descent velocity is too high, despite the Lander itself adhering to energy requirements.

Results and Conclusions: As a twist of fate, this test—which was performed with a layer of snow on the ground—actually ended in the worst possible way, but was still considered a success by the team. After releasing the Lander, the parachute properly opened up and began to slow the Lander. However, due to crosswind, the Lander ended up hitting the side of the test building before reaching the ground. While this impact absorbed horizontal velocity, the decrease in coefficient of restitution which results from striking brick instead of snow meant that the most amount of force possible was applied to the Lander body. The Lander ultimately landed on the ground next to the test building.

Observing the Lander after landing, the Lander landed on its side as anticipated. While the backwards drift experienced speaks to the increase in horizontal drag coefficient introduced by the parachute, the parachute itself performed exactly as designed. Inspecting the Lander, there were minimal signs of damage. It was clear that the Lander had impacted the building on its top Cupola plate; despite this, there was minimal chip damage to one of its protrusions. Meanwhile, there was a small fracture to one of the temporary 3D printed body plates. This fracture was small and appears to have been a further fatigue of a previous crack accidentally made during assembly.

While the Lander did gain visible marks and small damage, the rest of the Lander appeared completely functional. Given that the two temporary body plates will be replaced after VDF with Onyx nylon, the team feels assured that the Lander can descend safely without breaking itself apart.

Figure 7.10: Lander Drop Test Setup

Figure 7.11: Lander Drop Test Result

145

7.2.13 ABCS Physical Testing — VT.P.2.1

Test Objective: Fulfill requirement: G.2.4.1 TD: Verify that the ABCS can function correctly through physical testing at a factor of safety of at least 1.5. This test is mission critical for flight and operation of the ABCS.

Success Criteria: The ABCS can withstand the maximum simulated drag load of 120N applied on each Aeroplate with a factor of safety at or above 1.5, meaning 180N each.

Why it is Necessary: The test ensures that the ABCS will be operational for the flight of the vehicle.

Methodology:

1. The system will be anchored vertically to a beam.
2. Attach cables to each of the paddle struts and then apply 55 kg of tension in order to simulate the downwards force on the entire system simultaneously. This will simulate the flight load with a safety factor of 1.5. If the ABCS performs under this load without breakage, then the ABCS has passed the test.

Impact of Results: If the system performs as expected when the maximum anticipated force is applied, then no further action needs to be taken and the ABCS can be fully integrated into the launch vehicle. If there is a problem encountered during testing, modifications will be made to the system and retested until the desired outcome is achieved. This test has the added benefit of showing how well the motor can handle applied torque from the system while encountering a force.

Test Data:

Subsystem	Results from Pull 1	Results from Pull 2	Final Status
ABCS	No damage	No damage	PASS

Table 7.4 Test Data

Results and Conclusions: It was concluded that the ABCS structure and apparatus could withstand the forces exerted by drag during ascent. This means that the ABCS can reliably perform its operations without the structure losing its integrity during flight.

7.2.14 ABCS Battery Testing — VT.P.2.2

Test Objective: Fulfill requirement S.P.2.7: The battery powering the ABCS must be able to withstand idle operation for a minimum of 2 hours.

Success criteria: The ABCS would be able to receive adequate power from the battery for 2 hours powered on.

Why it is necessary: This test will ensure that the ABCS will be able to function when necessary during the flight of the vehicle.

Methodology:

1. The motor assembly system will be connected to a multimeter and the battery. As the motor is deployed, the current will be measured which will then be used to calculate how long the battery can support active motor usage.
2. To test the idle operation of the motor assembly it will be connected to the battery and multimeter and left turned on in the idle position. The voltage will be recorded every 0.25 hours until at least the 2 hour mark is reached. The voltage drop will then be analyzed in order to determine if it adequately meets the voltage needs of the system.

Impact of Results: If the test goes as expected, the battery and motor combination is adequate and is ready to be fully integrated into the launch vehicle. If the battery will not be able to withstand the idle operation for the full 2 hours, then modifications will be made and further tests will be made until this is able to be accomplished.

Calculations:
Battery voltage and capacity: 3300mAh at 11.1V
System current draw (at 5V):

Component	Teensy 4.0	BMP280	BNO085	Motor Driver (Idle)	Total
Max Current Draw	120mA	5mA	10mA	50mA	185mA

Table 7.5: ABCS Component Current Draw

Hours of idle operation: 3300mAh / 185mA = ~17 hours

These calculations suggest that the system, when in idle state, could last for up to and possibly longer than 17 hours of operation. The motor driver is put into idle mode while the launch vehicle is on the pad to conserve power. Once the IMU detects the upward force from the motor being fired, it switches the motor driver into an active state where more power is drawn but the motor has holding torque.

Results and Conclusions:
Theoretical Calculations: Based off the theoretical calculations, the ABCS system should be able to stay in a powered-on state for well over the 2-hour requirement on the pad. This is mainly because the motor can be enabled or disabled to allow the use of holding torque at the cost of higher power consumption.

7.2.15 **ABCS IMU Testing — VT.P.2.3**

Test Objective: Fulfill requirement S.P.2.8: The data output from the inertial sensor must be useful for the MCU. If the output from the MCU is raw data, additional electronics must be designed to convert raw data into a usable format for the MCU.

Success criteria: The data outputted from the inertial sensor is accurate.

Why it is necessary: This data would be used in order to monitor the behavior of the launch vehicle during flight so that any necessary adjustments to the ABCS can be made.

Methodology:
1. To test the IMU the sensor will first be turned to 45, 90, and 180 degrees in order to compare the output data to reality.
2. A second test will verify the IMU's acceleration accuracy by tilting the sensor which should have an outputted acceleration equal to gravity.

Impact of Results: If the test goes as expected, the IMU will be fully integrated into the system's software. If the test does not perform as expected, troubleshooting will be done to determine the source of the issue whether it is hardware or software based and testing will continue until the IMU is accurate.

Test Data:

Subsystem	Actual Rotation (degrees)	Measured Rotation (degrees)	Final Status
ABCS IMU Rotation Sensor	0	0.05	PASS
	45	44.97	
	90	90.32	
	180	181.10	

Table 7.6: Test Data

ABCS IMU Accelerometer Measurement of Gravity: The IMU data was tested as the lower airframe containing the ABCS electronics was rotated at varying speeds and acceleration. The IMU gravity reading was consistent while the angular acceleration reading was also constant. This is extremely important in determining if something has gone wrong during launch and to prevent the airbrakes from causing any extra damage or issues.

Results and Conclusions: The conclusion of this test was that the IMU is a reliable and accurate way to measure angle and angular velocity. This means that the IMU can be depended on for identifying dangerous situations, allowing the ABCS to successfully close and stay closed during any malfunction.

7.2.16 **ABCS Activation Testing** — VT.P.2.4

Test Objective: Fulfill requirement S.P.2.6: The ABCS must be able to fully activate and deactivate control surfaces in under 5 seconds.

Success Criteria: The ABCS can operate within the allotted time of 5 seconds.

Why it is necessary: This will ensure that the system is able to operate as quickly as necessary during flight.

Methodology:

7. An analysis will be done in order to determine how long it should take for the aeroplates to be fully deployed.
2. In order to fully test the activation/deactivation time, the plates will be loaded with 45 kg of tension evenly split between the three plates. The system will then be timed as it activates and deactivates in order to verify that it is within the allotted time of 5 seconds.

Impact of Results: If the test goes as expected no changes to the ABCS are necessary. If the activation and deactivation are not each able to be completed in the allotted time, modifications to the software and/or hardware will be made, and testing will continue until the requirement is met.

Results and Conclusions: The ABCS system was actuated successfully within 5 seconds under load. This means that the ABCS will be able to perform its function within reasonable to help with hitting the target apogee.

7.3 Derived Requirements and Verification Plans

Requirement ID	Requirement Summary	Verification Type(s)	Verification Plan ID(s)	Verification Plan / Prerequisite Requirement Summary	Status
N.1.1	All work will be completed by the team specifically for this year's competition. A mentor will assist with handling of potentially explosive or flammable devices.	D	N/A	PSP-SL members shall demonstrate the new work they have completed through milestone documentation and presentations.	In Progress
N.1.2	The team will provide and maintain a project plan describing all aspects of the project.	D	N/A	The team will submit an up-to-date project plan with all milestones.	In Progress
N.1.3	For security reasons Foreign National team members will be identified by PDR.	D	N/A	The team will submit a list of FN team members with PDR.	Complete
N.1.4.1-3	The team will create launch week team member roster by CDR consisting of students engaged throughout the year and a single adult mentor.	D	N/A	The team will submit a list of team members and the project mentor with CDR.	Complete
N.1.5	The team will engage more than 200 participants in STEM activities.	D	N/A	The team will submit relevant outreach activity forms within two weeks of a given activity.	In Progress
N.1.5.1[TD]	The team will host virtual software tutorials for its members and the greater college community	D	N/A	The team will submit relevant outreach activity forms within two weeks of a given activity.	Incomplete
N.1.6	The team will establish a social media presence.	D	N/A	The team will submit a list of active team social media accounts.	Complete
N.1.7-10	All deliverables will be properly formatted and emailed to the USLI team by the specified deadlines.	D	N/A	The team will submit properly formatted deliverables on time at all milestones.	In Progress
N.1.7.1	All subteams will complete milestone editing 3 days prior to the official NASA deadline. After this time only the Project Management team will have access to the documentation to perform final edits.	D	N/A	The team will submit properly formatted deliverables on time at all milestones.	In Progress
N.1.11	The team will use proper teleconferencing equipment for all calls with the USLI team.	D	N/A	The team leads will perform professional video calls for all milestone meetings.	In Progress
V.1.12	The launch vehicle will use USLI standard launch rails and pad configurations.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
N.1.13	The team will identify an experienced mentor.	D	N/A	The team will submit information about the team mentor in CDR.	Complete

N.1.14	The team will track, and report hours spent working on all milestones.	D	N/A	The team will submit member timesheets with all reports.	In Progress
N.1.14.1[TD]	The team will set up a software tool to allow members to submit their working hours.	D	N/A	The team will submit member timesheets with all reports.	In Progress
V.2.1	The vehicle's apogee shall be between 3,500 and 5,500 feet.	P		The team will conduct analyses and tests to verify this requirement with the ABCS active and deactivated. This verification will also include the vehicle demonstration flight.	In Progress
B.2.1.2 [TD]	The launch vehicle will actively control its apogee using an AeroBraking Control System (ABCS). Using the ABCS, the vehicle will reach within 15 ft of the PDR target apogee.	P		The ABCS team will conduct a multifaceted verification of the ABCS system to ensure its ability to function as intended.	Complete
N.2.2	The team will declare a target altitude at PDR.	D	N/A	The team will submit its target altitude in PDR.	Complete
A.2.3	The launch vehicle shall contain a commercially available barometric altimeter for recording apogee.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
G.2.4	The vehicle shall be designed to be recoverable and reusable.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
G.2.4.1 [TD]	The vehicle shall withstand all expected flight loads with a minimum safety factor of 1.5.	P (A, T)	VT.P.2.1 VT.P.1.2 VT.P.1.10	All subteams will independently verify the strength of their subsystems through analysis and testing.	Complete
V.2.5	The launch vehicle shall have a maximum of 4 independent sections.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.2.5.1-2	Couplers at inflight separation points shall be at least 1 cal in length. Nose cone couplers shall be at least ½ cal in length.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.2.6	The launch vehicle shall be able to launch within 2 hours of flight authorization.	D	D.M.2.1	VDF will demonstrate the team's ability to prepare the launch vehicle for flight.	Complete
V.2.6.1 [TD]	The launch vehicle will be assembled in a quality conducive assembly area separate from the launch site. A quality conducive assembly area has (but is not limited to) the	D	D.M.2.1	VDF will demonstrate the team's ability to prepare the launch vehicle for flight.	Complete

150

	following attributes: climate control not necessitating thermal protective clothing, bright overhead lighting, and access to tools and components.				
V.2.7	The launch vehicle and payload shall be able to remain in the flight ready configuration for at least 2 hours.	P		All subteams will perform battery drain testing on their subsystems.	Complete
V.2.7.1 TD	The launch vehicle and payload shall be able to remain in the pre-flight state for at least 18 hours.	P		All subteams will perform battery drain testing on their subsystems.	Complete
V.2.7.2 TD	The transition between the pre-flight state and flight ready state will not require the disassembly of the launch vehicle.	I	I.M.3.1	The systems manager will inspect all checklists to ensure procedural compliance.	In Progress
V.2.8-9	The vehicle shall be capable of being launched via a 12 VDC firing system as provided by the launch services provider	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.2.10	The launch vehicle shall use an APCP motor.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.2.10.1-2	The final motor choice shall be declared by CDR. Any changes after CDR must be approved by the RSO.	D	N/A	The team will submit its motor selection in the CDR milestone report.	Complete
V.2.11	The launch vehicle will be limited to a single stage.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.2.12	The total impulse of the launch vehicle shall not exceed 5120 Ns (L-Class).	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.2.13.0-3	Pressure vessels on the vehicle must be approved by the RSO and maintain safe standards.	N/A	N/A	No pressure vessels will be included in the vehicles design.	Complete
V.2.14	The vehicle shall have a minimum stability margin of 2.0 cal at rail exit.	P	D.M.2.1,	The avionics and construction subteams will independently verify the launch stability of the vehicle. Compliance will also be demonstrated during VDF.	Complete

151

B.2.14.1 TD	The ABCS shall not reduce the stability margin below 2.0 cal at any point, under any failure mode.	P	D.M.2.1,	The team will perform FMEA and other analyses on the ABCS system to ensure compliance. Compliance will also be demonstrated during VDF.	Complete
V.2.15	The vehicle shall not have any structural protuberance forward of the burnout CoM. Excepting aerodynamically insignificant camera housings.	I/A	I.M.1.1	The team will inspect the PDR design for forward structural protuberances. If any are present, the team will perform CFD analysis to ensure aerodynamic insignificance.	Complete
V.2.16	At rail exit the vehicle shall have a minimum velocity of 52fps.	P	D.M.2.1,	The team will perform launch analysis to ensure proper rail exit velocity.	Complete
V.2.17	A subscale rocket will be successfully flown by CDR.	D	N/A	The team will submit subscale altimeter data with CDR.	Complete
V.2.17.1	The subscale rocket shall resemble and perform similarly to the full-scale rocket but will not be the full-scale rocket.	I	I.M.1.2	The team will inspect the subscale vehicle design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.2.17.2	The subscale rocket shall contain an altimeter to record apogee.	I	I.M.1.2	The team will inspect the subscale vehicle design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.2.17.3	The subscale rocket will be newly constructed for the 2021 competition	I	I.M.1.2	The team will inspect the subscale vehicle design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
N.2.17.4	Proof of the subscale flight shall be included in CDR	D	N/A	The team will submit subscale altimeter data with CDR.	Complete
N.2.18	The team shall complete the following demonstration flights.	P	N.2.18.1-2	The team will verify all prerequisite requirements.	In Progress
N.2.18.1	The team will fly the launch day vehicle in its final configuration in order to validate its flight capabilities. This Vehicle Demonstration Flight (VDF) has the following success criteria.	P	V.2.18.1.1-9	The team will verify all prerequisite requirements.	Complete
G.2.18.1.1	The vehicle and recovery system will have functioned as designed.	P		All subteams will complete post-launch system assessments.	Complete
N.2.18.1.2	The full-scale rocket must be newly designed and constructed for the 2021 competition.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
P.2.18.1.3	The payload does not have to be flown during VDF.	N/A	N/A	The team overrides this requirement with N.2.18.2.2.	Complete
P.2.18.1.3.1-2	If the payload is not flown, a mass simulator will be used to simulate the payload mass	P		If included, the effect of the payload mass simulator will be quantified by the payload team.	Complete

	and will be located in approximately the same location as the payload CoM.				
P.2.18.1.4	If the payload effects the external surface of the rocket or manages the total energy of the vehicle, those systems will be active during VDF.	I	I.M.3.1.1	Before VDF, the systems manager will ensure all protrusions and energy management systems are present.	Complete
V.2.18.1.5	During VDF, the vehicle shall use the declared launch day motor.	I	I.M.3.1.1	Before VDF, the systems manager will ensure the declared launch day motor is installed in the vehicle.	Complete
V.2.18.1.6	The vehicle shall have the launch day ballast configuration for the VDF.	I	I.M.3.1.1	Before VDF, the systems manager will inspect the vehicle for proper ballasting	Complete
N.2.18.1.7	The team will not modify the vehicle after VDF without permission from the RSO.	D	N/A	The vehicle present at LRR will be identical to the vehicle discussed in FRR.	Complete
N.2.18.1.8	Altimeter data will be provided in the FRR report to prove a successful flight	D	N/A	The team will submit VDF altimeter data in FRR.	Complete
N.2.18.1.9	VDF must be completed by the FRR submission deadline. If a re-flight is required, an extension may be granted.	D	N/A	The team will submit VDF altimeter data in FRR	Complete
N.2.18.2	The team will fly the launch day payload aboard the launch day rocket in a successful Payload Demonstration Flight. This PDF will be considered successful if the vehicle experiences stable ascent and the following requirements are met.	P	P.2.18.2.1-3	The team will complete all prerequisite requirements for PDF.	Incomplete
P.2.18.2.1	The payload will be fully retained until the intended point of deployment, and all R&D mechanisms will function as intended and suffer no damage	I	I.M.3.2	All subteams will complete post-launch system assessments.	In Progress
N.2.18.2.2 **TD**	VDF will contain the final payload system, unless waiting until the completion of the payload would bar the team from satisfying requirement N.2.19.1	I	I.M.3.1	The systems manager will inspect the vehicle for proper installation of the payload system before flight.	Complete
G.2.18.2.3 **TD**	Test launches will only be attempted if all subsystem designs are frozen and thorough assembly protocols have been created.	I	I.M.3.2	The systems manager and project management team will conduct a survey of subteam leads and confirm their confidence in the vehicles ability to have a safe and successful flight.	Complete
N.2.19	An FRR Addendum will be required for teams completing PDF or VDF re-flight after the FRR report deadline.	D	N/A	The team will submit FRR Addendum if required.	Incomplete

153

N.2.19.1	The FRR Addendum must be submitted for all teams whose circumstances require its submission.	D	N/A	The team will submit FRR Addendum if required.	Incomplete
N.2.19.2	If the PDF fails, the team will not be permitted to fly at the competition launch.	N/A	N/A	N/A	Complete
N.2.19.3	If the PDF partially fails, the team may petition the RSO for permission to fly the payload at launch week.	N/A	N/A	N/A	Complete
N.2.20	All separable components will have the team's name and Launch Day contact information clearly visible.	I	I.M.3.1	The systems manager will inspect the launch vehicle and payload for proper labeling before all flights.	Incomplete
N.2.22.0-10	The vehicle will not use any of the following prohibited design features or modes: • Forward Firing Motors • Motors that expel titanium sponge • Hybrid Motors • Motor Clusters • Friction Fit Motors • Exceed Mach 1 at any point • Ballast exceeding 10% of the unballasted weight • Transmitters with individual power greater than 250 mW • Transmitters which create excessive interference • Excessive / dense metal. Lightweight metal will be permitted for structural purposes	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.3.1^{TD}	The vehicle will contain an In-Flight Video Recording (IFVR) system to record flight video for downloading after recovery.	P		The IFVR team will verify the functionality of the IFVR system through a variety of DIAT methods.	Complete
V.3.1.1^{TD}	The IFVR will have at least two sensors, aligned aft and radially, and may have a sensor aligned forward.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
V.3.1.2^{TD}	The IFVR will be considered a vehicle element, not a payload experiment.	D	N/A	The construction team will be solely responsible for the IFVR and IFVR documentation will be included in the vehicle construction section of all reports.	Complete

A.3.1	Vehicle recovery process will abide by the requirements A.3.1.1 – A.3.1.13.	P	A.3.1.1 – A.3.1.13	The team will complete all prerequisite recovery requirements.	Complete
A.3.1.1	The main parachute will be deployed no lower than 500 feet.	P		The team will ensure the proper deployment of the main parachute through a variety of verification and design methods	Complete
A.3.1.2	The apogee event will contain a delay of no more than 2 seconds.	P		The team will ensure the proper deployment of the drogue parachute through a variety of verification and design methods	Complete
A.3.1.3	The motor will not be ejected at any point.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.1.4 TD	The recovery process will be designed to minimize shock to the vehicle.	P		The team will ensure the minimization of shock through various subteam requirements.	Complete
A.3.2	The team will perform a ground ejection test for all electronically initiated recovery events.	T	N/A	The team will submit ejection test results with FRR.	Complete
A.3.3	Each independent section of the launch vehicle will have a maximum kinetic energy of 75ft-lbf (101J).	P		The team will ensure acceptable landing energy through verification up to and including post launch examination of flight telemetry.	Complete
A.3.4	The recovery system will contain redundant, commercially available altimeters.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.5	Each altimeter will be equipped with a commercially available, dedicated power supply.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.6	Each altimeter will be armed (placed into the flight-ready state) by a dedicated mechanical arming switch.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.7	The A&R system shall not be capable of disarmament due to flight sources.	P		The team will design and test the avionics bay to ensure that disarmament due to flight sources is impossible.	In Progress
A.3.8	A&R electrical circuits will be completely independent of payload electrical circuits.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.9	Removable shear pins will be used for both parachute compartments.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements.	Complete

				Relevant design aspects will be frozen after the submission of PDR.	
A.3.10	The recovery area will be limited to a 2,500 ft. radius from the launch pad.	P		The team will verify the acceptability of the recovery area through a variety of methods.	Complete
A.3.11	The descent time of the launch vehicle (apogee to touch down) must be less than 90 seconds.	P		The team will verify the acceptability of the vehicle descent time through a variety of methods.	Complete
A.3.12	The launch vehicle will have a tracking device which transmits its position to a ground station.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.12.1	Any untethered component of the launch vehicle will contain a tracking device.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.12.2	All electronic tracking devices will be fully functional during launch day.	I	I.M.3.1	Before launch, the systems manager will inspect all tracking devices' downlinks.	In Progress
A.3.12.3 TD	Any tethered component of the launch vehicle will contain a tracking device.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.13	The recovery system will not be adversely affected by other electronics devices during flight.	P		The team will verify the electronic resilience of the avionics system through a variety of methods.	Complete
A.3.13.1	Recovery system altimeters will be located in a compartment separated from other RF/EM emitting devices.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete
A.3.13.2-4	Recovery system electronics will be shielded from other RF/EM emitting devices.	P		The team will verify the electronic resilience of the avionics system through a variety of methods.	Complete
P.4.2	The payload will consist of a planetary lander capable of ejection during descent which will self-right during or after landing. After leveling the system will take a 360-degree panoramic photo of the landing site and transmit the photo to the team.	P	P.4.3, D.M.2.2	The team will complete all prerequisite requirements and demonstrate success in the payload demonstration flight.	In Progress
P.4.3	The landing system will adhere to requirements P.4.3.1.-P.4.3.4.4	P	P.4.3.1.-P.4.3.4.4	The team will complete all prerequisite requirements.	In Progress

P.4.3.1	The landing system will be completely jettisoned from the launch vehicle between 500 & 1000 ft AGL. The landing system must land within the external borders of the launch field. The landing system will not be tethered to the launch vehicle.	P		Once specific subteam requirements defined by the payload team have been verified, this requirement will be verified.	Complete
P.4.3.2	The vehicle will land in an upright orientation or will be capable of self-orienting autonomously.	P		Once specific subteam requirements defined by the payload team have been verified, this requirement will be verified.	InProgress
P.4.3.3	The landing system will self-level within 5 degrees of vertical.	P (A, T)	VT.P.1.8	Once specific subteam requirements defined by the payload team have been verified, this requirement will be verified.	In Progress
P.4.3.3.1	The lander must autonomously self-level.	P		Once specific subteam requirements defined by the payload team have been verified, this requirement will be verified.	In Progress
P.4.3.3.2	The landing system must record pre- and post-leveling orientation data. This data will be provided in PLAR	P		Once specific subteam requirements defined by the payload team have been verified, this requirement will be verified.	In Progress
P.4.3.3.2.1	PDF orientation data will be provided in FRR	D	N/A	The team will submit PDF orientation data in FRR.	Complete
P.4.3.4	After self-leveling the lander will produce a 360-degree panoramic image of the landing site and transmit it to the team.	P		Once specific subteam requirements defined by the payload team have been verified, this requirement will be verified.	In Progress
P.4.3.4.1	Image receiving hardware will be located within the team's assigned preparation or viewing area.	D	I.M.3.1	The team will display image receiving hardware to the NASA RSO before launch.	In Progress
P.4.3.4.2	Only transmitters on board the vehicle during launch will be permitted to operate outside of the preparation or viewing areas.	D	I.M.3.1	The team will display image receiving hardware to the NASA RSO before launch.	In Progress
P.4.3.4.3	After landing, the payload may use transmitters with a power greater than 250 mW.	N/A	N/A	N/A	Complete
P.4.3.4.4	The team will provide the 360-degree panoramic image in PLAR.	D	N/A	The team will submit the final panoramic image in PLAR.	Incomplete
P.4.4	The payload will adhere to requirements P.4.4.1-6	P	P.4.4.1-6	The team will complete all prerequisite requirements.	In Progress
P.4.4.1	Black Powder and/or similar energetics will only be used for in-flight recovery systems.	I	I.M.1.1	The team will inspect the vehicle and payload design at PDR to ensure compliance with NASA requirements. Relevant design aspects will be frozen after the submission of PDR.	Complete

P.4.4.2	Teams will abide by all FAA and NAR rules and regulations.	I	I.M.3.1	The systems manager will inspect the vehicle and payload before launch to confirm FAA and NAR compliance.	Complete
P.4.4.4	UAS payloads will be tethered to the vehicle and will not be released until RSO permission has been granted.	D	N/A	The team will inform the RSO of the relative location of the payload throughout flight.	Complete
P.4.4.5	UAS payloads will abide with all FAA regulations.	I	I.M.3.1	The systems manager will inspect the vehicle and payload before launch to confirm FAA and NAR compliance.	Complete
P.4.4.6	Any UAS weighing more than .55lbs will be registered with the FAA and be marked with its registration number.	I	I.M.3.1	The systems manager will inspect the vehicle and payload before launch to confirm FAA and NAR compliance.	Complete
P.4.5 TD	The payload team will be responsible for the design, manufacture, and operation of the ABCS	D	N/A	Project management will monitor the proper division of labor across the team.	In Progress
H.5.1	The team will use a launch and safety checklist which will be included in FRR and used in LRR and for all launch day operations	D	N/A	The team will submit all checklists with FRR.	Complete
M.5.1.1 TD	The team will utilize checklists for all pre-flight operations including but not limited to: A&R assembly, Payload assembly, Motor installation, and Vehicle integration.	D	N/A	The systems manager will create and review all checklists before use.	In Progress
M.5.1.2TD	The team will not launch a vehicle until the Systems Manager is satisfied with the status of all pre-flight checklists.	D	I.M.3.1	The systems manager will receive confirmation of checklist completion from all subteam leads.	In Progress
H.5.2	The team will identify a student safety officer who is responsible for all sub requirements of requirement M.5.3.	D	N/A	The team will submit information regarding its selected safety officer in the Proposal	Complete
H.5.3	Safety officer responsibilities are defined in H.5.3.1 -H.5.5	P	H.5.3.1-H.5.5	The team will complete all prerequisite requirements	In Progress
H.5.3.1	The safety officer will monitor team activities will an emphasis on safety during operations H.5.3.1.1-9 and H.5.3.2-4.	D	S.1.1	The safety officer will affirm their responsibility for the safety of the team.	In Progress
H.5.3.1.1-9	Safety officer will oversee all of the following operations: • Vehicle and Payload design • Vehicle and Payload construction • Vehicle and Payload Assembly	D	S.1.1	The safety officer will affirm their responsibility for the safety of the team.	In Progress

	• Vehicle and Payload ground testing • Subscale launch tests • Full-scale launch tests • Launch Day • Recovery Activities • STEM Engagement Activities				
H.5.3.2	Ensuring the implementation of safety procedures for construction, assembly, launch and recovery.	D	S.1.1	The safety officer will affirm their responsibility for the safety of the team.	In Progress
H.5.3.3-4	Maintain and lead the development of team hazard analyses, failure mode analyses, and MSDS/chemical inventory data.	D	N/A	The team will submit hazard analyses and FMEAs in all relevant milestone reports.	In Progress
H.5.4	The team will follow all guidance from the local rocketry clubs RSO and will be in constant communication to ensure safety.	D	S.2.1	All team members will sign pledges affirming their intention to follow all local, state and federal regulations regarding the project.	Complete
H.5.5	The team will abide by all rules set by the FAA	D	I.M.3.1	The systems manager will inspect the vehicle and payload before launch to confirm FAA and NAR compliance.	Complete
N.6.1	At the NASA Launch Complex, the team must satisfy requirements N.6.1.1-4	P	N.6.1.1-4	The team will complete all prerequisite requirements.	In Progress
N.6.1.1	Teams must pass LRR during launch week.	D	N/A	The team will pass LRR during launch week.	Incomplete
N.6.1.2	The team mentor must be present for vehicle preparation and launch.	D	S.3.1	The team will not proceed with launch procedures without the team Mentor.	In Progress
N.6.1.3	The scoring altimeter must be presented to the NASA scoring official upon recovery.	D	N/A	The NASA RSO will receive the scoring altimeter after flight.	Incomplete
N.6.1.4	Teams may only launch once.	D	N/A	The team will only attempt a single flight.	In Progress
N.6.2.1	At Commercial Spaceport Launch Sites (local launch fields), the team must satisfy requirements N.6.2.1-8.	P	N.6.2.1-8	The team will complete all prerequisite requirements.	In Progress
N.6.2.1	The launch must occur at a NAR or TRA insured launch.	D	I.M.3.1	The systems manager will inspect the vehicle and payload before launch to confirm FAA and NAR compliance.	In Progress
N.6.2.2	The launch site RSO will inspect the rocket and payload and determine its flight-readiness.	D	I.M.3.1	The team will not launch until receiving RSO approval.	Incomplete
N.6.2.3	The team mentor must be present for vehicle preparation and launch.	D	S.3.1	The team will not proceed with launch procedures without the team Mentor.	In Progress
N.6.2.4	The team mentor and Launch Control Officer (LCO) will report any anomalies during ascent or recovery on the Launch	D	N/A	The team will submit LCOR after flight	Incomplete

	Certification and Observations Report (LCOR).				
N.6.2.5	The scoring altimeter will be presented to the team's mentor and the RSO.	D	I.M.3.1	The RSO will receive the altimeter after flight.	Incomplete
N.6.2.6	The mentor, RSO, and LCO will complete all applicable sections in the LCOR.	D	N/A	The team will submit LCOR after flight.	Incomplete
N.6.2.7	The RSO and LCO shall not be affiliated with the team, team members, or academic institution.	D	N/A	The RSO and LCO will affirm their status on the LCOR.	Incomplete
N.6.2.8	Teams may only launch once.	D	N/A	The team will only attempt a single flight.	In Progress

Table 7.7: Derived Requirements

7.3.1 Vehicle Subteam Requirements

Requirement ID	Requirement Summary	Satisfies Project Requirement:	Verification		Verification Plan Summary	Status
			Type (s)	Plan ID(s)		
S.V.1	The nose cone material will not interrupt RF signals.	V.2.17.2	D	VD.V.1	Attempt to communicate with components using RF signals through the nosecone.	Complete
S.V.2	The vehicle will reach an altitude of 4100' feet within a margin of error of ε = 200ft with no effect from airbrakes.	V.2.1	A	VA.V.2	The team will analyze predicted altitude through OpenRocket and/or RAS Aero simulations. Data from VDF will be reviewed after flight.	In Progress
S.V.3	The vehicle and its individual components will withstand at least 2 times the expected stresses without experiencing plastic deformation or destruction at any point during flight.	G.2.4.1	A	VA.V.3	The team will perform FEA simulations on all load bearing components and perform nondestructive testing on safety critical components.	Complete
S.V.4	The vehicle will remain in proper orientation for the duration of the flight.	V.2.14	A/T	VAT.V.4	OpenRocket and/or RASAero simulations will model flight path deviation, and the flight path will be monitored during VDF.	Complete
S.V.5	Critical flight components will always remain on the interior of the launch vehicle during flight.	V.2.15	A	VA.V.5	Team will use SolidWorks and/or ANSYS simulations to construct vehicle with vital components secured in the interior which will then be confirmed by inspection during construction.	Complete
S.V.6	The vehicle body and structure will be manufacturable with facilities accessible to the		I	VI.V.6	All design and purchases will be finalized with confirmation of proper facilities to manufacture said design.	Complete

	team or purchased as constructed.					
S.V.7	The vehicle will be constructed within the specified mass, diameter, and height limits with the utmost precision as laid out in the proposal sheet to ensure it does not break apart under extreme stress.	V.2.5	I	VI.V.7	Once construction on the rocket is complete it will be compared to all design specifications and measured to ensure compliance	Complete
S.V.8	The vehicle will have its Coefficient of Drag (Cd) determined.		A/D	VAD.V.8	Drop test of a 3D printed scaled airframe model with an accelerometer attached to it and a velocity sensor to measure terminal velocity OR the team will inspect results of the Subscale flight, and apply scaling.	Complete
S.V.9	The launch vehicle will have a minimum thrust-to-weight ratio of 5:1.	V.2.16	I	VI.V.9	OpenRocket simulations will confirm the launch vehicle's thrust-to-weight ratio to be at least 5:1.	Complete
S.V.10	IFVR will be able to capture video for three hours continuously.	V.3.1	T	VT.V.9	The fully equipped IFVR system can be run for three continuous hours to verify memory and power capacity.	Complete
S.V.11	IFVR will capture forward, aft, and outward facing view for entire launch	V.3.1.1	D	VD.V.11	All three cameras will be tested on a mockup of the rocket to verify full video coverage of all viewpoints.	Complete
S.V.12	Each subcomponent of the IFVR (one camera, computer, power source and memory card) will not weight more than 0.5lbm	V.3.1	T	VT.V.12	All fully assembled subcomponents of the IFVR will be weighed independently.	Complete
S.V.13	All protrusions of the IFVR will contain housings that render the protrusions aerodynamically insignificant.	V.3.1	A	VA.V.13	Proper and extensive calculations will be conducted to endure that the housings are aerodynamically insignificant.	Complete
S.V.14	The IFVR initiation system will be easily accessible and not require deconstruction.	V.3.1	D	VD.V.14	This design requirement can be demonstrated during construction and verified by successful initiation	In Progress
S.V.15	The IFVR will contain a notification system as to when the cameras are recording.	V.3.1	T	VT.V.15	The IFVR subsystems will be tested with their corresponding notification systems to ensure that footage is being captured.	Complete
S.V.16	The IFVR systems will be secured so that the footage provided is clear and steady.	V.3.1	D	VD.V.16	The IFVR system will be tested in flight conditions and secured and shaking will be analyzed.	Complete

Table 7.8 Vehicle Subteam Requirements

7.3.2 Recovery Subteam Requirements

Requirement ID	Requirement Summary	Verification Type(s)	Verification Plan ID(s)	Verification Plan Summary	Status
S.A.1	Shock cord will be adequately long for each parachute.	D	VD.A.1	The subscale vehicle launch will demonstrate that the shock cord length is appropriate. For the main parachute this will be 60′ and for the drogue parachute this will be 30′.	Complete
S.A.1.1	Parachutes will be tied to the shock cord off center to prevent two airframe sections from knocking together after separation.	I, D	VID.A.1.1	The team will inspect the shock cord and parachutes to ensure they are tied together off center. Subscale vehicle launch will demonstrate that the two sections separate without colliding.	Complete
S.A.1.2	Shock cord will be z-folded with tape in appropriate increments to prevent tangling while being stored in the vehicle and to reduce shock during deployment.	I	VI.A.1.2	The team will inspect the shock cord stored within the vehicle and ensure it is folded to prevent tangling and reduce shock.	Complete
S.A.2	Parachutes will open consistently within an appropriate distance range or time frame to allow for full deployment after ejection.	T	VT.A.2 Parachute Drop Test	The parachute drop test will verify the drogue and main parachutes successfully deploy at the correct points of flight. For the drogue parachute, this is opening no more than 1s after being released, and for the main parachute, this is opening no more than 150′ after being released.	Complete
S.A.2.1	Parachutes will be completely protected with a Nomex blanket on the side of the ejection charges.	T	VT.A.2.1 Black Powder Ejection Test	The black powder ejection test will verify the parachutes are completely protected from the ejection charges.	In Progress
S.A.2.2	Parachutes will be packed loosely to slide out easily during ejection.	I	VI.A.2.2	The team will inspect parachute packing before each flight.	Complete
S.A.2.3	The main parachute will utilize a slide ring to reduce shock loading during deployment.	I	VI.A.2.3	The team will inspect the preparation of the parachute prior to flight and verify the use of a slide ring before launch.	Discontinued
S.A.3	The black powder canisters will create appropriate separation between the airframe sections.	T	VT.A.3 Black Powder	The black powder ejection test will verify the black powder canisters are able to create 6′ of separation on the ground.	Complete

			Ejection Test		
S.A.4	All avionics coupler components will be secured throughout the duration of flight. No components will be freely suspended within the compartment.	I	VI.A.4	Team will inspect avionics coupler and ensure components are secured.	Complete
S.A.4.1	Avionics coupler components will be organized. Wires and cords will be grouped together to prevent entanglement and damage.	I	VI.A.4.1	Team will inspect avionics coupler and ensure all components are organized and grouped together to prevent entanglement.	Complete
S.A.4.2	Avionics coupler components must be able to withstand all shock loads.	D	VD.A.4.2	The subscale launch will demonstrate that all avionics coupler components remain in place throughout the duration of flight.	Complete
S.A.5	Altimeters will record accurate readings and perform according functions throughout the duration of flight.	I	VI.A.5	The team will inspect that all altimeter related requirements have been fulfilled before PDR submission. Major design considerations will be frozen after this point.	Complete
S.A.5.1	Altimeters will continue to function across all likely flight temperatures.	T	VT.A.5.1 Altimeter Continuity and Battery Drain Test	The altimeter continuity and battery drain test will verify the altimeters can achieve continuity and provide readings in a temperature range from 35°F to 75°F. This range represents the likely temperature extremes for flight scenarios.	Complete
S.A.5.2	Both altimeters will achieve and maintain continuity consistently throughout flight.	T	VT.A.5.2 Altimeter Continuity and Battery Drain Test	This test will verify that the two altimeters are able to establish and maintain continuity in flight. This will be signaled by continuity beeps in sets of 3.	Complete
S.A.5.3	Altimeters will consistently ignite ejection charges at specific times throughout flight. The primary altimeter will ignite drogue and main charges before the redundant altimeter.	T	VT.A.5.3 Altimeter Ejection Vacuum Test	The altimeter ejection vacuum test will simulate the ascent and descent of the vehicle and verify each altimeter ignites at the correct time. For the primary altimeter, this means lighting the drogue charge at apogee and the main charge at an altitude of 900′. For the redundant altimeter, this means lighting the drogue charge 2s after apogee and the main charge at an altitude of 700′.	Complete

S.A.6	Altimeter batteries will function properly and ensure successful altimeter function for the duration of flight.	I	VI.A.6	The team will inspect that all battery related requirements have been fulfilled and ensure the coupler design meets flight expectations before PDR. Major design considerations will be frozen from this point forward.	Complete
S.A.6.1	Altimeter batteries will supply usable voltage for 1 hour longer than the given pad time of 2 hours.	T	VT.A.6.1 Altimeter Continuity and Battery Drain Test	The altimeter continuity and battery drain test will verify the altimeter batteries' ability to power the altimeters for a 3-hour duration. Voltage readings will be taken every 30 minutes to ensure the altimeters would continuously function.	Complete
S.A.6.2	The avionics coupler will include battery shielding or casing to prevent battery damage in case of ballistic impact. This casing must not be compromised by any other coupler components.	I, D	VID.A.6.2	Team will inspect avionics coupler and ensure batteries are correctly located within casings. Subscale vehicle launch will demonstrate the integrity of the casings.	Complete
S.A.6.3	Altimeter batteries will not fail to function at any likely launch temperature. They will function properly at a variety of temperature extremes.	T	VT.A.6.3 Altimeter Continuity and Battery Drain Test	The altimeter continuity and battery drain test will verify the altimeter batteries work at both 35°F and 75°F temperature extremes. These bounds represent the extremes for likely launch temperatures.	Complete
S.A.7	Key switches will prevent disarmament of the altimeter and ejection systems throughout flight. Only key switches will be able to engage or disengage these systems.	I, D	VID.A.7	The team will inspect the avionics coupler upon launch preparation and ensure the system is engaged. Subscale vehicle launch will demonstrate that no flight forces disengage the system.	In Progress

Table 7.9 Recovery Vehicle Requirements

7.3.3 Payload Subteam Requirements

Requirement ID	Requirement Summary	***Satisfies Project Requirements (If Applicable):***	Verification		Verification Plan Summary	Status
			Type(s)	**Plan ID(s)**		
S.P.0	The overall mass of the payload systems shall not exceed 16lbm.	N/A	T	VT.P.0.1 VT.P.0.2 VT.P.0.3 VT.P.0.4	Measure the combined mass of the Payload experiment.	In Progress

S.P.0.1	The overall mass of the lander subsystem shall not exceed 3lbm.	N/A	T	VT.P.0.1	Measure the individual mass of the Lander subsystem.	In Progress
S.P.0.2	The overall mass of the retention and deployment subsystem shall not exceed 5lbm.	N/A	T	VT.P.0.2	Measure the individual mass of the R&D.	In Progress
S.P.0.3	The overall mass of the ABCS shall not exceed 8lbm.	N/A	T	VT.P.0.3	Measure the individual mass of the ABCS.	In Progress
S.P.1.1	When the lander lands, the lander will remain in an operational state.	G.2.4.1 TD	A, D, T	VT.P.1.13	Test function after landing and analyze possible failure modes.	In Progress
S.P.1.2	Once deployed and free in the air, the lander should maintain a 6" clearance from all elements of the main vehicle.	G.2.18.1.1 P.2.18.1.4 P.4.3.1	D		During PDF, demonstrate that no vehicle components collide during descent and stay reasonably outside of this range.	In Progress
S.P.1.3	The landing distance between any element of the main vehicle and lander should be greater than 10'.	G.2.18.1.1	D		Measure to ensure that the final landing distance is greater than the allotted distance.	Incomplete
S.P.1.4	Upon activation, the lander will fully deploy from the vehicle in under 5s.	P.4.2 P.2.18.2.1 P.4.3.1	D, T	VT.P.1.2 VT.P.1.1	Static test the functionality of the R&D system to deploy in under the allotted time frame.	In Progress
S.P.1.5	The lander should be able to orient in terrain with a surface irregularity of 5" maximum crest height relative to trough and with maximum 6' distance between local crests.	P.4.2 P.4.3.2 P.4.3.3	A, D		Design to reliably function during the projected worst case geometric situation.	Incomplete
S.P.1.6	The lander will be deployed under main parachute descent between an altitude of 700' and 500' AGL.	P.4.2 P.4.3.1	A, D, T	VT.P.1.1 1	Verify through on-board altimeter data post-landing.	In Progress
S.P.1.7	The lander must establish signal connectivity with the ground station capable of transmitting the image upon landing.	P.4.2 P.4.3.4	D		Static test of the transmission capability of the sender and receiver.	Incomplete

S.P.1.8	When taking a panoramic photograph, no component of the lander will obstruct the view of the cameras.	P.4.2 P.4.3.4	D		Test PICS to ensure a high-quality image can be produced.	Incomplete
S.P.1.9	Lander must be able to withstand 10 mph wind while grounded without being moved.	P.4.2 P.4.3.2 P.4.3.3	D, T	VT.P.1.9	Test the ability of the Lander to remain upright in an in-situ wind test.	In Progress
S.P.1.10	The final panoramic photo produced and transmitted must be of a high enough quality to inspect the lander's surrounding area and horizon.	P.4.2 P.4.3.4	I, T	VT.P.1.7	Team verifies the result of image processing after the mission has completed.	Incomplete
S.P.1.11	Both the lander and its associated subsystems must have sufficient battery life to be in a launch-ready state for at least 2 hours.	V.2.7	A, T	VT.P.1.4 VT.P.1.5 VT.P.1.6	All batteries must be drain tested to ensure proper functionality.	In Progress
S.P.1.12	The lander and its associated subsystems must be able to sustain a pre-flight state for a minimum of 18 hours.	V.2.7.1 TD	A, T	VT.P.1.4 VT.P.1.5 VT.P.1.6	All batteries must be drain tested to ensure proper functionality.	Incomplete
S.P.1.13	After the panoramic photo has been produced, the GCS must display the panoramic photo.	P.4.2 P.4.3.4	T	VT.P.1.7	Team verifies the result of image processing after the mission has completed.	Incomplete
S.P.1.14	Camera must be able to take a photo above the maximum dirt level within 10' radius of the landing site by 6".	P.4.2 P.4.3.4	T	VT.P.1.7	Place the lander in a similar environment as it will be expected to perform in and see it the photos it takes is clear of the trough.	Discontinu ed
S.P.1.15	Lander must be able to transfer image data to ground control station within 1mi.	P.4.2 P.4.3.4	T	VT.P.1.3	Move the lander 1 mile from the GCS and test whether it can transmit the image. Almost test if it gets blocked by the dirt (of the trough).	Incomplete
S.P.1.16	Lander must be able to land within 1mi of ground control station.	P.4.3.1 P.4.3.4	A, D		Measure after PDF to ensure that the final landing distance is less than the allotted distance.	In Progress

S.P.1.17	Lander must have some way to transmit its landing location.	N/A	I		The Lander will contain an operational GPS transmitter throughout the mission.	Incomplete
S.P.1.18	Payload must be securely contained during flight until deployment.	P.2.18.2.1	D, T	VT.P.1.1 VT.P.1.2 VT.P.1.3	The retention subsystem successfully retains the Lander during VDF.	In Progress
S.P.1.19	The retention method must protect the lander from all flight loads such that it remains operational.	G.2.4.1 TD	D, T	VT.P.1.1 VT.P.1.2	The retention subsystem successfully protects the Lander under simulated flight loads.	In Progress
S.P.1.20	Lander system will have team name and launch day contact information clearly visible on the lander itself.	N.2.20	I		The team verifies the presence of both items on the body.	Incomplete
S.P.1.21	Payload system must be able to transition from pre-flight to flight ready without taking apart the rocket, through usage of the GCS.	V.2.7.2 TD	D	VT.P.1.1	The team will demonstrate that the system will be capable of modulating between these states.	Incomplete
S.P.1.22	Lander subsystem must be able to transition to a state of autonomous orientation.	P.4.3.3.1	D		The team will demonstrate that the system will be capable of modulating between these states.	Incomplete
S.P.2.1	The ABCS shall never put the vehicle fins into a stall condition under any failure mode.	B.2.14.1 TD	A, D		The ABCS will be verified utilizing aerodynamic simulation methods. The ABCS will be shown not to induce a stall condition during VDF.	In Progress
S.P.2.2	The ABCS shall never reduce the stability margin of the vehicle below 2.1cal under any failure mode.	B.2.14.1 TD	A, D		The team will verify the stability modification of the vehicle through OpenRocket.	In Progress
S.P.2.3	When used, the ABCS will bring the vehicle altitude to within 100ft of the target apogee.	B.2.1.2 TD	D		The vehicle and ABCS altimeters will produce final apogee data for review.	Incomplete
S.P.2.4	If the ABCS suffers a mechanical failure, the vehicle will not deploy the ABCS.	B.2.14.1 TD G.2.18.1.1	D		The ABCS will be shown to only operate in a completed, non-broken state.	Incomplete
S.P.2.5	The ABCS will only operate after the vehicle burn has completed.	B.2.1.2 TD B.2.14.1 TD	D		The ABCS will be shown to respond to the simulated flight	Incomplete

					loads associated with a successful burn.	
S.P.2.6	The ABCS must be able to fully activate and deactivate control surfaces in under [5s] seconds.	B.2.14.1 TD	T	VT.P.2.4	The ABCS Mechanical Subsystem will be tested to ensure its complete operation time is under the allotted time.	In Progress
S.P.2.7	The battery powering the ABCS must be able to withstand idle operation for a minimum of 2 hours.	V.2.7	T	VT_P.2.2	Battery drain tests will be conducted on the ABCS.	Incomplete
S.P.2.8	The data output from the inertial sensor must be useful for the MCU. If the output from the MCU is raw data, additional electronics must be designed to convert raw data into a usable format for the MCU.	N/A	D, T	VT_P.2.3	The inertial sensor can successfully communicate useful data to the MCU.	Incomplete

Table 7.10 Payload Subteam Requirements

7.4 Budget

7.4.1 Line-Item Budget

Item	Quantity	Unit Cost	Shipping Cost	Extended Cost	Subteam	Manufacturer
4-40 Nylon Shear Pins	2	$5.78	$6.37	$17.93	Avionics and Recovery	Apogee Components
Gram Scale	1	$14.99	$1.05	$16.04	Avionics and Recovery	Amazon
Tracker LiPo Batteries	1	$19.95	$1.40	$21.35	Avionics and Recovery	Amazon
Press-In Nuts	1	$8.76	$3.39	$12.15	Avionics and Recovery	McMaster-Carr
Eyebolts	2	$3.21	$3.38	$9.80	Avionics and Recovery	McMaster-Carr
Plumbers Putty	1	$2.96	$0.21	$3.17	Avionics and Recovery	Amazon
22 AWG Stranded Wire	2	$5.28	$0.74	$11.30	Avionics and Recovery	Amazon
LiPo Battery Charger	1	$13.99	$0.98	$14.97	Avionics and Recovery	Amazon
Multipurpose 6061 Aluminum, 5/8" x 5/8", 3 Feet Long	1	$10.42	$17.55	$27.97	Construction	McMaster-Carr
Multipurpose 6061 Aluminum, 5/8" x 5/8", 2 Feet Long	1	$7.49		$7.49	Construction	McMaster-Carr
Wine Stoppers	1	$4.99	$0.41	$5.40	Avionics and Recovery	Amazon
Altimeter Mounting Posts	2	$3.98	$2.64	$10.60	Avionics and Recovery	Apogee Components

Terminal Blocks	4	$3.69	$2.63	$17.39	Avionics and Recovery	Apogee Components
4-40 Nylon Shear Pins	2	$5.78	$2.63	$14.19	Avionics and Recovery	Apogee Components
MJG Firewire Initiators	1	$48.00	$13.82	$61.82	Avionics and Recovery	MJG Technologies
TB6600 4A 9-42V Stepper Motor Driver CNC Controller, Stepper Motor Driver Nema tb6600 Single Axes Hybrid Stepper Motor for CNC	1	11.52	$0.81	$12.33	Payload-Airbrakes	Amazon
Arducam Camera Shield OV2640 (x2)	1	51.98	3.99	$55.97	Payload	UCTRONICS
Arducam 1/3" M12 Mount Camera Lens	1	7.99	3.99	$11.98	Payload	UCTRONICS
Arducam 1/2.5" M12 Mount Camera Lens	1	9.99	3.99	$13.98	Payload	UCTRONICS
Pmod MicroSD Card Breakout (x2)	1	15.72	7.99	$23.71	Payload	Digi-Key
NUCLEO-F446RE Development Board (2x)	1	29.8	7.99	$37.79	Payload	Digi-Key
MIKROE BNO080 Breakout Board	1	27.04	7.99	$35.03	Payload	Digi-Key
Sparkfun GPS-15210 Breakout Board	1	40	7.99	$47.99	Payload	Digi-Key

BMP280 Barometric Pressure & Altitude Sensor (x2)	1	19.9	10.65	$30.55	Payload	Adafruit
Micro Lipo USB LiIon/LiPoly charger	1	5.95	10.65	$16.60	Payload	Adafruit
Mini SWD 0.05" pitch connector (x5)	1	7.5	10.65	$18.15	Payload	Adafruit
Qwiic JST SH 4-Pin Cable - 50mm (x5)	1	4.75	10.65	$15.40	Payload	Adafruit
USB C to SD/microSD Card Reader	1	10.99	0	$10.99	Payload	Amazon
Raspberry Pi 4 (2GB)	1	46.99	0	$46.99	Payload	Amazon
RPi USB C Power Supply	1	12.79	0	$12.79	Payload	Amazon
USB A to B Cable	1	6.49	0	$6.49	Payload	Amazon
WebCam	1	29.99	0	$29.99	Payload	Amazon
Micro-SD	1	7.24	0	$7.24	Payload	Amazon
M2 Screws	1	9.99	0	$9.99	Payload	Amazon
Metric Tap Set	1	12.37	0	$12.37	Payload	Amazon
Velcro Straps	1	12.97	0	$12.97	Payload	Amazon
Coupler, Airframe, and Bulkheads	1	140	38.87	$178.87	Construction	MadCow Rocketry
Motor tube, retainer, and rail buttons	1	28.9	14.93	$43.83	Construction	MadCow Rocketry

Centering Rings and Switch Band	1	16	12.99	$28.99	Construction	MadCow Rocketry
2 Masterhacker 1kg, 1.75mm PLA	1	39.98	2.8	$42.78	Payload-Airbrakes	Masterhackers
10x Adhesive Mount 1/4" 20 Nut	3	$7.26	$-	$21.78	Construction	McMaster
Velco Cinch Straps	1	$12.97	$-	$12.97	Payload	Amazon
Metric Tap Set	1	$12.37	$-	$12.37	Payload	Amazon
M2 Screw Set	1	$9.99	$-	$9.99	Payload	Amazon
Motor Tube	1	$9.00	$14.93	$23.93	Construction	MadCow
Motor Retainer	1	$12.95	$-	$12.95	Construction	MadCow
1010 Rail button	1	$6.95	$-	$6.95	Construction	MadCow
G10 Fiber Glass Sheet 3/32"	1	$14.00	$12.85	$26.85	Construction	Wildman
3" G12 Switch Band	1	$4.00	$12.99	$16.99	Construction	MadCow
3"x38mm Centering Ring	2	$6.00	$-	$12.00	Construction	MadCow
3"x9" Coupler	1	$22.00	$-	$22.00	Construction	MadCow
3" Stacked Bulkhead	2	$10.00	$-	$20.00	Avionics	MadCow
1/4"-20 Eyebolt	1	$3.21	$-	$3.21	Avionics	McMaster
H148R Reload	1	$34.99		$34.99	Construction	Wildman
3"x5' Fiberglass Tube	1	$100.00	$38.87	$138.87	Construction	MadCow
48in. Rocketman High Performance CD 2.2 Parachute	1	$115.00	$-	$115.00	Avionics and Recovery	Rocketman Parachutes

USB Data Transfer Kit	1	$24.95	$9.30	$34.25	Avionics and Recovery	PerfectFlite
144in. Rocketman High Performance CD 2.2 Parachute	1	$385.00	$-	$385.00	Avionics and Recovery	Rocketman Parachutes
StratoLoggerCF Altimeter	1	$54.95	$9.30	$64.25	Avionics and Recovery	PerfectFlite
3" x 24" PVC	1	$5.60	$-	$5.60	Systems	Home Depot
15 5/16-18 Locknut	2	$3.74	$-	$7.48	Systems	Home Depot
3/8 x 250 ft Rope	1	$27.19	$-	$27.19	Systems	Home Depot
3" PVC Flange	1	$16.32	$-	$16.32	Systems	McMaster - Carr
3" PVC 90 deg	1	$11.21	$-	$11.21	Systems	McMaster - Carr
1" PVC Flange	1	$7.01	$-	$7.01	Systems	McMaster - Carr
45mm Bearing	1	$20.99	$-	$20.99	Systems	McMaster - Carr
50 5/16 Spring Washer	1	$13.38	$-	$13.38	Systems	McMaster - Carr
5/16-18 1' Allthread	7	$3.57	$-	$24.99	Systems	McMaster - Carr
10 5/16-18 3/8" Hex Bolt	1	$6.82	$-	$6.82	Systems	McMaster - Carr
1.25 Square Steel Tube	1	$7.99	$-	$7.99	Systems	McMaster - Carr
10 5/16-18 2.75" Hex Bolt	1	$4.11	$-	$4.11	Systems	McMaster - Carr
1"x1"x1' Aluminum Stock	1	$4.92	$-	$4.92	Systems	McMaster - Carr
10 1/2-13 2.5" Hex Bolt	1	$7.49	$-	$7.49	Systems	McMaster - Carr

50 1/2-13 Locknut	1	$10.07	$-	$10.07	Systems	McMaster - Carr
3"x5' PVC	1	$7.92	$-	$7.92	Systems	McMaster - Carr
.25" Thrust Bearing	2	$4.40	$-	$8.80	Systems	Servocity
.25" Set Screw Hub	1	$4.99	$-	$4.99	Systems	Servocity
.25" Set Screw Collar	1	$1.69	$-	$1.69	Systems	Servocity
.25" x 2" D Shaft	1	$1.69	$-	$1.69	Systems	Servocity
2 in Plastic Wheel	1	$3.99	$-	$3.99	Systems	Servocity
GoBilda Servo	1	$27.99	$-	$27.99	Systems	Servocity
CUI AMT102 Encoder	1	$23.63	$-	$23.63	Systems	Digikey

Table 7.11: Line Item Budget

7.4.2 **Funding Plan**

The team has a total budget of $12,300 for the competition. Due to the travel to Huntsville no longer being an associated cost of the competition, the team now has a budget of $7,750 for the technical aspects of the project, but only has $1,483 of this goal remaining to be raised. This year, the team has made several requests from the Department Heads of the Engineering Departments at Purdue. The team has applied to many grants and is still waiting to hear back from two different Purdue grants for the competition to cover the remaining costs. There are several subteams underbudget, so the team is confident in funding the rest of the project.