Project Casper

Flight Readiness Review

(FRR)

Purdue University 2020

500 Allison Road
West Lafayette, IN 47906
Purdue Space Program

Table of Contents

Acronyms and Abbreviations

Acronym / Abbreviation	Definition	Acronym / Abbreviation	Definition
PSP	Purdue Space Program	LED	Light-Emitting Diode
SL	Student Launch	LiDAR	Light Detection and Ranging
ABS	Acrylonitrile Butadiene Styrene	LRR	Launch Readiness Review
AGL	Above Ground Level	MAVLink	Micro Air Vehicle Link
AP/APCP	Ammonium Perchlorate (Composite Propellant)	MCC	Mission Control Computer
BJT	Bipolar Junction Transistor	MCS	Mission Control Software
BOM	Bill of Materials	MCU	Mission Control Unit
CAD	Computer-Aided Design	MMS	Mission Management System
CDR	Critical Design Review	MPH	Miles Per Hour
CF	Carbon Fiber	NAR	National Association of Rocketry
CFD	Computational Fluid Dynamics	NASA	National Aeronautics and Space Administration
CFRP	Carbon Fiber Reinforced Polymer	N/A	Not Applicable
CG	Center of Gravity	OT	Operational Testing
CM	Center of Mass	PDB	Power Distribution Board
CP	Center of Pressure	PDR	Preliminary Design Review
CPA	Control Panel Assembly	PDU	Power Distribution Unit
CTI	Cesaroni Technology Incorporated	PETG	Polyethylene Terephthalate Glycol
DC	Direct Current	PIC	Pilot-In-Command
DHA	Display Head Assembly	PLA	Polylactic Acid
DIU	Digital Imaging Unit	PPE	Personal Protective Equipment
DT	Developmental Testing	RC	Radio Controlled
DTED	Digital Terrain Elevation Data	RF	Radio Frequency
ESC	Electronic Speed Controller	RGB	Red/Green/Blue
FAA	Federal Aviation Administration	RSO	Range Safety Officer
FCC	Flight Control Computer	RTB	Return To Base
FCS	Flight Control System	R&D	Retention and Deployment
FEA	Finite Element Analysis	R&VP	Requirements and Verification Plan
FMEA	Failure Modes and Effects Analysis	SITL	Software In The Loop
FOS	Factor of Safety	SLI	Student Launch Initiative
FRP	Fiberglass-Reinforced Polymers	SME	Subject Matter Expert

FRR	Flight Readiness Review	SOW	Statement Of Work
GCS	Ground Control System	SRM	Solid Rocket Motor
GPIO	General Purpose Input and Output	STEM	Science, Technology, Engineering, and Mathematics
GPS	Global Positioning System	SS	Stainless Steel
GUI	Graphical User Interface	TAP	Technical Advisory Panel
HGL	Handheld GPS Locator	TRA	Tripoli Rocket Association
HTPB	Hydroxyl-Terminated Polybutadiene	UAV	Unmanned Aerial Vehicle
IMPS	Ice Mining and Procurement System	UAS	Unmanned Aerial System
IMU	Inertial Measurement	USB	Universal Serial Bus
IRI	Indiana Rocketry, Incorporated	VDF	Vehicle Demonstration Flight
I_{SP}	Specific Impulse	VSD	Vehicle Status Delay
I/O	Input/Output	V&V	Verification and Validation
LCD	Liquid Crystal Display	WBS	Work Breakdown Structure

1. FRR Report Summary

The information in the following sections summarizes information about the 2020 PSP-SL team, its mentor, and the launch vehicle it will be using in this year's NASA (National Aeronautics and Space Administration) Student Launch competition.

1.1. Team Summary

Team Name	PSP-SL (Purdue Space Program - Student Launch)
Mailing Address	2604 Bristlecone Dr., West Lafayette, IN 47906
2020 Team Mentor	Victor Barlow
2020 Mentor Contact Information	vmbarlow@purdue.edu | (765) 414-2848 (Cell)
2020 Mentor TRA / NAR Certifications	NAR 88988, TRA 6839 TAP, Level 3 Certified

Table 1.1: PSP-SL Team Summary

1.2. PSP-SL 2020 Executive Board

Position	Name	Email
Project Manager	Luke Perrin	lperrin@purdue.edu
Assistant Project Manager	Michael Repella	mrepella@purdue.edu
Safety Team Lead	Noah Stover	nstover@purdue.edu
Payload Co-Team Lead	Josh Binion	binionj@purdue.edu
Payload Co-Team Lead	Hicham Belhseine	hbelhsei@purdue.edu
Avionics & Recovery Team Lead	Katelin Zichittella	kzichitt@purdue.edu
Business Team Lead	Natalie Keefer	keefern@purdue.edu
Social & Outreach Team Lead	Skyler Harlow	sharlow@purdue.edu
Construction Team Lead	Lauren Smith	smit3204@purdue.edu
Construction Team Mentor	Zach Carroll	carrollz@purdue.edu

Table 1.2: PSP-SL Executive Board

1.3. Launch Vehicle Summary

The following information provides a summarized version of the launch vehicle to be constructed by the PSP-SL team for this year's competition.

1.3.1. Launch Vehicle Size and Mass

The 2020 PSP-SL launch vehicle is a 6” inner diameter based launch vehicle. The launch vehicle is 127” long (tip to tail), including a 36” long nose cone (5:1 Von Karman), a 48” upper airframe, a 2” switch band, a 40” lower airframe, and a 1” long retainer. The predicted mass of the launch vehicle is 53.1lbm. The nose cone, two body tubes, three trapezoidal fins and the switch band are composed of G12 filament-wound composite fiberglass. The internal components contain a UAV (Unmanned Aerial Vehicle) payload system, two parachutes, a recovery system, the avionics bay, and a camera payload.

PSP-SL Launch Vehicle Dimensions	
Overall Launch Vehicle Diameter	6.17”
Overall Launch Vehicle Length	127”
Number of Sections (Outer Dia.)	3
Gross Lift Off Weight	53.1lbm
Rail Size	144” x 15-15

Table 1.3: General Launch Vehicle Dimensions

1.3.2. Final Motor Choice

The 2020 PSP-SL team will be using a CTI 4 grain L1115-0 solid rocket motor with the characteristics shown in Table 1.4.

PSP-SL Final Motor Choice			
Manufacturer	Cesaroni Technology Inc. (CTI)		
Model	L1115-0		
Fuel	Ammonium Perchlorate, NH4CIO4 (AP 200)		
Oxidizer	Atomized Aluminum, Al		
Thrust Profile	Regressive		
Overall Weight	4404g	Propellant Weight	2394g

Table 1.4: Final Motor Choice

1.3.3. Recovery System

After thorough analysis and comparison, the 2020 PSP-SL team has decided to use the following altimeters and recovery hardware:

Avionics & Recovery	
Main Parachute	Skyangle Cert-3 XXL (120")
Main Deployment	800' AGL (Above Ground Level) (700' AGL redundant)
Drogue Parachute	Fruity Chutes Classic Elliptical (24")
Drogue Deployment	Apogee (+1s redundant)
Primary Altimeter	Altus Metrum Telemetrum
Redundant Altimeter	Missile Works RRC3+ Sport

Table 1.5: Avionics and Recovery Overview

1.3.4. Target Altitude

The target altitude for the 2020 PSP-SL team shall be 4325' above ground level (AGL). This altitude was chosen via a weighted-average estimate of the expected launch conditions in Huntsville and simulations of the full-scale vehicle's flight trajectory in OpenRocket, RASAero, and MATLAB.

1.4. Payload Summary

Figure 1.2: Complete Payload System

"The Friendly Ghost" - Autonomous Unmanned Aerial System (UAS)

The chosen payload is comprised of an unmanned aerial vehicle (UAV) and a portable ground control station. The UAV is capable of fully autonomous or remotely piloted flight and will be equipped with a lunar ice mining and storage system. The ground control station (GCS) will control and monitor the UAV and launch vehicle telemetry. The UAV will be mechanically stored and retained in the launch vehicle during flight and recovery, and upon landing will autonomously move to a recovery zone to extract and store a lunar ice sample.

2. Changes Made Since Critical Design Review

2.1. Changes Made To Vehicle Criteria

Construction / Vehicle

The lower airframe has been increased in length from 38” to 40”. This change was made to move the Center of Mass of the launch vehicle forward with respect to the Center of Pressure, which resulted in a slight increase of stability (0.12cal increase according to the OpenRocket model).
In addition, a trailing edge fin bevel has been added to each of the three fins, which is very similar to the leading edge fin bevel that was already part of the design at the Critical Design Review stage. This change was made to ensure a more streamlined flow of air over the fin surface, and to reduce flow separation off of the trailing edge to reduce energy losses due to pressure drag.
Due to a failed vehicle demonstration flight (VDF), the first launch vehicle which was constructed between CDR and FRR submission was damaged. This vehicle is being rebuilt, and as a result will likely differ in unballasted mass from CDR predictions. During the failed VDF it was discovered that the original vehicle was substantially underweight, and the asymmetric weight of the payload led to notable changes in flight characteristics. To solve these two issues an adjustable ballast system was attached to the aft end of the R&D System used on the new vehicle, with the capability to provide between 0 and 3¾ lbs of ballast mass.

Avionics and Recovery

The Telemetrum altimeter (v2.0b) was badly damaged in the Vehicle Demonstration Flight, so the team purchased a new one (v3.0) to use in all future flights as the primary altimeter. Once the original Telemetrum is repaired by the manufacturer Altus Metrum, it will be used as a simple tracker for the lower airframe in order to prevent the possibility of losing it again. The terminal blocks on the RRC3+ Sport were replaced with new ones because incorrect handling caused the screws to become severely stripped. The new Telemetrum as well as the RRC3+ Sport with the updated terminal blocks will undergo the Altimeter Continuity Test and the Altimeter Ejection Vacuum Test again prior to the reflight in order to ensure the requirements can still be met with these changes (these re-tests will be documented in the FRR Addendum). Additionally, the team will ensure the main parachute is packed extremely loosely inside the upper airframe because the Vehicle Demonstration Flight rose concerns about the ability of the main parachute to exit the upper airframe quickly enough to fully open at the required altitude.

There were a few documentation errors in the Critical Design Review report and presentation that have been addressed for Flight Readiness Review. One error was that it had been reported that the drogue shock cord is 20’ long and made of ½” tubular nylon and the main shock cord is 40’ long and made of ½” tubular nylon. In actuality, the drogue shock cord is 30’ long and made of ⅜” tubular kevlar and the main shock cord is 60’ long and made of ⅜” tubular kevlar. Also, the estimated descent velocity under the drogue parachute had been reported to be 130.9 ft/s. After review of the MATLAB code that had originally calculated this value, it was discovered that the drogue parachute had been modeled to be smaller than it actually is. When this was corrected, the estimated descent velocity under the drogue parachute was recalculated to be 93.9 ft/s, which is a much more acceptable value.

2.2. Changes Made To Payload Criteria

Since CDR, a number of design modifications have been made to the payload system. The UAV has seen several design modifications since CDR. Modifications to the UAV's electrical design were made to accomodate for electromagnetic interference. The size of the lunar ice procurement scoops was decreased to improve the UAV's ability to take off from the UAV retention system. The electrical system controlling the lunar ice procurement system was redesigned, allowing for independent control of each motor and increasing system reliability. The lunar ice procurement was also rotated on one side of the UAV such that the motors are on the same side allowing for compact wiring. The R&D system has also undergone some minor changes since CDR. A second, identical rack and pinion system was added to the opposite end of the UAV retention sled to mitigate a failure mode in which the UAV could not be safely retained if inverted upon launch vehicle landing. The embedded software controlling the R&D system also changed since CDR. The software controlling the serial communication between the system's microcontroller and the XBee radio was simplified significantly from its CDR form.

2.3. Changes Made to Project Plan

Since CDR, the team has used Microsoft Office Timeline to create a more visualized timeline which shows critical events between CDR and the end of the 2019-2020 competition. Additional social outreach events which occurred since CDR have been documented, requirements and verification plans have been reviewed and updated to have a more in-depth and accurate set of team-derived requirements, and testing plans have been updated with test results as testing has occurred. The funding plans have undergone an overhaul as a result of the additional cost necessitated by a second vehicle and payload demonstration flight. These changes are all implemented in Section 8.

3. Launch Vehicle Summary

3.1. Design and Construction of Launch Vehicle

3.1.1. Chosen Design

The launch vehicle design chosen for FRR consists of three main parts: the nose cone & upper airframe, avionics bay, and lower airframe. The total length of the built launch vehicle is measured at 127.00”, with a nose cone length of 36.00”, an upper airframe length of 48.00”, an avionics switch band connecting the upper and lower airframe that is 2.00” long, and a lower airframe which is 40.00” long. The overall length of the launch vehicle offers a good distribution of mass - the average Center of Mass (CM) is located at 76.412” and moves the fin set far enough aft to have good stability, as having the fin set far aft moves the Center of Pressure (CP) far aft.

The launch vehicle has a maximum outer diameter of 6.17” (upper and lower airframe body tube sections), and a maximum inner diameter of 6.00” (upper and lower airframe body tube sections). This diameter was chosen to maximize the available interior tube cross sectional area (and thus volume) for the payload and avionics section, which allowed an easy integration of the Payload Retention & Deployment (R&D) system, as well as the Avionics bay (see sections 6.3 and 4.1-4.4 respectively).

The fin set of the launch vehicle consists of three fins, equally spaced at 120° from each other. The fin set of three fins that has been chosen and manufactured creates less drag than a set of four fins would, and also helps the launch vehicle gain more altitude, as three fins weighs less than four. Fewer fins also help the motor accelerate the launch vehicle more easily, because of the reduced mass and drag compared to four fins. All three fins approximately weigh 2.28lbm, including their 1.5” high fin tabs. The epoxy fillets approximately weigh 1.76lbm .

The fin shape that has been chosen and manufactured is a trapezoidal “almost-clipped” delta fin shape. The chosen fin shape has a root chord of 12.00”, a tip chord of 4.0”, a height of 6.25”, a sweep length of 7.58” and a sweep angle of 50.5°. The thickness of the fin is approximately 0.1875”. The fin tab height is 1.5”. The fin also features a beveled leading & trailing edge for reduced dynamic drag and for better streamlining. The shape has been designed to optimize stability, while keeping dynamic and induced drag reduction in mind, and manufacturability (which was proven as manufacturing and installation were relatively easy processes).

The chosen motor that was installed is the Cesaroni Technology Inc. L1115 Classic 4 Grain Solid Rocket Motor (SRM). It was successful in giving the rocket enough thrust to reach the targeted apogee during the first demo launch on 02/15/2020. This will be discussed more in Section 5.3.

3.1.1.1. Structural Elements

Nose Cone & Upper Airframe Section

The upper airframe consists of the two main parts:

1. The nose cone assembly.
2. The 48” long upper airframe tube.

The nose cone has been designed and manufactured with drag reduction and optimal streamlining in mind, as well as with an increased internal volume, which helps house part of the payload Retention& Deployment system, as it interfaces with the upper payload coupler. The nose cone assembly consists of two main parts, which are the metal tip and a tipless cone made of G10 fiberglass. The metal tip is designed to be screwed onto the threaded upper interior of the tipless cone. The shape of the assembled nose cone is 5:1 Von Karman. The nose cone has a maximum diameter of 6.17” at its base, as the rest of the airframe, and is designed to be 36” long. The nose cone assembly design was proven to be sturdy enough, when even though the nose cone hit the ground at a higher velocity than what it was designed for after the failure of the drogue chute and parachute deployment during the Full-Scale Launch demonstration flight, it only suffered minor cracks near the base of the fiberglass cone. It was also proven to be easily manufacturable, since the new full scale launch vehicle nose cone differs slightly with the old full scale launch vehicle, within the expected manufacturing error.

The built nose cone assembly was also proven to have a good aerodynamic performance during the ascent of the full scale vehicle launch during the demonstration flight, since the nose cone perfectly withstood pressure at maximum velocity and the launch vehicle followed a smooth and as-expected trajectory. The aerodynamic performance of the nose cone was also validated using SolidWorks flow simulation, which is discussed more thoroughly in Section 3.1.1.3.2.

The upper airframe tube has been designed to be 48” long, with an outer diameter of 6.17” and an inner diameter of 6.0”. It is a single part made of G10 fiberglass, with holes to attach one 1515 rail button, four shear pins, and six screws/bolts for the payload Retention & Deployment system. The upper airframe is tasked with containing the main recovery gear of the launch vehicle (the main parachute), as well as interfacing with the payload and avionics bays. The upper airframe tube was initially cut to the correct length of 48”, then marked for the necessary holes that need to be drilled into it, which include the four shear pin holes at the interface with the avionics bay and the necessary holes for the rail button and payload retention & deployment system.

Avionics Bay Section

The avionics bay consists of:

- A G10 fiberglass coupler with an outer diameter of 6” to fit inside the upper and lower airframe which has a length of 14”
- Two G10 fiberglass bulkheads, made of 6” and 5.78” bulkplates, both epoxied together

- A G10 fiberglass switch band around the middle coupler with a length of 2", inner diameter of 6"and outer diameter of 6.17"
- Four off-the-shelf black powder canisters (not taking structural loads)
- Two steel threaded rods, cut in length of 16"
- Two steel I-bolts on each bulkhead to attach the shock cords
- Four 3D-printed PLA Switch Holders
- 3D-printed PLA Altimeter/Battery Sled
- 3D-printed PLA Camera Sled
- One 1515 rail button, aligned with the upper airframe & lower airframe rail buttons
- Epoxy connections

The avionics bay is assembled together by epoxying the switch band onto the middle of the avionics coupler. A 6" and a 5.78" bulkplate are epoxied together to create each bulkhead, after they have been lined up with a hole for an I-bolt to be attached in the middle. The threaded rods are also inserted into holes on the bulkheads. The camera sled is mounted onto the threaded rods. The switch holders and camera sled are epoxied inside the coupler in their specified locations, below the holes on the switch band. The 1515 rail button is inserted into a hole on the switch band.

Lower Airframe Section

The lower airframe assembly consists of:

1. The motor tube that houses the motor casing
2. The motor casing
3. The motor retainer
4. Three centering rings
5. The 40" long lower airframe
6. A fin set consisting of three fins, equally spaced at 120° from each other
7. One 1515 rail button, aligned with the upper airframe & avionics switch band rail buttons
8. Four shear pins that interface with the avionics coupler
9. Epoxy connections and internal and external epoxy fin fillets
10. The drogue chute
11. The drogue chute's shock cord that is epoxied onto the motor casing

The lower airframe components have been manufactured from G10 fiberglass including the fins, centering rings, motor tube, and lower airframe. Off-the-shelf parts of the assembly include the motor casing, motor retainer, drogue chute, kevlar shock cord, 1515 rail button, and shear pins. The fin set component is one of the most important components of the launch vehicle, since it provides stability by moving the Center of Pressure aft, while the internal structure that is bonded together with epoxy takes all the thrust, and thus force and stress, from the motor. The design integrity has been validated with Finite Element Analysis for motor thrust, dynamic drag, and lift forces on the fins. The flow characteristics have been validated with SolidWorks flow analysis, as well as from the ascent of the full scale launch vehicle during flight demonstration, where the fins provided the expected stability for the launch vehicle to follow a smooth trajectory and the structure was observed to be intact.

3.1.1.2. Electrical Elements

Avionics Bay Wiring

Each of the altimeters is wired to a corresponding battery to receive power. The Telemetrum altimeter, used for the primary main and drogue release, is connected to a 3.7V LiPo battery and the RRC3+ Sport altimeter, used for the redundant main and drogue release, is connected to a 9V alkaline battery. Furthermore, each altimeter is connected to its own external switch so that it can be turned either on or off from outside the vehicle.

The Telemetrum is wired to the primary ejection charges for drogue and main. Both the main and drogue parachute have their own ejection charge. The redundant altimeter, the RRC3+ Sport, is also connected to the redundant main and drogue ejection charges. These redundant ejection charges have a one second delay in release, and are used to release the corresponding parachute if the primary ejection charges have failed. In the event where there are no failures, the redundant charges go off harmlessly. Therefore, all four ejection charges fire at some point during the flight.

Avionics Switches

Two 0.827" X 0.591" X 0.543" rocker switches are utilized for the avionics system (one for each of the primary and redundant altimeter systems). Two other rocker switches are also used to turn the camera system on or off and to start or stop recording. Switch holders secure the switches to the inside of the coupler while still allowing them to be accessed from the outside of the vehicle. They are sized to house the switches with as little excess material as possible and have a curve that conforms to the inner diameter of the coupler to ensure a secure fit. Additionally, wire sheaths are placed around each pair of switch wires in order to increase organization and ensure the wires are not pulled out of place when the altimeter sled is inserted into the avionics bay.

Avionics Board (Altimeter) and Battery Retention

Within the avionics bay and on the threaded rods, the avionics sled and battery compartment are combined into a single part. On one side is the Telemetrum and the 9V battery (for the RRC3+ Sport), and on the other side is the RRC3+ Sport and the 3.7V LiPo battery (for the Telemetrum). Placing each battery directly underneath (on the opposite side of the sled) its corresponding altimeter allows for the battery wires to need to cross as short a distance as possible. The altimeters are secured through nylon mounting posts that are screwed in and glued into place on the 3D printed avionics sled, as well as nylon screws on the top face of the altimeters. The batteries are placed into dedicated compartments that are built into the sled. The avionics sled is located aft of the camera sled, with the Telemetrum antenna pointing up as well as the opening to the batteries (to ensure they stay in place during launch). A "battery guard" part covers the opening to the batteries and serves to hold them in place when the launch vehicle is upside-down in the air while still allowing the batteries to be wired.

3.1.1.3. Important Component Design

3.1.1.3.1. Launch Vehicle Fins

A fin set has been built and integrated onto the lower airframe that consists of three fins, equally spaced at 120°. The set of three fins weighs less and creates less drag than a set of four fins would, and thus helps the launch vehicle gain more altitude. Each fin weighs 0.76lbm on average including the fin tab. All three fins together weigh approximately 2.28lbm, including the fin tabs. The total epoxy of the fin fillets (outer and inner) weighs 1.76lbm.

Using OpenRocket, the fin shape has been optimized for stability, manufacturability and reduced drag. The final fins have a trapezoidal, near clipped delta, fin shape. The chosen fin design has a root chord of 12.00”, a tip chord of 4”, a height of 6.25”, a sweep length of 7.58” and a sweep angle of 50.5°. The thickness of the fin is approximately 0.1875”. The fin tab height is 1.5”. The fin includes a leading & trailing edge bevel for better streamlining and reduced drag as well.

The team decided upon a 50.5° sweep angle for fins as it resulted in the farthest aft CP, which in turn resulted in higher vehicle stability. The 4” tip chord also provided the optimum stability to drag ratio. The team decided upon G10 fiberglass for the fins due to its strength and workability. In order to ensure the strength of the 0.1875” thick fiberglass fins, FEA was performed on the structure.

Flight FEA Results

FEA was used to aid in re-verification of the full-scale fin design, after the design changes for FRR, which included a larger leading edge fin bevel, when compared to the CDR leading edge fin bevel, and the addition of trailing edge fin bevel. The team analyzed the effect of dynamic drag forces on the fin edge and the result of the bending moments caused by lift and drag, on a model that is exactly dimensioned as the built fins.

For both the lift force (bending) FEA and dynamic drag force FEA , the same updated fin model was used, with the same material properties defined in both cases (G10 fiberglass) and the same fixing locations on the fin tab. Compared to the CDR fin design, the structural integrity is similar, with a slight improvement being noticeable when it comes to dynamic drag force stress experienced, which is lower with the updated design, but a small increase in the stress experienced by lift forces and the resulting bending moment.

Lift Force FEA Results

FEA for lift forces on the fin was done in Solidworks with an applied force of 50N at the tip of the fin, on a trapezoidal surface area of 0.2524in^2. The pressure on the specified area on the fin tip is 44.5397psi, which is approximately 3atm of pressure. The fin was fixed at the fin tab surfaces before the application of the force on the fin tip. This fixing simulates the way the fin is epoxied to the lower airframe and motor tube. This provides the team with a good safety factor for verification of the structural integrity of the fins.

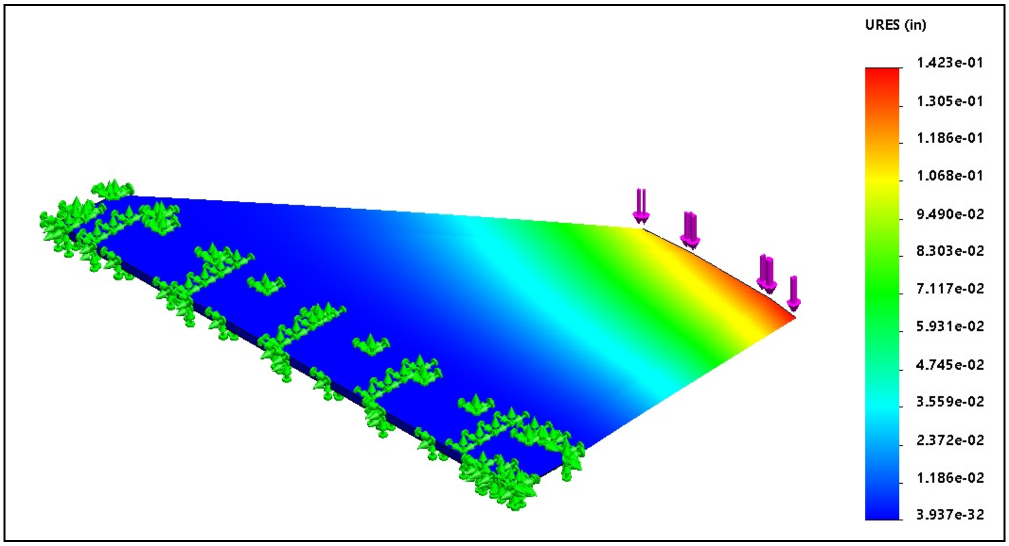


Figure 3.1: Fin Lift Force FEA Displacement Results

Figure 3.1 above shows a diagram with displacement caused by the bending force, with a maximum displacement of 1.423e-01" and a minimum displacement of 3.937e-32". The displacement is constant from fore to aft, with the smaller values towards the fin root and gradually larger values towards the fin tip.

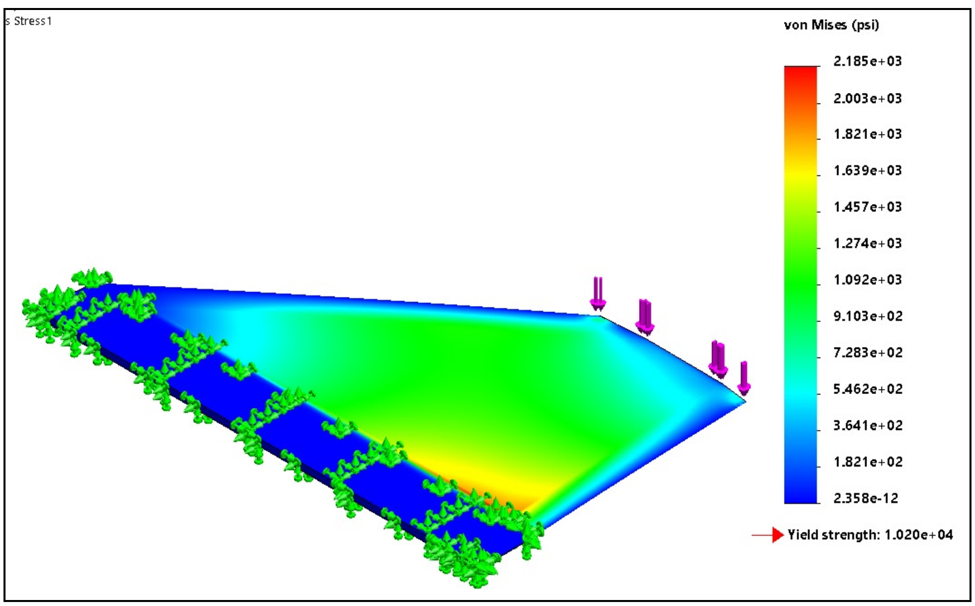


Figure 3.2: Fin Lift Force FEA Von Mises Stress Results

Figure 3.2 above shows a diagram of the Von Mises stresses experienced by the fin under the same conditions. The small red area on the rear corner of the root of the fin experiences the maximum stress, which is 2.185e+03psi and is well below the yield stress of the material, which is 1.020e+04psi. This simulation verifies the structural integrity of the fin, as there is no point exceeding the yield stress value by at least an order of magnitude. The values keep becoming gradually smaller values towards the centre of the fin and the minimum value is experienced along the leading & trailing edges of the fin, as well as the front corner of the root of the fin.

Dynamic Drag Force FEA Results

FEA for the dynamic drag forces on the fin was done in Solidworks with an applied force of 800N distributed along the leading edge of the fin, on a beveled surface area of 5.6588in^2. The pressure on the specified area on the fin tip is 31.8psi, which is approximately 2atm of pressure. This is approximately 2 times higher than the maximum pressure that is expected, as can be seen in the flow simulation pressure plots in the flow simulation sections. The fin was fixed at all of the five fin tab surfaces before the application of the force on the fin leading edge. The fixing that was done simulates the way the fin is glued onto the motor tube, lower body tube and centering rings with epoxy, which is shaped in fillets. This provides a strong safety factor for verification of the structural integrity of the fins, as it is highly unlikely for the fin to experience such substantial pressures on the fin leading edge, as the maximum velocity is well below Mach 0.5.

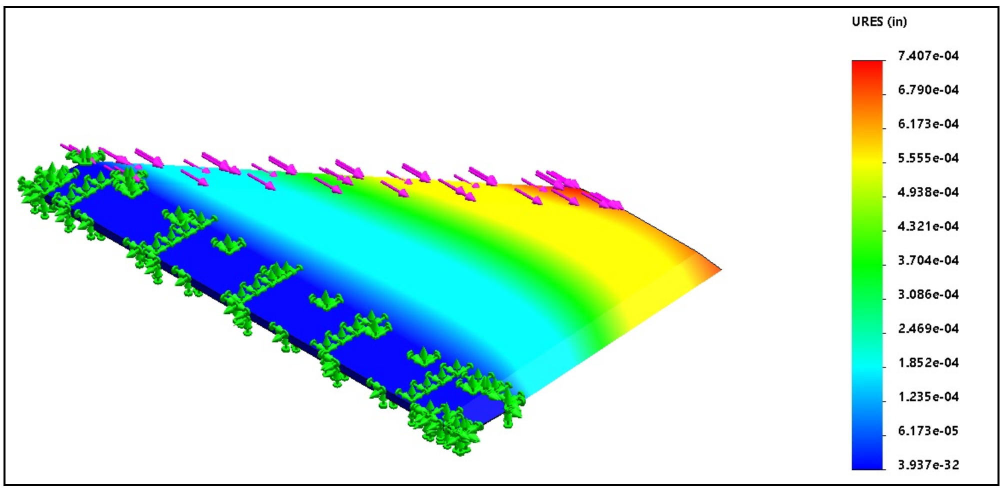


Figure 3.3: Dynamic Drag Force Displacement on Fin

Figure 3.3 above shows a diagram with displacement that is caused by the dynamic drag force, with a maximum displacement of 7.407e-04". The displacement is linear throughout the fin, with the smaller values towards the fin root and the gradually larger values towards the fin tip, to reach the maximum at the fin tip.

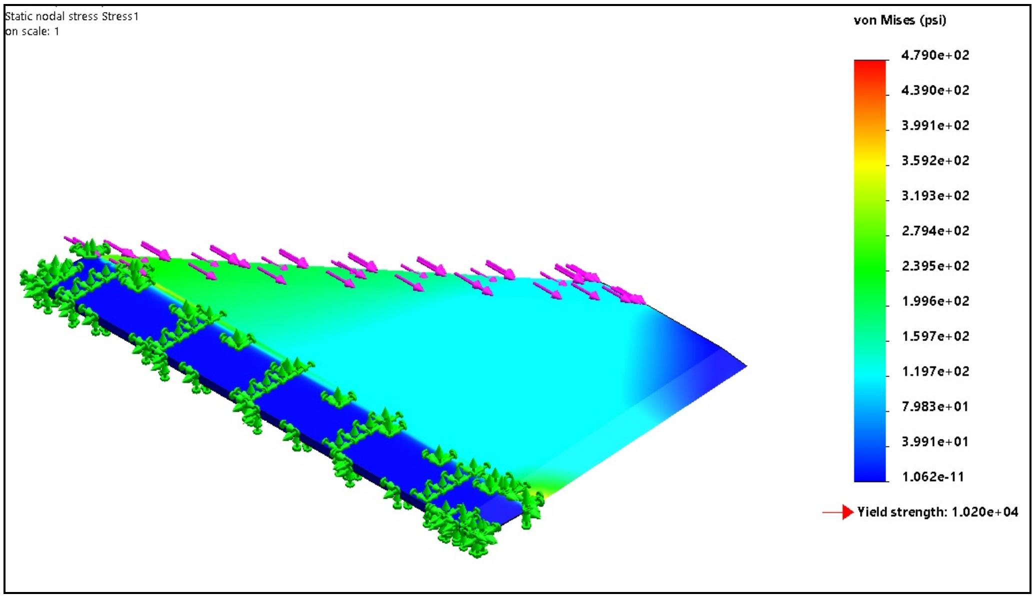
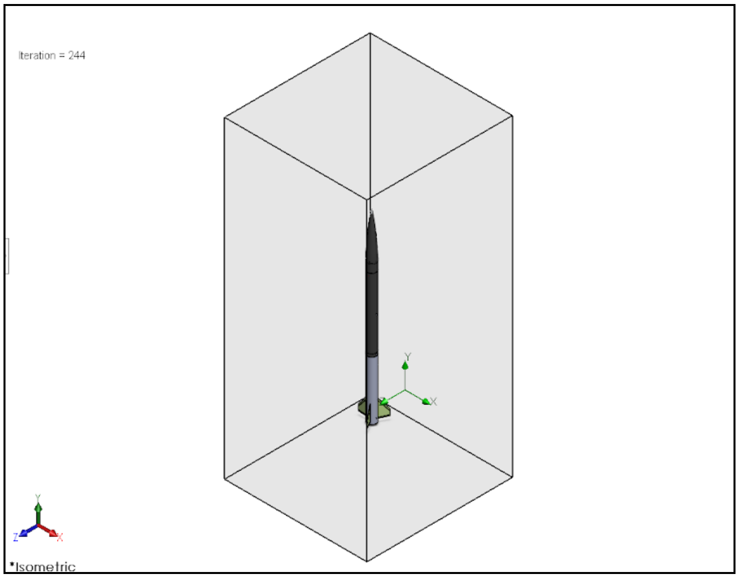


Figure 3.4: Dynamic Drag Force Von Mises Stress on Fin

Figure 3.4 above shows a diagram of the Von Mises stresses experienced by the fin under the same conditions. The Von Mises stress diagram has a small red area on the front corner of the root of the fin experiencing the maximum stress, which is 4.790e+02psi and is well below the yield stress of the material of 1.020e+04psi. This simulation verifies the structural integrity of the fin from this aspect as well, as it is unlikely to exceed the yield stress value by at least two orders of magnitude.

3.1.1.3.2. Updated Launch Vehicle Flow Analysis

Launch vehicle flow analysis is another important part of fin design verification, and is done using Solidworks. Launch vehicle flow analysis is used to verify the airflow over important airframe components, namely the nose cone and the fins to demonstrate how these will perform during flight. Nose cone and fin flow analysis helps verify the advantages of the chosen nose cone and fin shapes. In this updated flow simulation, the computational domain used a 3D model of the launch vehicle's airframe. This provided more accurate results compared to piecewise computational domains.



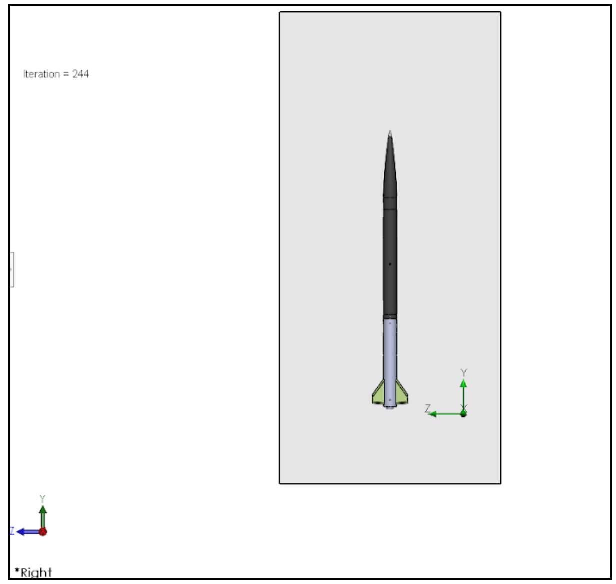


Figure 3.5: Isometric View of the Computational Domain (LEFT)
Figure 3.6: Side View of the Computational Domain (RIGHT)

The flow simulation assumes steady flow at a downward velocity of 560ft/s.

This flow simulation is for steady flow characteristics, with predefined air from Solidworks used as the fluid. The velocity setting is 560ft/s, and represents the flow conditions at the time when the motor shuts down and the launch vehicle has reached maximum velocity. This velocity magnitude is equal to 0.5 Mach at sea level, which is slightly larger than the maximum velocity magnitude predicted by OpenRocket simulations. It is assumed that the rocket follows a nearly vertical path during the motor burn, with gravity set to be in the -Y axis direction. These settings provide an accurate flow simulation for the launch vehicle, simulating the airflow conditions near maximum velocity, which is achieved at the moment the motor shuts down. Validity of the flow simulation and expectations about the results are based on the OpenRocket simulations, as well as further verifications conducted with RASAero II and hand/code calculations as well.

Fin & Lower Airframe Flow Analysis Results

This section focuses on the lower airframe flow analysis, which is one of the most significant parts to simulate air flow around, since the lower airframe contributes most to the launch vehicle's overall stability, as the triple fin set moves the CP toward the aft end to provide aerodynamic stability.

The results of the flow simulation, shown below in Figure 3.7, for the fins and lower airframe are as expected, as the flow around the lower airframe is smooth and laminar, as can be seen from the streamlines and the velocity contour.

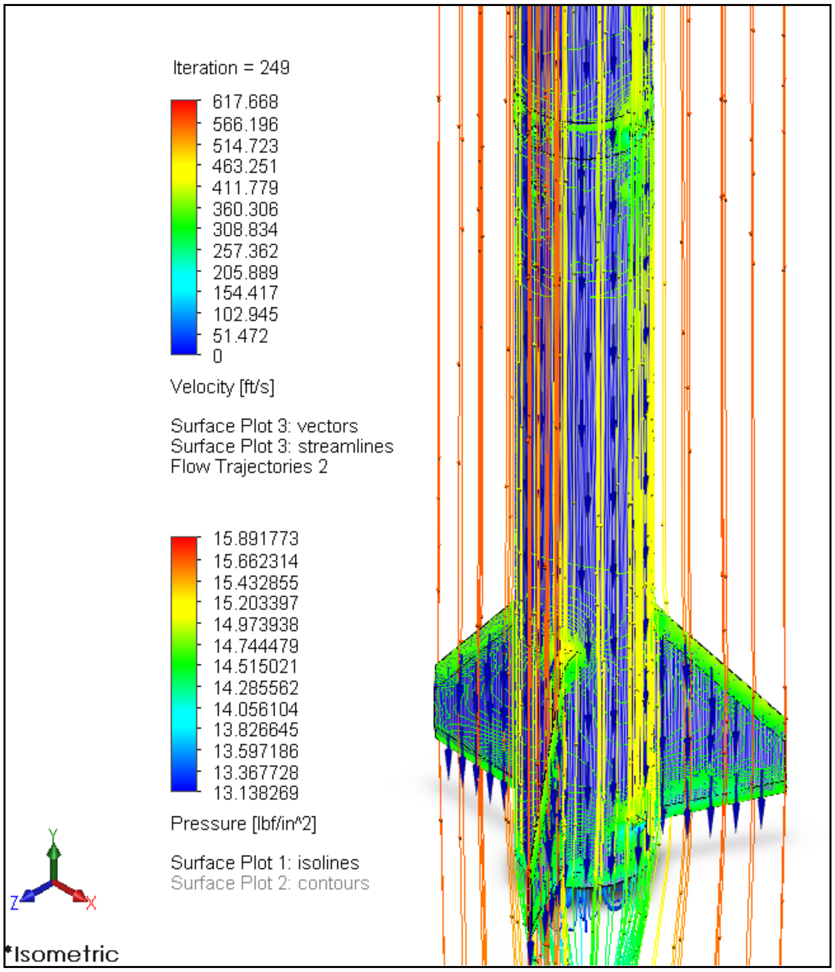


Figure 3.7: Full-Scale Lower Airframe Flow Analysis

Velocity Vectors & Streamlines Surface Plot

In the isometric view of Figure 3.8 below, the airflow can be seen moving downward in smooth streamlines, except for around the rail buttons and the leading edges of the fin root fillets, where velocity changes direction according to the vectors, which is expected. The surface plot shows the color of the streamlines and air velocity vectors, which are dark blue on the fins, as well as the whole lower airframe, meaning the air velocity near the surface of the launch vehicle is in the range of 0ft/s to 51ft/s. This is expected, as the air closest to the surface of the fins and the lower body tube the air forms a boundary layer, due to the air's viscosity, and thus airflow shearing, where the velocity is close to 0ft/s.

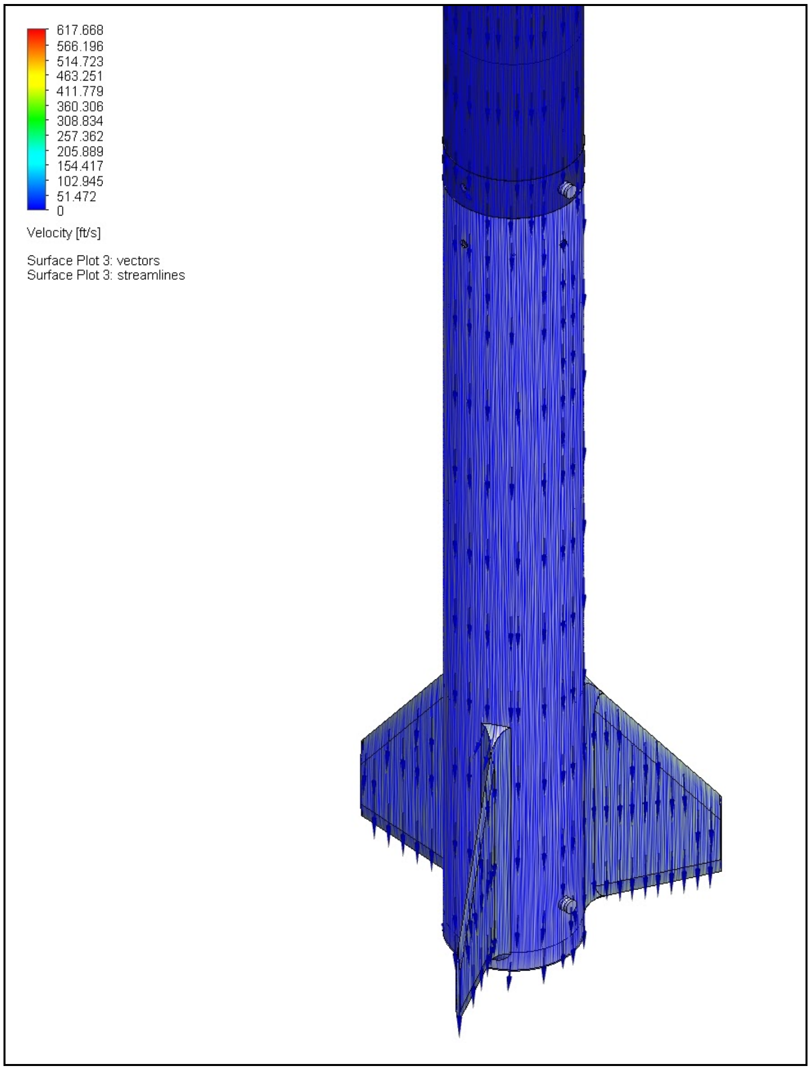


Figure 3.8: Velocity Vectors and Streamlines on Lower Airframe

Pressure Isolines Surface Plot

As seen from the isometric diagram of the pressure isolines contour plot, the pressure isolines of the incoming air are dense at the top of the avionics switch band, signifying several different levels of pressure in the same region and thus a rapid change in pressure. The isolines progressively become less dense toward the bottom of the airframe, which means there is a smooth change in pressure (range is within 14.2-14.9psi). The pressure increases again, progressing from between 14.2psi and 14.9psi to reach a maximum at the leading edges of the fins and at the front of the fin fillet roots (within 14.9psi to 15.4psi). At this point, the isolines become dense again, signifying a rapid increase in local pressure, followed by a decrease in density across the fin surface as the flow progresses toward the trailing edge of the fin (within the range of 13.8psi to 14.1psi) and the end of the lower airframe. There is also a rapid increase in pressure above each rail button, as they act as a stagnation point, while there is a rapid and dense pressure decrease behind each rail button due to flow separation.

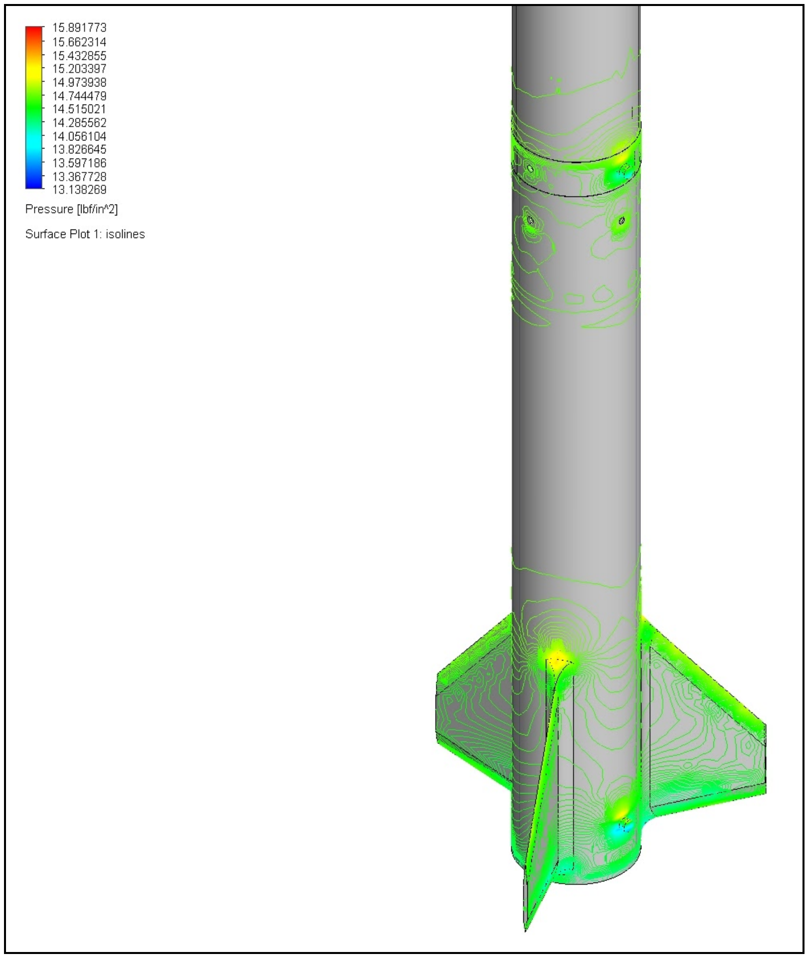
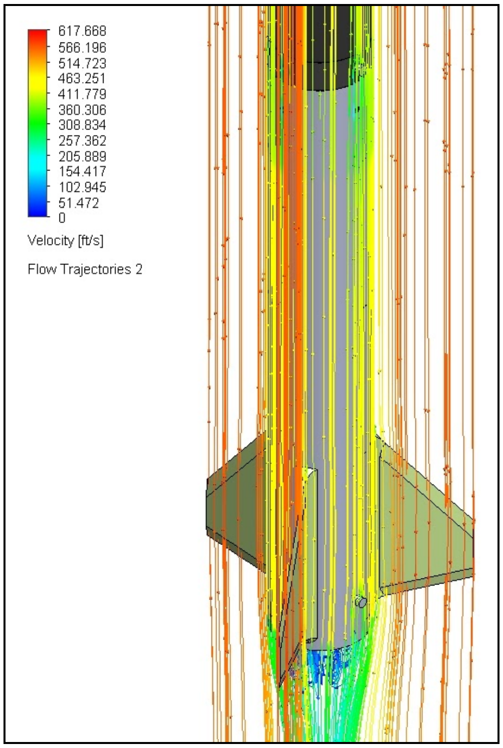


Figure 3.9: Isometric View of the Pressure Isolines Surface Plot on the Lower Airframe

Flow Trajectories with Velocity Contour

In the pictures below, flow trajectories can be seen, which have been contoured according to velocity magnitude, with a velocity setting at -560ft/s on the Y axis (the negation indicates the direction of the velocity). The maximum velocity of the air can be seen near the outer streamlines, which are mostly dark-orange (586.2ft/s) and red-colored, and has a magnitude of 617.7ft/s . The air velocity can be seen becoming gradually smaller in value as the streamlines become closer to the vehicle surface. The air velocity magnitude becomes significantly smaller near the green-colored area at the front of the fin root fillet, which is within the range of 257.4ft/s to 360.3ft/s. The air velocity values on the vehicle's surface can be seen approaching very small values toward the upper part of the airframe, at the locations of the vent holes, where the air velocity streamlines are colored cyan (reaching magnitudes as low as 147.8ft/s). This is expected due to airflow viscosity and shearing, since the air inside the launch vehicle is nearly stationary with respect to airflow outside of the airframe. The global minimum air velocity values can be found inside the airframe (0ft/s), where the flow velocities have random directions and very small magnitudes due to the airflow shearing caused by the vent holes in the airframe. The global minimum is also reached at the bottom of the motor tube, where air velocity magnitudes are in the range of 0-51.4ft/s. As can be seen from the flow trajectories, a vortex is formed in this region, again due to airflow shearing. This would be observed at the time the motor shuts down and the vehicle travels momentarily at maximum velocity, close to 560ft/s. While the motor is still operating, the airflow would be mostly influenced by the propellant gases exiting the motor nozzle at very high velocities and pressures. Below, both an isometric and a side view of the flow trajectories can be seen:



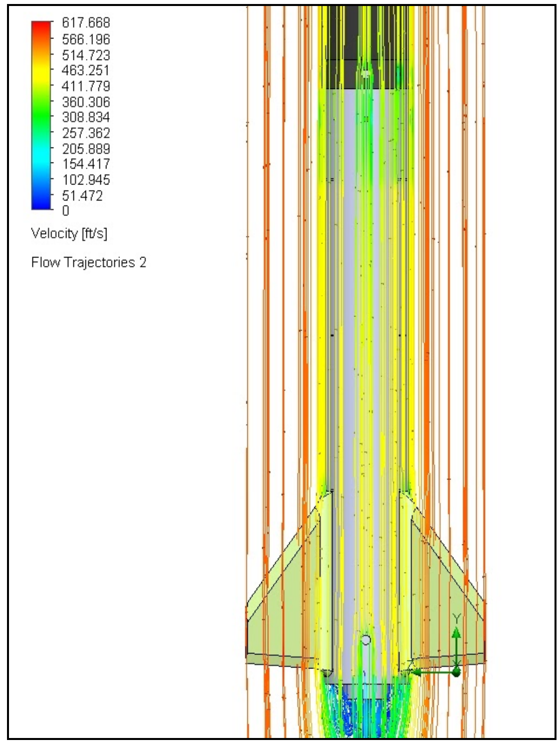


Figure 3.10: Isometric View of the Flow Trajectories on the Lower Airframe (LEFT)
Figure 3.11: Side View of the Flow Trajectories on the Lower Airframe (RIGHT)

Nose Cone Flow Analysis

Nose Cone Flow Analysis was conducted using Solidworks. This is the same study that was used for the lower airframe fin flow analysis, with steady flow conditions. The computational domain is the same and includes the whole vehicle, as seen in the previous section. This section of the flow analysis focuses on the nose cone, as well as part of the upper coupler and upper airframe.

The results of the flow simulation, shown below in Figure 3.12, are as expected, with smooth, laminar airflow around the nose cone and upper airframe. These results can be seen in the streamlines and the velocity contour, shown below.

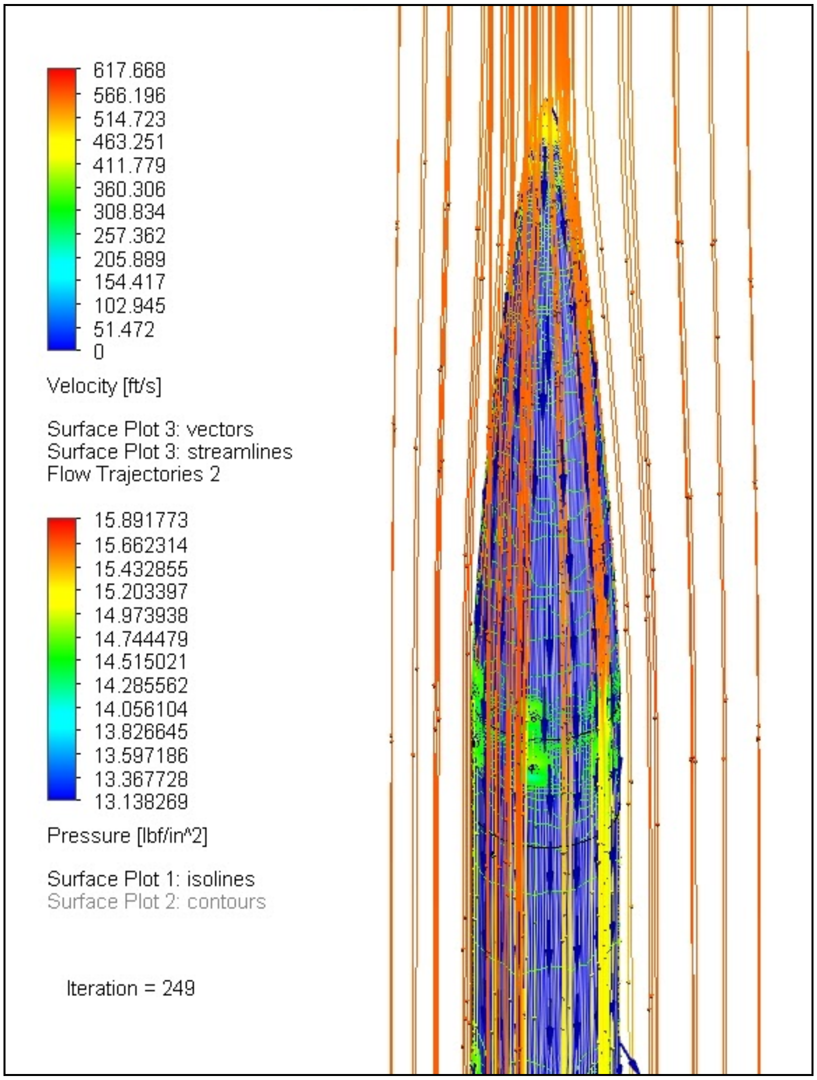


Figure 3.12: Flow Simulation Results Nose Cone & Upper Airframe

Velocity Vectors & Streamlines Surface Plot

In the isometric view of Figure 3.13 below, the airflow can be seen moving downward in smooth streamlines, except for the rail button on the upper airframe tube and the screwheads on the upper coupler, where the velocity changes direction according to the vectors, as expected. The surface plot shows the color of the streamlines and air velocity vectors, which are dark blue on the fins, as well as the whole lower body tube, meaning the air velocity near the surface of the launch vehicle is in the range of 0 to 51ft/s. This is expected, as the air closest to the surface of the nose cone and the upper airframe the air forms a boundary layer, due to the air's viscosity and thus, the occuring airflow shearing, where the velocity is close to 0ft/s.

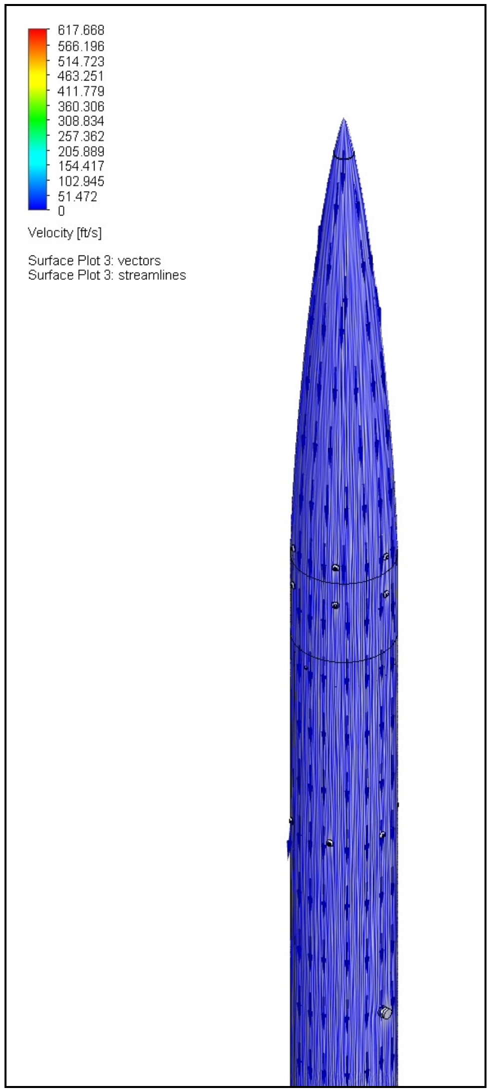


Figure 3.13: Velocity Vectors and Streamlines on Nose Cone & Upper Airframe

Pressure Isolines Surface Plot

Figure 3.14 shows a surface plot of pressure isolines on the nose cone and upper airframe. As seen from the plot, the pressure isolines of the incoming air are dense at the metal tip of the nose cone, which means there are several different levels of pressure in the same region, and thus a rapid change in pressure. These isolines progressively become less dense further down the airframe, which means there is a smoother change in pressure. The pressure values increase again around the screwheads, progressing through a range of 14.2psi to 15.4psi. The isolines at these regions also become dense again, showing a rapid increase in local pressure, and a radial decrease in density and magnitude around each of the screwheads. As the flow progresses towards the upper airframe, isolines become even less dense and are again within 14.2psi to 14.9psi, which is reasonable, since the airframe has a constant cross sectional area while progressing downwards, unlike the nose cone. Finally, rapid changes in pressure density and magnitude are observed in front of and behind the upper body tube rail button.

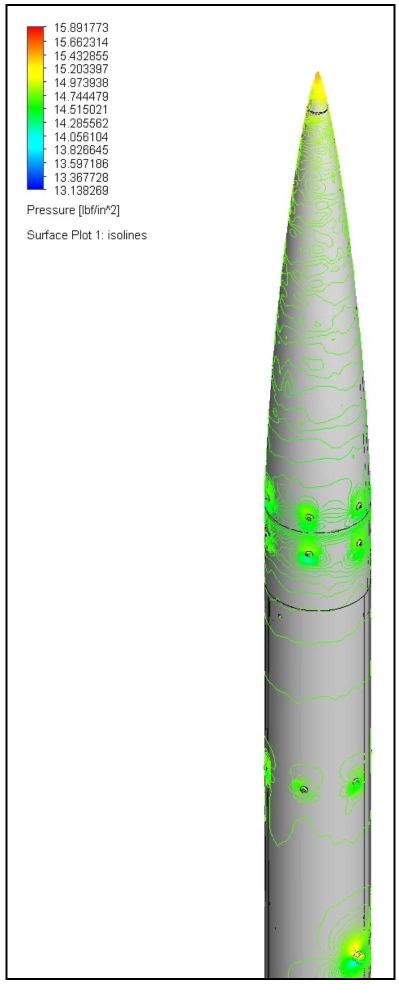
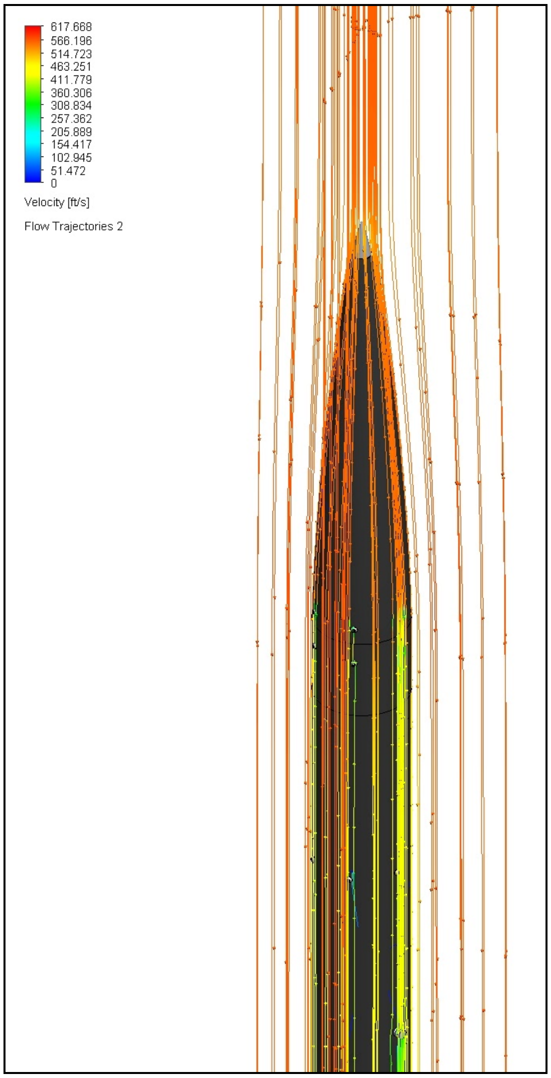


Figure 3.14: Isometric View of the Pressure Isolines Surface Plot on the Nose Cone & Upper Airframe

Flow Trajectories with Velocity Contour

In the pictures below, flow trajectories can be seen which have been contoured according to velocity magnitude, with a velocity setting at -560ft/s on the Y axis (the negation indicates the direction of the velocity). The maximum velocity of the air can be seen near the outer streamlines and has a magnitude of 617.7ft/s . The air velocity can be seen becoming gradually smaller in value the closer the streamlines are to the nose cone and the upper body tube, showing viscous effects. The air velocity values on the vehicle's surface can be seen approaching very small values at the upper airframe tube, at the locations of the screwheads and the rail button, where the air velocity streamlines reach magnitudes as low as 147.8ft/s. This is expected due to airflow viscosity & shearing, since the air behind each screwhead and the rail button is moving at much lower velocities when compared to airflow around the same cross sectional area. Inside the airframe the flow velocities have random directions and very small magnitudes due to the airflow shearing caused by the vent holes in the airframe.

Below, both an isometric and a side view of the flow trajectories can be seen:



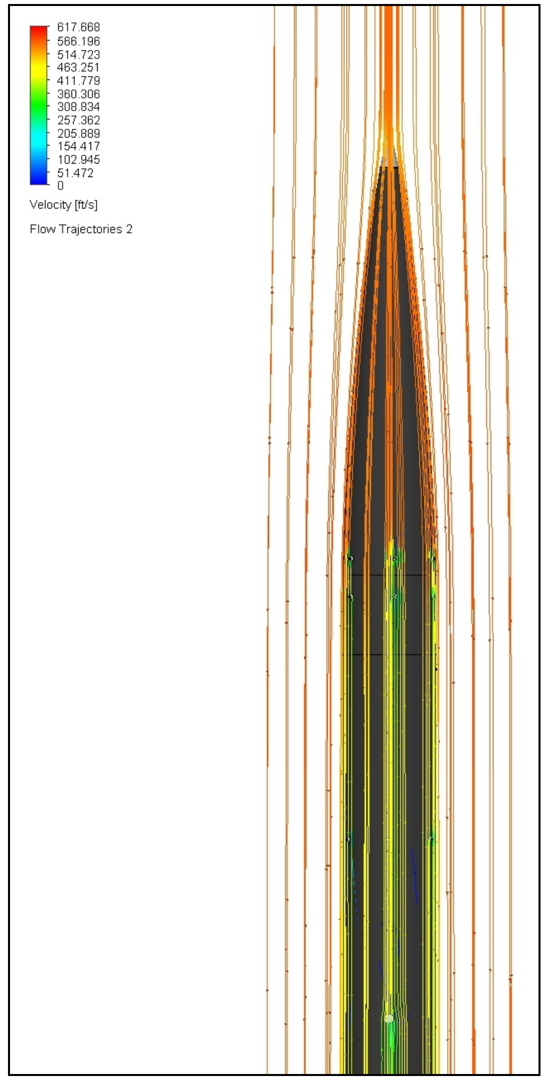


Figure 3.15: Isometric View of the Flow Trajectories on the Nose Cone & Upper Airframe (LEFT)
Figure 3.16: Side View of the Flow Trajectories on the Nose Cone & Upper Airframe (RIGHT)

3.1.1.3.3. Payload Parachute Bulkhead

Unlike the traditional bulkheads used in the avionics bay, the location and forces endured by the Main Parachute Bulkhead necessitate machining of the part from aluminum. The avionics bulkheads use clamping around a coupler to maintain their position inside the rocket, but that method is not an option at the forward of the rocket due to the payload bay. The use of aluminum enables the creation of structures not manufacturable out of plate fiberglass. These structures are a weight reducing web, and holes drilled around the radius of the part, allowing it to be mounted into the rocket directly. In order to simulate the worst-case scenario, the following analyses were performed with a 1800lbf load placed on a surface of equal diameter to flange on the chosen bolt that attaches to the main parachute. The material for each study was 6061 T4 Aluminum.

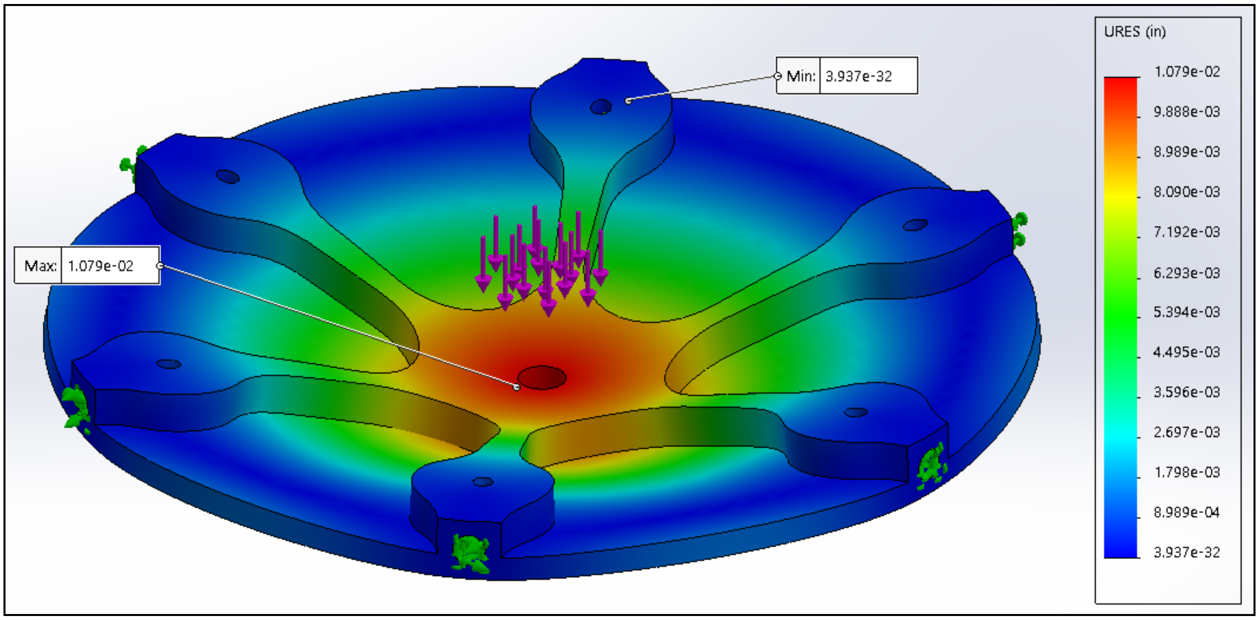


Figure 3.17: Displacement of Main Parachute Bulkplate (Scale: 55.6)

During the forces of main parachute deploy, the above displacement is expected to be present on this bulkplate. With a maximum displacement of .011", the plate can be considered to experience little to no change in shape during deployment.

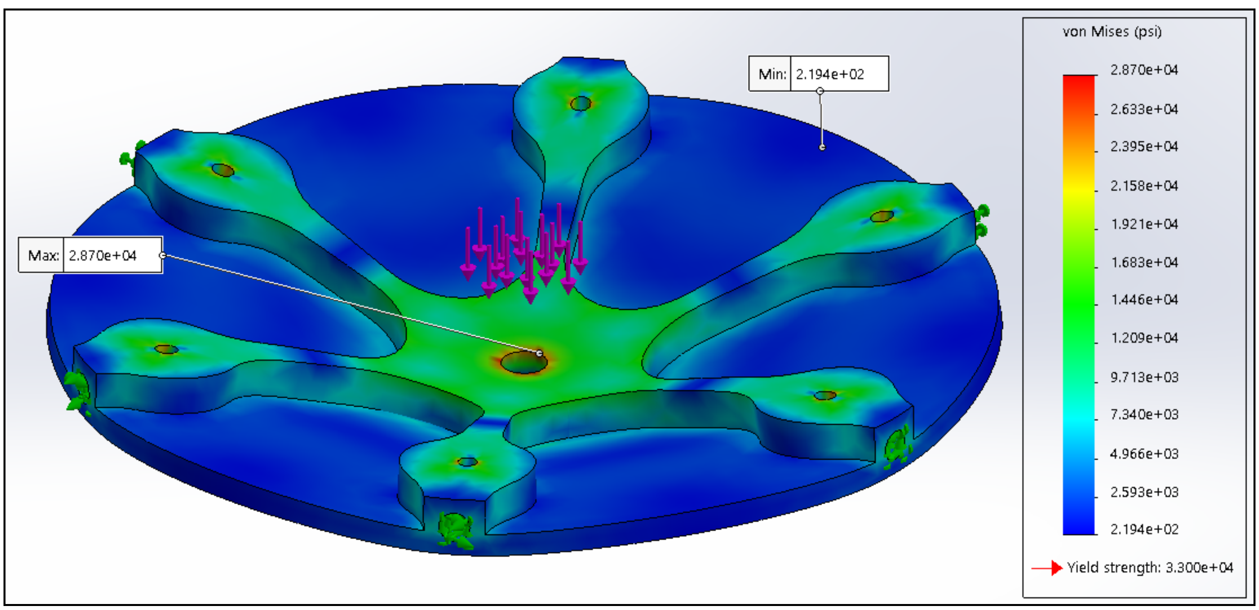


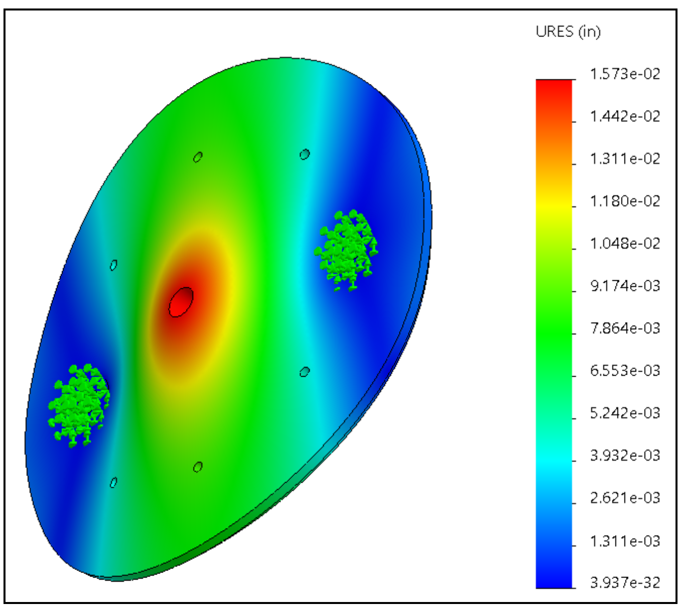
Figure 3.18: Von Mises Stresses within the Main Parachute Bulkplate (Scale: 55.6)

By iterating the part through a series of Von Mises FEAs the team has decided upon the above design to ensure that loads are accounted for with a meaningful factor of safety. The highest load on the part (2.87e+04psi) is below the yield strength of the material, and only appears as an edge effect around the attachment hole of the main parachute. The majority of the part is well below the yield stress of 6061, and as such can be considered reliable and safe to fly - even overbuilt.

3.1.1.3.4. Avionics Bay Bulkheads

The bulkhead design features a circular plate with varying diameters. The larger disk has a diameter of 5.998" and the smaller disk has a diameter of 5.775". The thickness of each respective disk is 0.125". This is to allow the bulkhead to fit perfectly into the coupler. The bulkhead has one 0.3" diameter hole in the center to fit an I-bolt, two 0.3" diameter holes located 2" away on either side to fit the threaded rods, and six additional holes with diameters suitable for 440 screws spaced evenly about the same circumference as the threaded rod holes. These holes are used to secure two 8g capacity black powder canisters and two terminal blocks, which are placed on opposite sides from each other on the bulkhead. The remaining two holes are used to feed the lighter connection wires from the interior of the coupler to the terminal blocks.

The material used in the bulkheads is A-glass fiber (a type of fiberglass). The appropriate material properties (such as elastic modulus, Poisson's ratio, shear modulus, and tensile strength) were retrieved from Matweb.com. A 1500lbf simulation was run to simulate the Von Mises forces acting on the bulkhead and the resulting displacement due to the main parachute opening (see Section 3.1.1.3.5). The force was simulated to be acting on the area on the inside of the bulkhead where the washer that holds the eye-bolt in place makes contact. Fixtures were placed on the areas on the outside of the bulkhead where the washers that hold the threaded rods in place make contact.



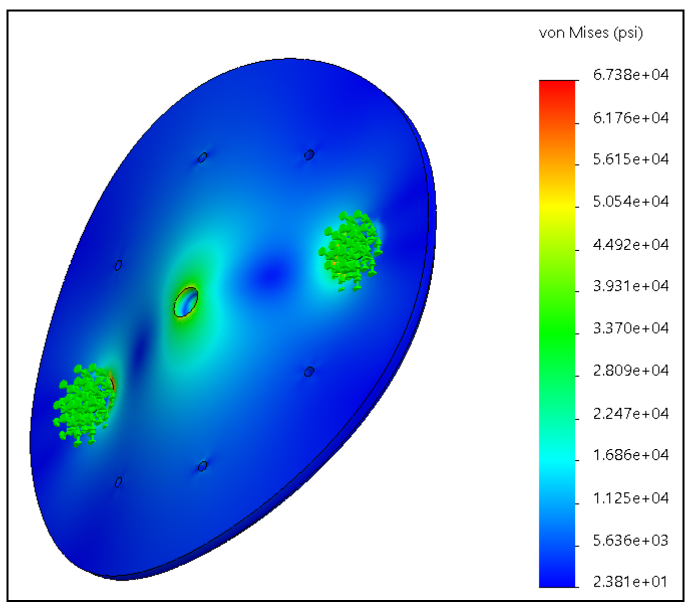


Figure 3.19: Displacement of Avionics Bay Bulkhead (LEFT)
Figure 3.20: Von Mises Forces on Avionics Bay Bulkhead (RIGHT)

Figure 3.19 shows a screen capture of the translational displacement of the bulkhead. The maximum experienced translational displacement is 0.01573", located around the eye-bolt hole in the center of the bulkhead. Figure 3.20 shows a screen capture of the Von Mises forces experienced by the bulkhead. The maximum experienced stress is 67.38ksi, located around the inside of the threaded rod holes as well as around the eye-bolt hole. This is far below the yield stress of the material, meaning that the bulkhead will not experience any deformation beyond the elastic range. This demonstrates that the team has chosen the proper material and thickness for this component to withstand the expected flight forces, particularly the deployment of the main parachute, where the most force is expected.

3.1.1.3.5. Main Parachute Shock/Tension Study and Calculations

The 2020 PSP-SL team wanted to expand the team's understanding of the forces on the launch vehicle as a result of the parachutes used. For this study, it is assumed that both parachutes are deployed. The body of the vehicle at this moment can be segmented as shown in Figure 3.21:

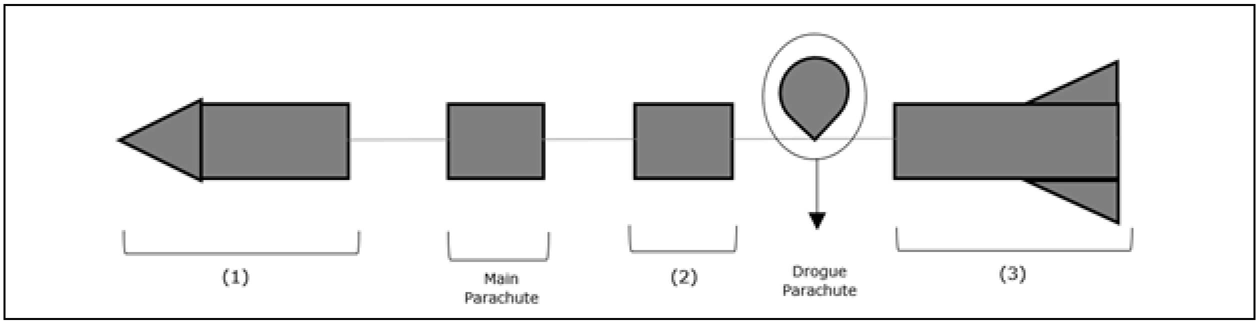


Figure 3.21: Separation of Vehicle into Bodies for Analysis

(1) Nosecone and upper airframe
(2) Avionics bay
(3) Lower airframe, nozzle, and fins

The calculations for the tension force consider the tension acting on the bulkheads by two different bodies. The calculations and diagrams for each body are as follows:

Body 1 – Vehicle

The vehicle consists of masses (1), (2), and (3). For this calculation it is assumed these masses act as a single body without fuel (53.2lbm). Figure 3.22 illustrates the forces acting on it:

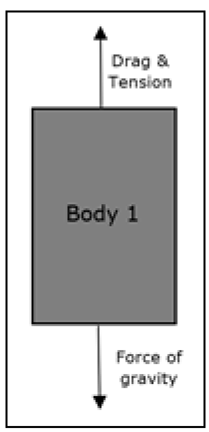


Figure 3.22: Body 1 Free Body Diagram

The drag and tension force acts upwards towards the main parachute and the force of gravity (F_g) acts downwards. According to Newton's second law, the force equals the object's mass times its acceleration. Hence the forces on body 1 can be written as:

$$Drag + Tension - F_g = (Mass_{Total} * Acceleration)$$

Therefore,

$$Tension = (Mass_{Total} * Acceleration) - Drag + F_g$$

The total mass of the body, drag force, and the force of gravity can be calculated as shown below. The free stream density and velocity values are calculated with a MATLAB script and found to be 0.002387slugs/ft^3 for free stream density and 41.27ft/s for free stream velocity. The coefficient of drag varies from one part of the body to the other and can be obtained from product specifications:

$$Mass_{Total} = Mass_{(1)} + Mass_{(2)} + Mass_{(3)} + Mass_{Drogue} + Mass_{Shock\ cord\ of\ drogue} = 49.20lbm$$

$$Drag = Coefficient_{Drag} * 0.5 * Density_{Free\ stream} * (Velocity_{Free\ stream})^2 * Area$$

$$Drag_{Total} = Drag_{(1)} + Drag_{(2)} + Drag_{(3)} + Drag_{Drogue} + Drag_{Shock\ cord\ of\ drogue} = 340.97lbf$$

$$Force\ of\ gravity = 32.2 * Mass_{Total} = 1582.96lbf$$

In order to calculate the acceleration, it is assumed that all three masses, including the drogue parachute, experience the same magnitude of acceleration. By using the graph of acceleration over time from the trajectory simulation code one can approximate the value of acceleration. In this case the acceleration of the body right before the parachute opens is considered so that the force it exerts on the bulkheads can be computed. This was approximated to be 0ft/s^2.

Hence the tension force acting on the bulkhead by body 1:

$$Tension\ 1 = 1241.99lbf$$

Body 2 – Main Parachute

Body 2 calculates the tension force the main parachute exerts on the bulkheads.

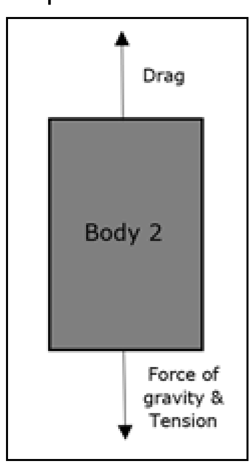


Figure 3.23: Body 2 Free Body Diagram

Most of the calculations are the same as with body 1. The main difference is that the tension acts downwards and so the calculations are as follows:

$$Drag - Tension - F_g = (Mass_{Main} * Acceleration)$$

Therefore,

$$Tension = Drag - (Mass_{Main} * Acceleration) - F_g$$

The total mass of the body, drag force, and the force of gravity can be calculated as shown below. The values for the free stream density (0.002387slugs/ft^3) and free stream velocity (41.27ft/s) are the same as with body 1:

$$Mass_{Total} = Mass_{(1)} + Mass_{(2)} + Mass_{(3)} + Mass_{Main} + Mass_{Shock\ cord\ of\ main} = 51.56lbm$$

$$Drag = Coefficient_{Drag} * 0.5 * Density_{Free\ stream} * (Velocity_{Free\ stream})^2 * Area$$

$$Drag_{Total} = Drag_{(1)} + Drag_{(2)} + Drag_{(3)} + Drag_{Main} + Drag_{Shock\ cord\ of\ main} = 24730.76lbf$$

$$Force\ of\ gravity = 32.2 * Mass_{Total} = 1658.97lbf$$

In this case the acceleration of the body right before the parachute opens is considered so that the force it exerts on the bulkheads can be computed. This was approximated to be 0ft/s^2.

Hence the tension force acting on the bulkhead by body 2:

$$Tension\ 2 = 230.72lbf$$

The sum of these forces gives the total tension force acting on the bulkhead:

$$Total\ Tension\ Force = Tension\ 1 + Tension\ 2 = 1472.71lbf$$

3.1.1.3.6. FRR Launch Vehicle Mass Margin

Post-Critical Design Review, the team was anticipating the launch vehicle to be lighter than originally expected. This led the team to conduct an analysis of the mass margin of the vehicle which was used for the first full-scale demonstration flight as the team headed into Flight Readiness Review. To find the mass margin, each component of the launch vehicle was weighed and documented. The results of this weighing gave the following table:

Component	Unit Weight (lbm)	Total Component Weight (lbm)
Main Parachute	3.125	3.125
Drogue Parachute	0.125	0.125
Quicklink (x1)	0.075	0.075
Lower Airframe	10.5	10.5
Motor case and three end pieces	3.1375	3.1375
Shock Cord 60	0.825	0.825
Threaded Rod (x1)	0.175	0.175

Drone	2.2	2.2
Upper Airframe and Nose Cone	16.625	16.625
Avionics plate	0.6625	0.6625
Nylock Nut (x1)	0.0125	0.0125
Washer (x1)	0.00375	0.00375
Rivet (x1)	0.003125	0.003125
Regular Nut (x1)	0.000625	0.000625
Heat Shield (x1)	0.1125	0.1125
Shear pin (x1)	0.000176	0.00017625
Shock cord 30	0.4125	0.4125
Total	37.995176	37.99517625

Table 3.1: Full-Scale Launch Vehicle Mass Margin

As can be seen, the total weight without the motor was only 38lbm. The weight of the motor is approximately 10lbm, but since no one on the team can handle the motor directly, this number remains a guess. Factoring in that weight gives a total weight of 48lbm, a full 7lbm below the original estimation of 55lbm. There are, however, a few caveats to this number.

First, the launch vehicle has not been painted in any way. The team fully anticipates painting the launch vehicle prior to Huntsville and has been budgeting between 1.5 and 2lbm for the weight, assuming a heavy coat. In addition, the payload of the launch vehicle came in under weight, but after realizing this, a few minor changes were implemented to take back some of the difference. Finally, the team has been experimenting with ballast weight. Since the weight was expected to be much higher, the altitude (as will be seen below in Mission Performance Predictions) will be much greater than the target altitude desired. Adding back in some ballast weight can help balance the stability margin lost from other parts coming in too light as well as drive the launch vehicle back towards the proper altitude.

Based on the Vehicle Demonstration Flight conducted so far (as discussed below in Demonstration Flight Results), the altitude achieved by this under-weight rocket with 3lbm of ballast was around 4500'. This is within 200' of the target altitude, but the winds were over 15mph, higher than anticipated for the launch day in Huntsville. In that launch, the vehicle experienced some major losses and therefore during the rebuild, the team will attempt to create a heavier version with a more easily-configured ballast system to help shave down the amount of mass margin left. Therefore, these mass margins are expected to change.

3.1.2. Documentation of Full-Scale Construction

The following steps were taken to complete full-scale construction:

- First, the bulkplates for the payload bay and the avionics coupler were measured for accuracy and they are drilled with the appropriate holes. The holes were used for linkage, and in the avionics bay, for threaded rods and connecting the avionics to the separation charges.
- Centering rings were epoxied together (and left to dry completely)
- Then, for added security in the avionics bay, two identical bulkplates for either end of the avionics bay were epoxied together while assuring that the holes align properly. These bulkplates were left to dry completely before usage.
- Next, epoxy was used to fasten three centering rings to the outside of the motor tube. These rings were placed 2.8”, 15.0”, and 24.5”, respectively, from the aft-most surface of the motor tube. The structure was left to sit to allow the epoxy to adequately dry.
- Next, a table saw was used to cut all sections of the airframe. This includes the upper airframe (48” long), payload coupler (6” long), avionics coupler (14” long), the avionics switch band (2”), and the lower airframe (40” long). After cutting, the edges of the airframes and couplers were sanded in order to remove fiberglass shards that may be present.
- Next, all collected data on hole locations was compiled and marked on the airframes and couplers of the launch vehicle. Furthermore, the sizes were marked alongside the markings to ensure that the holes were drilled in the right location and the right size.
- Before drilling, any holes that must line up were checked to ensure that holes would align. This was done by placing the airframes and/or couples in the desired orientation and shining a flashlight from the interior of the pieces. This made it easy to see the markings on both the interior and exterior, and ensured that the markings are aligned around the whole vehicle. When all markings are aligned on the entire vehicle, the holes are drilled. After each pair of holes was drilled, they were checked once again to further ensure that the holes are aligned.
- The fins were waterjet cut and sanded by Wildman Rocketry, to create a beveled leading edge. A beveled trailing edge feature was also added by the team, by sanding each fin in the Aerospace Science Lab at Purdue Airport.
- Next came dry-fitting the fins. The lower airframe was ordered with fin holes in it, so those slots did not need to be cut. The fins were dry fit to the slots by checking the fit between the two and sanding the pre-cut slots as needed until the fins can fit into the holes.
- Next, rail buttons were added to the launch vehicle. Because the holes had already been drilled for the rail buttons, it was simply a matter of securing the appropriate pieces into the holes of the launch vehicle. There is one bulkplate on the lower airframe, one on the avionics coupler, and one on the upper airframe.
- Next, the motor mount assembly (motor tube and centering rings) was added to the lower airframe assembly. Epoxy was used once again to do so, and the assembly was left to dry.

Figure 3.24: Letting the motor mount assembly epoxy dry

- Then, after the lower airframe and motor mount assembly had completely dried, the fins were added to the lower airframe assembly. Before epoxy was added, it was ensured that the fins were perpendicular to the lower airframe. Epoxy was added one fin at a time. This was done so that the fin may dry while vertical and perpendicular to the lower airframe, ensuring that the epoxy may dry without shifting due to gravity. The fin was left to dry completely before the lower airframe was rotated in order to add the other to fins.

Figure 3.25: Sanding the body tube before adding epoxy

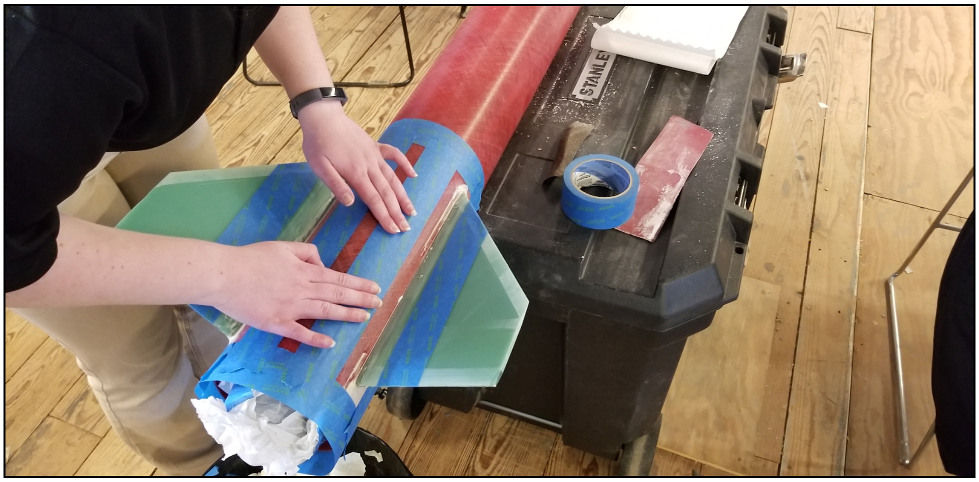


Figure 3.26: Applying tape to outline the fin fillets

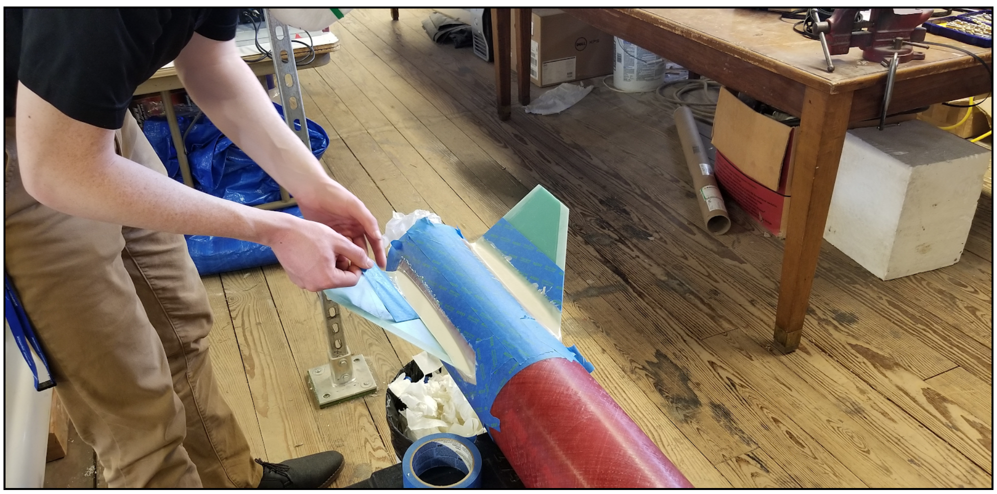


Figure 3.27: Removing the tape from the fillets after letting them set

- Finally, inner fillets were added to the fins and the lower airframe. This was done to secure the fins between the centering rings and onto the motor case. This was done in a similar fashion to the outer epoxy fillets on the fins. It was noted that this method is not optimal, and that completing the inner fillets first may be easier so that it is not so difficult to add epoxy on the inside of the launch vehicle.

3.1.3. As-Built Dimensional Drawings

3.1.3.1. Assembled Launch Vehicle

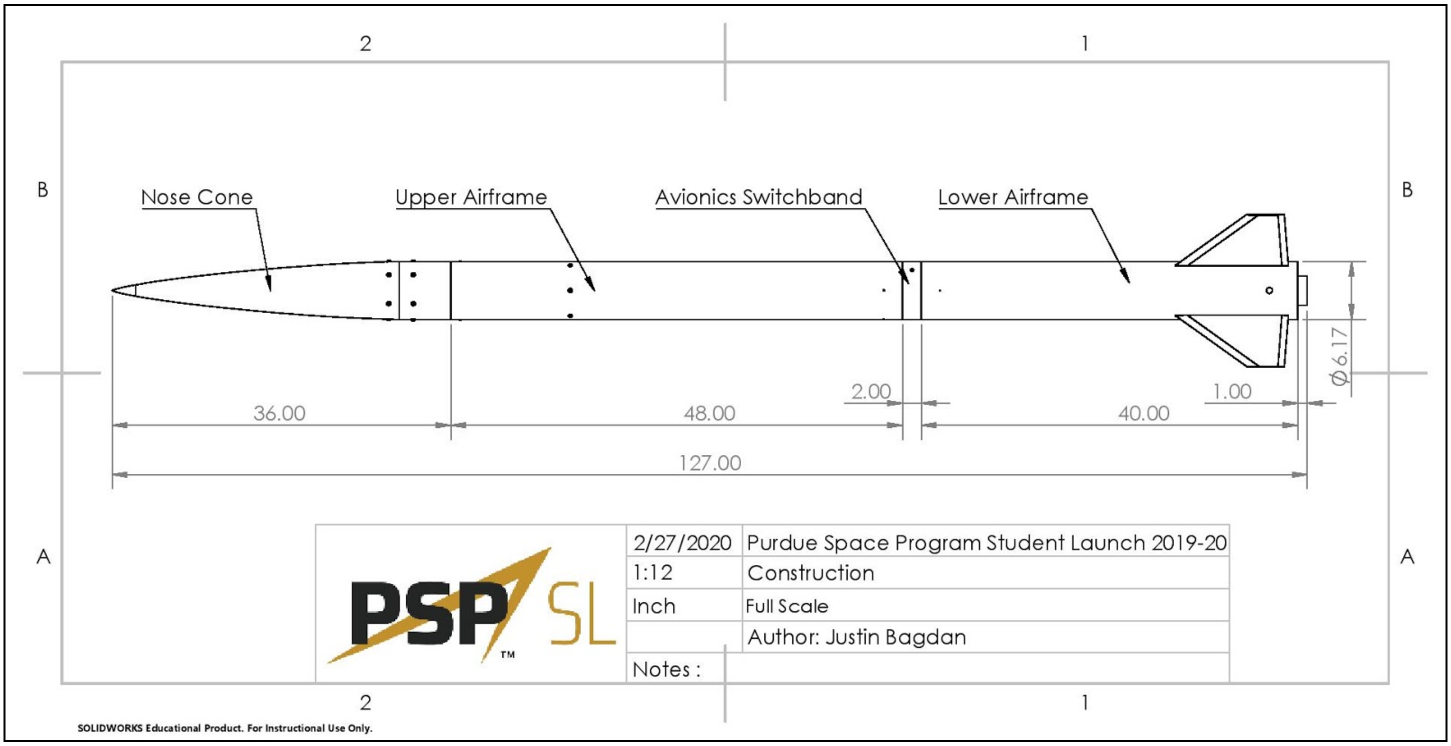


Figure 3.28: Assembled Launch Vehicle Dimensional Drawing

The launch vehicle measures 127” from the aft of the motor tube to the tip of the nose cone. The vehicle is composed of three main sections: a 36” nosecone, 48” upper airframe connected to a 40” lower airframe by a 2” avionics switch band. The aft of the motor protrudes the lower airframe 1”.

3.1.3.2. Lower Airframe Subsystem and Components

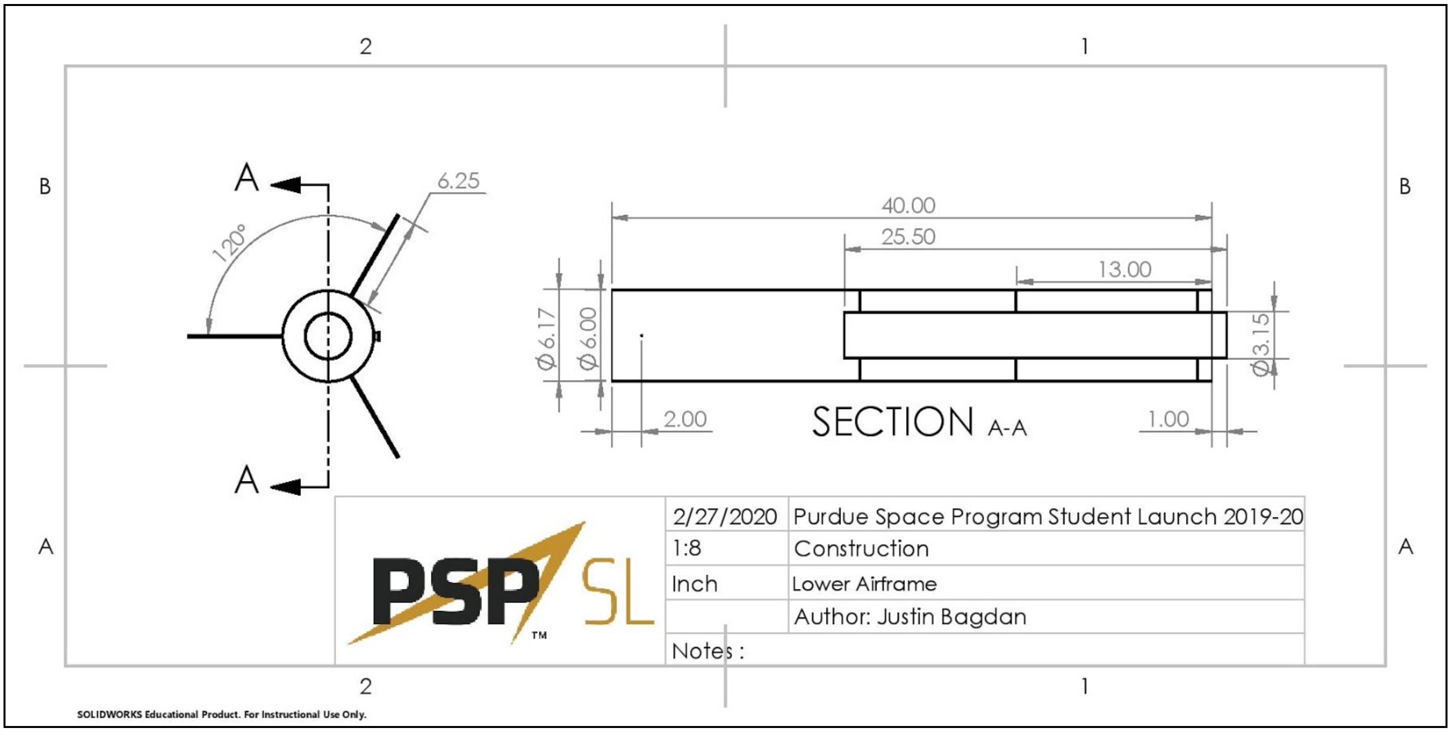


Figure 3.29: Lower Airframe Dimensional Drawing

The lower airframe of the launch vehicle measures 40" in length, and supports the motor, as well as the drogue parachute. The outer and inner diameters are 6.17" and 6.00" respectively, while the motor diameter is 3.15". Six shear pin holes are drilled 2" from the top of the lower airframe to allow for drogue to deploy at apogee. Three fins are used 120° apart and measure 6.25".

3.1.3.3. Avionics Bay Subsystem and Components

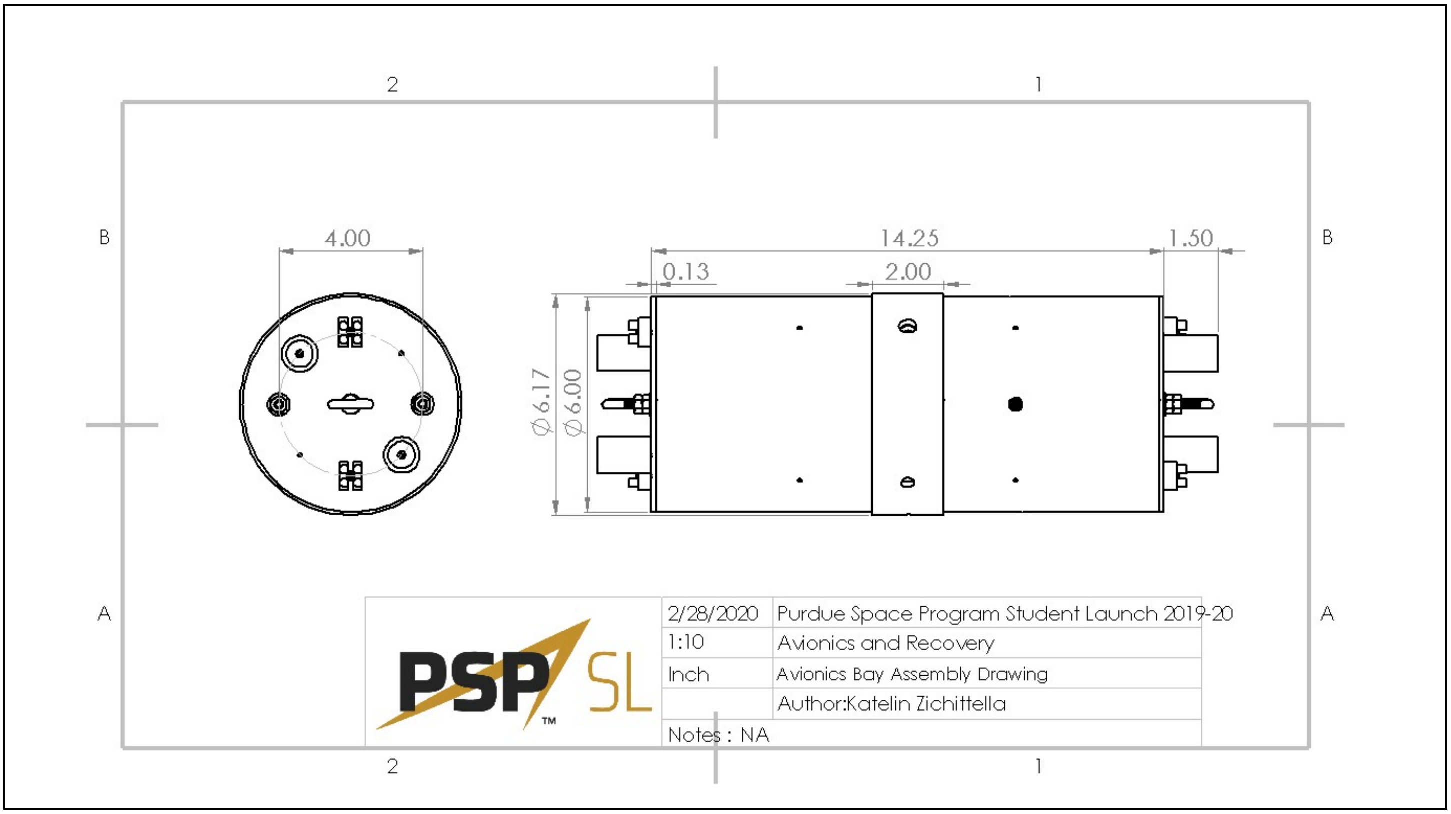


Figure 3.30: Full-Scale Avionics Bay Dimensional Drawing

The avionics bay has an outer diameter of 6", coupler length of 14", and total length of 17.25" when including the black powder canisters. It also has a switch band around the middle with a width of 2". The primary purpose of the avionics bay is to house the primary and redundant altimeter/ejection systems, provide an attachment point for the drogue and main parachutes, and house the secondary payload (camera) system.

3.1.3.4. Upper Airframe Subsystem and Components

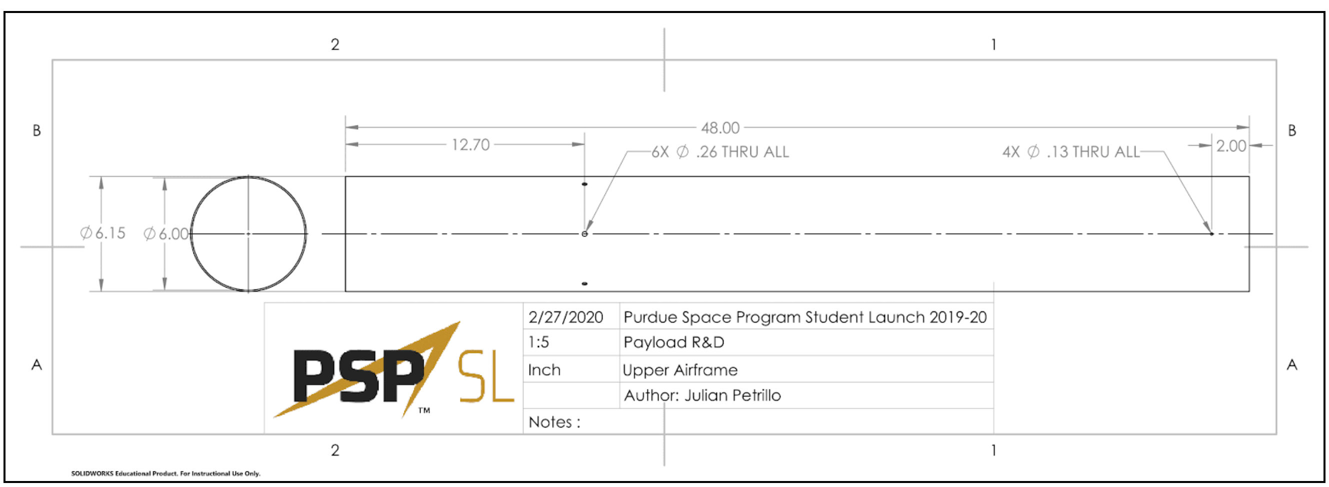


Figure 3.31: Full-Scale Avionics Bay Dimensional Drawing

The upper airframe of the launch vehicle is 48” long. The outer diameter of the upper airframe is 6.15” and the inner diameter is 6.0”. The upper airframe contains the main recovery gear of the launch vehicle, as well as the payload and avionics bays.

3.1.3.5. Nose Cone and Payload Subsystem and Components

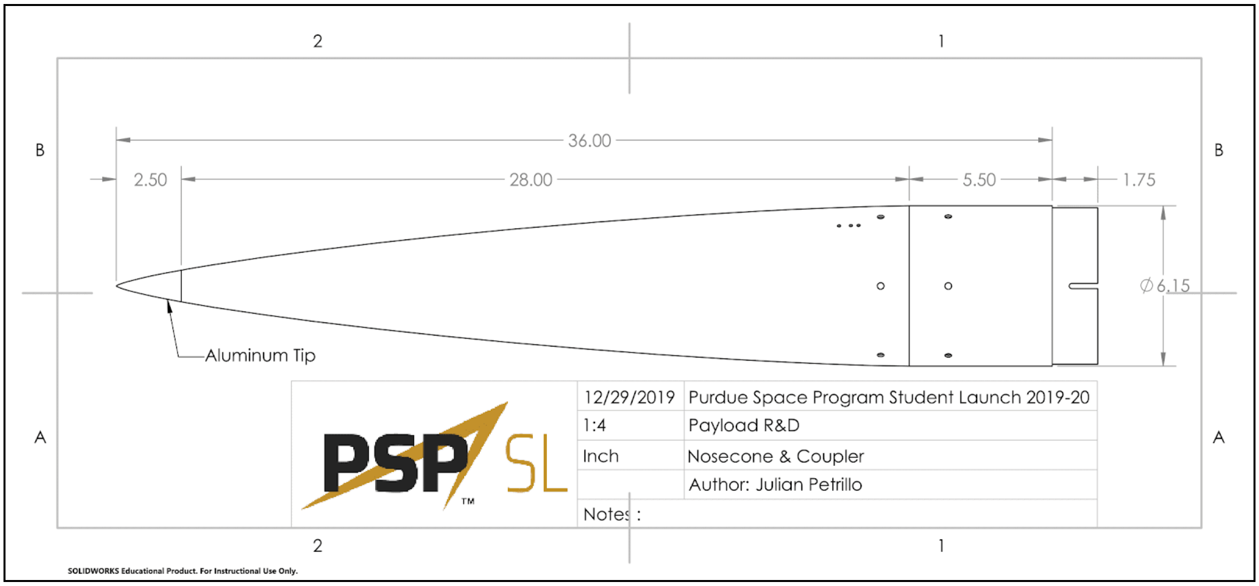


Figure 3.32: Nose Cone and Payload Coupler Dimensional Drawing

The nosecone of the launch vehicle is 36”, with an outer diameter of 6.15” and inner diameter of 6.0”. The nosceone is designed to reduce drag, features an increased interior volume for future payloads or avionics, and interfaces with the upper payload coupler.

3.2. Demonstration Flight Results

3.2.1. Flight Information

The flight demonstration was pivotal in terms of gaining a better understanding of the launch vehicle’s capabilities. A primary goal of the team was to ensure that the parachute was successful in deploying, so as to ensure a safe descent of the rocket. It was also critical for the payload to stay in place throughout the duration of the flight.
There were two test flights conducted by the team: the full-scale flight demonstration and the subscale flight demonstration.

Success Criteria for Test Flight

There were several criteria for assessing the success of the launch vehicle’s test flight. These criteria were introduced to ensure that the team could appropriately assess the success of its launch. These success criteria were as follows:

1. *Full Post-Flight Functionality of Components*
   The safety of the payload component is vital to the success of the team’s launch. It ensures the launch vehicle’s capability of protecting its vital internal components

2. *Successful Deployment of Parachute*
   The parachute deployment is essential to the safe descent of the launch vehicle, ensuring all of its components remain undamaged.
3. *Target Descent Kinetic Energy*
   It is vital to the safe descent of the launch vehicle that it descend with a particular velocity to ensure that the rocket has followed a path based on accurate predictions.

Results

The team was unable to achieve its first two success criteria. The payload was unable to perform its demonstration and also suffered considerable damage. The parachute wasn't successfully deployed, due to it being tightly-packed inside the upper airframe.

Launch Day Photos

Figure 3.33: Team photos before launch

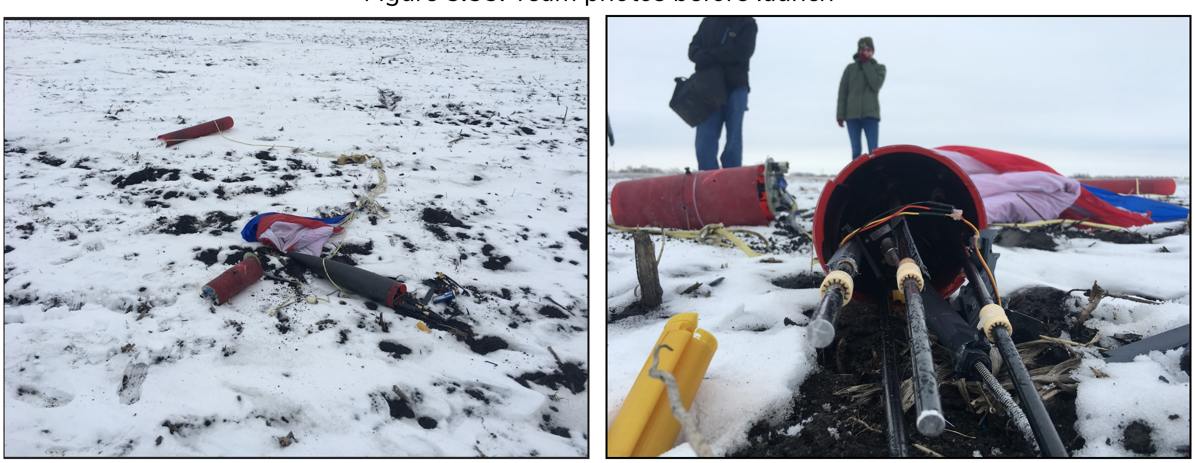


Figure 3.34: Team photos after launch

Full-scale Flight Demonstration Data

Vehicle Demonstration Flight	Conducted; failure
Payload Demonstration Flight	Conducted; failure
Date of flight	February 15, 2020
Location of flight	N 1000 W, Williamsport, Indiana
Launch Conditions	Temperature: 36F Winds: 14mph SSW Humidity: 68% Slightly to fully Overcast Cloud Ceiling: 6000 ft (15 min. before launch - METAR KDNV) 4000 ft (at launch)
Motor Flown	CTI L1115-0 4 Grain
Ballast Flown	Yes; 2.5lbs
Air-Brake System Presence	No design incorporated during test flight
Official Target Altitude [ft]	4325
Predicted Altitude from Simulations [ft]	4584
Measured Altitude [ft] (Primary / Secondary)	4488 / 4688
Rail Exit Velocity [ft/s]	63.98

Table 3.2. Full-Scale Demonstration Flight Data

Altimeter Flight Profiles

Primary Altimeter (Telemetrum)

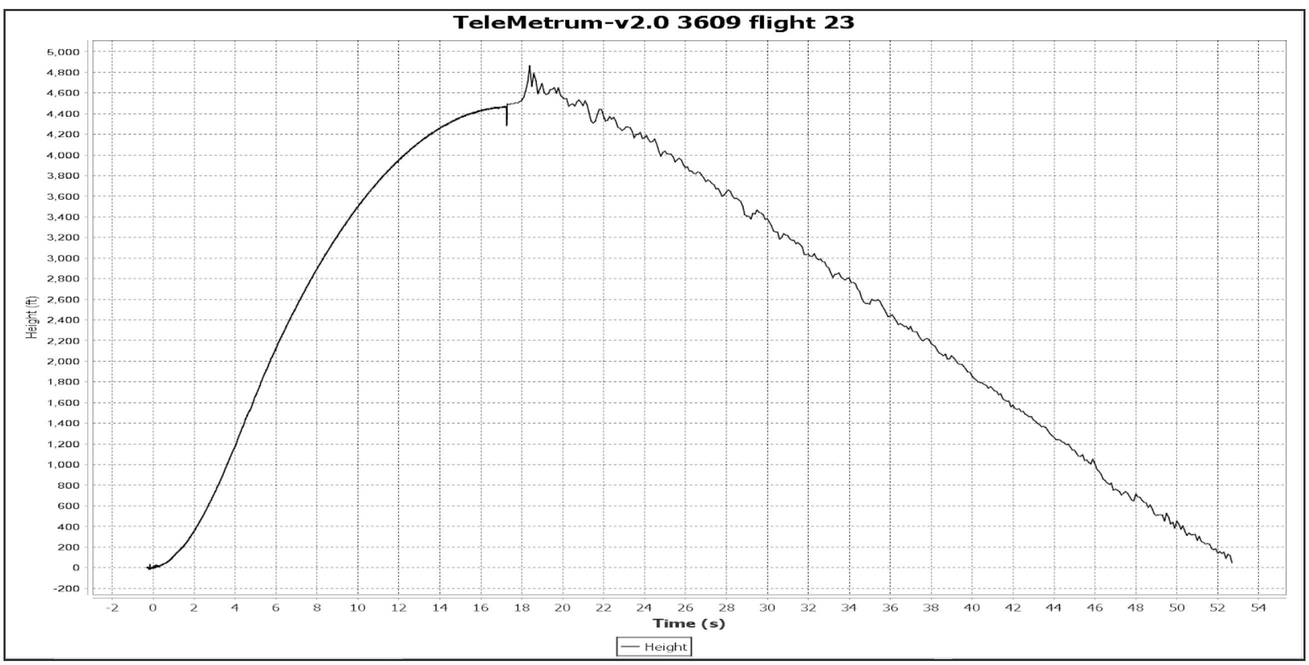


Figure 3.35: Telemetrum Altimeter Flight Profile

Redundant Altimeter (RRC3+ Sport)

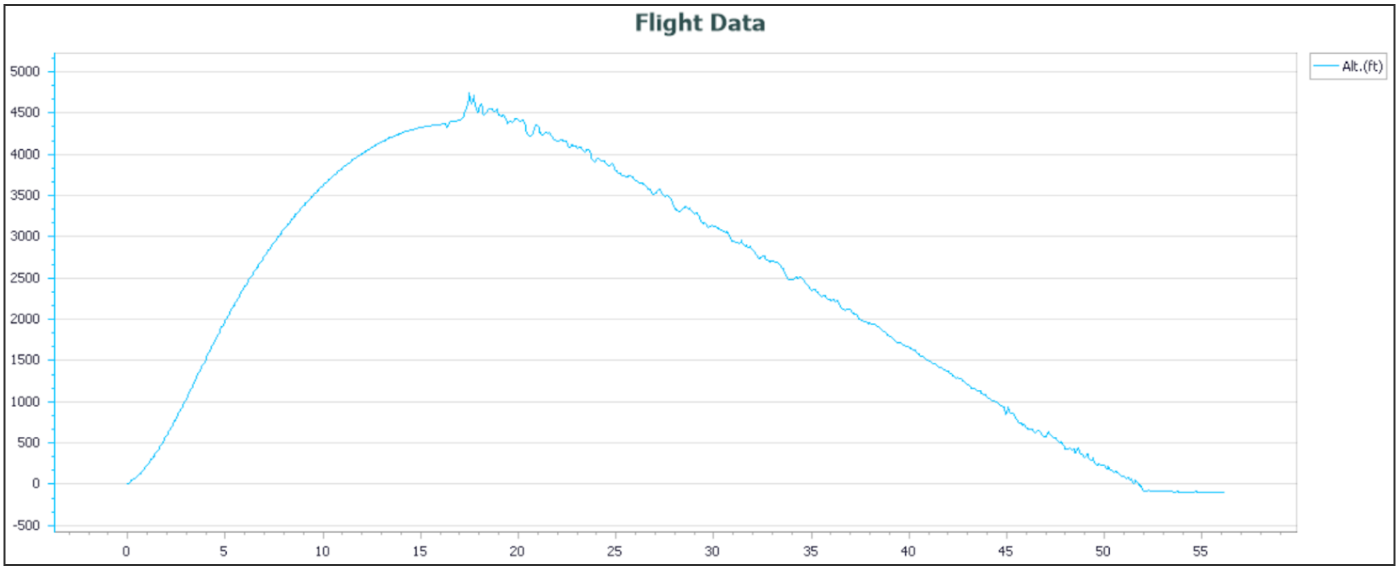


Figure 3.36: RRC3+ Sport Altimeter Flight Profile

3.2.2. Discussion of Launch Vehicle Performance

There are two points of failure in the recovery hardware. First, the quick link between the shock cord in the lower airframe and the avionics bay was not connected properly. At apogee, this caused the lower airframe to separate completely from the rest of the launch vehicle, along with the shock cords and the drogue parachute. Next, the main parachute was also packed too tightly. When the upper airframe and the payload bay separated, the main parachute stayed in the upper airframe and did not deploy. When the launch vehicle reached the ground, there was significant damage to many parts, namely the payload. Because of this, there was no payload demonstration. During the launch, however, the retention was successful and the payload stayed in place. The lower airframe was lost-apogee and subsequent separation occurred above the clouds and the airframe was unable to be tracked. Multiple searches were conducted spanning eight hours were conducted for the lower airframe, but none were successful. In the payload bay, the threaded rods were bent, the telemetrum lost an antenna, and the coupler, 3D printed parts, and switches must be replaced completely. The upper airframe had minimal damage. However, within the upper airframe the payload, as well as the retention and deployment, were completely destroyed and must be totally replaced. The nose cone only sustained a small hairline crack between two of the bolt holes. The damage was not comprehensive, but the nose cone will be replaced anyway. This is the total damage sustained from the flight. In order to ensure that these failures do not happen again, multiple changes will be made for the next full scale launch. First, a brightly-colored roll of duct tape will be brought to launch, and every time that a quick link or something similar is secured, a piece of duct tape will be wrapped around it. This will give observers and team members a very easy to see cue that indicated successful connections, and guaranteeing that all connections made will be strong and secure. Furthermore, the main parachute will be packed in a different way. A triangular fold was used to insert the main parachute. This is what is believed to have caused the main parachute to remain in the upper airframe because it was too tightly packed. By using a traditional cylindrical fold and ensuring that lower airframe is also present to pull on the main parachute, the main parachute will successfully deploy.

3.2.3. Simulation with Launch Day Conditions

On the day of launch, the forecast showed wind speeds of about 15mph. Based on that, the team used 15mph wind speeds to run the launch day simulations. Shown below are the resulting altitudes for each simulation run.

PSP-SL Launch Vehicle Pre-Launch Simulations	
0 Inc, 15mph	5428’
5 Inc, 15mph	5254’
10 Inc, 15mph	4951’
15 Inc, 15mph	4575’

Table 3.3. Launch Vehicle Pre-Launch Altitude Predictions

The results shown above were run using the most up-to-date OpenRocket model, which was 5lbm underweight. No ballast weight was added to perform these initial simulations. However, the team used the given results to decide to add 3lbm of ballast weight to the launch vehicle prior to launch. The ballast weight was in the form of an extra parachute, which was taped shut and added above the main parachute. Prior to launch, the team updated the OpenRocket simulations by adding this ballast weight, the results of which are shown below.

PSP-SL Ballasted Launch Vehicle Pre-Launch Simulations	
0 Inc, 15mph	5025’
5 Inc, 15mph	4851’
10 Inc, 15mph	4566’
15 Inc, 15mph	4192’

Table 3.4. Ballasted Launch Vehicle Pre-Launch Altitude Predictions

To estimate the drag coefficient, at first the most likely scenario, at 0 deg inclination and 15mph wind, was plotted in OpenRocket, with flight configuration, as described. The OpenRocket plot with Altitude, Total Velocity and Drag Coefficient vs Time can be seen in figure 3.37.

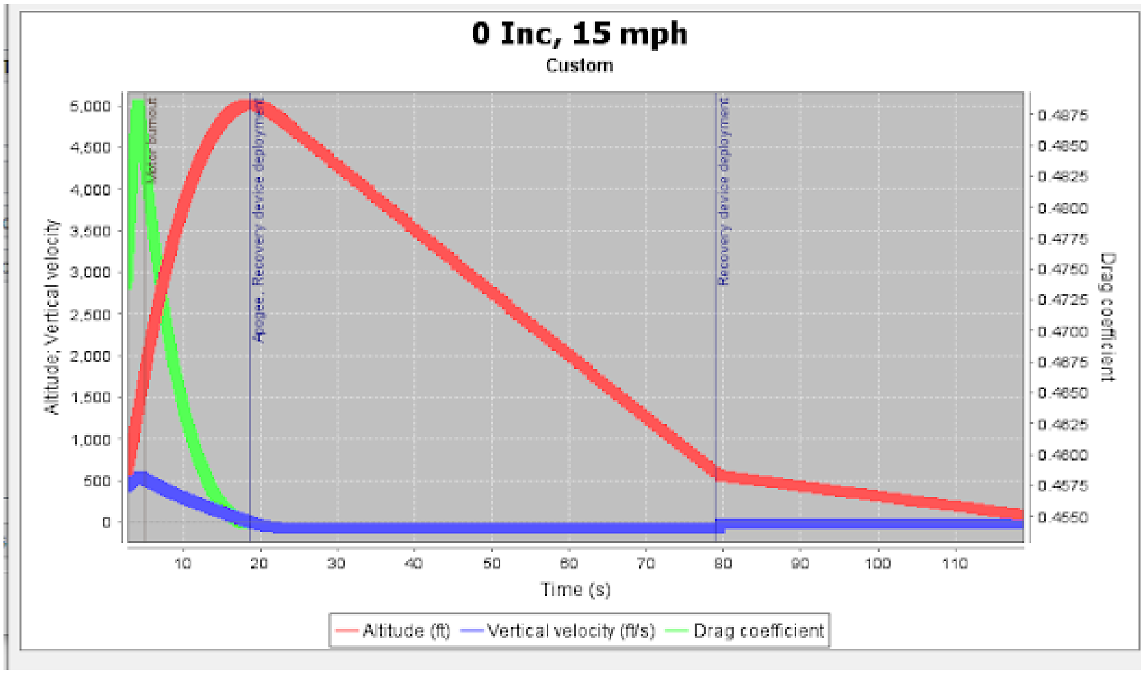


Figure 3.37: OpenRocket Altitude, Total Velocity and Drag Coefficient vs Time plot.

	Real Flight (Telemetrum / RCC3+)	OpenRocket Simulation
Apogee (ft)	4488 / 4688	4584
Maximum Velocity (ft/s)	462 / 507	562

Table 3.5: Real data Vs OpenRocket simulation data

The predicted apogee from OpenRocket (4584') is very close to the average altitude measured from the two altimeters (4588'). However, the maximum predicted velocity by open rocket deviates by a significant amount from the RCC3+ Sport data, and less from the Telemetrum data, which both provide lower velocities than the simulation. The reason for the deviation is that OpenRocket assumes ideal (laminar) flow conditions, as well as translational movement of the launch vehicle only, excluding rotational movement.

As can be seen in the chart, the estimated maximum drag coefficient from the OpenRocket simulation is Cd(max) = 0.49.

Then, hand calculations were done, for the boost time interval, from 0 to 4.48s, when the motor shuts down. Telemetrum data (denser sampling rate) was used to find an equation for velocity, using Excel to find a trendline for velocity vs time. Then, we tried to derive the drag coefficient, assuming it is constant, using the momentum principle:

$$(I)\ \Delta p = \int_0^{4.48} Fnet(t)dt \Rightarrow pf - pi = \int_0^{4.48} Fnet(t)dt \Rightarrow mf * vf = \int_0^{4.48} Fnet(t)dt$$

From the free body diagram of the rocket, we find that $(II)\ Fnet = Fmotor - Fdrag - Weight$, assuming that all forces are vertical (0 degree launch angle) and Weight remains constant over time, as well as that initial momentum is 0. Mass was approximated as the average mass between launch mass and mass after propellant burn, to simplify calculations. From (I) and (II), we get:

$$mf * vf = \int_0^{4.48} [Fmotor(t) - Fdrag(t) - Weight(t)]dt \Longrightarrow mf * vf = \int_0^{4.48} Fmotor(t)dt - \int_0^{4.48} Fdrag(t)dt - \int_0^{4.48} Weight(t)dt$$

$$\Longrightarrow mf * vf = \int_0^{4.48} Fmotor(t)dt - \int_0^{4.48} [1/2 * \varrho * v^2(t) * A * Cd]dt - \int_0^{4.48} [g * (mf + mi)/2\ ]dt$$

$$\Longrightarrow mf * vf = \int_0^{4.48} Fmotor(t)dt - 1/2 * \varrho * A * Cd * \int_0^{4.48} [v^2(t)]dt - [g * (mf + mi)/2\ ] * \Delta t$$

Then, the equation is rearranged to get the Cd:

$$\Longrightarrow Cd = [2/(\ \varrho * A * \int_0^{4.48} [v^2(t)]dt\ )] * [\int_0^{4.48} Fmotor(t)dt - mf * vf - g * (mf + mi)/2\ * \Delta t]$$

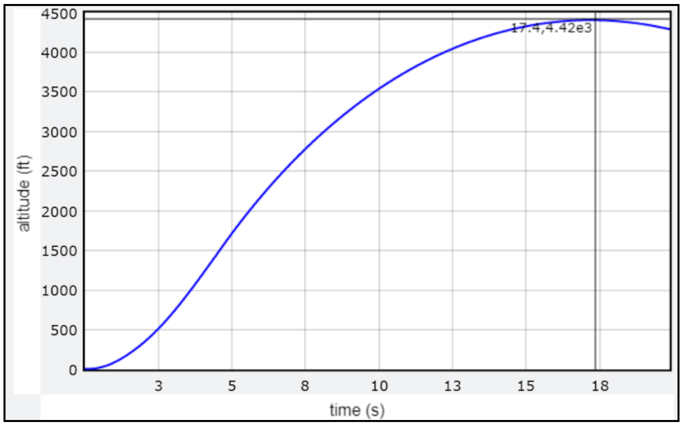
Then, the term v(t) is replaced with the trendline from excel, which is

$v(t) = -5.0019 * t^2 + 56.496 * t + 5.8061$ (with $R^2 = 0.9993$), and the integral $\int_0^{4.48} Fmotor(t)dt$ is just the motor's impulse, which is retrieved from thrustcurve.com, as 5015 Ns. Then, a python script is used to calculate the Cd, making use of the numpy polynomial functions and math libraries, to obtain Cd as Cd = 1.05.

Finally, this value is averaged with the OpenRocket simulation, to give Cd = 0.77 . This value is more reasonable and could explain the smaller maximum velocity compared to the OpenRocket simulation.

Then, a simulation was run using a Vpython script on GlowScript IDE, with the estimated Cd = 0.77, and the momentum principle to update momentum with a loop: $pf = pi + Fnet * \Delta t, with\ \Delta t = 0.001s$. For the motor burn phase, thrust curve data was used (from ThrustCurve.com) to create a trendline on Excel for the motor force , which was:

$Fmotor(t) = -39.632 * t^6 + 580.31 * t^5 - 3304.3 * t^4 + 9114.9 * t^3 - 12322 * t^2 + 7021.5 * t + 376.54$ (with $R^2 = 0.8692$). The trendline generated an area that was very close to the impulse of the motor, 5021.8Ns . Again, 0 degree launch angle is assumed, as well as initial momentum pi=0 and mass is approximated as average mass. Next, after the 4.48s mark, when the motor burn ends, the motor's force is removed from the calculation of Fnet and thus momentum update is dependent on Fdrag and Weight alone. The results can be seen in figures 3.38 and 3.39:



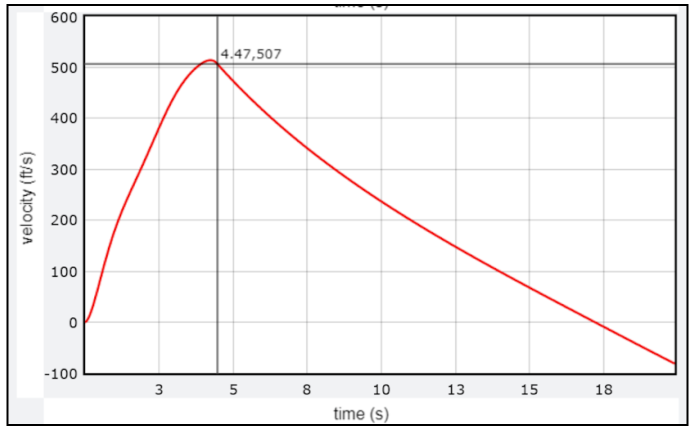


Figure 3.38: Altitude(ft) vs time(s) with VPython simulation (LEFT)
Figure 3.39: Velocity(ft/s) vs time(s) with VPython simulation (RIGHT)

From the altitude vs time and velocity vs time graphs, we get that apogee occurs at approximately 4420ft at 17.4s and the velocity at 4.47s is 507ft/s, with vmax = 515ft/s , which are all very close to the Telemetrum data.

3.2.4. Comparison to Subscale Flight

Metric	Predicted (OpenRocket)	Recorded
Wind Speed	15mph	12mph
Launch Angle	5 degrees	5 degrees
Apogee	677’	617’
Max Velocity	194ft/s	164ft/s
Ascent Time	7.1s	5.25s
Drift	47’	95’

Table 3.6: RRC3+ Sport Subscale Launch Flight Data (24 Nov 2019)

With data from both subscale and full scale launches, the team was able to draw the following conclusions about the integrity of design and scalability of the launch vehicle.

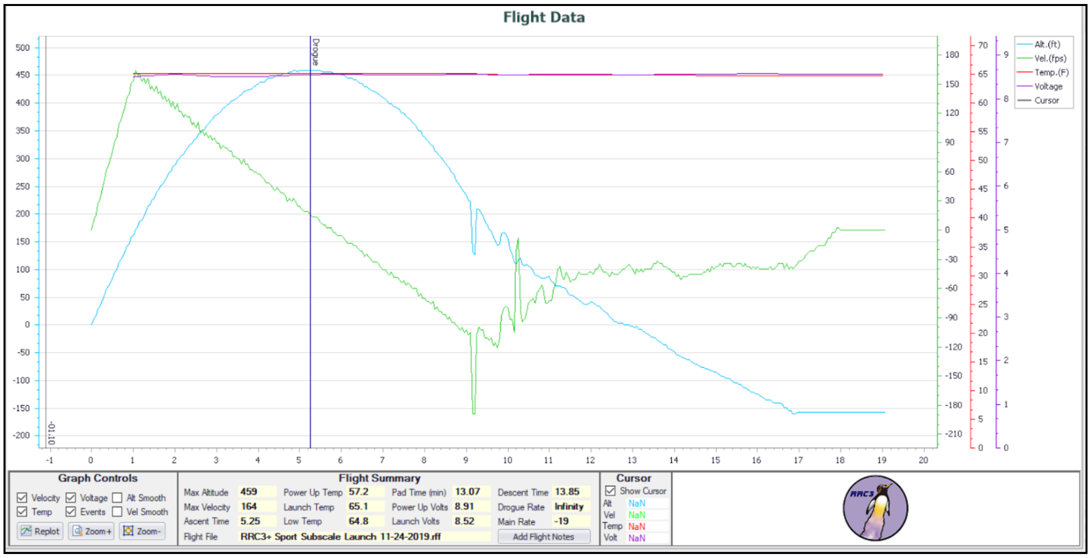


Figure 3.40: RRC3+ Sport Subscale Launch Flight Data

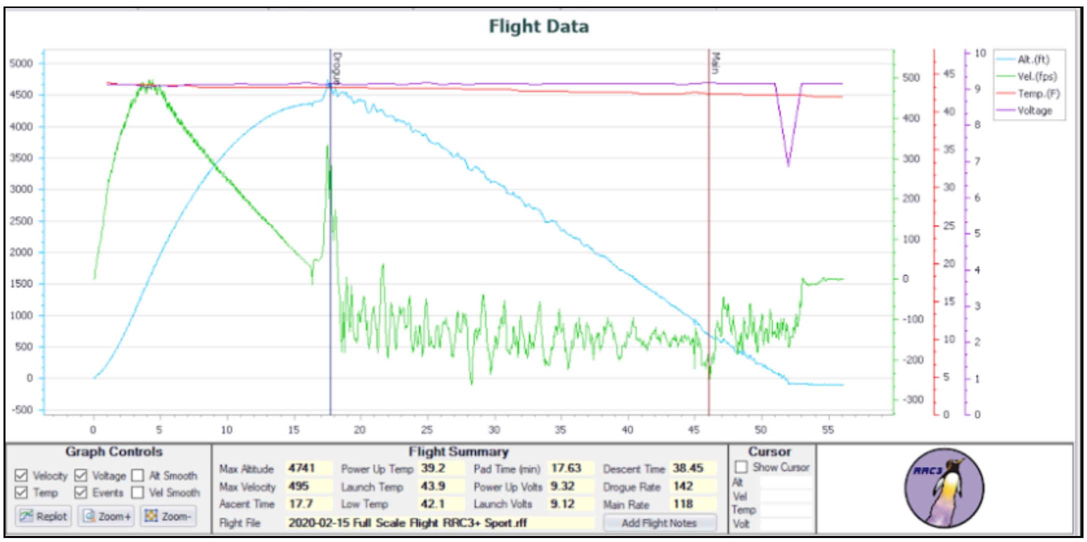


Figure 3.41: RRC3+ Sport Full Scale Launch Flight Data

As portrayed in the data above, both altitude and temperature of the vehicle stayed within a reasonable degree of precision between both flights. Both launch vehicles successfully reached apogee within predicted timeframes and degrees of predicted values. Another similarity between the two is an abrupt impact and varying velocity on descent. As detailed in this report, the full scale vehicle separated correctly but did not deploy the main parachute as intended.

3.2.5. Discussion of Payload System Performance

The payload system was included in the flight, but was destroyed and could not perform its goals due to the ballistic descent of the launch vehicle, the payload was destroyed. All indications suggest that the R&D system performed as intended up until the launch vehicle's impact with the ground. It is difficult to derive lessons learned from this flight which can be applied to the payload retention system, as the nose cone also failed upon impact, which blurs the line between payload retention system performance and nose cone performance. Due to the destruction of payload, no part of the payload mission sequence was carried out. The payload system's performance will now be validated by a secondary full-scale demonstration flight. A full write-up about the payload's performance during this flight will be provided in the FRR Addendum submitted in March 2020. The primary lessons the payload team learned from this failure are to be cognizant of the launch vehicle construction process and to take time after the payload system has been deemed ready for flight to observe how the vehicle is assembled on launch day and watch for errors.

3.2.6. Planned Future Demonstration Flights

Unfortunately, due to the unsuccessful nature of the demonstration flight, the team will proceed with another demonstration flight in which the team will fly the vehicle and payload in final flight configuration to ensure that the design is valid. This launch is tentative on a number of factors including flight readiness, weather, and sponsor availability. The date expected for this reflight is March 7, 2020 with a backup date of March 14, 2020.

3.2.7. Flight Reliability and Confidence

In order to verify the validity of the overall size, weight, and design of the launch vehicle and its successful flight, MATLAB, RASAero II, and OpenRocket simulations were all utilized. The launch was tested under several situations, from a 0-15 deg launch angle, and winds from 0-20 mph, and every combination of the two factors. While the exact details of the launch may have varied between the programs, the overall success of the rocket was predicted in all of them. To ensure that each individual section of the launch vehicle could withstand the various forces of the launch, finite element analysis was conducted on each of the external parts of the launch vehicle. For all analyses conducted, no indication of failure in the individual parts was predicted. Finally, there exist comprehensive safety checklists to guarantee that all important steps of assembly are completed, and completed safely. Document stating these steps of construction and safety procedures are reviewed prior to construction and launch, and are to be kept in the pockets of all members for reference during the entire construction and launch process in order to ensure the safety and success of the team. While the initial flight was unsuccessful, it was the result of two simple hardware mistakes, and has no bearing on the amount of confidence on the launch vehicle's performance as a whole. As described in 3.3.2, there are strong policies for each of the two issues to ensure that they don't happen again: brightly indicating complete connections and a more reliable parachute-packing method.

4. Avionics and Recovery

4.1. As-Built Avionics & Recovery FRR Design

Coupler

A coupler that is 14” long slides between the upper and lower airframe sections. It has an outer diameter of 5.998” and an inner diameter of 5.775”. It contains four holes with diameters suitable for 4-40 shear pins offset 3” from either side of the middle of the coupler. Four ⅜” diameter static port holes are located in the same circumference as the forward shear pin holes, offset 45°. This diameter was calculated to be ideal considering the overall volume of the avionics bay.

Switch Band

The switch band has an outer diameter of 6.17”, an inner diameter of 6”, and a width of 2”. There are six holes in the switch band; three on one side spaced 45° apart and three on the other side spaced 45° apart. Two holes on each side have a diameter of ⅜” and allow access to each of the four rocker switches from the outside of the vehicle. Another hole has a diameter of ½” and allows the camera to see outside of the vehicle. The final hole has a diameter of 5/32” and is used to secure one of the rail buttons to the switch band. The coupler contains identical holes underneath each of these holes in the final assembly. The switch band is primarily used to separate the upper and lower airframe so that they can function as two separate entities during launch and deployment.

Primary and Redundant Altimeters

Both the Altus Metrum Telemetrum and the Missile Works RRC3+ Sport are used for the recovery subsystem. The Telemetrum was chosen as the primary altimeter, while the RRC3+ Sport is the redundant altimeter. These two altimeters were chosen due to their high score on the decision matrix. While the Telemetrum had a higher cost, it had a significantly higher maximum height and smaller area than the other options. Additionally, the Telemetrum contains a GPS and telemetry system which put it over the other options. The RRC3+ Sport was the second highest ranking altimeter due to its cheaper price and its ability to store large amounts of flight data, making it a great alternative altimeter despite its large size. Also, in case of a failure in the primary altimeter, it would be less likely for the same failure to occur to a redundant altimeter of a different make and model.

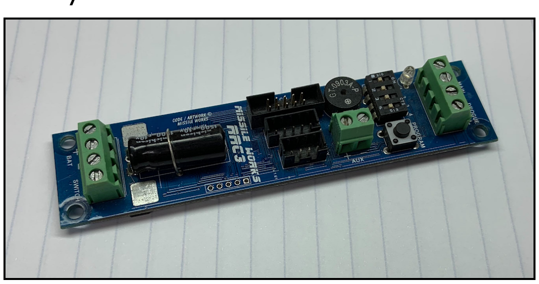


Figure 4.1: Missile Works RRC3+ Sport

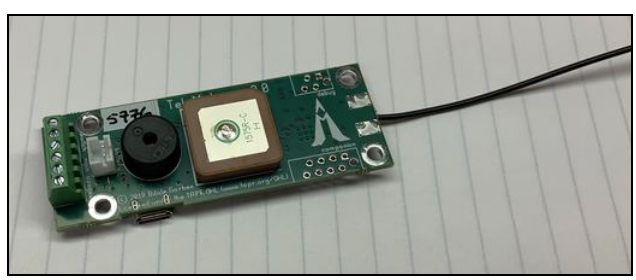


Figure 4.2: Altus Metrum Telemetrum

Ejection Charges

On the ejection charge type decision matrix, the black powder scored a total of 245 points, whereas the CO_2 ejection device received a score of 195. Comparing the two total point values, FFFFg black powder was the clear choice for the type of ejection charge that should be used. Specifically, black powder was chosen because it occupies less volume and leaves less residue. These advantages outweigh the advantage of the CO_2 canister being lighter. Black powder has also been used in the past, and has been found to be reliable. In terms of design, two 8g capacity black powder canisters (one primary, one redundant) in combination with masking tape, fireproof cellulose insulation, cable ties, and a section of latex glove are used to contain the black powder on each end of the avionics bay.

Switches

The switch design that is used is the rocker switch, as shown in Figure 4.3. This choice represents a middle ground between mechanical complexity and reliability. In addition to these design factors, this is the switch type that has been used on previous projects, and previous experience helps to ensure a reliable design. See Section 3.1.1.2 for more information about switch use and retention.

Figure 4.3: Avionics Bay Rocker Switch

Other Custom-Designed and 3D Printed Parts

See Section 3.1.1.2 for information about how these parts are used for altimeter, battery, and switch retention.

4.2. Chosen Parachutes and Attachment Hardware

4.2.1. Parachute Choices

The parachutes that have been selected for this year's design are the 24" Fruity Chutes Classic Elliptical for drogue and the 120" Skyangle Cert-3 XXL for main. The Fruity Chutes drogue parachute was selected because it has a much higher drag coefficient (1.5 - 1.6) and a much lower weight (2.2 oz) than the 24" Skyangle Cert-3 Drogue that was used last year, so it is much more optimized for this year's design. Generally, it scored very highly in the decision matrix. The Skyangle Cert-3 XXL main parachute was selected, even though it was not originally considered in the decision matrix, because it has a high enough carrying capacity to allow the heaviest section of the launch vehicle to land with a kinetic energy of less than 75ft-lbf, as specified in the NASA requirements. Originally, the Skyangle Cert-3 XL was chosen for the main parachute because it was the top scorer in the decision matrix and it has proven to be successful in past launches. Sizing up from the XL to the XXL allows for the beneficial properties of this series of parachutes to be maintained while making sure the one that is used is large enough for the vehicle's needs.

4.2.2. Attachment Hardware and Heat Shielding

The drogue parachute is attached to a 30' long, ⅜" tubular kevlar shock cord, while the main parachute is attached to a 60' long, ⅜" tubular kevlar shock cord. Harness/airframe interfaces include ¼" Stainless Steel (SS) quick links through the looped tether ends of the parachutes attached to ¼" SS I-bolts through the bulkheads on either end of the avionics bay.

To protect the parachutes from hot ejection charge gases, an 18" to a side square Nomex blanket wraps around each the drogue and main parachutes when they are packed inside the airframe.

4.3. As-Built Electrical System and Schematics

4.3.1. Electrical Components and Redundancy

The electrical system in the avionics bay was designed using a parallel system, employing complete electrical and physical redundancy as a means of achieving higher reliability, predictable performance, and remarkable safety. Each subsystem in the parallel system, which is completely separated from the other, features an altimeter, battery, switch, drogue ejection charge (release), and main ejection charge (release). Moreover, separating the parallel system entirely from the main system guarantees that the parachutes are released at the correct times even under the circumstance of multiple failures occurring within the primary system, therefore avoiding compromising the mission. The redundant altimeter is of a different make and model to ensure that there is minimal likelihood for the same type of error or failure to occur across both systems under the circumstance of an altimeter-specific failure occurring within the primary altimeter. Also, the redundant main charge is programmed to go off 100' lower than the primary main ejection charge, the redundant drogue ejection charge is programmed to go off one second after the primary drogue ejection charge, and the redundant ejection charges for both parachutes contain one more gram of black powder than the primary ejection charges. These factors all work together to contribute to the overall reliability and success in the processes of separation and deployment as prescribed in the mission requirements.

4.3.2. Wiring Diagram (Schematic)

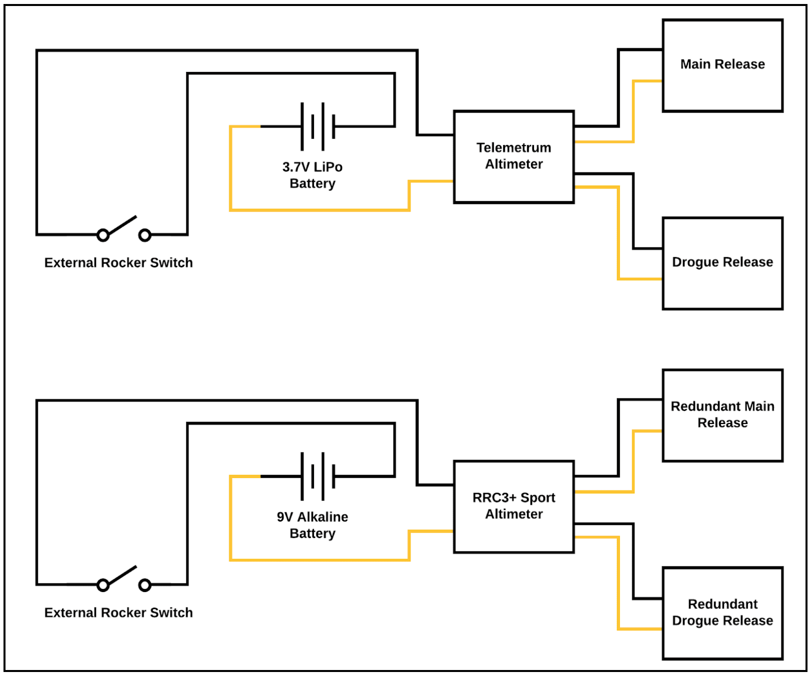


Figure 4.4: Avionics Wiring Diagram

See Section 3.1.1.2 for a description of the avionics bay wiring scheme.

4.4. As-Built CAD and Dimensional Drawings

4.4.1. Avionics Bay Assembly and Sub-Assemblies (CAD)

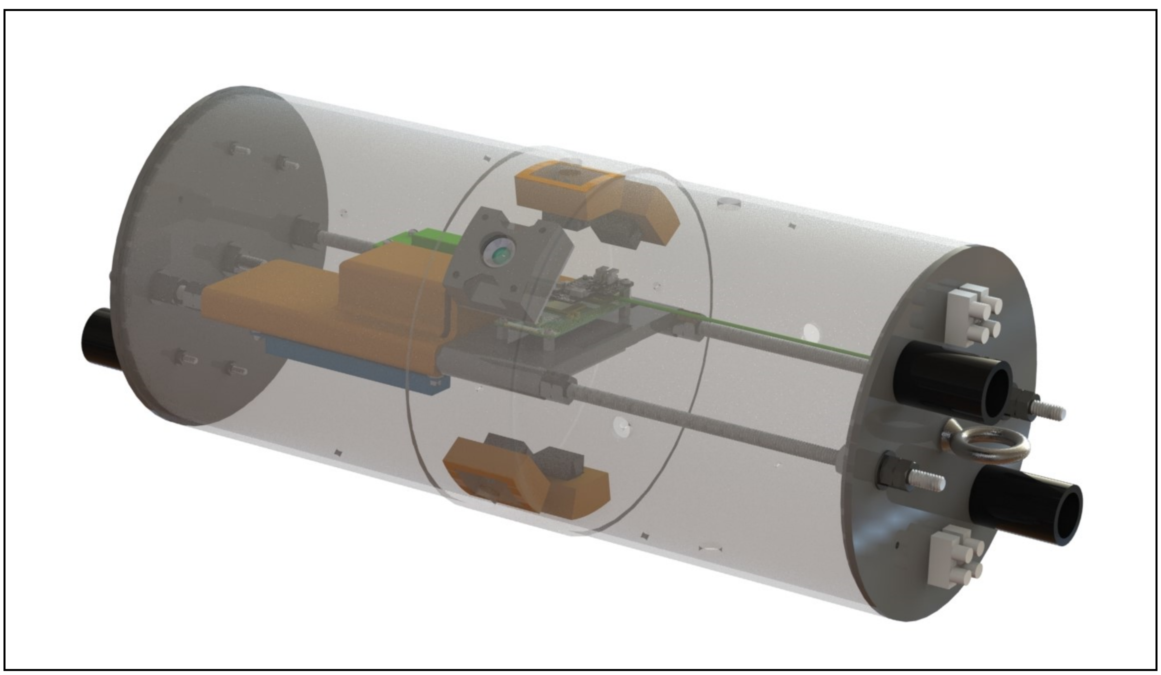


Figure 4.5: Full Avionics Bay Assembly

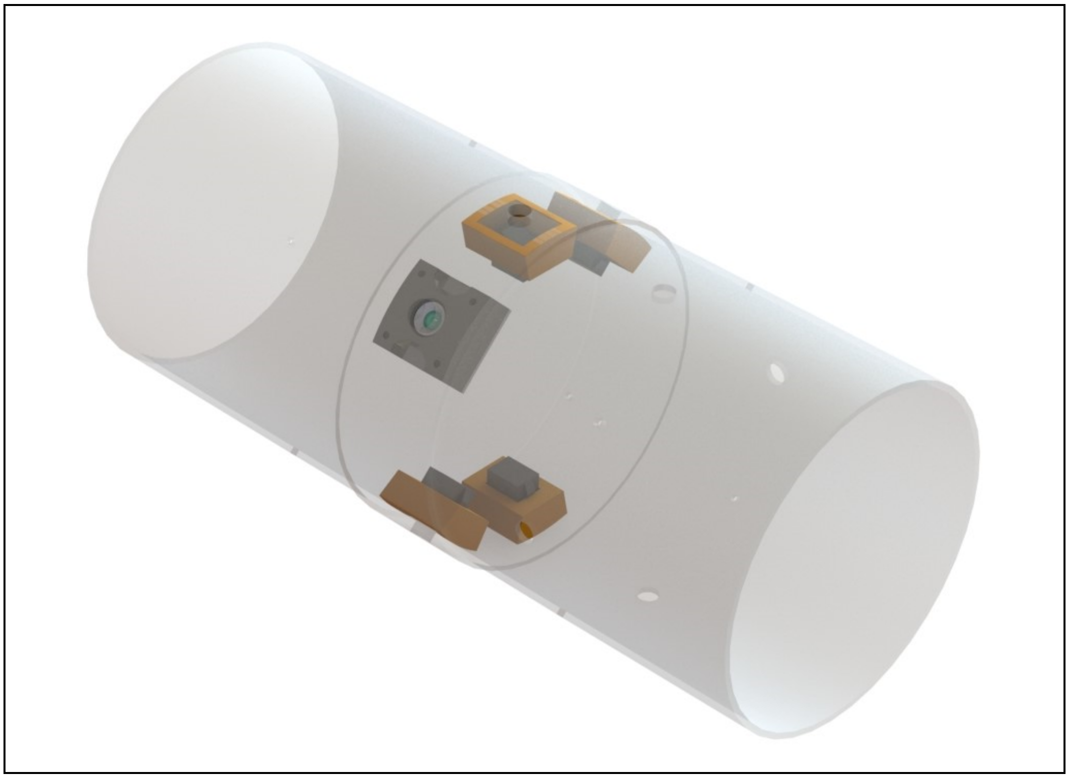


Figure 4.6: Avionics Coupler Assembly

Figure 4.7: Avionics Bulkhead Assembly

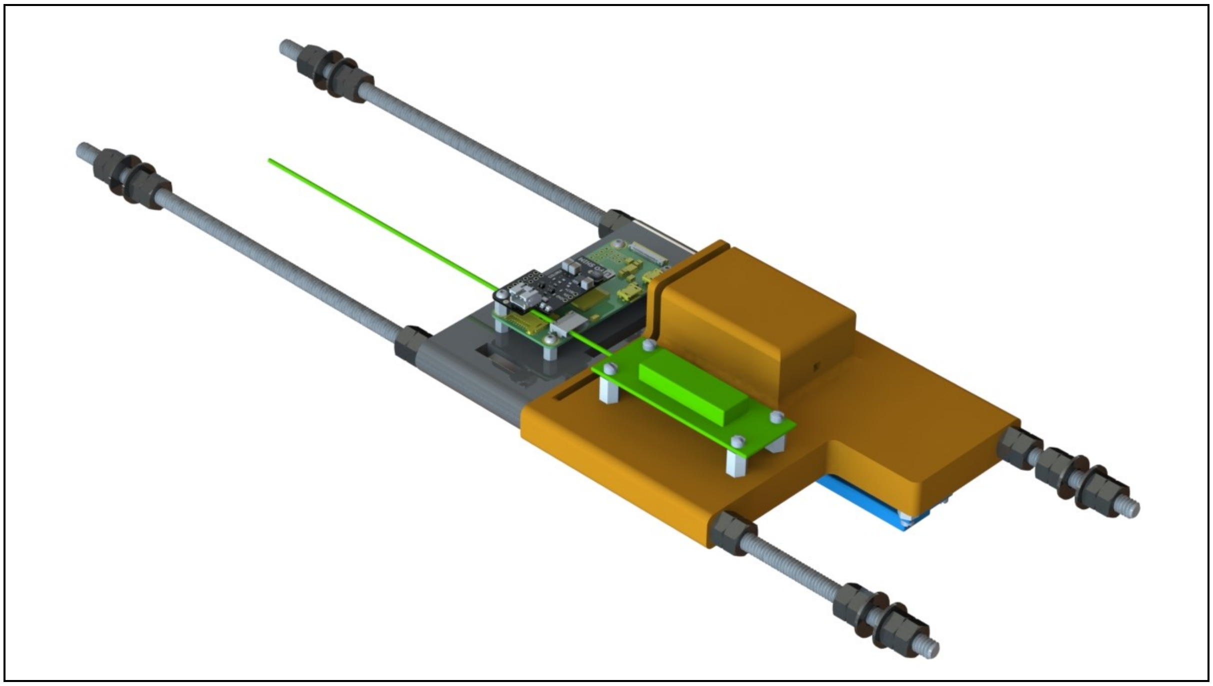


Figure 4.8: Avionics Sled Assembly

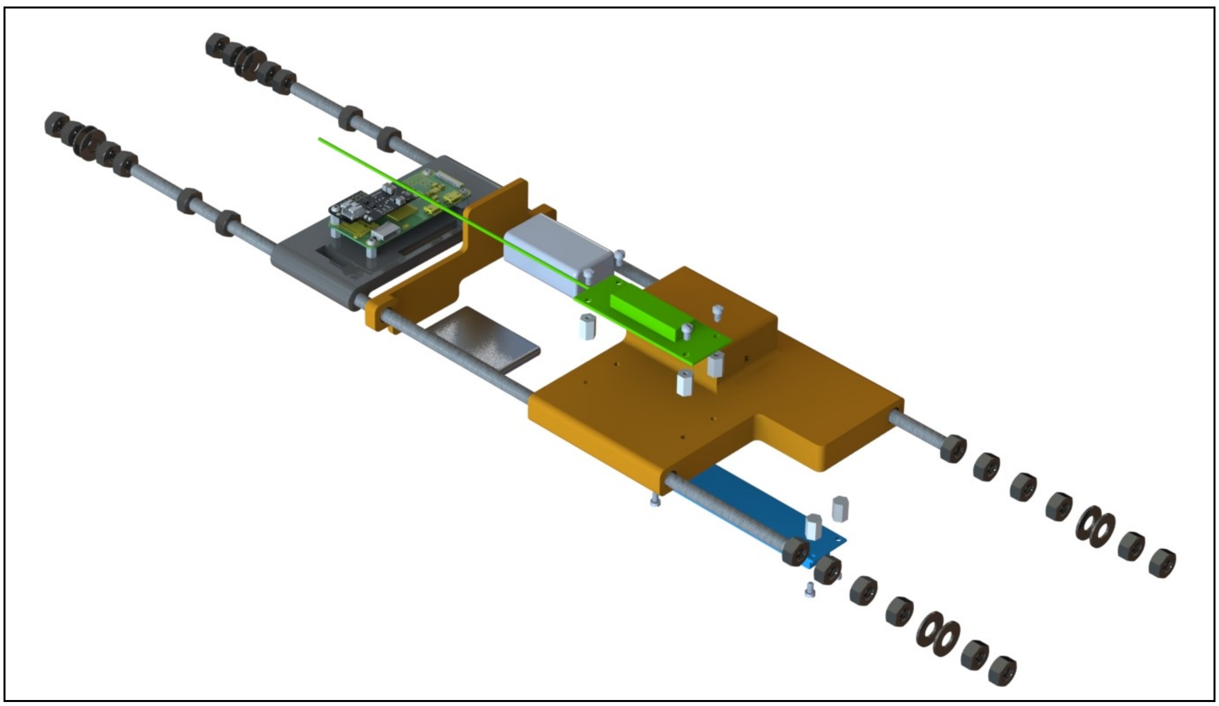


Figure 4.9: Exploded Avionics Sled Assembly

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

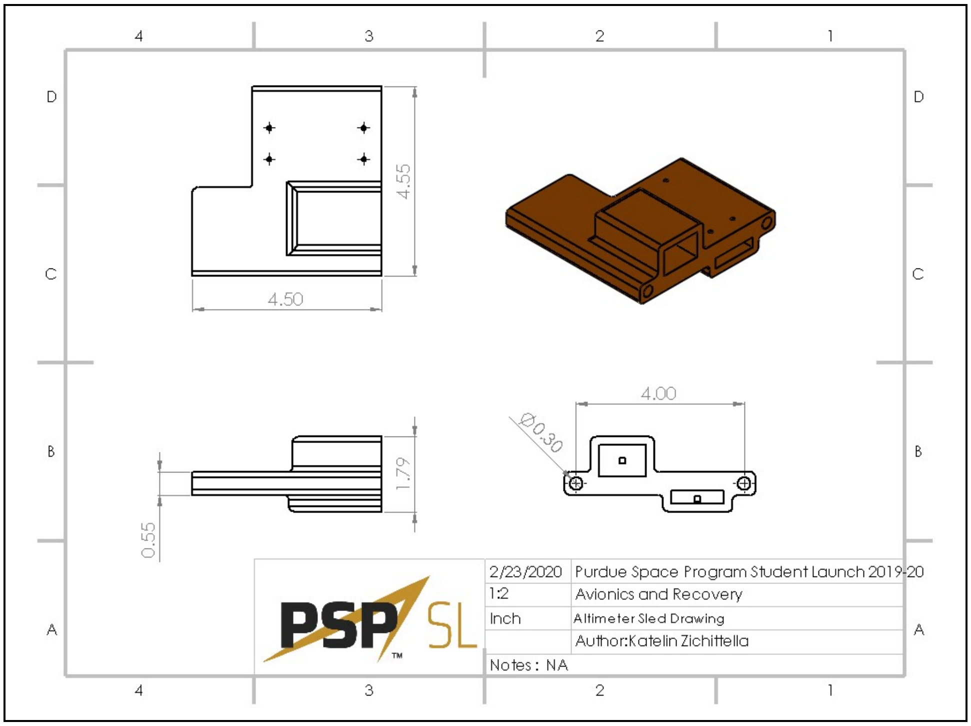


Figure 4.10: Altimeter Sled (With Built-In Battery Compartment) Dimensional Drawing

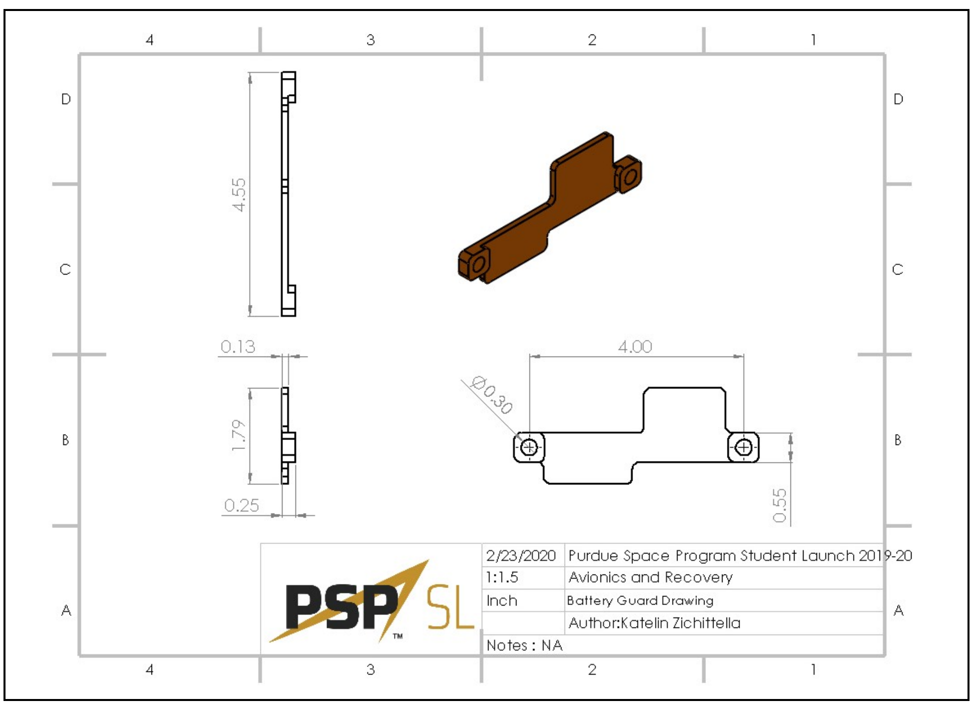


Figure 4.11: Altimeter Battery Guard Dimensional Drawing

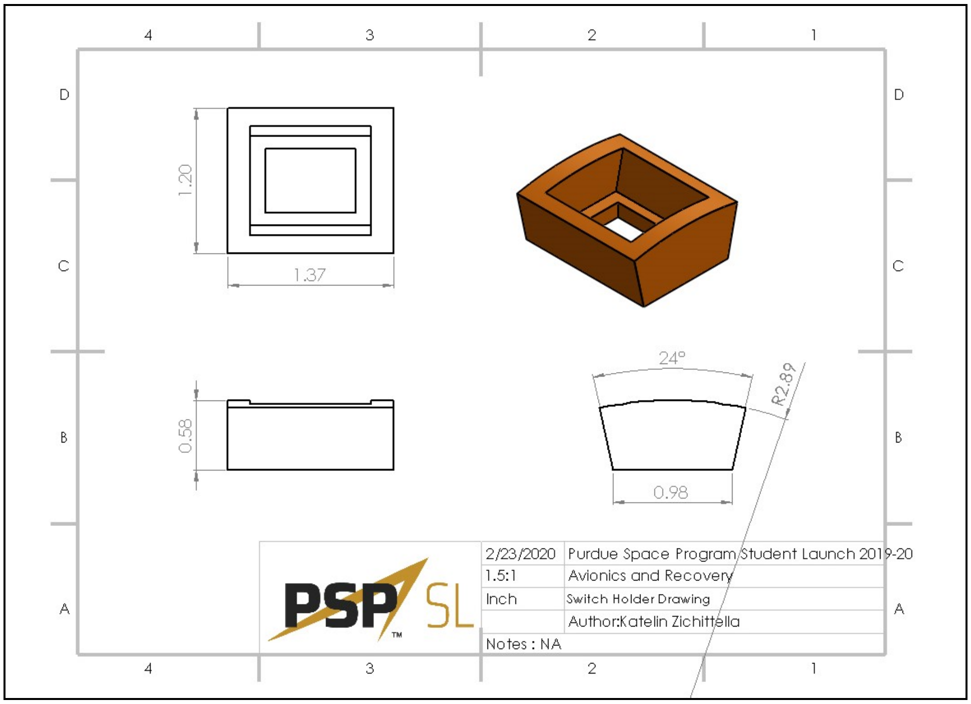


Figure 4.12: Avionics Bay Switch Holder Dimensional Drawing

4.5. Ejection Charge Sizing and Airframe Pressurization

Both parachutes are deployed via the use of black powder charges initiated by redundant altimeters. The primary drogue charge ignites at apogee with the redundant at apogee plus one second, and the primary main charge ignites at 800' AGL with the redundant at 700' AGL. The primary main charge contains 5g of FFFFg black powder, and the redundant main charge contains 6g of black powder (5g + 1g) in order to absolutely 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 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.

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

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.

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

$$P_{Bulkhead} = \frac{4 * F_{Pin,Failure}}{Area_{Bulkhead}} = \frac{394.1\ lbf}{28.27\ in^2} = 13.94 psi$$

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 "open" 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 of the nylon shear pins can be calculated. The final value is multiplied by 1.2 and always rounded up as a safety factor.

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

Upper Airframe Side (Main) Primary Ejection Charge

$$G = Mass_{BP} = 0.006 * (6\ in)^2 * (29\ in - 12\ in) * 1.2 = 4.406g \approx 5\ grams\ of\ black\ powder$$

(12" is subtracted from the open length of the upper airframe because the large main parachute located there significantly reduces the open volume of the upper airframe)

Upper Airframe Side (Main) Redundant Ejection Charge

$$G = 5g + 1g = 6\ grams\ of\ black\ powder$$

Lower Airframe Side (Drogue) Primary Ejection Charge

$$G = Mass_{BP} = 0.006 * (6\ in)^2 * 4in * 1.2 = 1.037g \approx 2\ grams\ of\ black\ powder$$

Lower Airframe Side (Drogue) Redundant Ejection Charge

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

4.6. Frequency, Wattage, and Range of Tracking Devices

The Telemetrum altimeter contains a 70cm ham-band transceiver for telemetry downlink as well as an on-board, integrated GPS receiver. More specifically, the RF transceiver is a TI CC1200 low power, high performance transceiver, and the GPS receiver is a u-blox MAX-8Q with an on-board passive patch antenna and asynchronous serial interface. The output power of the RF transceiver 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 Control Station during flight.

4.7. Electromagnetic Field Interference

The team makes use of four transmitters: one in the payload bay, two as part of the Ground Control Station, and one as part of the Telemetrum altimeter. Within the avionics bay, the components that would be the most sensitive to the electromagnetic fields that these transmitters generate are the lighters and the other altimeter (RRC3+ Sport). Shielded boxing and short connections are utilized to mitigate the possibility of electromagnetic interference. Also, the entire system was tested in the Vehicle Demonstration Flight, and no such harmful interference was observed.

4.8. Avionics and Recovery Testing

This section details the testing conducted by the Avionics and Recovery subteam in order to verify NASA and Team Derived Requirements. Each requirement is mapped to its own unique test identifier. The avionics test summary can be found below in Table 4.1, and test summary sheets can be found directly below the table. Each summary sheet explains the reason, method, and results of the related test. This includes references to the related NASA and Team Derived Requirements.

Req. ID	Test ID	Test	SUT	DT/OT	Status
3.12.2, T3.5	A_01	Altimeter Continuity Test	Altimeters	OT	Complete**
3.1.1, T3.4, T3.4.1, T3.4.2, T3.4.3	A_02	Altimeter Ejection Vacuum Test	Altimeters	OT	Complete**
3.2, T3.3	A_03	Avionics Ejection Black Powder Test	Ejection System	DT	Complete
3.12.2, T3.3	A_04	Avionics Battery Drain Test	Altimeter Batteries	OT	Complete
3.3, T3.1	A_05	Parachute Drop Test	Parachutes	OT	Complete

**Due to unsuccussful VDF, these tests will be redone prior to the reflight

Table 4.1: Avionics Test Summary Matrix

4.8.1. Altimeter Continuity Test - A_01

<table>
<tr><td rowspan="2">Test ID:
A_01

Test Name:
Altimeter Continuity Test

Related Requirements:
3.12.2, T3.5

Related Test IDs:
A_02</td><td>Objective and Tested Variables: This test ensures that continuity can be achieved when a lighter is connected to the drogue and main outputs of both the Telemetrum and RRC3+ Sport altimeters in a variety of temperatures. The tested variable is the number of beeps (or dits for the Telemetrum) that occur every five seconds after altimeter initialization.</td><td>Reason for Test: This test validates the use of each altimeter within the avionics bay of the launch vehicle. Each altimeter needs to achieve continuity when connected in the final system, and this test verifies the capability of the altimeters to do that at varying temperatures.</td></tr>
<tr><td colspan="2">Success Criteria: Each altimeter passes this test if it emits three beeps (or dits for the Telemetrum) every five seconds after the initialization routine for all three trials in both temperature extremes, indicating successful continuity for a dual deploy configuration.</td></tr>
<tr><td>Methodology</td><td colspan="2">Setup Details:
After each setup was arranged, the test apparatus was left in isolation while the number of continuity beeps (or dits) were counted.
1. A 9V battery and a switch were connected to the RRC3+ Sport altimeter. A lighter was also connected to each of the drogue and main outputs.</td></tr>
</table>

		2. The altimeter was powered on and allowed to complete its initialization routine. 3. The number of continuity beeps that were subsequently emitted was then recorded for each of the three trials. 4. The same procedure was repeated with the Telemetrum altimeter (but with a 3.7V LiPo battery and listening for *dits* instead). 5. The entire test was conducted in both the early fall and in the winter in order to verify that continuity for a dual deploy configuration in both hot and cold environmental conditions can be achieved.
	Possible Impacts	Analyzing the results from this test verifies the plan for the launch vehicle avionics bay. For the RRC3+ Sport altimeter, 3 beeps every 5 seconds in each of the temperature climates validates its inclusion in the avionics bay. For the Telemetrum altimeter, 3 *dits* every 5 seconds also verifies its inclusion. These results are critical to the design of the launch vehicle, as these altimeters are used throughout the flight, especially at apogee and at the main deployment altitude. No deficiencies were observed during the test.
Results **Status:** *Complete*		Testing comprised of trials in October and January to simulate the temperature extremes that could occur at the full scale launch and on launch day. Both altimeters met the success criteria in each of the temperature environments they were tested in. Therefore, there is significant confidence that continuity can be achieved for each altimeter in a variety of temperatures.

4.8.2. Altimeter Ejection Vacuum Test - A_02

<table>
<tr>
<td rowspan="2">Test ID:
A_02

Test Name:
Altimeter Ejection Vacuum Test

Related Requirements:
3.1.1, T3.4, T3.4.1, T3.4.2, T3.4.3

Related Test IDs:
A_01</td>
<td>Objective and Tested Variables: The objective of this test was to ensure that both the Telemetrum and RRC3+ Sport altimeters ignite the drogue ejection charge at apogee (or one second after apogee for the RRC3+ Sport) and the main ejection charge at the correct altitude during descent (800’) (or 700’ for the RRC3+ Sport).</td>
<td>Reason for Test: This test justifies the design of the avionics bay within the launch vehicle and verifies that the altimeters ignite the ejection charges at the correct times.</td>
</tr>
<tr>
<td colspan="2">Success Criteria: The Telemetrum altimeter passed this test if 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 800 ± 50’ for all three trials. The RRC3+ Sport altimeter passed this test if the drogue delay (the time between apogee and ignition of the drogue lighter) was between 0.75 and 1.75 seconds (as it is programmed to be 1 second) and the altitude the main lighter ignited at was between 700 ± 50’ for all three trials.</td>
</tr>
<tr>
<td>Methodology</td>
<td colspan="2">Setup Details:
The apparatus described in the steps below was reset for each trial. During each trial, the only interaction with the apparatus came from pumping air in or releasing air out of the container.
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 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 Altimeter One indicated when this was), the drogue lighter was expected to ignite (or one second after apogee for the RRC3+ Sport).
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</td>
</tr>
</table>

	the Altimeter One. The main lighter was expected to ignite at pressures corresponding to an altitude of 800’ (or 700’ for the RRC3+ Sport). 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.
Possible Impacts	The results of this test verify the planned design of the avionics bay, specifically the pairing of the RRC3+ Sport and Telemetrum altimeters with ejection charges. Verifying this design ensures the inclusion of the ejection charges is safe, and that they only ignite at the correct times in flight. Deficiencies occurred due to spatial limitations only allowing one person to conduct the test. With only one person switching between pumping air out and slowly letting it back in, the altimeters took longer to register that apogee had been reached. Another deficiency occurred when letting air back into the chamber, as this was difficult to do with the pliable putty. This deficiency resulted in some erratic descent profiles.
Results **Status:** *Complete*	Initial tests with the RRC3+ Sport altimeter failed, but after retesting it was determined that these failures were largely due to deficiencies in the test setup. Both altimeters therefore met the derived requirements and passed this test. It can therefore be said with reasonable confidence that the RRC3+ Sport and Telemetrum altimeters will consistently ignite the drogue and main ejection charges at the correct points in flight.

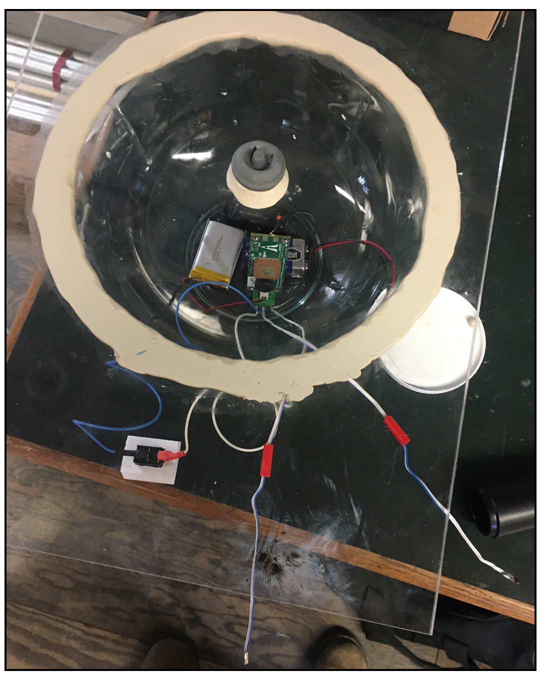


Figure 4.13: The Test Setup with the Telemetrum Altimeter in the Vacuum Chamber Ready for a Trial

4.8.3. Avionics Ejection Black Powder Test - A_03

<table>
<tr>
<td rowspan="2">Test ID:
A_03

Test Name:
Avionics Ejection Black Powder Test

Related Requirements:
3.2, T3.3

Related Test IDs:
N/A</td>
<td>Objective and Tested Variables: The objective of this test is to ensure that the black powder ejection system for the recovery components functions correctly. The tested variable is how much black powder should be used in each canister, measured in grams.</td>
<td>Reason for Test: This test justifies the use of black powder canisters within the avionics bay ejection system on the launch vehicle.</td>
</tr>
<tr>
<td colspan="2">Success Criteria: Each black powder canister passes this test if its ignition resulted in at least 6’ of separation of the avionics bay from the corresponding airframe, for at least one amount of black powder equal to or greater than 5g for the upper airframe and 2g for the lower airframe.</td>
</tr>
<tr>
<td>Methodology</td>
<td colspan="2">Setup Details:
The main setup for this test occurred outside in a large grass area. The airframes used for the test were laid on the grass and observers stood at a safe distance from the charges. There was more than enough room for the success criteria of 6’ of separation between airframe sections. A remote detonator was used to ignite the charges for this test.
1. The black powder canister on the upper airframe side of the avionics bay was filled with 5g 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 dog barf 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 wrapped in one of the Nomex blankets was placed into the upper airframe, and the avionics bay was reconnected to it using shear pins. The extension wire was 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.
4. 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 components. If they did indeed separate, the distance between them was measured in feet using the tape measure.
5. If the above success criteria was 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.
6. The procedure was also repeated for the black powder canister on the lower airframe side of the avionics bay (with the drogue parachute inserted), with 2g of black powder.</td>
</tr>
<tr>
<td>Possible Impacts</td>
<td colspan="2">The results of this test ensure the black powder canisters are safe to use within the avionics bay of the launch vehicle. Specifically, the separation distance of at least 6’ verifies each individual black powder canister. The overall verification of this system adds confidence that the launch vehicle will safely descend after reaching apogee. It is important to note that the parachutes were placed in their corresponding airframes but not attached to the bulkheads.</td>
</tr>
</table>

	This results in a possible test deficiency as it is unknown whether or not the black powder explosion would have been energetic enough to actually pull the parachutes out of the airframes while still resulting in the required 6’ of separation.
Results **Status:** Complete	Both the upper and lower airframe black powder canisters resulted in over 6’ of separation between the airframe and the avionics bay. Both black powder canisters have met the success criteria and have therefore passed this test. It can be said that the black powder ejection system will function correctly for the recovery components.

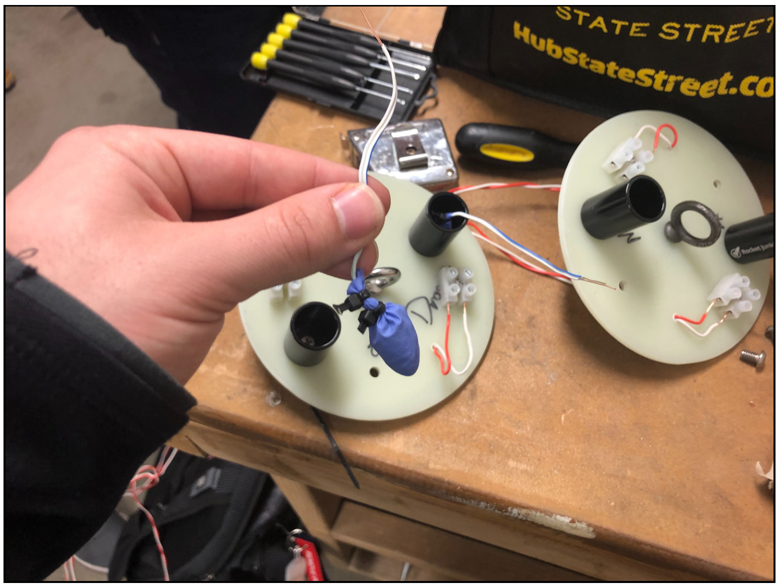


Figure 4.14: Setting up the Black Powder Charges

Figure 4.15: Connecting the Avionics Bay to the Upper Airframe

Figure 4.16: After Ignition of the Drogue Charge

Figure 4.17: Measuring the Distance of Separation

4.8.4. Avionics Battery Drain Test - A_04

<table>
<tr><td rowspan="2">Test ID:
A_04

Test Name:
Avionics Battery Drain Test

Related Requirements:
3.12.2, T3.2

Related Test IDs:
N/A</td><td>Objective and Tested Variables: This test ensures that the altimeter batteries can last for at least 3 hours, which is the maximum expected duration of the launch. The tested variable is each battery’s voltage over time.</td><td>Reason for Test: This test verifies that the batteries deliver enough voltage to the altimeters throughout the duration of the launch.</td></tr>
<tr><td colspan="2">Success Criteria: Each battery passed this test if, connected to its corresponding altimeter, the battery was able to keep it powered on for 3 hours as well as not drop below 3.2V for the LiPo battery or 8.0V for the alkaline battery (voltage was measured every 0.5 hours).</td></tr>
<tr><td>Methodology</td><td colspan="2">Setup Details:
After each battery was connected to its respective altimeter, they were left out on a table. The setup was only handled when taking voltage readings, and otherwise remained isolated throughout the duration of the test.
1. One new 9V battery was connected to the RRC3+ Sport altimeter using a 9V battery connector, and a switch was also connected.
2. The altimeter was powered on using the switch, and the system was left for 3 hours.
3. Every 0.5 hours, the voltage of the battery was recorded using a multimeter.
4. At the end of the 3 hours, it was checked if the altimeter was still powered on.
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 dits (which represent the current voltage level detected by the Telemetrum) was then recorded as the voltage measured for that interval of time.</td></tr>
<tr><td>Possible Impacts</td><td colspan="2">Successful completion of this test adds to the team’s confidence that the altimeters are able to return critical altitude values and initiate important flight events. The only possible deficiency in this test is due to the RRC3+ Sport altimeter being set to Pad Audio Power Saver Mode in an effort to reduce constant noise output over the 3 hour test duration. The team is confident that the power difference between this mode and the normal setting is nominal, and the RRC3+ Sport will still perform as desired during launch.</td></tr>
<tr><td>Results

Status: Complete</td><td colspan="2">The 9V battery never dropped below 8.0V for any of the recorded voltages during the test, and the RRC3+ Sport was still powered on at the conclusion of the test. Likewise, the 3.7V LiPo battery never dropped below 3.2V for any of the recorded voltages during the test, and the Telemetrum was still powered on at the conclusion of the test. Therefore, both batteries have met the success criteria outlined above and have passed this test. There is reasonable confidence that the altimeter batteries can last for the duration launch.</td></tr>
</table>

4.8.5. Parachute Drop Test - A_05

<table>
<tr><td>Test ID:
A_05

Test Name:
Parachute Drop Test

Related Requirements:
3.3, T3.1

Related Test IDs:
N/A</td><td>Objective and Tested Variables: The objective of this test is to ensure the drogue parachute opens within a consistent time frame and the main parachute opens within the expected distance after being ejected.

Success Criteria: After each trial the drogue parachute was dropped, the amount of time it took for it to come to a fully opened state was measured. It passed this test if the times measured in the three trials were all within 0.50 seconds of each other. The main parachute passed this test if it was at least 17% open after falling 50’ for all three trials (extrapolating this value ensures that the parachute would be 100% open after falling 300’).</td><td>Reason for Test: This test verifies the inclusion of the designated drogue and main parachutes in the design of the launch vehicle. These parachutes need to be reliable in order to ensure a safe descent of the launch vehicle after apogee.</td></tr>
<tr><td>Methodology</td><td colspan="2">Setup Details:
This test was conducted outdoors at a large parking garage. After the weight was secured to the parachute being tested in a given trial, it was lifted into the air and thrown over the edge.
1. The completed launch vehicle weighs roughly 50 lbs. Therefore, 50 lbs of weights were attached to the drogue and main parachutes separately for an estimate (via shock cord and quick link).
2. Through prior testing from last year, it was determined that approximately 50’ was an ample distance range for the drogue parachute to open from a correctly folded state. Therefore, it was folded in the packing configuration and dropped from a height of four stories (from the top of a nearby parking garage at about 50’).
3. Using a stopwatch, after each of the three trials the drogue parachute was dropped, the amount of time it took for it to come to a fully opened state was measured.
4. Similarly, the main parachute was folded in the packing configuration and dropped from the top of the parking garage.
5. For each of the three trials, the main parachute was filmed during its descent using a cell phone camera.
6. After landing, the footage was reviewed and an estimate was made of what percentage the parachute had opened to just before hitting the ground (0% is completely folded and 100% is fully open). An exponential model was considered when estimating the percentage of opening.</td></tr>
<tr><td>Possible Impacts</td><td colspan="2">Verifying the drogue and main parachutes ensures the launch vehicle has a safe and controlled descent after apogee. The method used for throwing the main parachute over the edge gives possibility for a test deficiency. Specifically, the main parachute was not thrown in exactly the same orientation during each trial, causing some slight variance in the data.</td></tr>
<tr><td>Results

Status: Complete</td><td colspan="2">For the drogue parachute, the times to open measured were all within 0.50 seconds of each other. Likewise, for the main parachute, the percentages open just before landing measured were all above 17%. Therefore, both parachutes have met the success criteria outlined above and have passed this test. It can be said with a reasonable amount of confidence that the drogue parachute will open within a consistent time frame and the main parachute will open within the expected distance after being ejected.</td></tr>
</table>

Figure 4.18: The Main Parachute Just Before Landing

5. Mission Performance Predictions

5.1. Trajectory Analysis

As discussed in the CDR report, the PSP-SL team has placed more focus on launch rail inclination this year while deciding to spend less time on the in-depth discussion of each wind case. For each analysis, two specific cases are described in-depth while a range of other cases are tabulated for ease of understanding. The first case is the ideal case of no wind and no rail inclination. Obviously, this is not feasible, but it gives the perfect performance of the team's launch vehicle. Following that case is a 10mph average wind speed case with 10° of launch rail inclination, which is assumed to be the most likely case since the estimated wind speed in early April for Huntsville, Alabama is 7-9mph and the launch rail is likely to be inclined away from spectators. The OpenRocket and RASAero models are modeled around the full scale launch vehicle after construction was completed. This includes masses added from epoxy and fasteners all of which slightly affect the center of gravity and the center of pressure.

5.1.1. As-Built Center of Pressure, Center of Gravity, and Stability

The launch vehicle model has updated Center of Gravity and Center of Pressure values which are based on small changes that occurred during the physical construction of the launch vehicle. The new Center of Gravity is 76.66'' from the tip of the nose cone and the Center of Pressure is 95.907'' from the nose cone. The stability margin at launch is 3.12cal which is above the NASA requirement of 2cal off the launch rail. These values are slightly further rearward than previously predicted and these changes result in a better performance from the vehicle which is fully explored in the following sections.

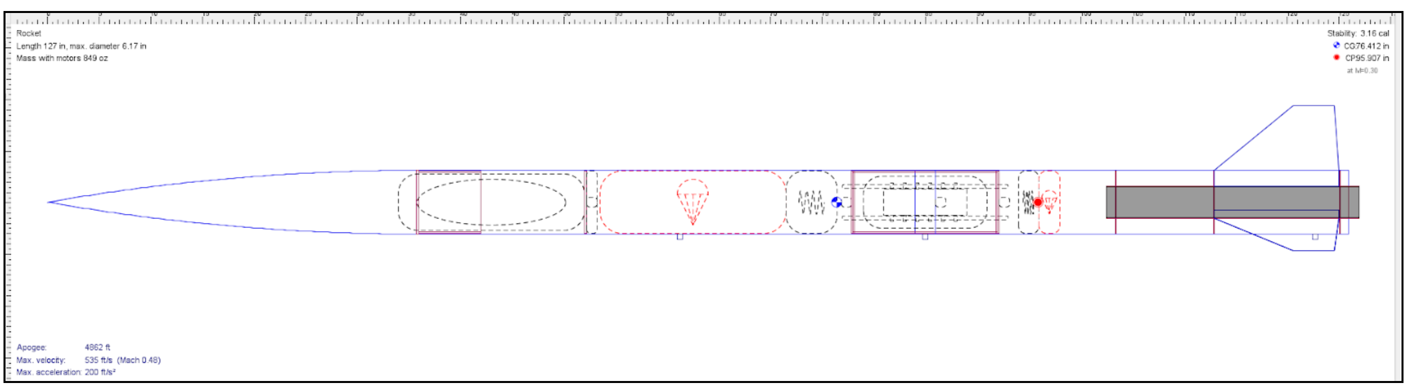


Figure 5.1: The schematic of the launch vehicle with the CG, CP and Stability Margin values

5.1.2. OpenRocket Altitude Simulations

10deg Incline, 10mph

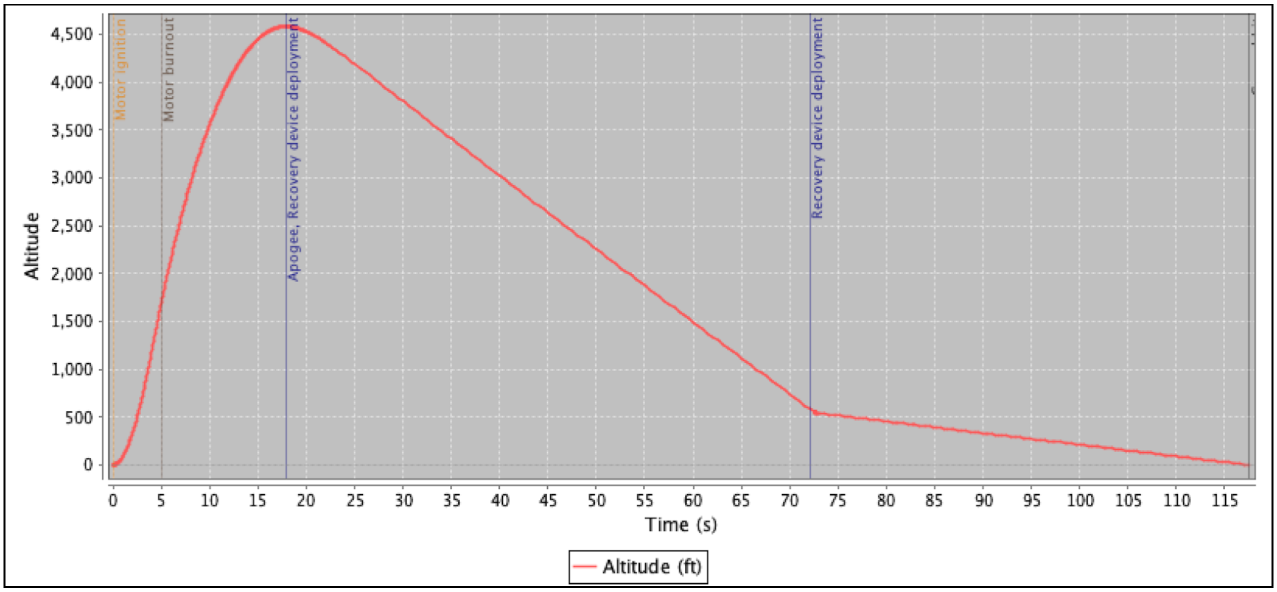


Figure 5.2: OpenRocket Simulation of Hypothesized Scenario for Huntsville Launch

As can be seen from the graph above, the rocket is simulated to reach a maximum altitude of 4582' above ground level. This is slightly above the target altitude of 4325' above ground level. In previous reports, there was a degree of uncertainty regarding these results due to the added weight of epoxy and fasteners. However, this OpenRocket model has been updated to include the final weight of the launch vehicle so these results have a higher degree of accuracy with respect to the physical flight.

15deg Incline, 20mph

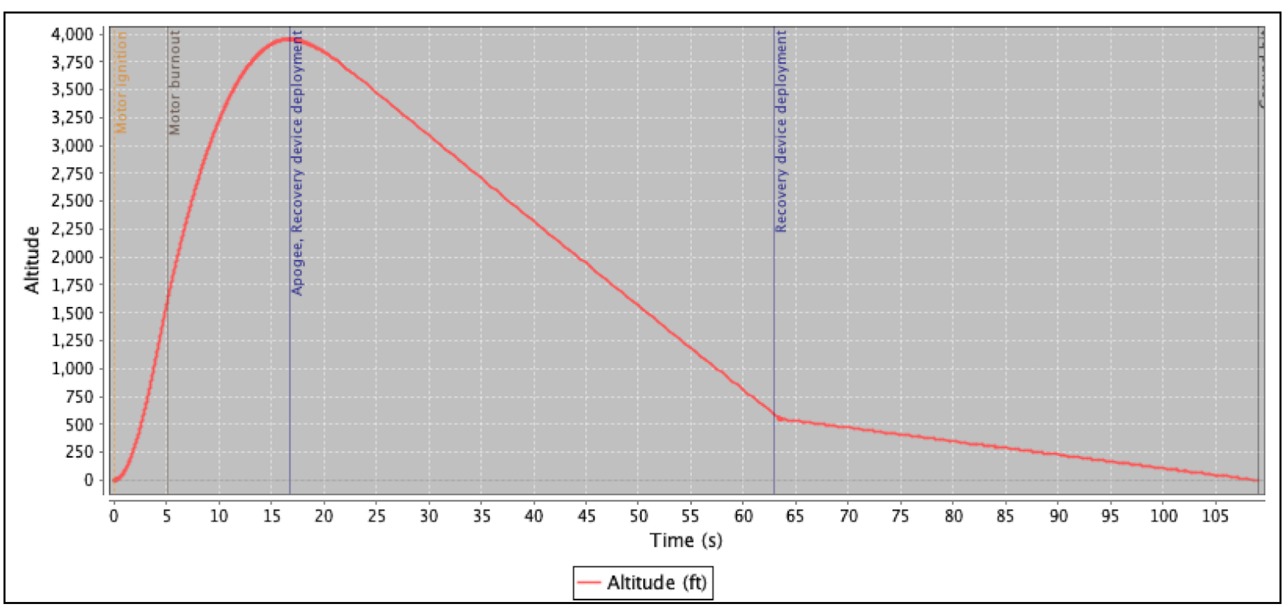


Figure 5.3: 15deg Inclination, 20mph Winds OpenRocket Simulation

The case of 15° inclination and 20mph winds is the worst case scenario that the team simulated. In this case, the max altitude the vehicle would reach is 3953' which is considerably lower than the team's target altitude. This case was simulated in order to assess the worst performance of the vehicle depending on the circumstance. This case is very unlikely to occur as the current prediction of launch day winds is around 5-10mph.

0deg Incline, 0mph

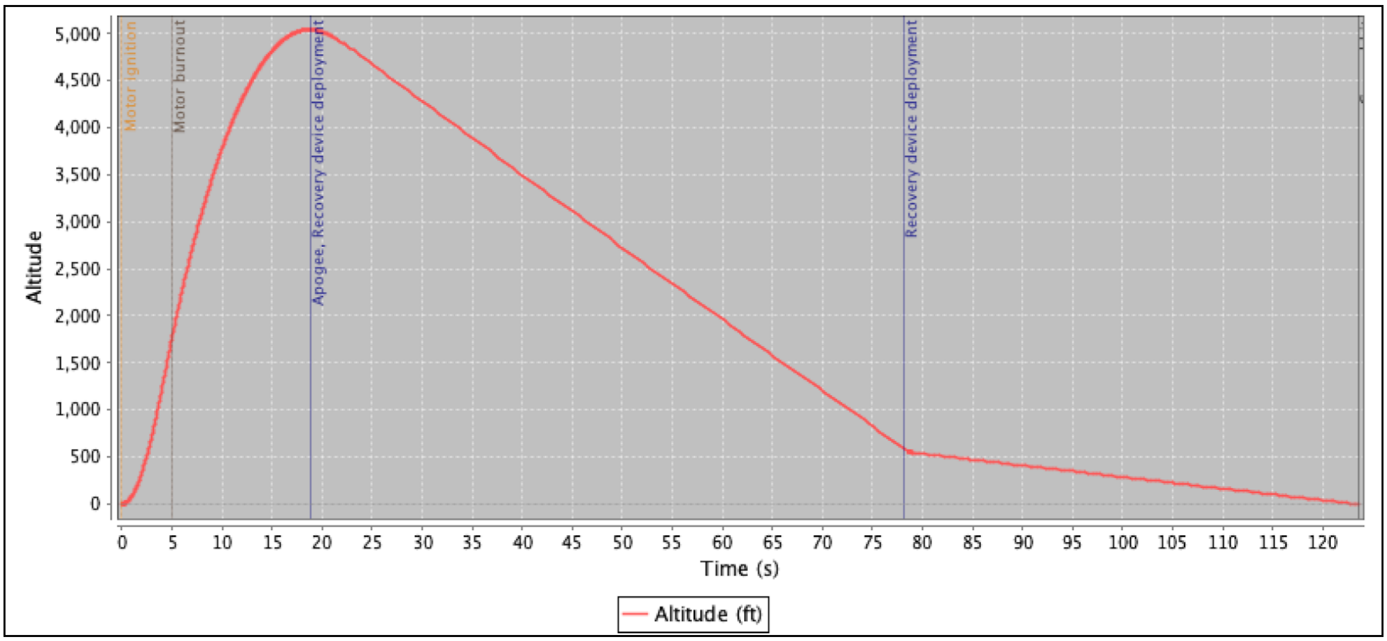


Figure 5.4: OpenRocket Simulation of Ideal Scenario for Huntsville Launch

The case of 0° inclination and 0mph winds is the best case scenario in terms of maximizing altitude. In this case, the max altitude the vehicle would reach is 5042' which is considerably greater than the team's target altitude. This case was simulated in order to assess the best performance of the vehicle depending on the circumstance. This case is very unlikely to occur for the same reasons as the 20mph case. However, it is important to know the range of performance for the launch vehicle as the launch day conditions have a certain degree of uncertainty.

5deg Incline, 10mph

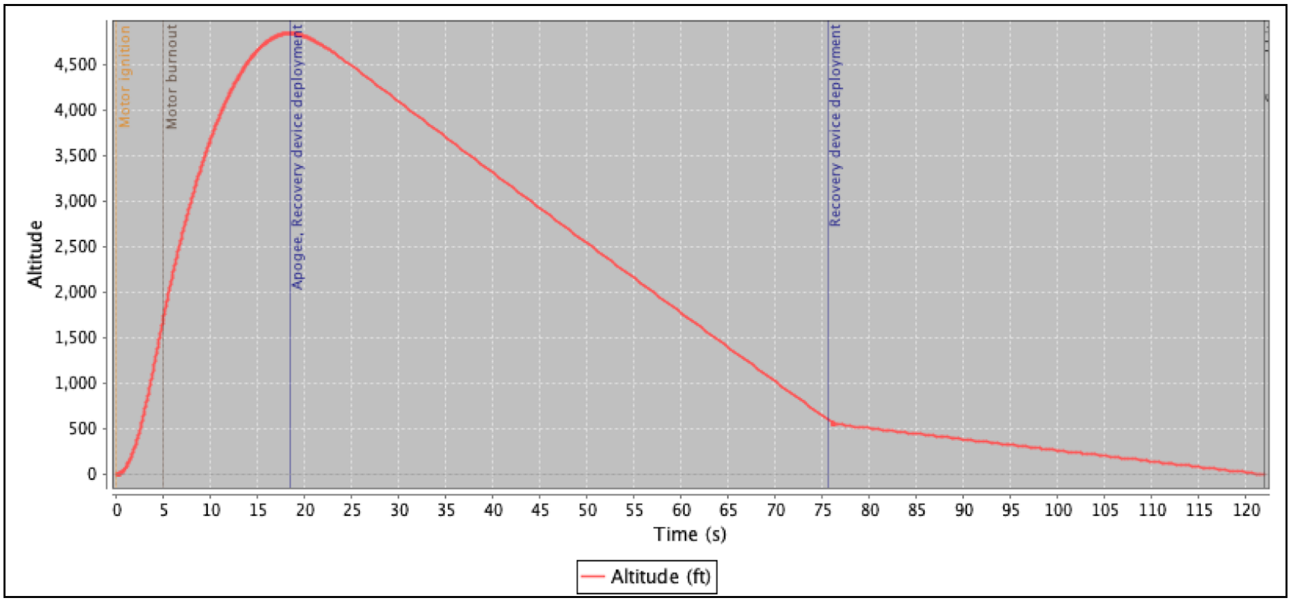


Figure 5.5: 5° Inclination, 10 mph Winds OpenRocket Simulation

The case of 5° inclination and 10mph winds is a case that is more realistic than the ideal scenario that the team simulated. In this case, the max altitude the vehicle would reach is 4837' which is considerably greater than the team's target altitude. This case is more likely to occur for the same reasons as it is closer to the ideal case that is predicted for the launch day.

15deg Incline, 10mph

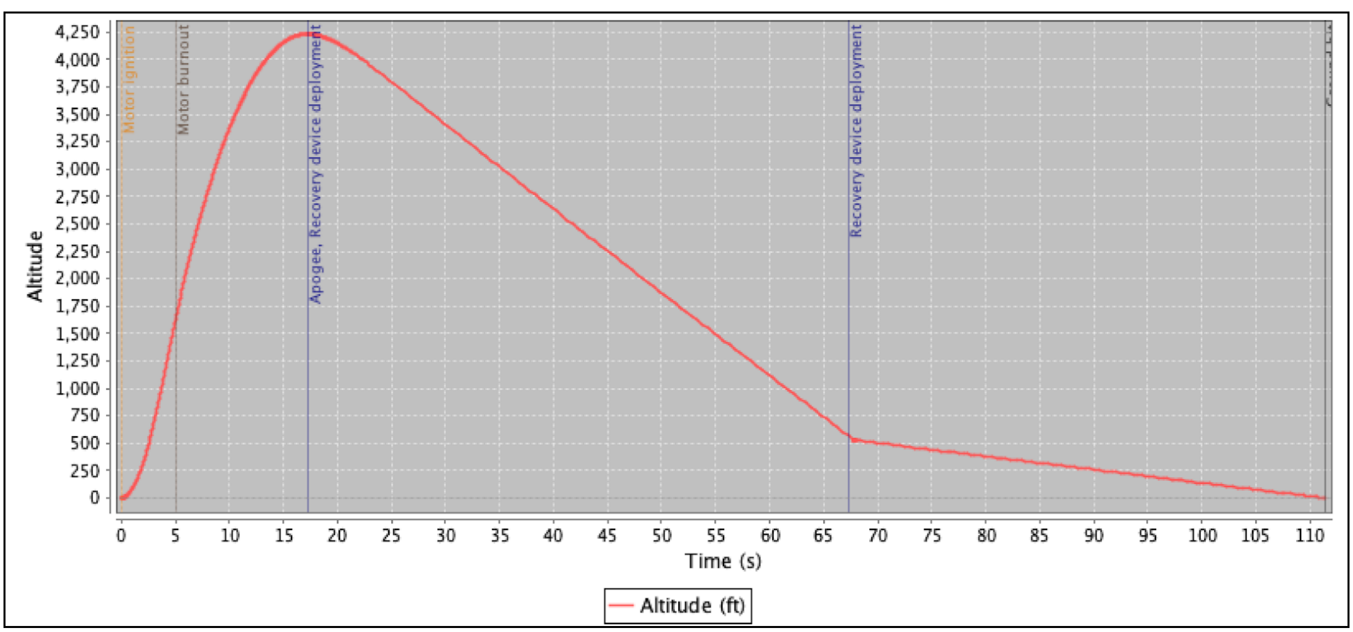


Figure 5.6: 15 Degree Inclination, 10mph Wind OpenRocket Simulation

The case of 15 degree inclination and 10mph winds is a case that is worse than the ideal case scenario that the team simulated. In this case, the max altitude the vehicle would reach is 4233' which is less than the team's target altitude. This case is more likely to occur for the same reasons as it is closer to the ideal case that is predicted for the launch day. This case also demonstrates how the inclination can affect the apogee on launch day which provides an insight into how small changes in the launch day condition can create a large change in the apogee of the launch vehicle.

Other factors, such as surface finish and the cross sectional airfoil of the fins, are variables that the team does not have implicit control over. The team cannot accurately measure surface smoothness to compare the real and digital models, which will account for some difference in the actual and expected altitudes. In addition, the only choices presented to the team when varying the fin's cross section are "square, rounded, or airfoiled". There is no direct input for edge thickness or taper length, further limiting the simulations.

All altitude simulations from which the graph above is derived were accomplished using OpenRocket 15.03 using the extended Barrowman calculation method and a six degrees of freedom Runge Kutta 4 simulation method. Geodetic calculations were evaluated using spherical approximation, and a 0.02s time step for simulation calculations was used. Further altitude calculations will be done in RASAero II using similar parameters, and will be discussed in the next section.

5.1.3. RASAero Altitude Verification

To further the analysis of inclinations and varying wind speeds, RASAero was used to verify the results. This year, it was seen as very important to understand how the wind speed and rail inclination can change the flight, so ensuring accuracy through multiple verifications is of utmost importance. The results yielded from the incline and wind speed stimulations in RASAero were consistent with OpenRocket as different conditions led to a higher altitude, with a slight amount of error.

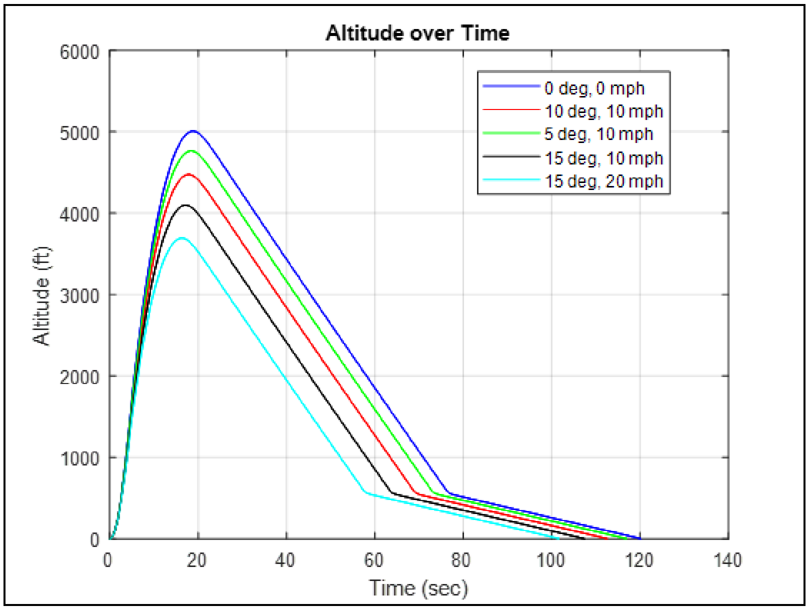


Figure 5.7: RASAero Simulation of Hypothesized Scenario for Huntsville Launch

For a 0 degree launch rail incline, and the absence of any winds, as expected the highest altitude is yielded. The altitude, shown by the dark blue curve is significantly higher than the team's targeted, but, as mentioned above, this is the most ideal situation which is incredibly unlikely to occur on launch day. The simulation had an altitude of 5006' compared to OpenRocket's 5042'.

The second case, shown in red, used a launch rail incline of 10°, with an anticipated wind speed of 10mph. The simulation is believed to be the most likely candidate for actual launch day conditions. With a launch rail incline of 10°, and with 10mph winds, a maximum altitude of 4475' is anticipated. For reference, OpenRocket had an apogee of 4582'. The important note here is that the target altitude is only 4325', so this case indicates more ballast may be needed. The team has not yet painted the rocket and believe that this difference will be enough to offset the apogee error of 150'. This difference is bearable, but the team hopes to be closer than that at the Huntsville flight.

The situation of a 5 degree incline with 10mph winds, shown in green, led to an altitude of 4764'. OpenRocket gave an apogee of 4837' for this case. This is one of the more likely situations to occur for the launch day, so keeping in mind the results of the simulation will give a good understanding of the launch vehicle's behavior being above the targeted altitude. This is a concerning value. If this case occurs, the team will be significantly off from the targeted altitude. Keeping this in mind, the team will look to lower this altitude through the addition of some ballast weight.

The case of 15 degree rail inclination with 10mph winds, shown in black, would anticipate a less than ideal scenario for the rockets anticipated launch. The altitude would come to 4098', which is a couple hundred feet below the targeted altitude. The OpenRocket simulation of this case yielded an apogee of 4233'.

Upon testing a 15° incline with 20mph winds, an altitude of 3692' was yielded. This was a worst case scenario for the launch conditions of the rocket as set by the competition. As expected, the conditions led to the lowest altitude of any of the cases. This case is incredibly low and while it is highly unlikely that launch will occur in these conditions, the team thought it important to understand how the conditions affect the launch. This case yielded the largest difference between OpenRocket and RASAero simulation results as OpenRocket had an apogee of 3953'.

Using both simulation software to test the conditions of differing inclines, and wind speeds helps to provide the team with a broader understanding of the results that would be yielded for the cases. The differences among each case would tend to be within 100', and OpenRocket would always create higher results.

Upon exploring this deviation, an apogee deviation of approximately 6% can be found, which comes from the differing ways that each software takes into account weights of components like body tubes. This is consistent with the team's findings.

Exploring the results of different software is always important, as relying on just one source to provide feedback does not assess all of the possible outcomes that a certain case can generate. It is always important to cross reference the results of software to ensure that each quirk a software may have to obtain results are understood and compared.

5.1.4. Trajectory Code

A MATLAB program was created to verify the values obtained from the OpenRocket and RASAero simulations. The code also accounts for different launch angles and different wind speeds. Three different launch angles (0, 5, and 10 degrees) and three different wind speeds (0, 5, and 10 mph) were all tested. The code takes into account the temperature at launch (all of the tests below were run at 25°C (77°F) as well as the change in air density with altitude. The thrust curve that was found from previous experimental data was also utilized, and the values were linearly interpolated to get a continuous graph.

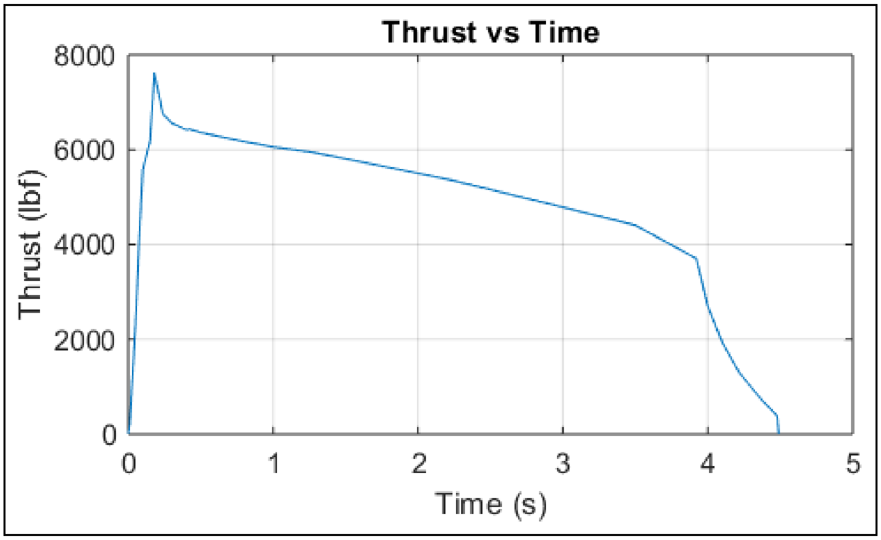


Figure 5.8: Interpolated Motor Thrust vs Time Plot

The code is split into four parts for the four phases of the flight: boosting phase, coasting phase, drogue parachute phase, and main parachute phase.

Boosting Phase: During the boosting phase, the launch vehicle's position is updated for a time step of 0.1s. Only the forces of gravity, drag and thrust are acting in this phase. This phase ends when the motor stops burning.

Coasting Phase: During this phase the launch vehicle does not experience thrust from the motors, so the only forces that the vehicle experiences are drag and gravity. Once the velocity becomes 0ft/s, the code moves onto the next phase.

Drogue Parachute Phase: In this phase, the drogue parachute is deployed, and the drag from the drogue parachute is also added to the other forces. This phase ends when the launch vehicle reaches an altitude of 800'.

Main Parachute Phase: In this phase the main parachute is deployed. It was assumed that the main parachute's radius increases linearly with time, and the total time it takes for the parachute to open was estimated to be 0.2s. With this, the drag from the main parachute is also calculated until the altitude reaches 0'.

Altitude vs Time Plots

0mph Wind Speed

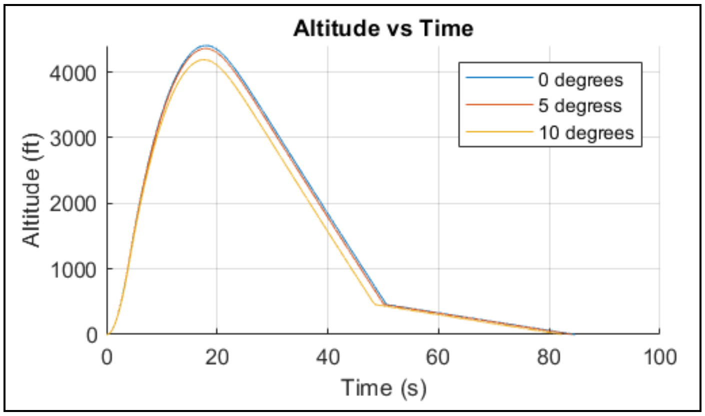


Figure 5.9: 0 mph Wind Speed Altitude vs. Time Plot

The apogee is 4461' with a 0 degree launch angle, 4360' with a 5 degree launch angle, and 4189' with a 10 degree launch angle.

5mph Wind Speed

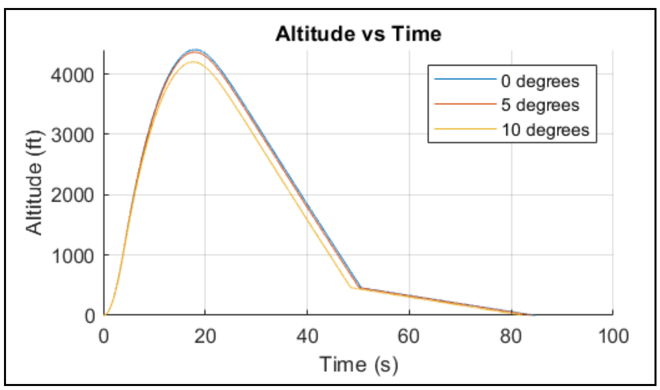


Figure 5.10: 5mph Wind Speed Altitude vs. Time Plot

The apogee is 4406' with a 0 degree launch angle, 4365' with a 5 degree launch angle, and 4202' with a 10 degree launch angle. The apogees of the 5 and 10 degree launches are higher for 5mph wind than 0mph wind. This could be due to the vehicle getting pushed by the wind instead of being opposed by it.

10mph Wind Speed

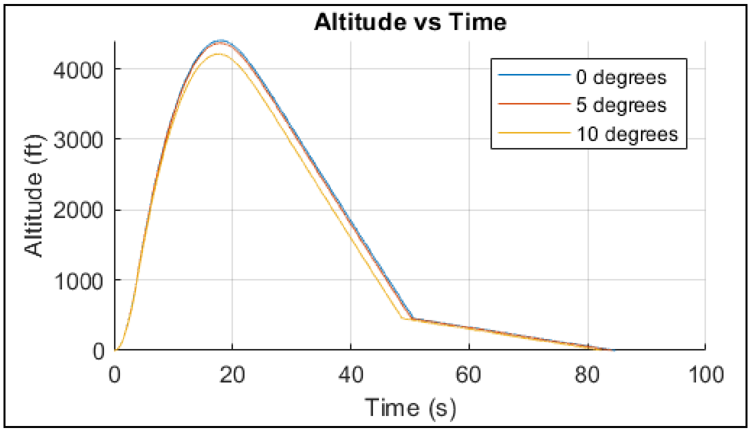
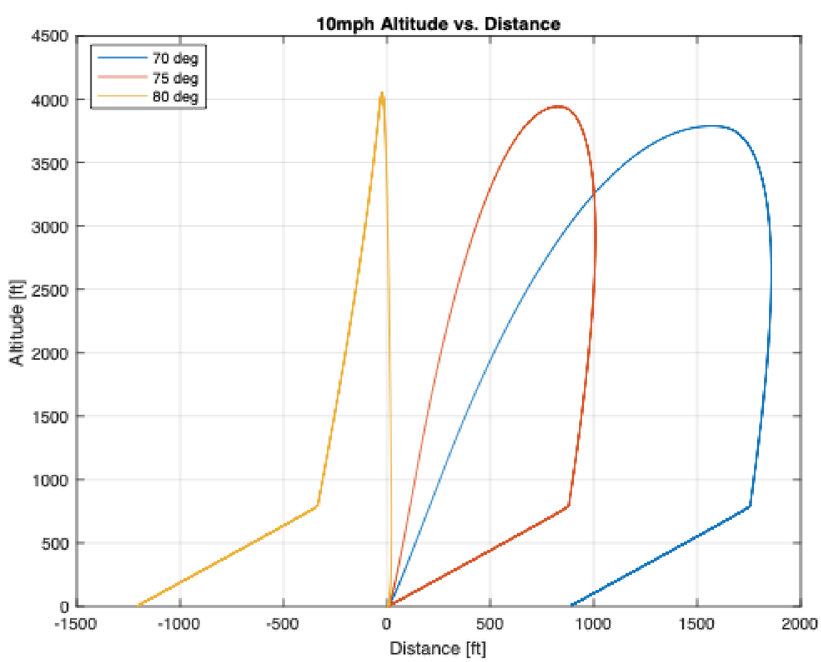


Figure 5.11: 10mph Wind Speed Altitude vs. Time Plot

The apogee is 4406' with a 0 degree launch angle, 4369' with a 5 degree launch angle, and 4213' with a 10 degree launch angle.

Drift Distance Plot

The following figure and table show drift distance calculations and simulations. Figure 5.12 shows drift values calculated from OpenRocket simulations plotted in MATLAB for a 10mph wind speed and expected launch day angles, and Table 5.1 compares values generated via this method with values generated via the calculation Drift = Descent Time * V_∞ over a range of possible launch day wind speeds at 0deg inclination.



Note: 90deg is normal to the ground

Figure 5.12: Drift Distance Plot for Estimated Huntsville Conditions

Crosswinds	Hand-Calc Drift	OpenRocket Drift
0mph	0’	9’
5mph	648’	685’
10mph	1340’	1400’
15mph	1995’	2200’
20mph	2605’	2625’

Table 5.1: 10mph Wind Speed Altitude vs. Time Plot

5.1.4.1. Subscale Launch Verification

Recorded Subscale Data (From the RRC3+ Sport Altimeter)

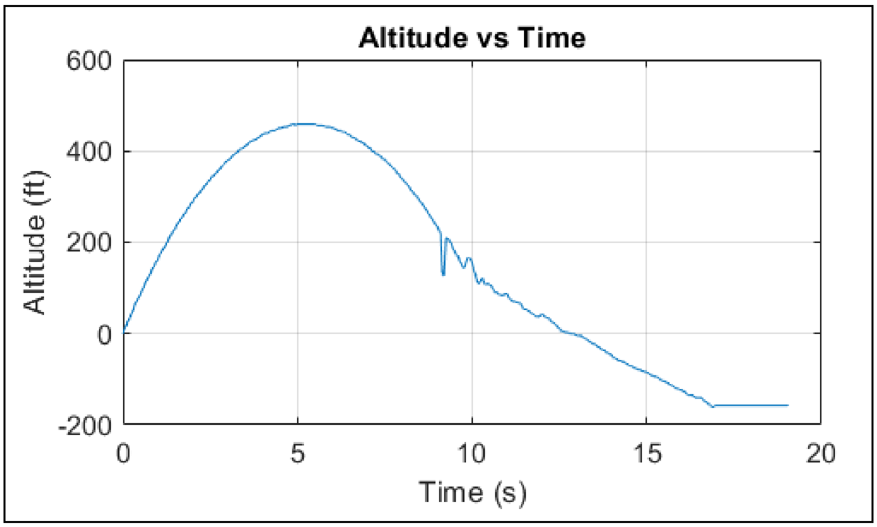


Figure 5.13: Recorded Subscale Altitude vs. Time Plot

The subscale launch was used to verify the accuracy of the MATLAB code. The subscale launch took place at an elevation of 698’, with 12mph winds, a 5 degree launch angle into the wind, and at a temperature of 42°F. The H114 motor thrust curve was found using experimental data.

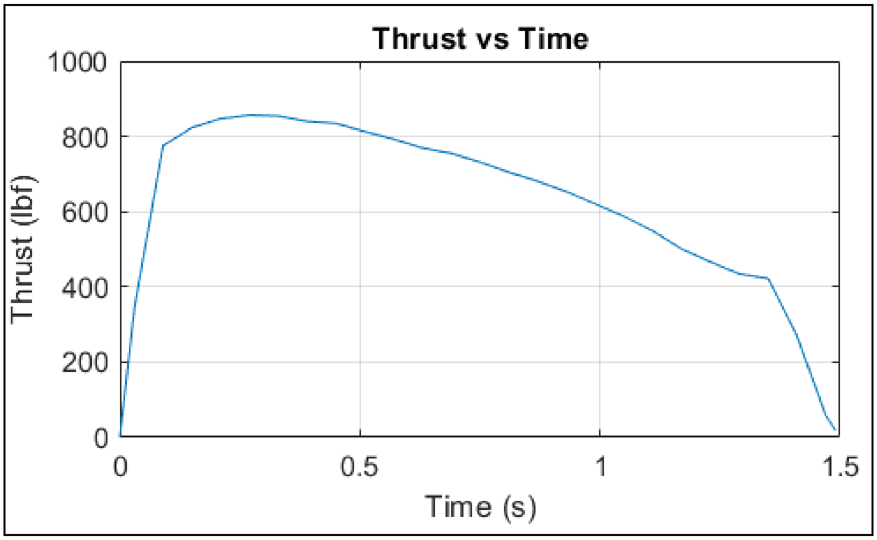


Figure 5.14: Subscale Thrust vs. Time Plot

The apogee recorded by the RRC3+ Sport altimeter was 617'. Using these as the launch conditions, the MATLAB code was able to predict the flight path.

Predicted Subscale Data

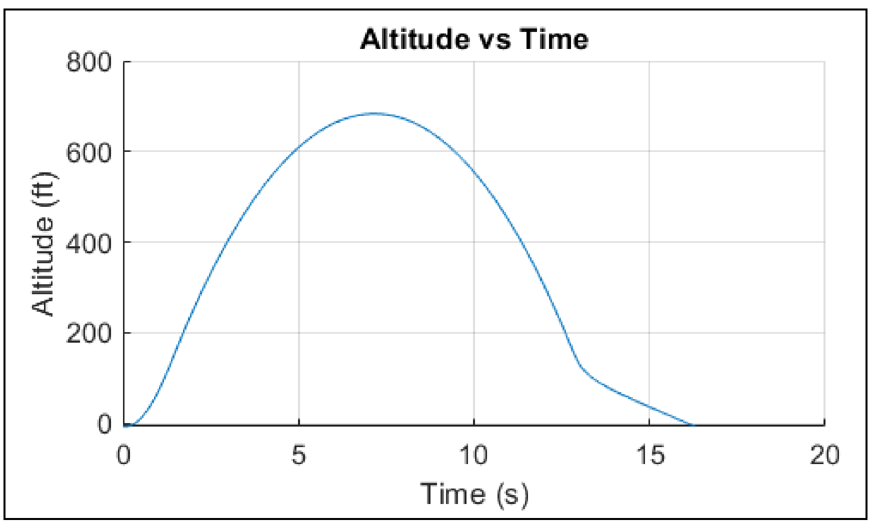


Figure 5.15: Predicted Subscale Altitude vs. Time Plot

The predicted apogee is 683'. There is a 10.7% error between the actual and predicted value for the apogee. This could be because of the way the angle is calculated. The MATLAB code assumes a constant angle, only depending on the initial launch angle. The code does not account for the drag and rotation caused by the launch vehicle being at an angle. Once these errors are rectified, the predicted results should be more accurate compared to the actual results.

5.1.4.2. Full Scale Launch Verification

Recorded Full Scale Data (From the Telemetrum Altimeter)

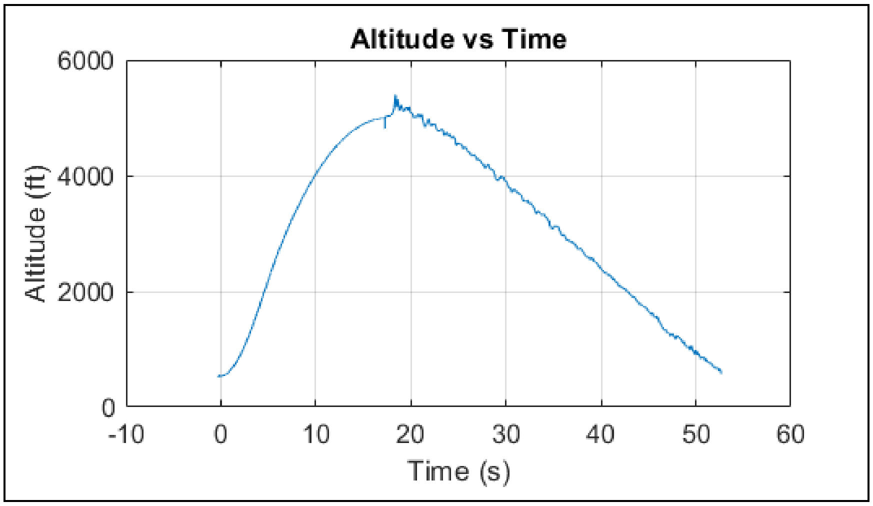


Figure 5.16: Recorded Full Scale Altitude vs. Time Plot

The full scale launch was also used to verify the accuracy of the MATLAB code. The full scale launch took place at an elevation of 163', with 15mph winds, a 5° launch angle into the wind, and at a temperature of 36°F. Apogee occurred at 4488' AGL. When this data is compared to that from the MATLAB simulation, similarities can be observed.

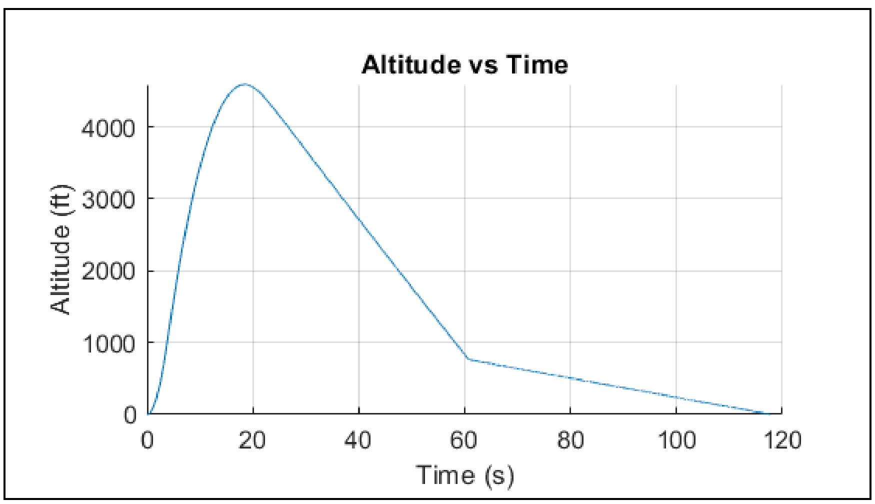


Figure 5.17: Predicted Full Scale Altitude vs. Time Plot

The predicted apogee is 4596'. There is a 2.41% error between the actual and predicted value for the apogee. This error is most likely to be caused by the code assuming the angle of the launch vehicle to be constant throughout the boosting and coasting phase. In reality, the launch vehicle's angle corrects to get closer to 0° during the flight due to the stability being higher than 1. Because of this assumption, the predicted apogee is less than the actual apogee.

5.2. Vehicle Characteristics

5.2.1. Stability Versus Time

5.2.1.1. OpenRocket

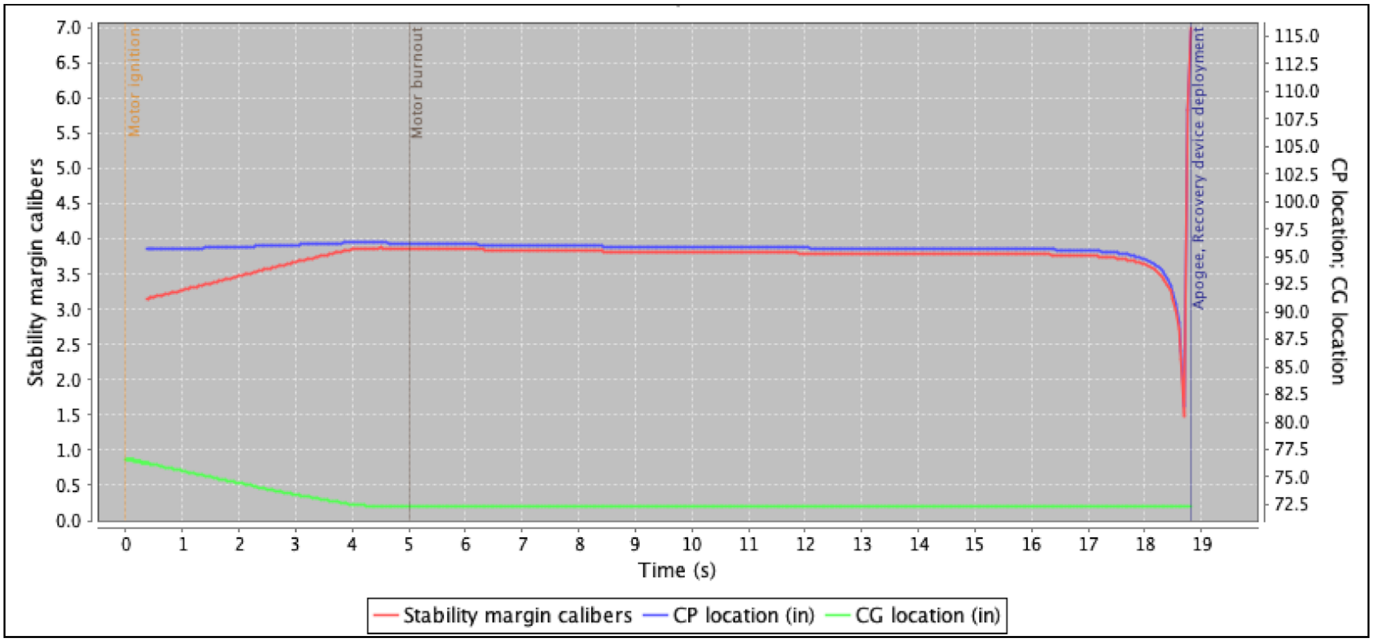


Figure 5.18: OpenRocket Stability vs. Time Simulation of Ideal Case

As seen from the graph above, the launch vehicle case exits the 144” launch rail with a minimum stability margin of 3.12cal, meeting the minimum requirement of two calibers. During the ascent phase, the launch vehicle does not experience a significant drop in stability until it reaches a low enough velocity that the fins cannot maintain aerodynamic stability. At this point, the launch vehicle begins slowing down significantly due to drag and gravity and starts arcing over as it approaches apogee. Despite this, the launch vehicle maintains above 3.5cal for nearly all of the boost and coast phase.

The center of pressure, the node where the total sum of all pressures acts on the vehicle, starts at a distance of 95.907” from the datum, which is deemed to be the tip of the nose cone. The center of gravity, a node where all moments about an axis of rotation equally oppose each other, begins at a distance of 76.66” from the datum of the launch vehicle, placing it 19.247” ahead of the center of pressure. During the burn time of the motor, the center of gravity moves forward at a constant rate due to the constant burn rate of the solid propellant. The total shift is 4.101”, or almost one full caliber.

5.2.1.2. RASAero Verification

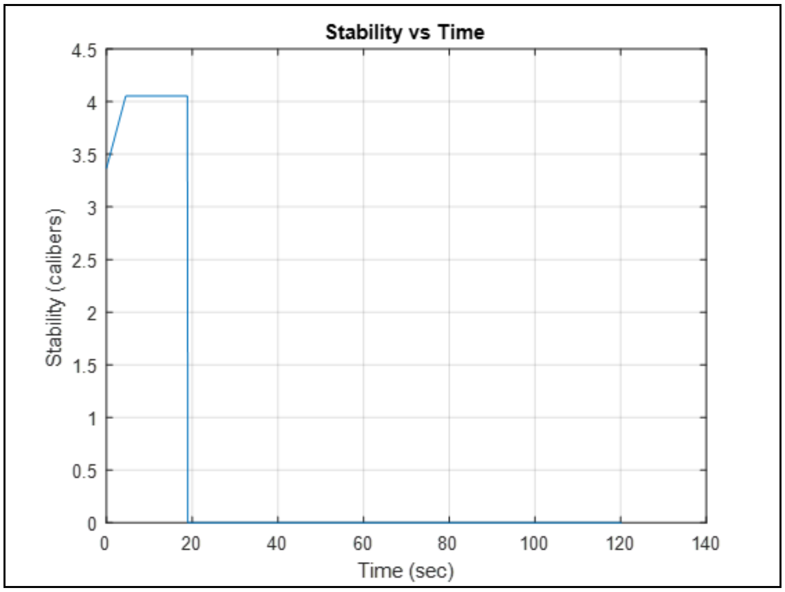


Figure 5.19: RASAero Stability vs. Time Simulation of Ideal Case (0 Degree Incline, 0mph)

The RASAero verification shows that the launch vehicle is never below the required 2.0cal of stability required off the launch rail. The vehicle starts at 3.37cal according to RASAero, implying a slight differential between its results and that from OpenRocket. However, both programs show the stability margin requirement is met.

Over the course of the flight, the stability margin increases as expected, to a value over 4 calibers. To get these values, RASAero needs to input the center of gravity. This value was taken from the OpenRocket model, implying some error. With this in mind, the center of pressure was calculated within RASAero, therefore it must be accurate to its means. CP from RASAero was calculated to be 96.61" from the aft end whereas OpenRocket found it to be 95.907" from the aft end. This slight difference begins to explain the error between the initial stability margin in both programs.

5.2.1.3. Avionics & Recovery Code

A stability vs time plot was generated from the MATLAB trajectory code to verify the results obtained from OpenRocket and RASAero.

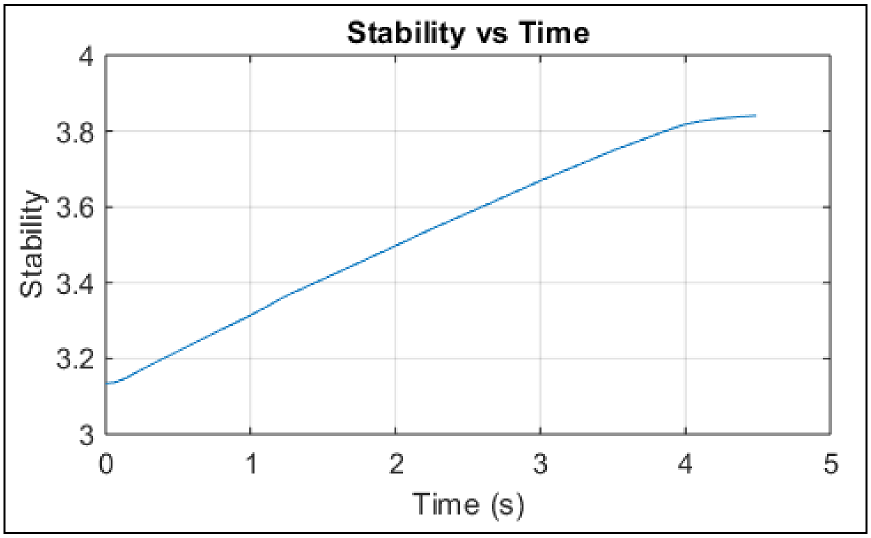


Figure 20: MATLAB Trajectory Code Stability vs. Time Plot

The plot above shows the stability vs. time of the vehicle from launch until the time when the motor shuts off. The plot takes into account the non uniform change in mass of the vehicle while ascending and assumes that the center of pressure stays constant throughout this phase. The stability starts at 3.1cal and reaches almost 3.8cal by the end of this phase.

5.2.2. Drag Versus Time

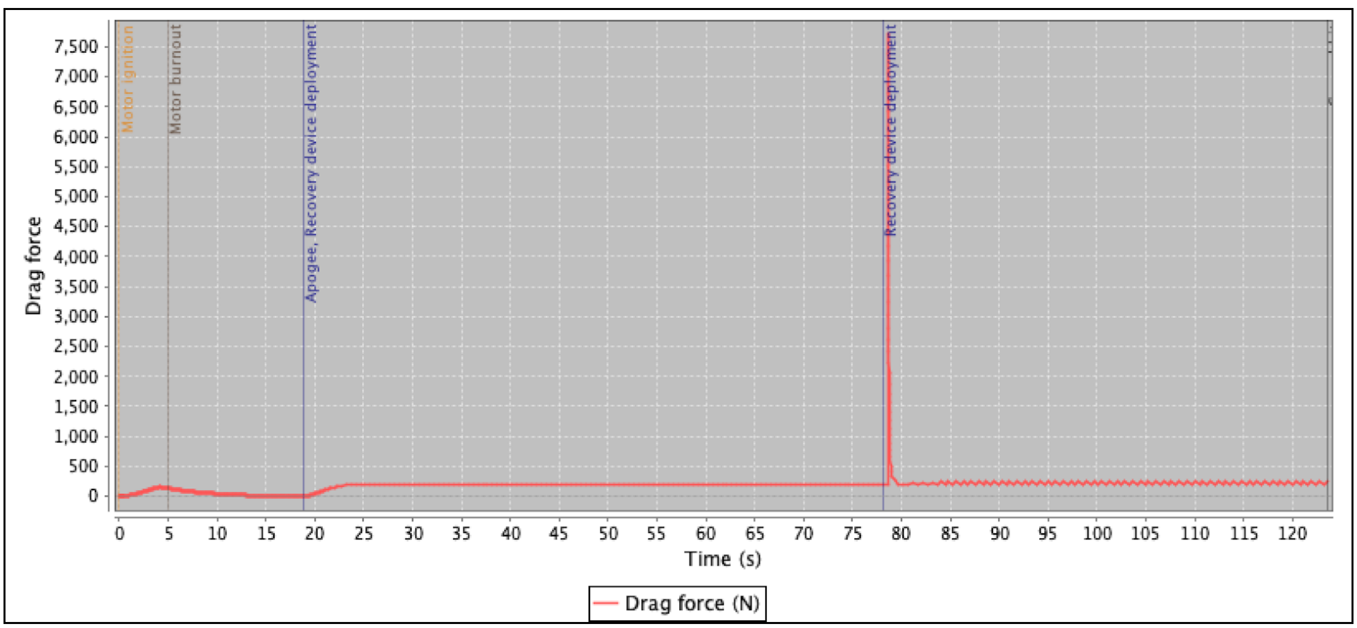


Figure 5.21: OpenRocket Drag vs. Time Simulation of Ideal Case

As shown by the figure above, the drag force stays around 210N during the majority of the mission. The drag spikes when the parachute is deployed which is expected given the nature and purpose of the parachute. According to OpenRocket, the wind speed is considerably less than the velocity of the launch vehicle so the different cases with wind speed and inclinations have little impact on the drag force according to the simulation.

5.2.3. Drift Distance Estimations & Hand Calculations

To calculate drift distance, the team used the equation stating drift distance equals the vehicle's descent time multiplied by the wind speed. This equation assumes that the wind blows in only one primary direction during descent. The 20mph case is over the allowed 2500' drift distance of the competition, but the team also recognizes the chance of being allowed to launch in 20mph winds is low, and the distance is under 2500' for 19mph wind speeds. The drift calculations should be performed with the assumption that apogee is reached directly above the launch pad.

5.2.3.1. OpenRocket Drift Estimation

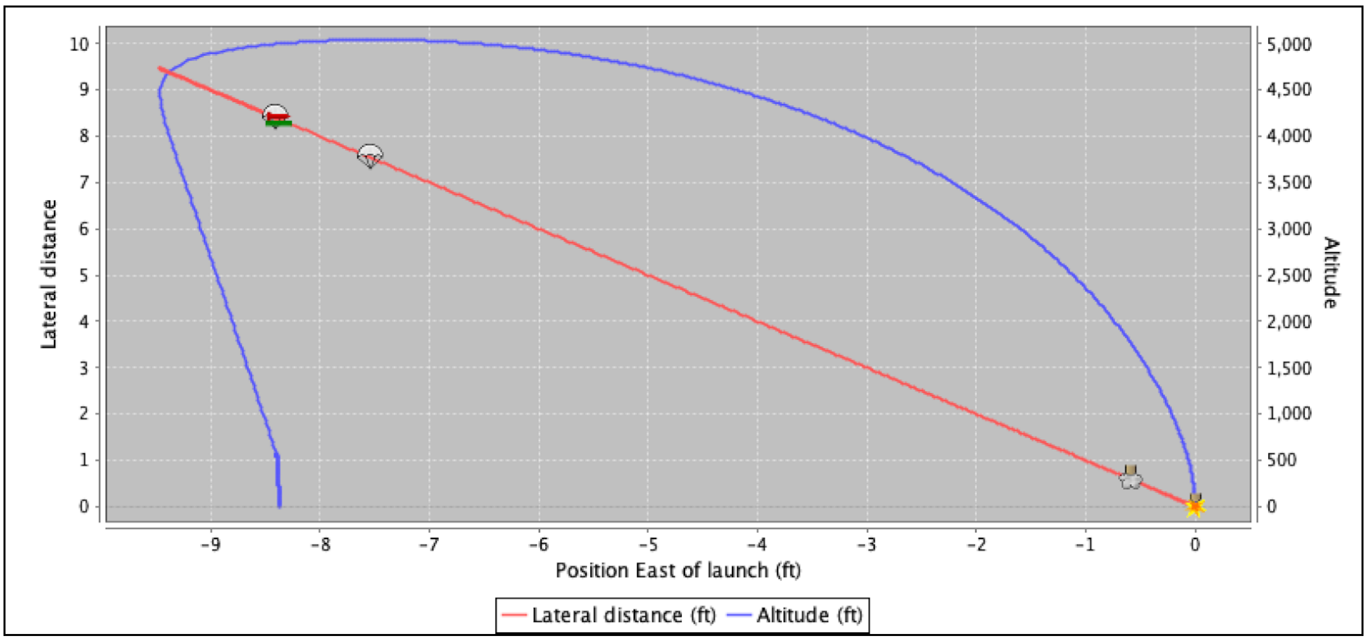


Figure 5.22: OpenRocket Simulation of Ideal Drift Distance Case

With an average wind speed of 0mph with 0.5mph standard deviation and 10% turbulence intensity, the simulated maximum drift distance during flight is roughly 9'. The launch vehicle travels nearly 9' west of the launch site as it tilts into the wind.

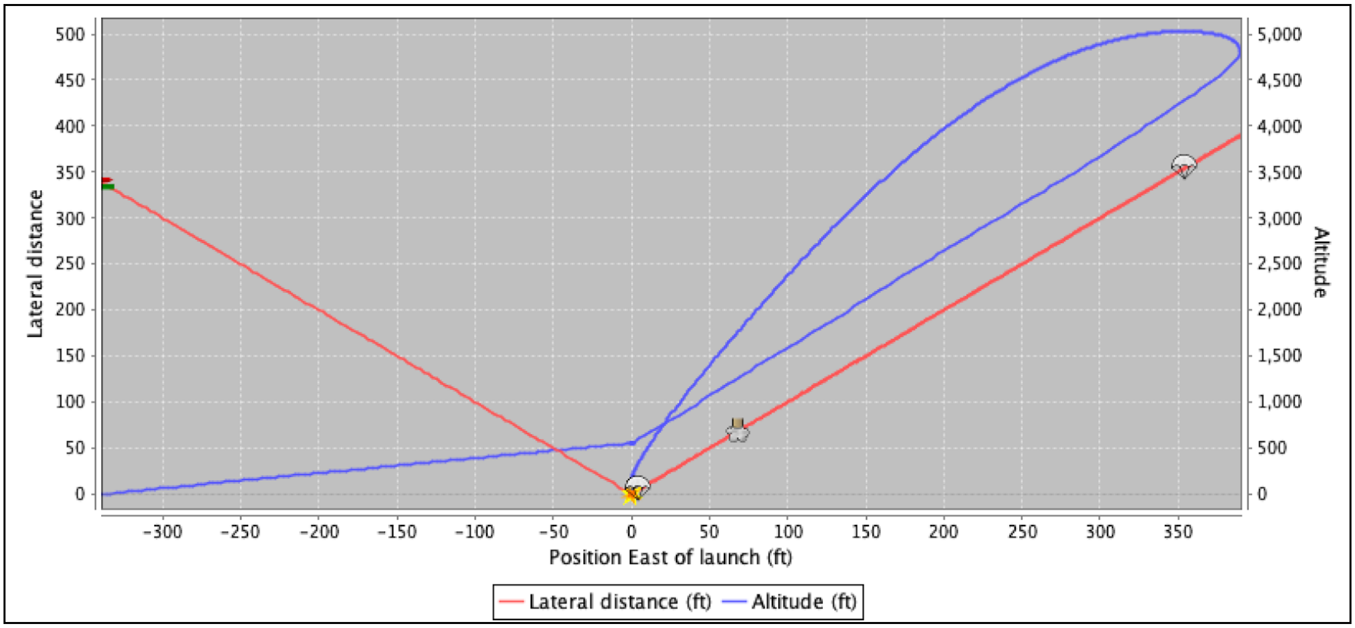


Figure 5.23: 0 Degree Inclination, 5mph Winds OpenRocket Drift Distance Simulation

With an average wind speed of 5mph with 0.5mph standard deviation and 10% turbulence intensity, the simulated maximum drift distance during flight is roughly 375'. The launch vehicle travels nearly 375' east of the launch site as it tilts into the wind, then drifts back over the launch site during recovery and continues heading west until touchdown 350' west of the launch position.

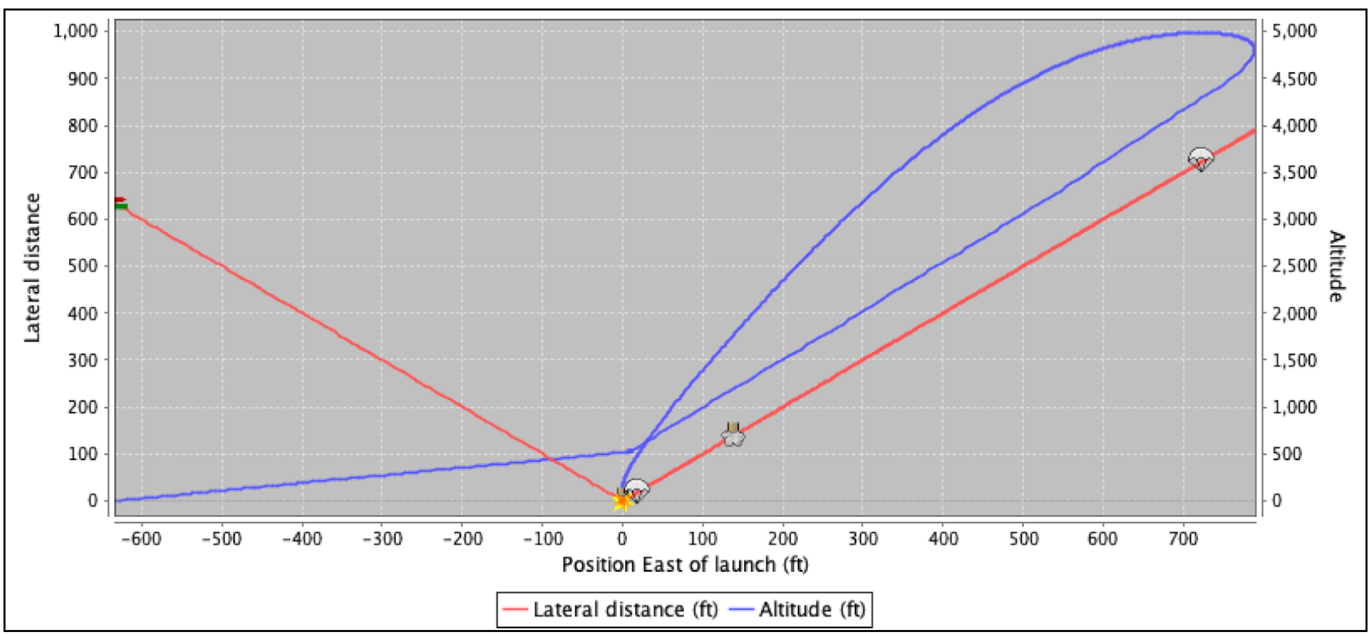


Figure 5.24: 0° Inclination, 10mph Winds OpenRocket Drift Distance Simulation

With an average wind speed of 10mph with 0.5mph standard deviation and 10% turbulence intensity, the simulated maximum drift distance during flight is roughly 775'. The launch vehicle travels nearly 775' east of the launch site as it tilts into the wind, then drifts back over the launch site during recovery and continues heading west until touchdown 650' west of the launch position.

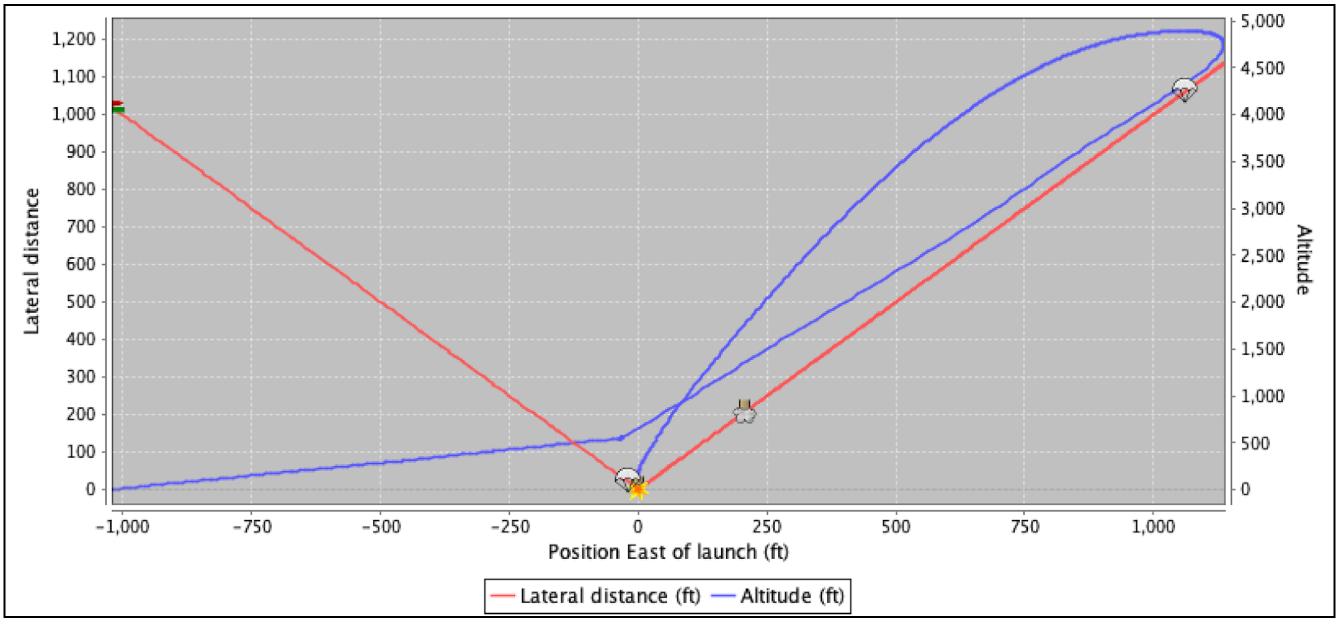


Figure 5.25: 0° Inclination, 15mph Winds OpenRocket Drift Distance Simulation

With an average wind speed of five miles per hour with 0.5mph standard deviation and 10% turbulence intensity, the simulated maximum drift distance during flight is roughly 1051'. The launch vehicle travels nearly 1051' east of the launch site as it tilts into the wind, then drifts back over the launch site during recovery and continues heading west until touchdown 1051' west of the launch position.

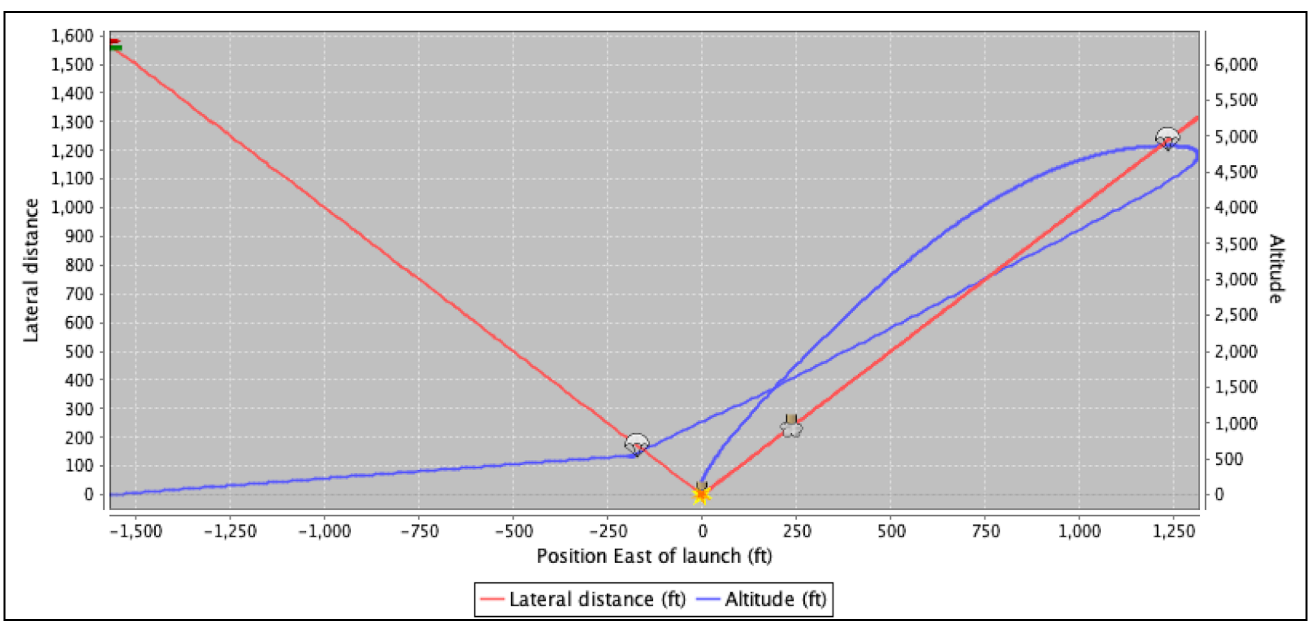


Figure 5.26: 0° Inclination, 20mph Winds OpenRocket Drift Distance Simulation

With an average wind speed of 5mph with 0.5mph standard deviation and 10% turbulence intensity, the simulated maximum drift distance during flight is roughly 1570'. The launch vehicle travels nearly 1315' east of the launch site as it tilts into the wind, then drifts back over the launch site during recovery and continues heading west until touchdown 1570' west of the launch position.

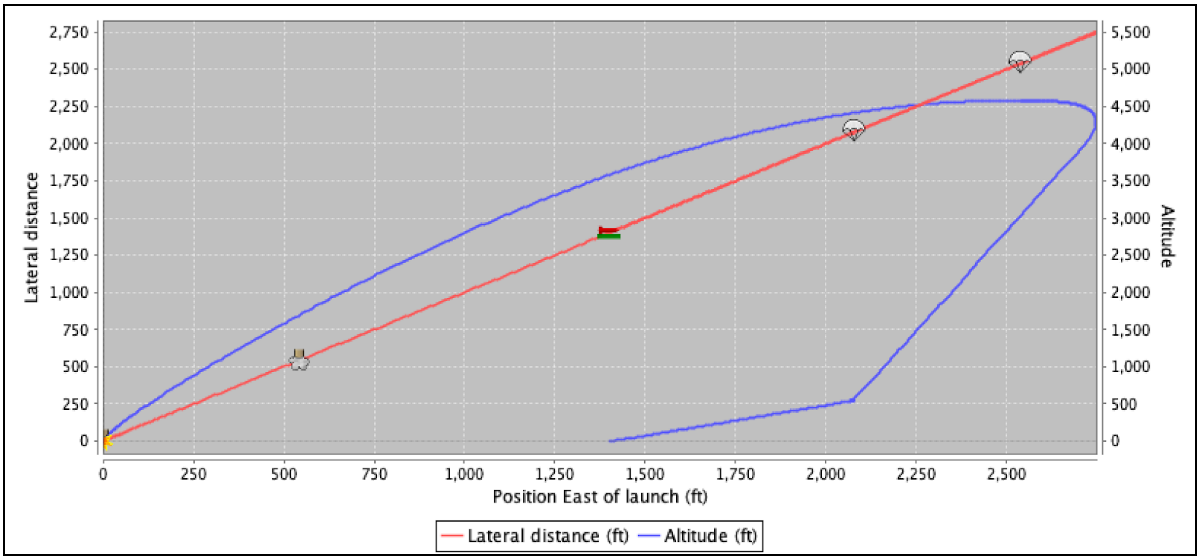


Figure 5.27: 10° Inclination, 10mph Winds OpenRocket Drift Distance Simulation

In this ideal case for the launch vehicle on the day of launch, the vehicle has a max lateral distance of roughly 2465' east of the launch site but only lands 1400' east of the launch position. This simulation of 10°of inclination and 10 mph winds show that the vehicle has its maximum drift distance while in the air but returns to the ground within the restriction of 2500' set by the NASA SL handbook.

5.2.3.2. RASAero Drift Calculation

For drift, the same trials are not used. The reason for this is that the ranking of launch likelihood included three trials of 10mph winds, but no discussion of 5mph of 15mph winds. Therefore, the drift was nearly identical in these three trials. In addition, the rail inclination is mostly meaningless as it is impossible to tell how the rail will be inclined with respect to the wind. Since it is assumed the rails will be inclined away from spectators rather than into the wind, the wind may add to the drift instead of subtract from it. Therefore, the trials took the rail inclination to be 0° and simply varied the wind speed.

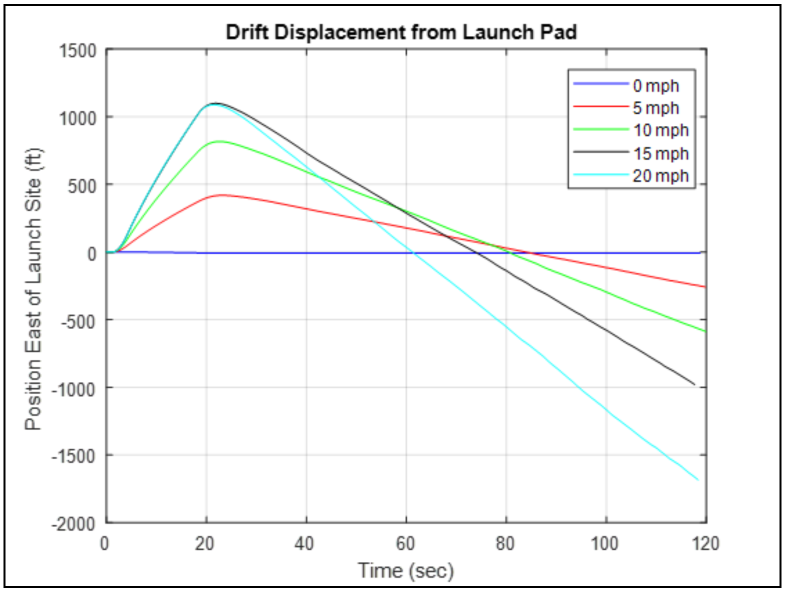


Figure 5.28: RASAero Drift Simulations

As expected, the drift for a launch vehicle under no crosswind or rail inclination has nearly no drift as shown by the dark blue curve. The launch vehicle does drift minimally prior to motor burnout, but the value is less than 0.1'. Compared to OpenRocket, the value is about 9' less, but that value is fairly negligible.

The 5mph winds case is shown by the red line. This case is very feasible since winds in early April in Huntsville historically are about 7mph. It is important to note that the graph shows displacement. Therefore, if launched in these conditions, by the time the launch vehicle lands, it will have moved approximately 321'. OpenRocket had a value of 410' of drift in this case for comparison. From burnout, the drift in RASAero is about 740'. This value more accurately showcases the amount of drift as it neglects some of the variability of the rail inclination. In either case, the values are well within the 2500ft requirement.

The team has determined the 10mph winds case is the most realistic case for launch day. As a result, the green line holds the most meaningful results. The graph shows a displacement of 638'. Taking the distance from the burnout location (to neglect the drift-back in the event that the launch is into the wind), the drift will be around 1475'. These values are well within the drift requirement.

In the event of 15mph winds, the launch vehicle drifts around 951' by the time it reaches the ground, as shown by the black line. From burnout, drift is approximately 2190'. This drift is still within competition limits. Drift could become an issue if the rail inclination is with the wind, but the team is confident that the drift requirement will be met.

The drift for 20mph winds, shown by the cyan line, is approximately 1240'. However, the drift from burnout is approximately 2875', which is above competition limits. The team is confident that the

NASA team will not allow the vehicles to launch in such conditions, so this is not too concerning. The best way to mitigate this value is to deploy the main parachute lower, but since this is an unlikely case, the team feels it is best to understand this possibility, but not plan for it.

In every case, the displacement values between the two programs, OpenRocket and RASAero II, were within 200ft, implying a level of precision. The team believes this precision will also translate to accuracy in the real-world.

5.2.3.3. Hand-Calculations / Code Estimation

To calculate the drift distance of the launch vehicle by hand, the team used the following equation:

$$Drift = t_f * V_\infty * sin(\theta)$$

In the equation above, t_f is the total flight time (the entire time the wind causes lateral movement), V_∞ is the free stream velocity, and Θ is the launch angle. This equation assumes that the wind blows in only one direction during the launch vehicle's ascent. It also assumes that the launch rail is canted at 5° during the launch and that the apogee occurs directly above the launch rail. Although the 20mph case results in a drift distance of over the allowed 2500', the team recognizes that the likelihood of 20 mph winds at the time of launch is low. In addition, the drift distance for wind speeds under 20 mph is within the allowed 2500'.

Launch Rail Angle [deg]	Wind Speed [mph]	Drift Distance From Pad [ft]
0	0	~0
0	5	684
0	10	1340
0	15	1995
0	20	2605

Table 5.2: Drift Distance Calculations for 0 Degree Inclination Angle and 0-20mph Wind Speeds

Although this equation provides a good estimate of the drift distance at each wind speed, the assumptions made by this equation result in a higher degree of error. As shown below, OpenRocket estimates the drift distance for the case closest to the most likely case, with a 0 degree inclination and 10 mph winds, to be 750' at the most, with the launch vehicle coming back toward the launch site until it touches down at approximately 0 ft. This estimation by OpenRocket assumes, like the equation used for hand calculations, that the wind is constant in both speed and direction from the time of launch until the launch vehicle touches down. Since the OpenRocket simulation works with more variables than the equation for the hand calculations, the two estimates will have slightly different results.

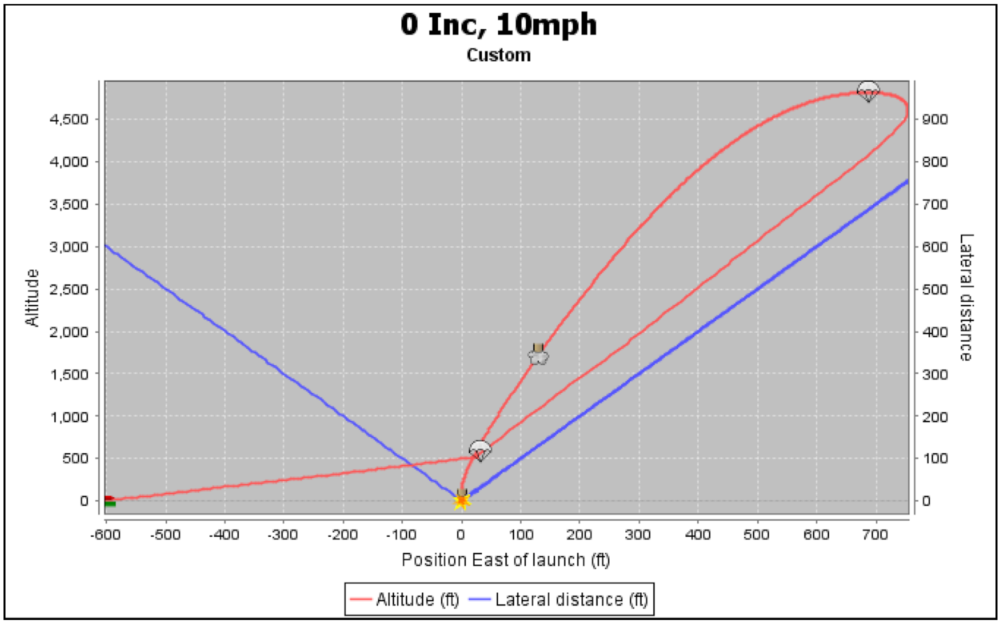


Figure 5.29: OpenRocket Drift Estimation vs. Hand Calculations with 0 Degree Inclination, 10mph Winds

However, the discrepancy between the OpenRocket simulation and hand calculations is not always constant. As shown in the figure below, the worst case scenario done by hand calculations, the 0 degree inclination and 20mph winds case, is well within the maximum allowed drift distance for the competition, according to OpenRocket, while the hand calculations estimate the drift distance to be much greater.

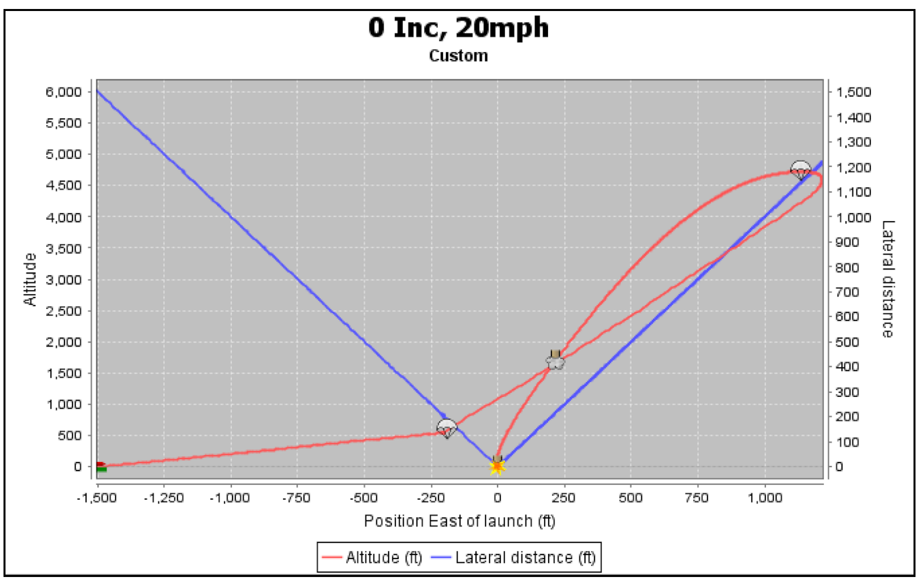


Figure 5.30: OpenRocket Drift Estimation vs Hand Calculations with 0 Degree Inclination, 20mph Winds

As shown above, the hand calculations provide a good estimate of the drift distance of the launch vehicle. However, the team will be using multiple sources to check the simulations and calculations, since the assumptions made by each affect the end result.

5.3. Kinetic Landing Energy

Using the MATLAB simulation, which records velocity at every time step and the mass at every time step, the kinetic energy of the vehicle can be calculated. It assumes that the velocity of the vehicle and the two parachutes are equal to each other. It also assumes that when the drogue parachute deploys, the horizontal component of the velocity becomes zero. This means that wind speed does not matter for the landing kinetic energy.

During drogue deployment, vertical velocity, and thus total kinetic energy, are at their maximum when the launch angle is 5°. However, there is minimal difference between the values at 5° and 10°. Wind speed has no impact on either values.

Wind Speed [mph]	Launch Angle [deg]	Total Kinetic Energy [ft-lbf]	Vertical Velocity [ft/s]
0	0	764.04	31.26
5	5	787.91	31.69
5	10	784.54	31.68
10	5	787.91	31.69
10	10	784.54	31.68

Table 5.3: Drogue Deployment (Time = ~Apogee + 1s) Kinetic Energy and Vertical Velocity

During main deployment, the total kinetic energy and vertical velocity are relatively the same regardless of launch angle or wind speed.

Wind Speed [mph]	Launch Angle [deg]	Total Kinetic Energy [ft-lbf]	Vertical Velocity [ft/s]
0	0	13,500	93.85
5	5	13,500	94.04
5	10	13,400	94.58
10	5	13,500	94.04
10	10	13,400	94.58

Table 5.4: Main Deployment (Altitude = ~500'), Kinetic Energy and Vertical Velocity

During landing, the total kinetic energy and vertical velocity are at their maximum at a launch angle of 10 degrees. Generally, as launch angle increases, the vertical velocity and total kinetic energy also increase. Wind speed had no impact on either set of values.

Wind Speed [mph]	Launch Angle [deg]	Total Kinetic Energy [ft-lbf]	Vertical Velocity [ft/s]
0	0	142.86	13.51
5	5	143.41	13.54

5	10	148.87	13.62
10	5	143.41	13.54
10	10	148.87	13.62

Table 5.5: Landing (Altitude = ~0'), Kinetic Energy and Vertical Velocity

6. Payload System

Figure 6.1: Pre-UAV-launch Integrated Payload System

6.1. Payload Overview

6.1.1. Mission Statement

The mission of the unmanned aerial system (UAS) is to safely identify, extract, and recover a simulated lunar ice-sample with an unmanned aerial vehicle (UAV) deployed from a high-powered rocket. The UAV will be mechanically retained in the payload bay of the launch vehicle during flight in a fail-safe retention and deployment (R&D) system. The UAV will be deployed from the launch vehicle after it has completed its flight. The UAV will be capable of semi-autonomous flight, navigation, and ice sample recovery. Any and all phases of the mission will have pre-programmed contingencies along with the option of immediate manual override and mission termination.

6.1.2. Mission Overview

The mission is divided into five distinct phases with each phase decomposed into functional events that describe the operational mission path along with alternative (contingency) mission paths. The five phases are Vehicle Launch and Recovery, UAV Deployment and Integration, Signaled Takeoff, Recovery Area Search and Ice Procurement, and Sample Recovery. The mission and phases will be decomposed into a series of functional flow block diagrams. This also includes contingency planning in the case the autonomous mission planner reaches the necessary criteria to terminate the mission. In order for the UAS to successfully complete its mission, it must complete all functions and phases listed in the diagram in Figure 6.2 below.

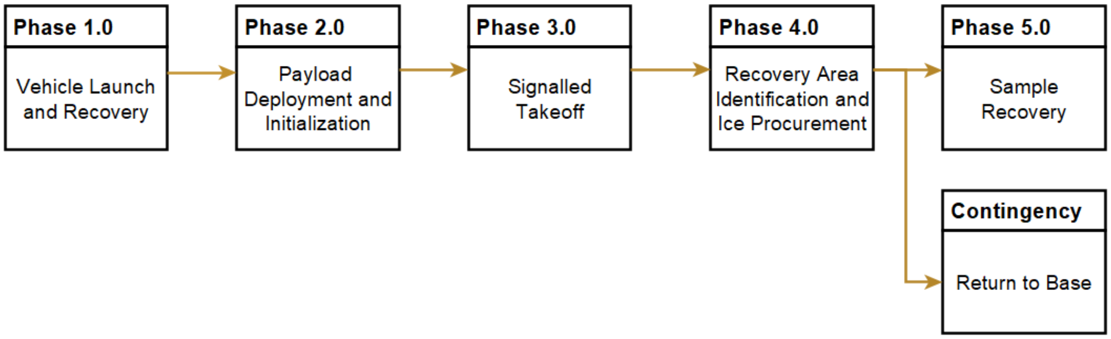


Figure 6.2: Payload Mission Profile

6.1.3. Changes since CDR

Since CDR, a number of design modifications have been made to the payload system. These design changes have largely been the result of developmental testing, with the purpose of optimizing various facets of the design that became more clear during the construction of the system.

The UAV has seen several design modifications since CDR. For example, shielding has been added to electrical components and high-current-carrying wires to mitigate the effects of electromagnetic interference. Also, the size of the lunar ice scoops decreased from a maximum diameter of 1.25” to 1.0”. This change was made after testing of the CDR scoop design resulted in a lunar ice yield 3-4 times greater than the 10mL requirement. Decreasing this dimension of the scoop allows the UAV more clearance when deploying from the payload bay. The electrical design of the lunar ice mining system has also been modified since CDR. The BJT-based electrical design was replaced by a more robust, H-bridge design built around the TB6612FNG motor driver chip.

The R&D system has also undergone some minor changes since CDR. A second, identical rack and pinion system was added to the opposite end of the UAV retention sled. Developmental testing of the initial design demonstrated that the UAV may not be completely retained on the sled at orientations in which it is upside-down. Friction of the UAV against the deployment rail was found not to be high enough to keep the UAV retained on the sled in this situation. An identical servo-actuated rack-and-pinion system was therefore added to the sled to fix this issue. The embedded software controlling the R&D system also changed since CDR. The software controlling the serial communication between the system’s microcontroller and the XBee radio was simplified significantly from its CDR form. These simplifications removed unused XBee features and made debugging the software significantly easier.

6.2. UAS Design

6.2.1. Airframe and Propulsion

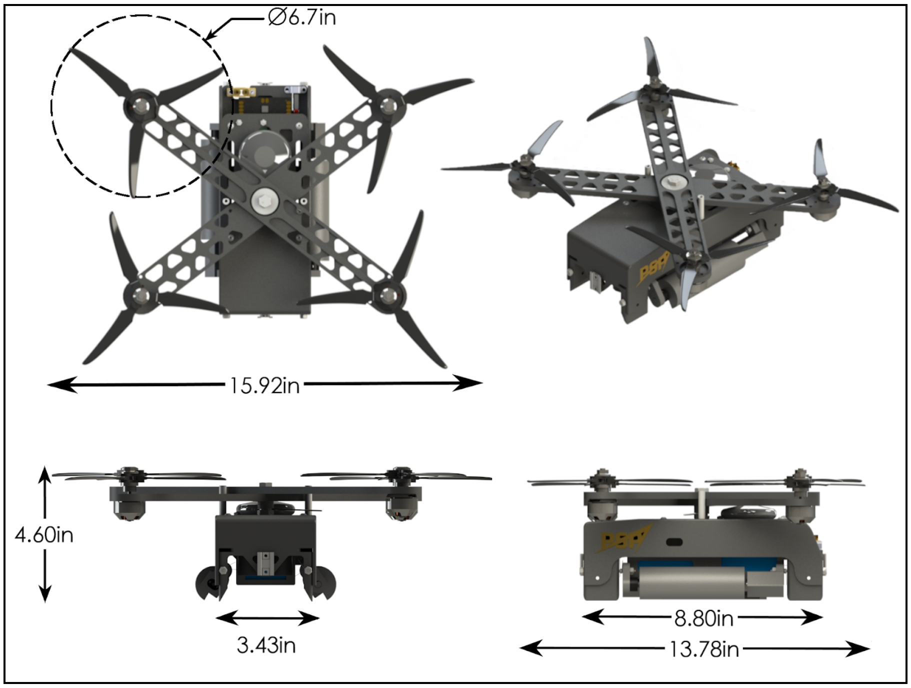


Figure 6.3: Full UAV Three View and Isometric

The final design of the UAV utilizes features to increase its functionality and uniqueness while maintaining simplicity and manufacturability. The fundamental format of the UAV's design is modularity, allowing for multiple subsystems to be operated upon independently, while maintaining an overall ability to function as a single system once assembled. This approach has allowed the team to divide the construction process into defined chunks, allowing for increased efficiency in construction. Even as the first completed build of the UAV was nigh destroyed, the physical rebuild process proved trivial in some respects; any modifications that were required were quickly resolved without interrupting the progress of different personnel. With the assistance of the UAV's primary structural material, 3D printed PLA plates, the production of complex, yet robust geometry was rapid and effective.

This design employs a single pivot point between two armatures near the geometric center of the UAV. Each armature has, attached to it, a lift producing motor and propeller assembly; the wiring and electronic speed controllers (ESC's) are slung underneath and fastened to the armatures. Following activation, this assembly can actuate from a confined storage state into a flight ready configuration. This was achieved using a torsion spring at the pivot point of the armatures; this functional system is known as the "X-Wing Mechanism". The structural frame of this design consists of only two plates, separated by vertical standoffs, and attached to the X-Wing Mechanism through its central structural bolt. These attachment plates provide as much space as is required to lock electronics in place while maintaining high manufacturability and protective capability. Under the bottom plate of the UAV is a complex, 3D-printed structure which provides a mounting place for the UAV's battery as well as the ice mining subsystem.

The ultimate goal of the UAS is the usage of the ice mining system, and as such, the ice mining system has been attached with priority on ground accessibility. While the rest of the airframe facilitates flight, the lower structure is designed to provide ample points of attachment and flexibility for the purposes of ice mining systems. Meanwhile, at the same time, this airframe was designed to be compatible with the R&D systems, and as such, provides places of attachment for the R&D sled for constraint in all directions of motion during flight and landing. The form and function of the airframe also yields to the constraints of the R&D system during deployment, utilizing interactions between the UAV and the sled to enable the UAV to reorient and take flight when instructed.

6.2.1.1. Frame Design

The UAV frame includes a central plate skeleton which houses electrical components and provides structure. Upon these plates sits the X-Wing Mechanism, which moves via a passive spring actuation after activation from the R&D system's sled. In order to avoid any damage to the battery, it is installed underneath the bottom plate along with two leg structures that also hold the ice mining system. Covering the entire UAV is a protective shell known as the Aero Package.

Figure 6.4: UAV Exploded View Render

6.2.1.1.1. Plate Structure

For the design of the UAV frame, the team pursued the use of plates for its main structural components and for housing the electronics. The frame is designed in a way that considers the accessibility of the electronics while remaining modular enough to add or attach new components as necessary. Since electronics are primarily housed between the structural plates, the team felt that they would be sufficiently protected from damage in the event of a crash; while this remains true for flights under its own power, this level of protection has been deemed insufficient in the event of an entire vehicle crash while within the retention system. This was confirmed during the first test vehicle flight when the payload system was destroyed by the ballistic landing of the launch vehicle. As for standard controlled and powered flights of the UAV however, collision resilience has been deemed sufficient for intended purposes.

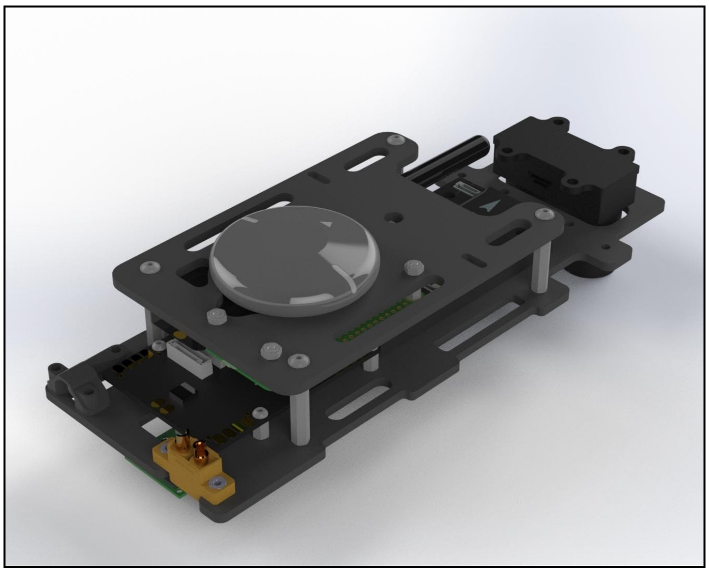


Figure 6.5: Plate Structure Assembly Render and Image

6.2.1.1.2. *Leg Structure*

The most complex geometric part of the UAV is its landing leg structure. These legs attach to the ice mining system slung underneath the airframe while also containing the UAV's battery. The leg design allows the ice mining system to rest on the arms of the R&D sled while the UAV is locked on the sled. The ice mining system is attached by pins running axially through each leg and is positioned in such a way so as to fit on top of the sled and be able to stay out of the way of the launch vehicle structural rods as the UAV exits the vehicle.

Since this part is the first load-bearing part to come in contact with the ground upon landing, its shape and structural integrity have been under close supervision. While this part is intended to break apart or crush on landing before any other parts do, it still needs to be structurally sound enough to perform its job without incurring excess weight upon the UAV. To that end, through use of finite element analysis (FEA) and topology optimization, the stiffness to weight ratio has been optimized in

CAD. Below is the developed topology optimization mesh generated to reduce the overall mass of the model by 80%.

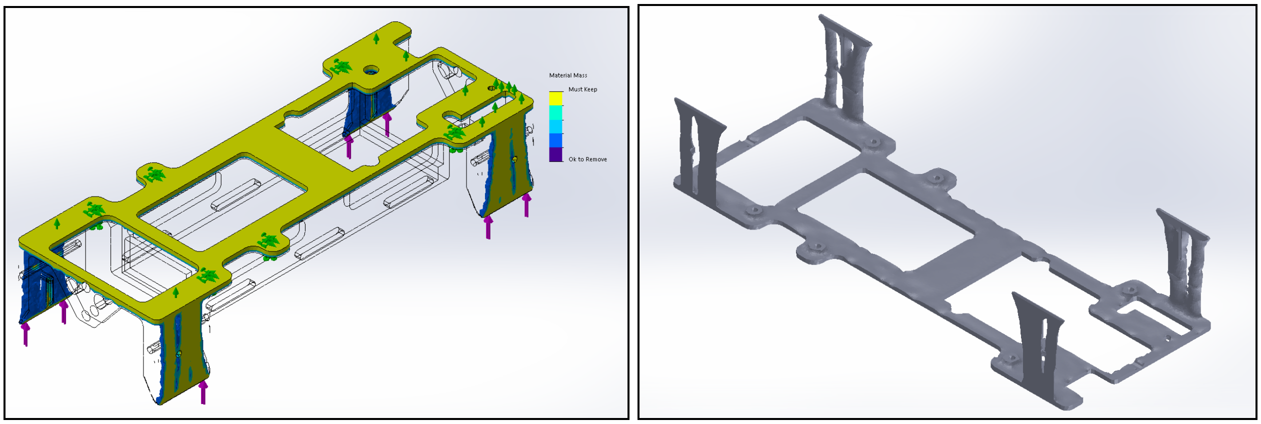


Figure 6.6: Leg Topology Optimization FEA and Final Mesh

6.2.1.1.3. X-Wing Mechanism

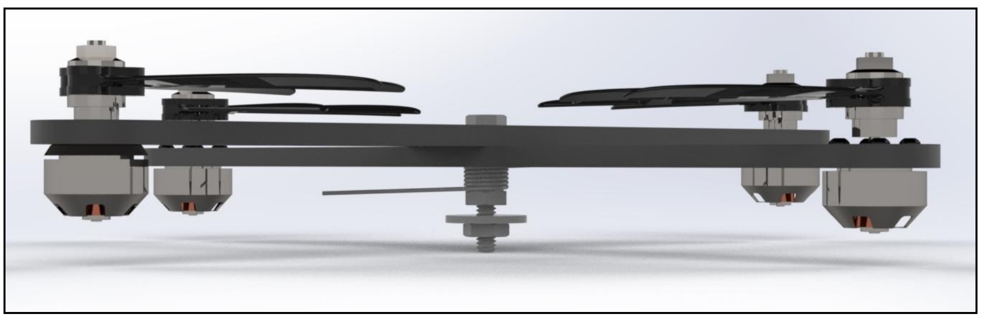


Figure 6.7: X-Wing Mechanism Open (Profile)

A fear the design team had was whether the torsion spring would be able to maintain the armatures in a static position while in flight. An unforseen quirk of the way that quad-propeller UAVs are operated is that the armatures appear to separate further during flight. Despite the fact that the armatures appeared to open up on command, the old 3.1in-lbf torsion spring was swapped out for a 4.5in-lbf model. The larger spring required only minor adjustments in spacing; the newly installed torsion spring allowed for greater flexibility in the tightening of the X-Wing mechanism to a desired amount of friction and play. The X-Wing Mechanisms that have been constructed have functioned as intended through hundreds of actuations and have been deemed clear to integrate and fly.

6.2.1.2. Propulsion System

The propulsion system is a set of Electronic Speed Controllers (ESCs), brushless direct current (BLDC) motors, and propellers that work together to produce thrust that drive the UAV. Selection for each of these components primarily focused on the following objectives: minimizing weight while maximizing efficiency and vehicle stability. The propulsion system makes use of 6.7in folding propellers to minimize the retained configuration envelope while maximizing contact area in the flight configuration. The motors selected mount underneath the X-Wing mechanism to limit vertical envelope, and also meet the maximum expected flight power requirements. The four individual ESCs that interface with the motor also meet this power requirement.

6.2.2. Ice Mining and Procurement System

6.2.2.1. Scoop Design

The design employed one large cylindrical scoop that rotates around an axis and collects the ice pieces as it spins. Below is an image depicting this design:

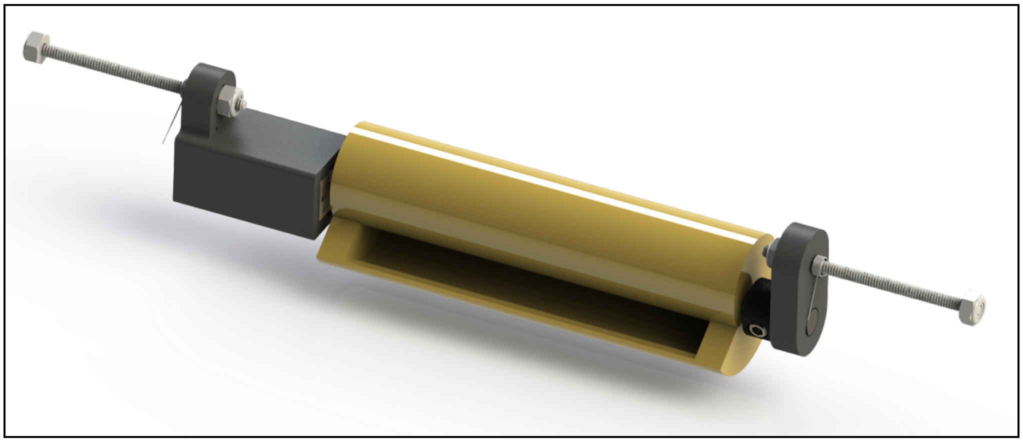


Figure 6.8: Ice Mining Assembly

Through testing, the team discovered that the scoops fit in the opening while retained in the launch vehicle. However, when the UAV attempts to fly out of the Retention and Deployment system the scoops make contact with structural guide rods impeding the UAV's smooth takeoff. To fix this issue the scoop diameter was made smaller. Instead of the largest diameter being 1.25", the largest diameter is now set to 1" to help solve the problem of the scoop catching on the R&D rods. This did decrease the volume of how much "lunar ice" that the scoop is able to collect. With the original scoop, it was able to collect about 25mL of ice per scoop if completely full. With its reduced size, testing has shown that each scoop is able to collect 15mL of ice if completely full. This is a significant reduction, but testing indicates that the scoops each consistently collect more than 10mL, summing up to a total volume that meets double the ice collection requirement.

6.2.2.2. Airframe Interface

The interface between the airframe and ice mining system is capable of movement by design. The scoop is attached between the legs of the drone via two mounts, one housing the motor and the other acting as an arm. The mounting hardware, shown in Figure 6.9 below, serves the same basic function of allowing the whole ice mining system to swing away from the drone. The mounts are attached to the legs via a nylon threaded rod. This allows the whole ice mining system to sit directly against the bottom casing of the drone or to freely swing radially away from the UAV. The purpose of this range of motion is to achieve three crucial goals. The first goal is to have the UAV fit within the rocket while it is stored on the sled for launch. The second goal is for the UAV to be able to fit past the guide rails of the payload bay on either side of the UAV. It is possible for the UAV, with the mining system attached, to be able to fit within the rocket but when trying to take off, be impeded by the mining system. This problem comes down to two things, the orientation of the scoops and the size of the scoops.

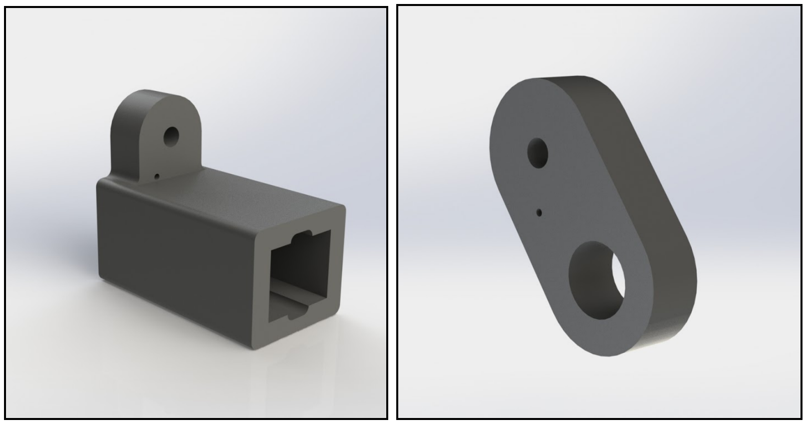


Figure 6.9: Motor Mount and Ice Clamshell Mount

6.2.2.3. Electrical Design

The electrical design of the IMPS is tasked with controlling the actuation of the system. Brushed DC motors were chosen to drive each scoop in the system. Brushed DC motor technology was chosen due to its simplicity and its relative weight with respect to other types of motors stepper motors. The specific model of brushed DC motor that was chosen is pictured below in Figure 6.10.

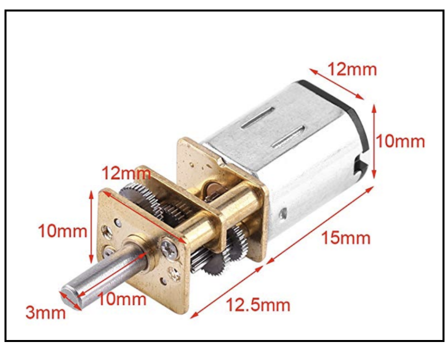


Figure 6.10: IMPS Brushed DC Motor

To drive this motor, the TB6612FNG h-bridge motor driver has been added to the design in place of the BJT-based circuit previously employed. The TB6612FNG adds robustness to the system, allowing the motors to be driven independently, as well forward and backward. The motor power is supplied directly from the 11.1V LiPo battery on the UAV. This is a change from the CDR design, in which the motors ran on the 5V supply from the Raspberry Pi Zero. This change was made to mitigate the possibility of drawing more current than the Raspberry Pi can supply, “browning out” the device. Developmental testing indicated that the motors operate nominally, albeit at an increased speed, at this voltage. Figure 6.11 below shows a schematic of the IMPS electrical system.

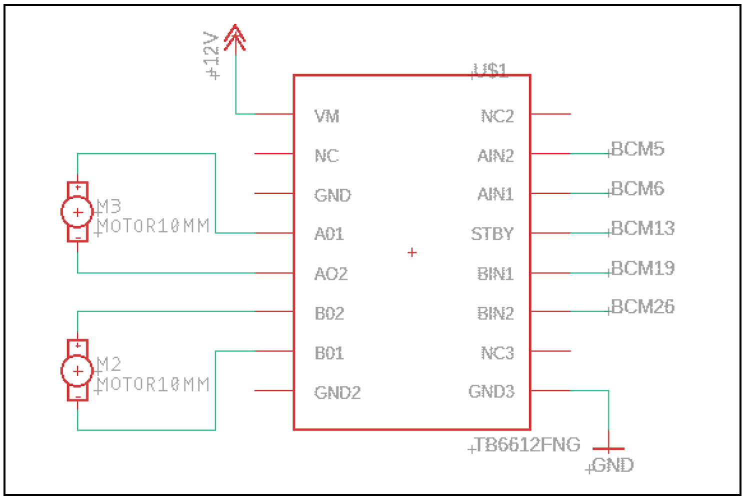


Figure 6.11: IMPS Motor Drive Circuit Schematic

6.2.3. Flight Control and Mission Management

6.2.3.1. Flight Control Hardware

The flight control system provides the UAV with attitude and altitude control and is comprised of a flight control computer and an integrated GPS and compass unit. The flight control computer (FCC) uses an integrated sensor set, capable of measuring barometric pressure, 6-axis acceleration, magnetometer data, and GPS data. The Pixhawk 4, chosen as the FCC, uses this data to perform all low-level control tasks. Higher level control is maintained by the the Mission Control Unit (MCU). The MCU, realized in the form of a Raspberry Pi Zero W, manages the navigation of the vehicle to lunar ice recovery sites, communication with the GCS, and image recognition. Both of these devices, pictured below, are mounted on the central plate of the UAV, necessary to easily maintain the many electrical connections with their peripherals on-board the vehicle.

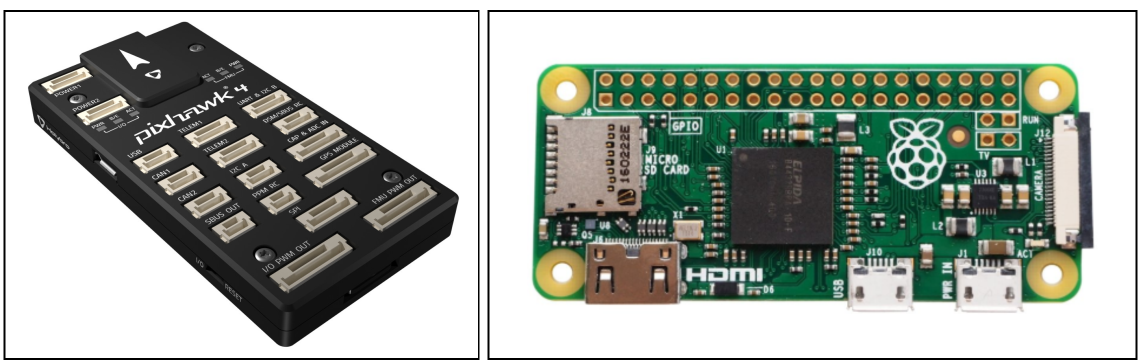


Figure 6.12: Flight Control Computer (Left) and Mission Control Unit (Right)

In addition to the sensors built into the FCC, the UAV is equipped with an AGL altimeter for measuring above-ground-level (AGL) data and a digital image unit (DIU) for identifying lunar ice recovery zones. The AGL altimeter utilizes a LiDAR lite v3 to accurately measure the vehicle's altitude. While the FCC is equipped with a barometric altimeter, the addition of a LiDAR-based system increases the accuracy and fidelity of the system when landing. The DIU utilizes a Raspberry

Pi Camera to acquire high-resolution images of the ground directly beneath the UAV. These images are processed by the MCU to identify lunar ice recovery areas.

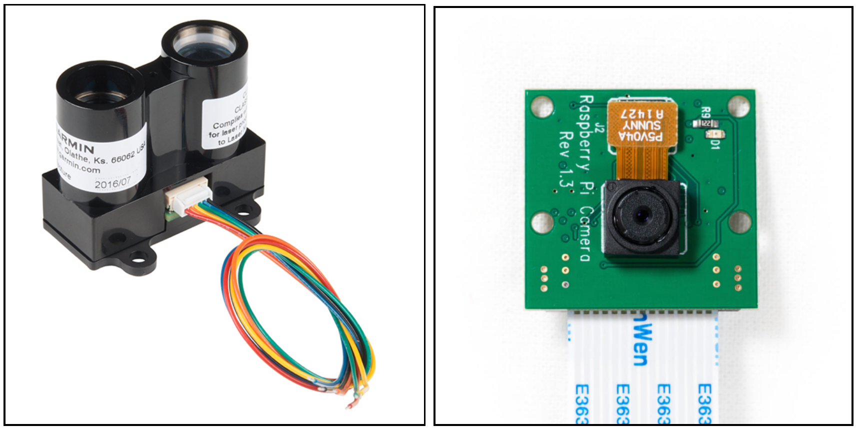


Figure 6.13: AGL Altimeter (Left) and Digital Imaging Unit (Right)

6.2.3.2. Software Design

The software design of the UAV can be broken down into two primary tasks: navigation to the lunar ice recovery site and landing at the recovery site. The navigation algorithm uses GPS data gathered before the flight as the basis for traveling to the recovery site. Image data from the DIU is also integrated into this algorithm as seen in the Figure 6.14 below.

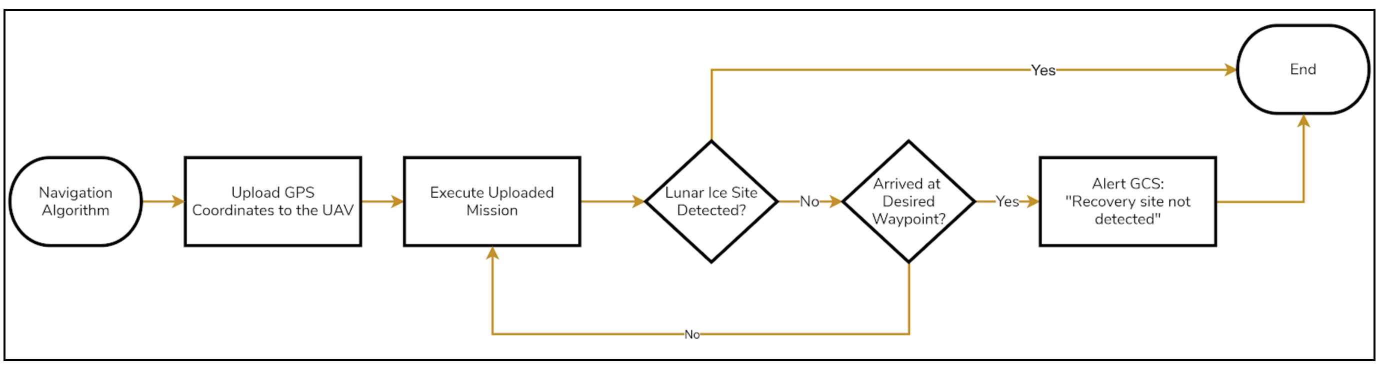


Figure 6.14: Top-Level Navigation Algorithm

Once the UAV arrives above a lunar ice recovery site, it must be able to visually detect the site so that it can make an accurate landing. The image processing algorithms developed to handle this task detect the contours of shapes in the image and compare their color with the known hue of the lunar ice recovery sites. If the algorithm decides that it has found a recovery site, it computes the centroid of the site, thus giving the relative position of the UAV with respect to the site. Finally, a PID control algorithm is employed to keep the UAV situated above the center of the site as it descends toward the ice.

6.2.4. UAV Electrical Design

6.2.4.1. Power Distribution

The primary purpose of the UAV electrical design is to distribute proper voltages and currents to the various UAV electrical components. At the heart of the electrical design of the UAV is a 11.1V, 3600mAh lithium polymer (LiPo) battery. This power source is capable of meeting the high discharge demands of this kind of system without compromising on stringent weight requirements. The power supplied by this battery is distributed through the use of the Pixhawk 4 Power Management Board, seen below in Figure 6.15.

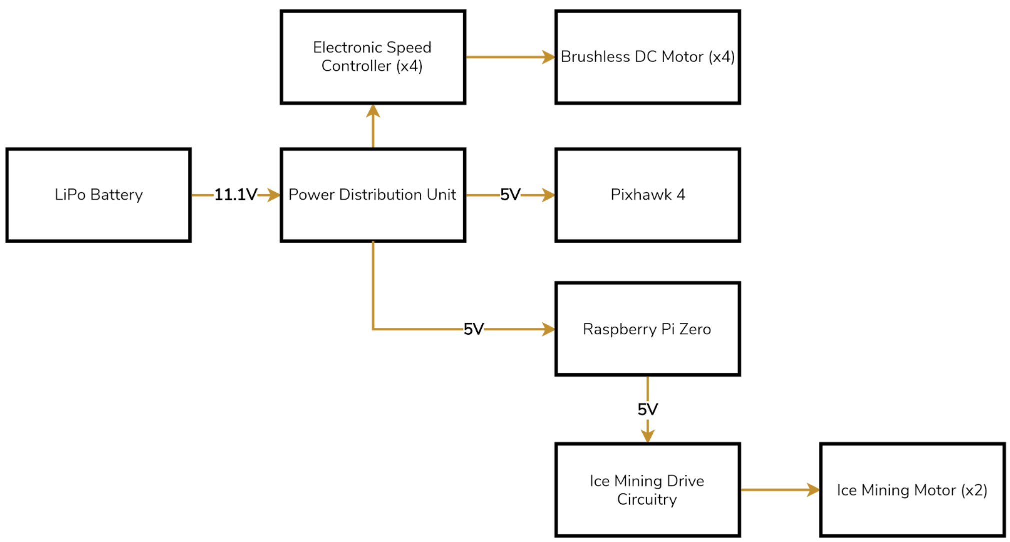


Figure 6.15: UAV Power Distribution Flow Diagram

This design makes use of the Pixhawk 4 Power Management Board's built-in voltage regulation, which yields a clean 5V signal that can be used to power other components on the UAV.

By far the biggest source of power consumption on the UAV is the propulsion system. As such, understanding the relationship between the vehicle's power draw and its expected available flight-time is critical. An analysis of the propulsion system's power consumption was performed using the eCalc xcopterCalc online calculator, a popular tool utilized by the hobbyist RC community. The results of the analysis are displayed below in Table 6.1.

UAV Power Consumption Data
Hover Flight Time: 10.1 Minutes
Single Motor Power Consumption (Hover): 50.5 W
Single Motor Power Consumption (Full Throttle): 102.5 W

Table 6.1: UAV Power Consumption Data

In addition to supporting the power consumption and distribution requirements of the UAV, the electrical design must integrate the UAV's sensor package, facilitate communication between the FCC and MCU, and drive the IMPS. Figure 6.16 below gives the full system schematic for the electronics on-board the UAV. Of particular note is the serial interface between the FCC and the MCU, used to facilitate communication of high-level control commands to the FCC.

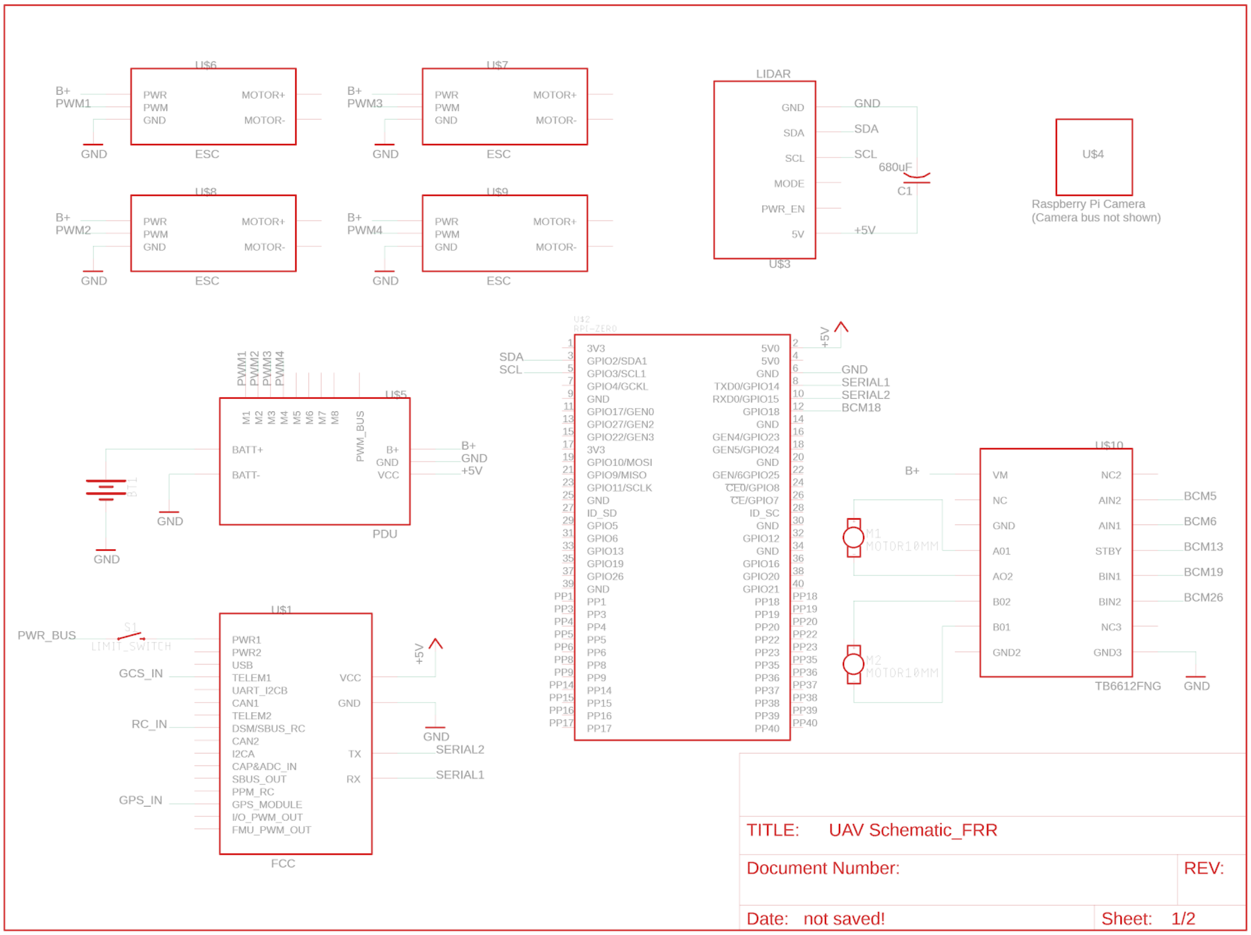


Figure 6.16: UAV Electrical Schematic

6.2.4.2. EMI Mitigation

Electromagnetic interference (EMI) was interfering with GPS signals being received by the GPS. The high density of wires underneath the GPS caused radiated EMI, which in turn, caused the GPS coordinates to be incorrect. To mitigate this disturbance, there is an addition of copper foil shielding tape between the GPS and the wires that lie beneath the GPS. This copper foil helps to mitigate the electromagnetic field that is contributed due to the current running through the wires and was chosen in part for its limited additional weight and in part for its high-conductivity. Copper was chosen due to its high-conductivity which offsets the magnetic field more than a high resistance material, which would be better suited for if the EMI was current interference.

6.2.5. Ground Control Station

The GCS provides a physical interface between the pilot in command and the UAV. It includes any and all communication interfaces between an operator, the UAV, and the payload retention and deployment system that are necessary to complete the mission. Its functionalities include monitoring telemetry data, pulling UAV image data, autonomous mission planning, monitoring mission status, and flight mode switching. In summary, the GCS will combine functionalities commonly seen in laptop GCS setups with an interactive mission control panel that will allow for quick and informative decision making. The GCS will run parallel to a Taranis Q X7 Radio Controlled (RC) transmitter that will act as a redundancy in case the GCS is unable to control the UAV and/or manual control of the aircraft is required. The GCS can be seen below in Figure 6.17.

Figure 6.17: GCS tabletop configuration

No notable changes have been made to the physical construction of the GCS. The GCS electrical design has had slight modifications that include a PCB redesign of the power distribution board (PDB) that better met the system's power requirements. Software has seen significant development to the point where testing and limited operation may be conducted through the GCS. Construction and testing of the GCS has shown that the GCS may perform its expected function as built, and no enhancements or design revisions are seen to be necessary.

6.2.5.1. Physical Hardware

Physically, the primary GCS structure is comprised of a Pelican 1550 case with carbon fiber panels. The two components that pilot in command interfaces with are the Display Head Assembly (DHA), and the Control Panel Assembly (CPA). The DHA is primarily a single 17.6" monitor that will display real-time flight data, image data, and mission data relevant to safe and informed UAV operation. The CPA is a set of switches, buttons, LEDs, and a keyboard that provides complete control over the UAV during flight testing and general operation. The GCS may be mounted onto a tripod if necessary, or may be operated from a table.

6.2.5.2. Electrical Hardware

The electrical design of the GCS includes the PDB, the control panel board (CPB), and the Raspberry Pi 4 that functions as the station's computer. The PDB serves several purposes related to power distribution, battery monitoring and battery display control, and sound system amplification. Modifications were made to the PDB to support a commercially purchased voltage step down circuit to replace voltage regulator on the original board. The original board's voltage regulator did not provide a steady 5V rail and did not supply enough power for the GCS computer. The CPB has a dedicated microprocessor that detects any changes in a switch's state and also forwards feedback to the operator using LEDs. Seen below in Figure 6.18 are both the PDB and CPB.

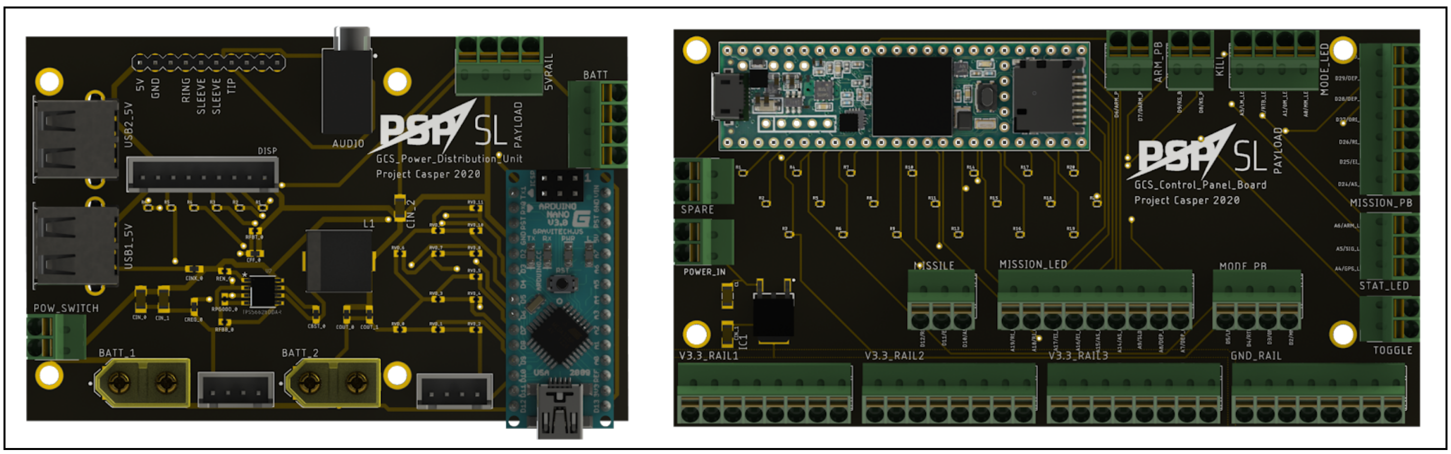


Figure 6.18: Payload GCS Power Distribution Board (Left) and Control Panel Board (Right)

6.2.5.3. Software

Much of the software for the GCS has been created. Almost the entire Graphic User Interface is complete with the exception of the strip charts to display flight data. The interface can be seen below. In addition to the interface, back end code has been put in place so the software can communicate to the Retention and Deployment electronics. In the coming weeks additional functionality will be implemented so the software can interpret and display telemetry data from the UAV. All retention and deployment communication has been implemented and tested.

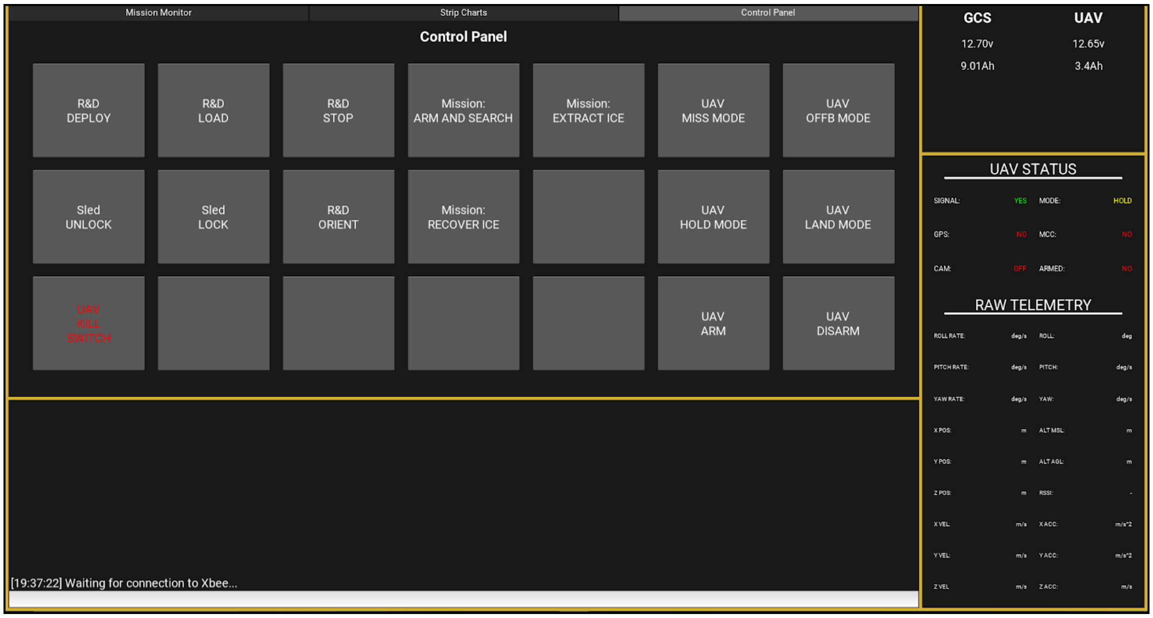


Figure 6.19: GCS Software Interface

6.3. Retention and Deployment Design

6.3.1. R&D System Overview

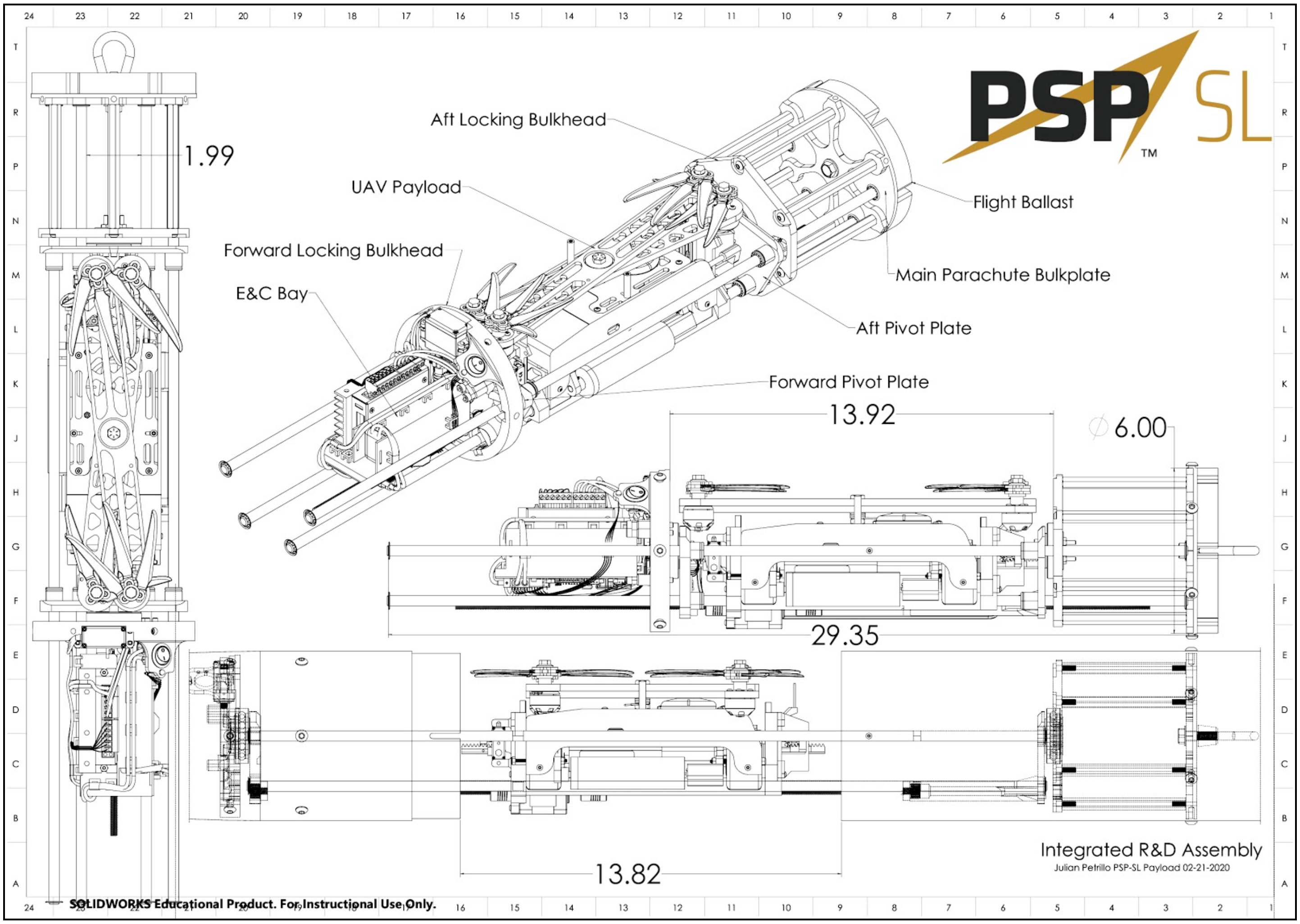


Figure 6.20: Critical Dimensions and Components of the R&D System

The R&D system is comprised of the UAV Retention System, the Locking System, the Axial Expansion System, the UAV Orientation Control System, and the R&D electronics system. These systems work together to safely hold the UAV payload within the rocket throughout the course of the flight and to facilitate a successful deployment of the UAV after landing.

6.3.2. UAV Retention System

The UAV retention system is designed to safely retain the UAV during launch vehicle flight and during axial deployment then subsequent orientation. The UAV retention system, seen in Figure 6.21 below, uses a set of servo-controlled rack and pinion linear actuators to control the release of the airframe's passive X-Wing mechanism, to prevent any undesired vertical motion of the UAV, and to isolate power from the FCC while the UAV is inside the launch vehicle.

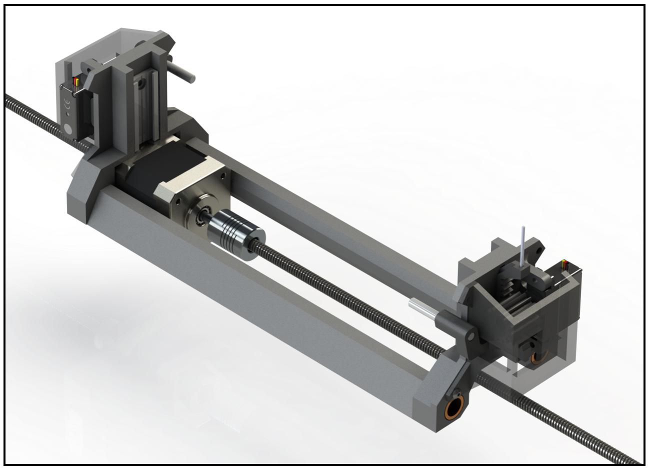


Figure 6.21: UAV Retention System

The configuration of the UAV retention system has been modified to greater complete it's role of safe retention of the UAV during flight deployment. Testing and integration of the UAV with retention system exposed issues for the UAV while being deployed. Deployment cases in which the UAV was upside down caused one end to dip beneath it's expected envelope and contact the ground: a design flaw resulting from the use of single servo to control sled locking only on one end of the UAV. Deployment in a dirt field would in this orientation would likely a component on the UAV to catch leading to system failure. To mitigate such a risk, an identical servo was added to the other side of the sled such that UAV is held down on both ends. This servo uses identical signals for locking and unlocking the UAV and would simply be wired in parallel with the previously existing servo such that no revisions were required to R&D electronics or software. Additionally, the set of dowel rods that previously interfaced with the UAV's legs were removed as they added no benefit.

6.3.3. Locking System

In the unlikely event of a complete payload failure it is critical that one feature remains, the capability to retain the UAV in a safe state until landing and disassembly. This capability is referred to as Fail-Closed design of the R&D System. In flight, two primary forces exist which may expand the R&D system, causing rapid unplanned deployment of the UAV. At launch, the entire rocket experiences intense vibration which could dislodge or loosen critical components. Additionally during main parachute deployment, the rocket rapidly decelerates due to the increased drag; this deceleration results in large forces at section attachment points.

In order to be considered a successful design, the R&D locking system must be able to resist the above forces in worst case scenarios, including complete power loss. Ideally the system will also add minimal additional hardware to the system, in order to reduce weight and complexity.

The final locking system design makes use of the already present linear motion rods and orientation servo. The primary function of these systems will be discussed in later sections. Notches cut in the linear motion rods provide a detent that is interlocked with the forward and aft locking bulkhead before flight. This interlocking provides a robust load path between the upper airframe and nose cone. Note in Figure 6.22 that the load path completely bypasses the entire Axial Expansion and UAV Orientation system. This allows those systems to be designed solely kinematically, with little regard to intense flight loads.

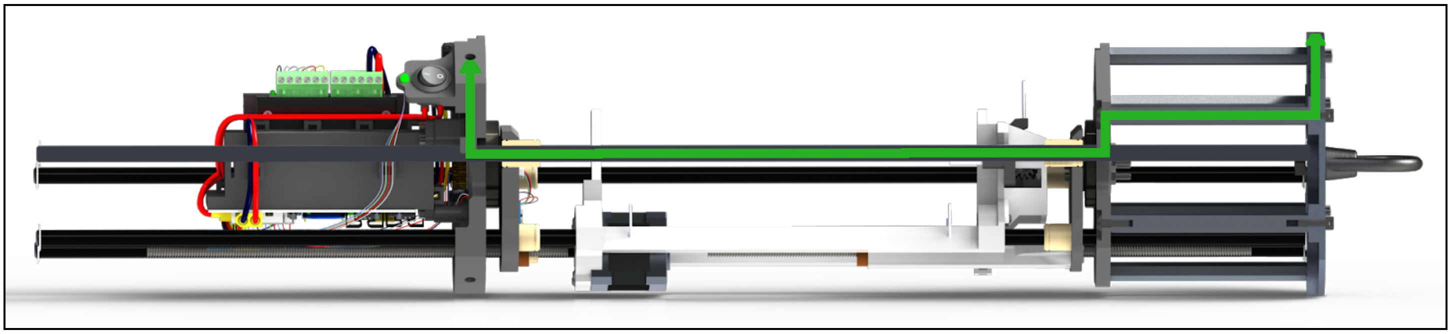


Figure 6.22: R&D section view showing a load path from the nose cone to the upper airframe (green)

While the notch detent system provides a load path for any axial flight loads, it would remain susceptible to vibration or off axis loads without a system preventing the rotation of rods and by extension, the unlocking of the detent notches. This is accomplished using the orientation servo motor and drive system. It is well known that a worm gear drive can only be driven in one direction. Using this fact and properly aligned gears that reduce movement between gear teeth without engagement (backlash), it becomes impossible for the system to be rotated (and by extension unlocked) without the activation of the orientation servo motor. The entire locking system was tested under a tension of 300lbs without failure, ensuring a factor of safety of 2 across the system.

After landing, the orientation servo motor and drive system are used to rotate the system into a state in which neither the linear motion rods or their corresponding retaining rings collide with the locking bulkheads. (Figure 6.23, Left vs. Right) This state is confirmed with a limit switch attached to the forward locking bulkhead making contact with the Axial Expansion leadscrew. Once the system is in this state it is considered unlocked, and the UAV deployment process continues.

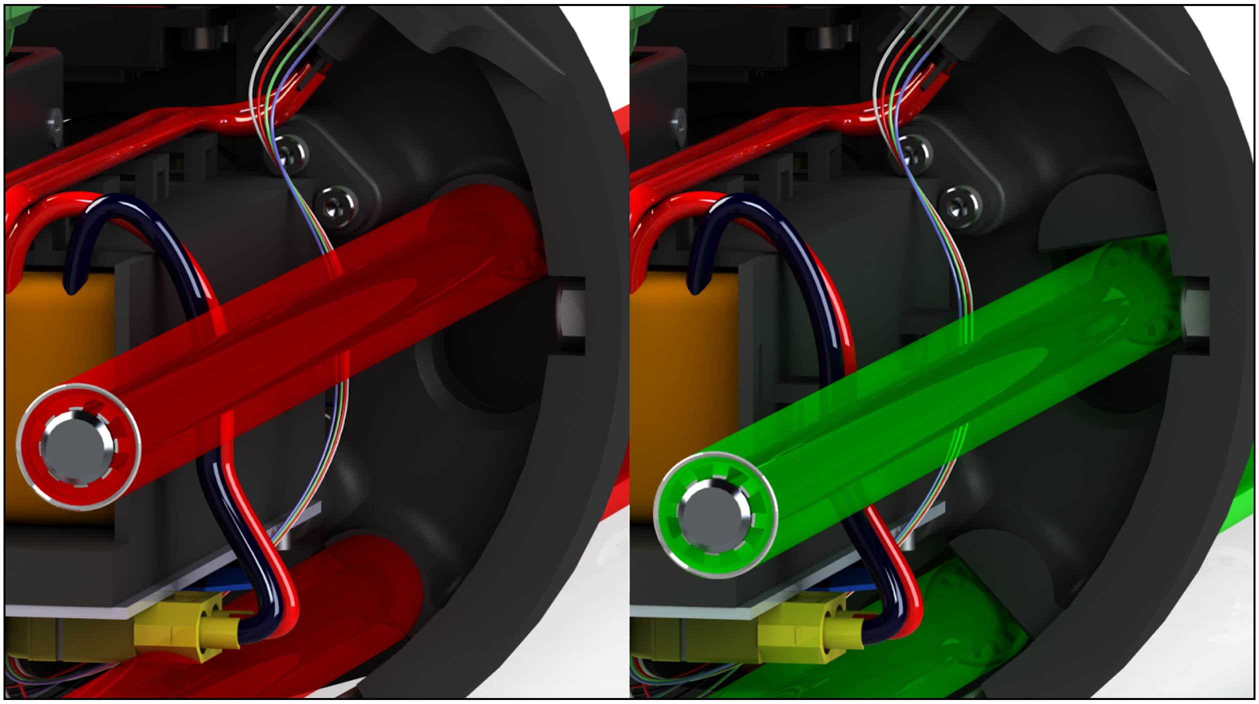


Figure 6.23: Linear Motion Rods Locked vs. Unlocked
(Red and Green Cylinders indicate a “bounding box”)

6.3.4. Axial Expansion System

After safe landing and unlocking, the Axial Expansion System provides the UAV a clear flight path by moving both the UAV Sled and the nosecone relative to the upper airframe. The linear motion is controlled by 4 aluminum linear motion rods, and is powered with a dual shaft stepper motor and 2 lead screws. The 4 linear motion rods sit in a series of linear bearings which allow them to slide freely, only constrained by end mounted push-on retaining rings. These rings prevent asymmetrical loads in the system from causing the rods to disengage from one pivot plate before the other. Two of the linear motion rods also pass through the UAV Retention Sled, providing it support and alignment.

The UAV Retention Sled houses the dual shaft NEMA 17 stepper motor, which is attached via flexible couplings to right handed and left handed lead screws fore and aft respectively, shown in Figure 6.24. When the system is ready for expansion, the electronics bay commands stepper to run for a predetermined number of steps, resulting in an precise expansion of 16 inches. The handedness of the leads screws ensures that the UAV Retention Sled remains centered between the nose cone and upper airframe throughout this process. The Axial Expansion System has the effect of clearing the linear motion rods from the forward and aft locking plates, allowing the UAV Orientation Control System to function.

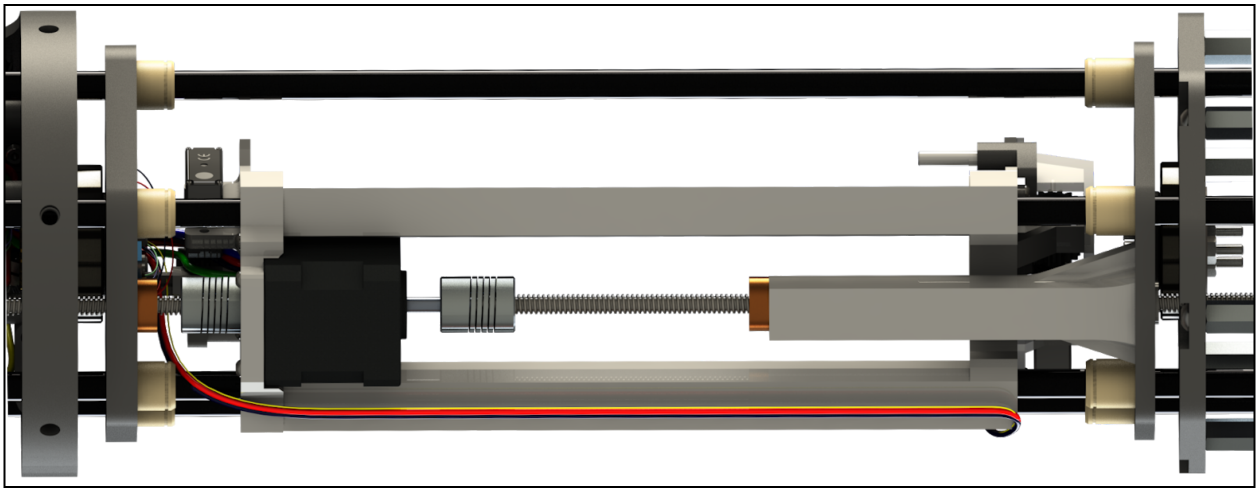


Figure 6.24: Underside of R&D System (UAV not shown)

6.3.5. UAV Orientation Control System

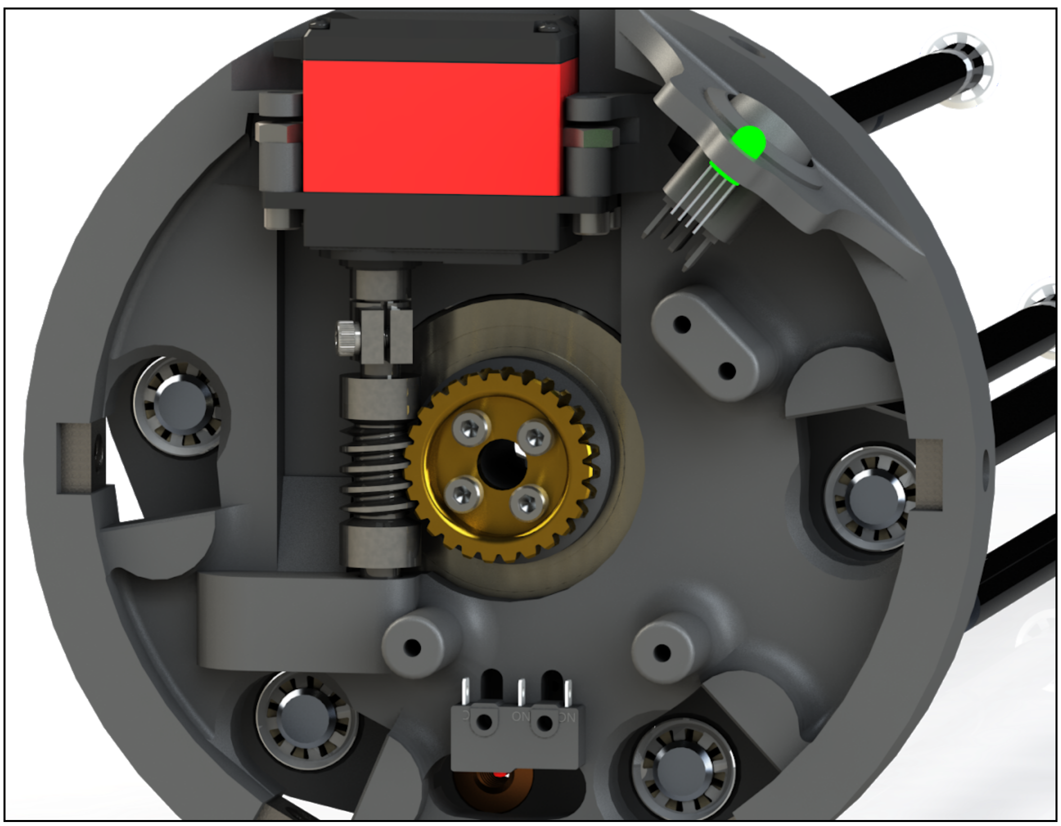


Figure 6.25: Forward R&D Subsystem (Electronics Bay not shown)

Due to the chaotic nature of rocket recovery, the post-flight axial orientation of the upper airframe and by extension the UAV is unknown. The UAV Orientation Control System acts to align the UAV's vertical direction with gravity, such that it can take off vertically without interference from the ground or the rest of the R&D System.

The motion is controlled through a closed loop system consisting of a 6 axis accelerometer and a continuous rotation servo motor. Using data from the accelerometer, the orientation servo rotates a worm drive which slowly tilts the bay to the UAV launch orientation. The worm drive gives the system additional precision, and prevents any risk of backdrive.

6.3.6. R&D Electrical Design

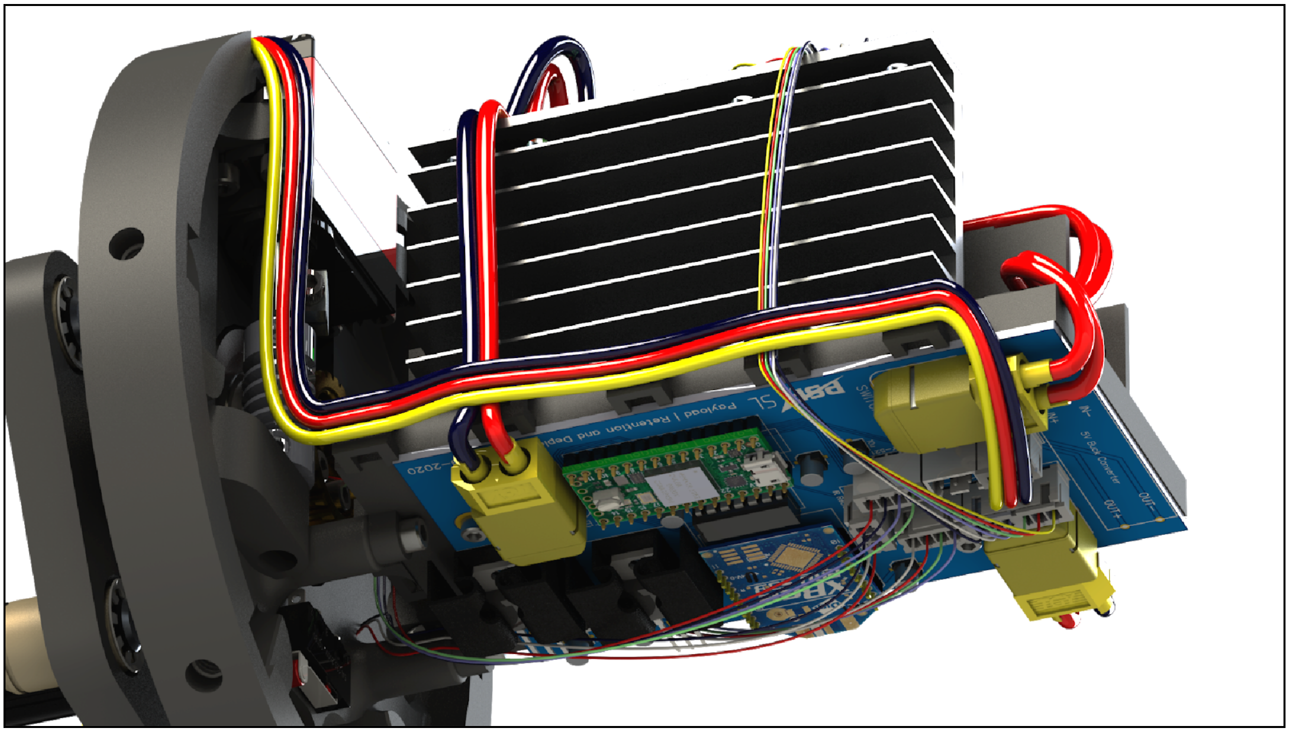


Figure 6.26: Underside of R&D Electronics Bay

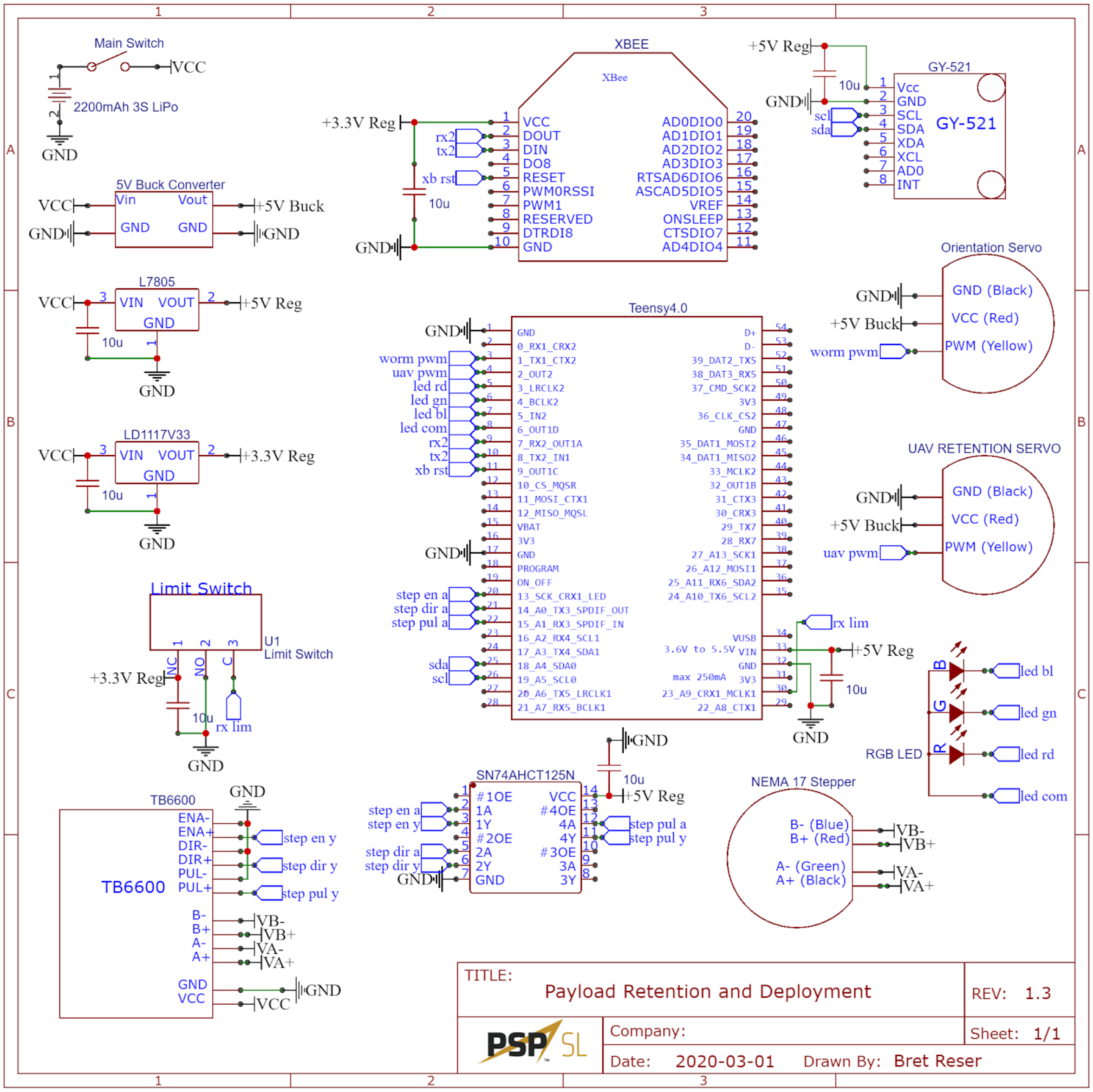


Figure 6.27: R&D Electronics Schematic

At a very high level, a remote operator uses the ground control station to control all electromechanical motion devices during the payload deployment process. This control is wireless, as the R&D electrical subsystem receives long-range wireless commands from the GCS via an XBee Pro 900-HP embedded RF module, which forwards the wireless RF data to a central Teensy 4.0 (arduino-based) microcontroller via serial communication. From there, the Teensy software validates the packet, and follows the instructions in the packet. The received instruction will command the Teensy to either take a certain action or return data from various sensors such as the MPU-6050 IMU. Since it is important to know an instruction was received, the subsystem will always return a packet containing at minimum a confirmation, regardless of whether or not the instruction specifies returning data.

For the operator on launch day, remote operation of the R&D system for deployment will most likely resemble the following:

1. Following a successful recovery, the payload bay must be unlocked. The operator sends the “unlock bay” command, which uses the CR servo to drive the worm-gear until a limit switch is pressed, indicating the bay is unlocked. The operator may elect to run the “get angle” command before and after unlocking, to check if the angles calculated from the MPU-6050 IMU data make sense.
2. After unlocking the bay, the operator configures the stepper for normal operation with the “set stepper defaults” command, then turns the stepper on with “stepper enable”, and finally sends the “move stepper inches” command, which calculates and sends the number of steps needed for the stepper motor to expand the bay a certain number of inches via the lead-screws (16” needed for full expansion).
3. Next, the UAV sled must be oriented upright for proper takeoff. The operator can now run the “orient bay” command, which uses the closed loop CR servo and IMU system to orient the bay to a certain angle with respect to gravity. In this case, the bay should be oriented to 0 deg, which corresponds to upright. It should be noted that the operator could run the “get angle” command to check if the UAV is already upright after expansion, which would eliminate the need for orientation.
4. Finally, the operator runs the “uav servo set” command to set the uav servos to the unlocked position. Now, the UAV is ready for takeoff.

In the event that deployment doesn’t follow this ideal sequence of events, there are many additional functions available to the operator to allow for flexibility. These cover a wide range of functionality, from testing connectivity with a ping, to stopping all motors, to fetching raw digital data from various sensors.

Powering this entire system is a 2200mAh 3S 25C LiPo battery, which has enough capacity to stay in standby for the required minimum of 2 hours post-flight and then run a full deployment procedure. For the current implementation, this means the battery must support the following loads:

- ~4.5A@12VDC to drive NEMA 17 stepper motor for 1min
- At most 1A@5VDC to drive the orientation servo for 1min and UAV retention servo for 30s
- ~100mA@5VDC to power Teensy 4.0 microcontroller for 2hrs
- ~At most 290mA@3.3VDC to power XBee Pro 900 HP for 2hrs
- ~50mA@5VDC for all other low power devices combined for 2hrs

Based on these estimates, using the 2200mAh battery grants a FOS = 2.2.

To reduce the occurrence of hardware failures and safety issues, the following corrective actions were taken:

- Ruggedized battery holder to completely enclose battery in protective walls to prevent puncture of cells
- Switched to locking JST connectors to mitigate risk of disconnection
- Tinned leads of all wires to improve reliability of terminal block connections
- Cut all wires to length and added many zip-tie points per wire to minimize load on wires and to prevent snags
- Added cable sleeving to wires that must move during deployment to prevent entanglement

6.4. Payload Testing and Flight Reliability Confidence

6.4.1. Payload Test Plan

6.4.1.1. Background

The Project Casper payload is an ice-mining capable small unmanned aerial system (sUAS) consisting of a fully autonomous unmanned aerial vehicle (UAV), a portable and robust ground control station (GCS), and a fail-safe retention and deployment (R&D) system that houses and protects the UAV in the launch vehicle. These tests are being conducted to ensure that the sUAS meets all determined performance specifications, operational capabilities, and complies with all of the team-derived and NASA payload requirements detailed in 2020 NASA SL Handbook. Most importantly, these tests are conducted to ensure that the payload system can perform the mission safely and reliably.

The test articles or systems under test (SUT) for this test program are the UAV, the GCS, and the R&D system. The UAV is an optionally piloted unmanned electrical aircraft that can be controlled using an RC Radio Transmitter or SiK telemetry radio. It is equipped with two identical ice mining systems that are each capable of extracting the minimum required 10ml of ice. The UAV is electrically powered and has an estimated flight time of at least 10 minutes. The GCS is a portable and mission integrated control system that allows for complete command and control of both the UAV and R&D systems. The GCS collects data from the UAV and R&D systems to display the TSPI of the UAV under operation, the R&D configuration data, and finally the UAV's telemetry. The R&D system houses and protects the UAV inside the launch vehicle during launch vehicle ascension and descension, then deploys the UAV into a flight-ready configuration.

6.4.1.2. Purpose of Tests

This test program is being conducted primarily to comply with the requirements provided by NASA as well as the payload team-derived requirements, but will also performed to develop the payload system. All of the payload requirements requiring testing for verification will have at least one test completed, however, it is likely that many tests will be completed to validate each requirement to ensure confidence in system capability. A vast majority of the testing will be spent ensuring that the UAV, GCS, and R&D meet the internally defined performance requirements found in the payload team-derived requirements.

In addition to meeting these performance and operational requirements, the testing will also determine its mission suitability to ensure that the sUAS can safely and reliably fulfill the mission as designed. The payload system will be tested and evaluated in the mission environment for which it was designed both in simulation and in a physical testing environment. The payload system will be put through several different operational scenarios that may be encountered during its mission and its performance and capability will be documented.

The test program will also allow for the documentation of both enhancing characteristics and deficiencies for each of the SUT. The identification of enhancing characteristics, specifically for the UAV, will allow for the increase of operational capabilities (e.g. flight envelope or operational range). The identification of system deficiencies will allow for subsequent identification of underperforming equipment that may require a change to mission operation or system design.

6.4.1.3. Scope of Tests

The payload test program will be divided into two phases: the developmental testing (DT) phase, and operational testing (OT) phase. The DT phase will primarily consist of component-level, subsystem, and individual system testing to verify and document performance characteristics. The OT phase will primarily consist of verifying mission capability. OT will ultimately determine the effectiveness and reliability of the UAS for its designed mission. A table listing the tests and their progress is shown in Table 3-1. Each of these tests are mapped to a single requirement, however, some requirements have more than one test.

Req. ID	Test ID	Test	SUT	DT/OT	Status
4.3.2	PT_01.1	IMPS Stand Test	UAV	DT	Complete
	PT_01.2	Onboard Ice Mining Test	UAV	OT	In Progress
T4.6	PT_02.1	Variable Pitch-Orientation Launch Test	UAV/R&D	DT	Complete
	PT_02.2	Variable Roll-Orientation Launch Test	UAV/R&D	DT	Complete
T4.7	PT_03.1	Flight Controller Tuning	UAV	DT	In Progress
T4.8	PT_04.1	SITL Ice Recovery Testing	UAV/GCS	DT	In Progress
	PT_04.2	Recovery Area Identification Testing	UAV/GCS	OT	Incomplete
T4.9	PT_05.1	RF Comms Testing	All	DT	Incomplete
T4.10	PT_06.1	Thrust Stand Testing	UAV	DT	Complete
T4.11	PT_07.1	Battery Drain and Power Testing	All	DT	In Progress

Table 6.2: Payload Test Summary

6.4.2. IMPS Stand Test - PT_01.1

Test ID: PT_01.1 **Test Name:** IMPS Stand Test **Related Requirements:** 4.3.2 Related Test IDs: PT_01.2	**Objective and Tested Variables:** To confirm the ice mining and procurement system's ability to extract different shapes and sizes of simulated lunar ice material. The test variable is the volume of collected material. **Success Criteria:** The test is successful if the IMPS extracts 10+ mL of each sample of simulated lunar ice material.	**Reason for Test:** This test is integral to verifying that the IMPS is capable of meeting the mission requirement of collecting at least 10 mL of lunar ice. Additionally, since the exact material properties of the simulated lunar ice is unknown, analyzing the system's performance with different materials may inform small changes of the IMPS design moving forward.
Methodology	1. Place simulated lunar ice material in a 1'x1' containment unit. Enough lunar ice material should be used such that a depth of at least 2" is created. 2. A test stand shall be developed to simulate how the IMPS mounts to the UAV. Place the test stand, with the IMPS attached, on top of the simulated lunar ice material. 3. Run the IMPS for 15 seconds. 4. Measure the total volume of material collected in each scoop component of the IMPS. 5. Repeat steps 1-4 for at least 3 different simulated lunar ice materials over varying shapes, sizes, and textures.	
Possible Impacts	Successful completion of this test confirms that the RF systems of the payload have the range necessary to cover all potential distances seen on launch day. A failure of this test could lead to a component-level redesign of the system, such as adding a higher power antenna to increase range.	

Results
Status: Complete

Trial	Number of Rotations	Starting Orientation	Ending Orientation	Shaken?	Amount Collected
1	Fill to capacity	---	---	No	15 mL
2	1	Scoop opening up	Scoop opening up	No	11.5 mL
3	2	Scoop opening up	Scoop opening up	No	12.5 mL
4	1.5	Scoop opening up	Scoop opening down	No	7.5 mL
5	1.75	Scoop opening up	Scoop opening right	Yes	2.5 mL

6	2	Scoop opening up	Scoop opening up	Yes	13 mL

From these tests the team was able to confirm that when the scoop ends with the opening up for 180° the scoop will be able to collect more than the minimum 10 mL required. However, when the scoop is within 180° when the opening is facing the ground the scoop will collect either 10mL or less. When programming this in the future, the team will have the scoop ending roughly within the same area as it starts.

6.4.3. On-Board IMPS Test - PT_01.2

Test ID: PT_01.2 **Test Name:** On-Board IMPS Test **Related Requirements:** 4.3.2 **Related Test IDs:** PT_01.1	**Objective and Tested Variables:** To confirm the ice mining and procurement system's ability to extract simulated lunar ice material under flight conditions. The test variable is the volume of collected material.	**Reason for Test:** This test is integral to verifying that the IMPS is capable of meeting the mission requirement of collecting at least 10 mL of lunar ice. Additionally, this test ensures that the IMPS properly integrates into the overall UAV system and is capable of containing sampled material while the vehicle flies away from the recovery site.
	Success Criteria: The test is successful if the IMPS extracts and contains 10+ mL of simulated lunar ice material.	
Methodology	1. Create a simulated lunar ice recovery area by placing a 3' diameter of simulated lunar ice material in the center of a 10'x10' tarp. The lunar ice material should have an average depth of 2". 2. Fly the UAV 100' above the simulated recovery area. 3. From 100' AGL, slowly land the vehicle on the simulated recovery area. 4. Upon landing, remotely trigger the IMPS to begin extracting simulated lunar ice material. 5. After 15 seconds, trigger the IMPS to stop lunar ice extraction. 6. Fly the UAV at least 10' linearly away from the recovery area and land the vehicle. 7. Measure the volume of lunar ice material collected by the IMPS.	
Possible Impacts	Successful completion of this test indicates that the current design of the IMPS system is capable of collecting the proper amount of lunar ice material. Changes to the interface between the ice mining system and the UAV could result from this test.	
Results **Status:** In Progress	This test is not yet completed.	

6.4.4. Variable Pitch-Orientation Launch Test - PT_02.1

Test ID: PT_02.1 **Test Name:** Variable Pitch-Orientation Launch Test **Related Requirements:** T4.6 **Related Test IDs:** PT_02.2	**Objective and Tested Variables:** Determine the maximum angle at which the R&D system can still successfully deploy the UAV. This test should push the UAV retention system to failure, thus finding the point at which UAV deployment should no longer be attempted. The test variable is the angle of the payload bay with respect to the ground. **Success Criteria:** This test is successful when an angle with respect to the ground in which UAV deployment is no longer possible is found.	**Reason for Test:** This test is necessary to gain a better understanding of the limits of the R&D system. This limit can then be compared to predicted landing orientations to determine compliance with mission requirements. This data can be compared with the data found in PT_02.2 to create a grid of potential UAV launch orientations.
Methodology	1. Place the UAV inside the payload bay in the configuration in which it will land during the mission. 2. Prop the upper-airframe up off the ground, such that the entire assembly with the payload bay enclosed makes an angle of 5° with the ground. 3. Remotely signal the R&D system to initiate the UAV deployment sequence. Take note of how the R&D system responds to its orientation with respect to the ground. 4. After the UAV deployment sequence is complete, initiate deployment of the UAV. 5. If the UAV successfully takes off in step 4, repeat steps 2-4 in 5° increments. Repeat until the UAV is no longer able to deploy. 6. Once the take off is no longer successful, reduce angle by 1° until take off is successful. 7. Repeat steps 1-6 propping the nose cone up off of the ground instead of the upper-airframe.	
Possible Impacts	If the payload team decides that the angle found in this test is not large enough, design modifications to increase this maximum angle might be made. If the team decides that the range is large enough, the range bounds will be noted and be used for go/no-go before UAV launch.	
Results **Status:** Complete		

Trial	Pitch Angle (Degrees) (Negative values corresponding with the Nose Cone pitching down)	Pass/Fail
1	0	Pass
2	-5	Pass
3	-10	Fail
4	-8	Fail

5	-7	Pass
6	2	Pass
7	5	Pass
8	7	Fail
9	6	Fail

From these data it is determined that the pitch angle range for a successful take off is between -7° and 5°. Outside of this range, the autonomous launch of the drone cannot be guaranteed and manual operation will be engaged.

6.4.5. Variable Roll-Orientation Launch Test - PT_02.2

Test ID: PT_02.2 **Test Name:** Variable Sled Orientation Test **Related Requirements:** T4.6 **Related Test IDs:** PT_02.1	**Objective and Tested Variables:** Determine the maximum angle with respect to the roll axis of the payload bay in which the UAV can successfully deploy from the sled. This test should verify how precise the gyroscopic reorientation system within the broader R&D system needs to be. The test variable is the payload sled roll angle. **Success Criteria:** This test is successful when an angle with respect to the payload bay axis, in which UAV deployment is no longer possible, is found.	**Reason for Test:** This test is necessary to gain a better understanding of the limits of the R&D system. Identifying how far off-axis the deployment sled can be, while still enabling a successful take-off, will provide information about the necessary precision of the R&D reorientation system. This data can be compared with the data found in PT_02.1 to create a grid of potential UAV launch orientations.
Methodology	1. Place the UAV inside the payload bay in the configuration in which it will land during the mission. 2. Separate the nose cone and the upper-airframe, simulating the beginning of the UAV deployment process. 3. Manually rotate the sled on which the UAV sits 5° from the ideal take-off orientation. 4. Initiate deployment of the UAV. Take note of how the orientation of the sled affects the UAV's takeoff. 5. If the UAV successfully takes off in step 4, repeat steps 2-4 through the angles ±10°, ±12° and ±15°.	
Possible Impacts	If the payload team decides that the angle found in this test is not large enough, design modifications to increase this maximum angle may be made. If the team decides that the range is large enough, the range bounds will be noted and be used for go/no-go before UAV launch.	
Results		

Status: Complete

Trial	Roll Angle (Degrees) (Positive values corresponding with a clockwise motion as viewed from the aft)	Pass/Fail
1	0	Pass
2	5	Pass
3	10	Pass
4	12	Pass
5	15	Fail
6	-10	Pass
7	-12	Pass
8	-15	Pass

From these data it is determined that the roll angle range for a successful take off is between -15° and 12°. Outside of this range, the autonomous launch of the drone cannot be guaranteed and manual operation will be engaged.

6.4.6. Rate Controller Tuning - PT_03.1

Test ID: PT_03.1

Test Name: Rate Controller Tuning

Related Requirements: T4.7

Related Test IDs: N/A

Objective and Tested Variables: Tune the flight controller's (angular) rate and attitude controller to improve flight qualities and reduce the effects of noise and disturbances. The test variables are roll rate, pitch rate, and yaw rate PID gains, attitude proportional gain, and vehicle response.

Reason for Test: This test ensures that the UAV is properly tuned to improve flight quality, increase efficiency, reduce vibrations that may affect onboard hardware, and reduce the likelihood of a crash. Failure to perform this test may lead to poor handling qualities, reduced flight time, and a reduction in the performance of other vehicle hardware.

Success Criteria: The test is successful if changes to the PID gain parameters result in an improvement to the vehicle's response to a setpoint angular rate (roll rate, pitch rate, or yaw rate) and increased maneuverability.

Methodology

Testing of the vehicle's angular velocity response will involve the use of pre-programmed mission files that will utilize the offboard control capability of the flight controller. Each of these pre-programmed mission files will focus on either roll, pitch, or yaw, and will supply a brief step function commanding a roll, pitch, or yaw rate shortly after takeoff. The UAV will then land be tuned automatically before being flown again until results are satisfactory. These pre-programmed missions will be tested in simulation before they are tested on the UAV.

	1. Place the UAV in a flight ready configuration such that it is powered and ready to takeoff. 2. Establish and ensure a connection between the GCS and UAV. 3. Load and autotuning script and begin adjusting either roll, pitch, or yaw. 4. After the UAV lands, adjust the PID parameters using the Ziegler-Nichols method. 5. Repeat steps 1-4 until results are satisfactory.
Possible Impacts	Successful completion of this test will allow for smoother, more efficient flight of the UAV.
Results **Status:** In Progress	This test is not yet completed.

6.4.7. SITL Ice Recovery Testing - PT_04.1

Test ID: PT_04.1 **Test Name:** SITL Ice Recovery Testing **Related Requirements:** T4.8 **Related Test IDs:** PT_04.2	**Objective and Tested Variables:** Verify the performance of the UAV's vision-guided descent algorithm in a simulated environment. The test variable is the UAV targeted landing accuracy and landing velocity.	**Reason for Test:** This test is essential for verifying the performance of the vision-guided descent algorithm. As this phase of the mission involves the landing of the UAV, successful completion of this event in a software environment is essential to mitigating the safety risks posed by testing on the flight vehicle. Successful completion of this test is required before performing PT_04.2 which involves repeating this procedure with the physical UAV.
	Success Criteria: This test is considered successful if the UAV lands softly within 1' of the center of the lunar ice recovery area. A "soft" landing is defined as a maximum landing velocity of 2 ft/s.	
Methodology	This test is completely performed in a software environment due to the associated risks with landing the UAV while its software is still in development. As such, this test will be performed many times to test new versions of the landing software. Each of the following steps should therefore be followed in the context of a software simulation. 1. Place a simulated lunar ice recovery area on the ground plane. This recovery area should be 10'x10' with a target circle of diameter 3' at the recovery area's center. 2. Position the UAV approximately 100' above the recovery area, offset 10' from the recovery area's center. 3. Run the UAV's vision-guided descent algorithm. Record the velocity of the UAV throughout its descent and take note of the quality of the descent. Is the control system tuned for accurate, efficient performance? 4. If the UAV's landing velocity and landing position meet the given success criteria, repeat the procedure at least 3 additional times, varying the initial lateral position offset from the recovery area up to 25'. Take note of how the vision-guided descent algorithm reacts to different amounts of initial offset.	

Possible Impacts	This test will be conducted many times as the landing algorithm is further developed. This test directly impacts the development of this algorithm and how it will be implemented on the UAV.
Results **Status:** In Progress	This test is not yet completed.

6.4.8. Recovery Area Identification Testing - PT_04.1

Test ID: PT_04.2 **Test Name:** Recovery Area Identification Testing **Related Requirements:** T4.8 **Related Test IDs:** PT_04.1	**Objective and Tested Variables:** Verify the performance of the UAV's vision-guided descent algorithm. The test variable is the UAV targeted landing accuracy and landing velocity. **Success Criteria:** This test is considered successful if the simulated UAV lands softly within 1' of the center of the lunar ice recovery area. A "soft" landing is defined as a maximum landing velocity of 2 ft/s.	**Reason for Test:** This test is essential for verifying the performance of the vision-guided descent algorithm.
Methodology	This test closely mirrors PT_04.1, in which the vision-guided descent algorithm is tested in a software environment. This test should not be attempted until PT_04.1 has been successfully completed. This test should be completed in an open area where it is safe to fly a UAV to heights up to 100'. 1. Construct a lunar ice sample recovery area. This recovery area should be 10'x10' with a target circle of diameter 3' at the recovery area's center. 2. Fly the UAV approximately 100' above the recovery area, offset approximately 10' from the recovery area's center. 3. Run the UAV's vision-guided descent algorithm. Record the velocity of the UAV throughout its descent and take note of the quality of the descent. Is the control system tuned for accurate, efficient performance? 4. If the UAV's landing velocity and landing position meet the given success criteria, repeat the procedure at least 3 additional times, varying the initial lateral position offset from the recovery area up to 25'. Take note of how the vision-guided descent algorithm reacts to different amounts of initial offset.	
Possible Impacts	Results from this test directly inform the development of the landing algorithm and its implementation on the UAV. This test informs the tuning of the PID controller for guiding the vehicle's landing.	
Results **Status:** Incomplete	This test is not yet completed.	

6.4.9. RF Comms Testing - PT_05.1

<table>
<tr>
<td rowspan="2">Test ID:
PT_05.1

Test Name:
RF Comms Test

Related Requirements:
T4.9

Related Test IDs:
N/A</td>
<td>Objective and Tested Variables: Verify the range of the wireless communication systems for sending data between the GCS and UAV. The test variable is the wireless data link range.</td>
<td>Reason for Test: This test ensures that proper communication between the GCS and the payload system can be achieved over any range that could reasonably be expected during the mission.</td>
</tr>
<tr>
<td colspan="2">Success Criteria: This test is successful if all data links demonstrate a maximum point-to-point range of at least 1 mile.</td>
</tr>
<tr>
<td>Methodology</td>
<td colspan="2">The UAS has three separate data links that each must complete this test. These data links include the 900 MHz XBee radios, the 915 MHz Holybro telemetry transmitters, and the 2.4 GHz RC transmitter. The following procedure shall be completed for each of these data links to ensure healthy wireless connections can be established. Note: The details of the procedure outlined below is slightly different for each data link. Consult their documentation for details specific to each product.
1. Establish the “local” end of the test setup. This includes the RF receiver that is stationary throughout the test. In the mission, this receiver is located in the GCS. The receiver should be placed 2-3’ above the ground, connected to a device that can record RSSI and packet loss. Power the receiver on.
2. Utilizing a GPS-enabled phone (or other such device), walk the “remote” RF receiver .25 miles away from the local receiver.
3. Power the remote receiver on. Measure the amount of time it takes for a connection to be established between the two devices.
4. Record the RSSI and packet loss reported by the local RF receiver.
5. Power the remote receiver off.
6. Repeat steps 2-5 in increments of .25 miles up to 1 mile.</td>
</tr>
<tr>
<td>Possible Impacts</td>
<td colspan="2">Successful completion of this test confirms that the RF systems of the payload have the range necessary to cover all potential distances seen on launch day. A failure of this test could lead to a component-level redesign of the system, such as adding a higher power antenna to increase range.</td>
</tr>
<tr>
<td>Results
Status: Incomplete</td>
<td colspan="2">This test is not yet completed.</td>
</tr>
</table>

6.4.10. Thrust Stand Testing - PT_06.1

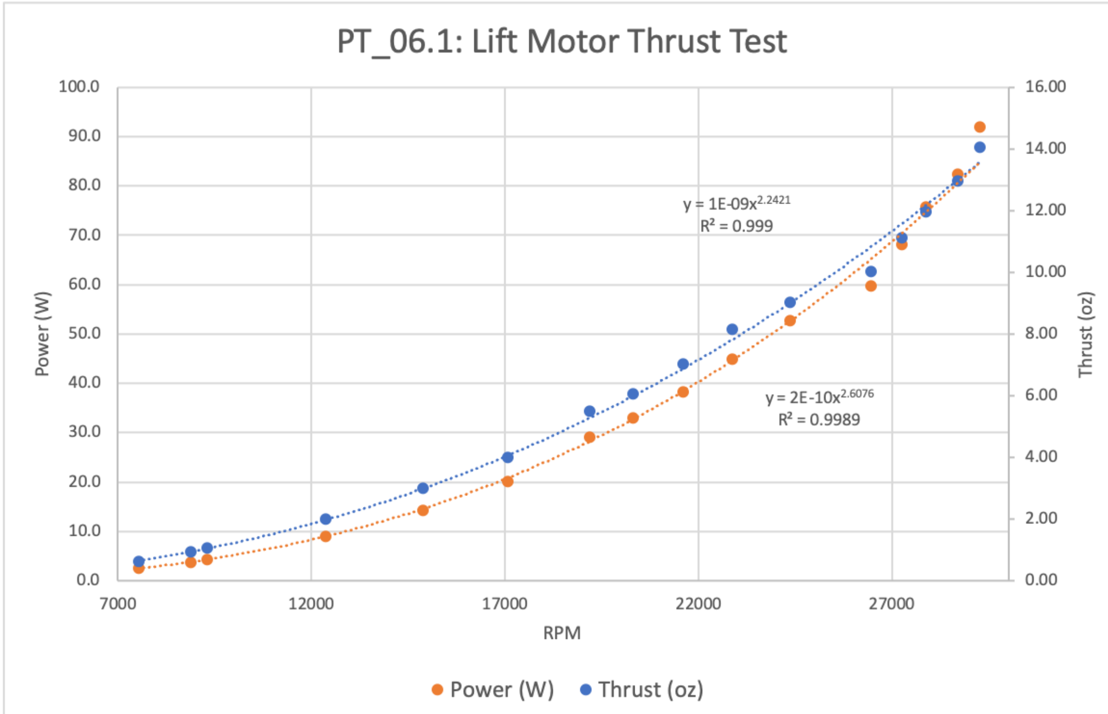
<table>
<tr><td rowspan="2">Test ID:
PT_06.1

Test Name:
Thrust Stand Testing

Related Requirements:
T4.10

Related Test IDs:
N/A</td><td>Objective and Tested Variables: Verify that the UAV airframe can withstand reasonably expected flight loads and measure motor power usage as a function of thrust. The test variable are the motor thrust, power usage, and RPM.</td><td>Reason for Test: This test is necessary to validate that the motor is capable of providing steady thrust for a given throttle input, and to measure the power output and RPM as a function of the propulsion assembly's thrust.</td></tr>
<tr><td colspan="2">Success Criteria: This test is considered successful if the motor's power usage at hover thrust is ±20% within expected power usage, and the maximum motor thrust is at minimum double the hover thrust.</td></tr>
<tr><td>Methodology</td><td colspan="2">A thrust stand with a built-in PWM generator will be used to monitor motor thrust, power usage, and RPM. The propulsion assembly is mounted on a thrust stand, and the ESC is interfaced with the thrust stand. As the thrust stand does not provide any means to store test data, the display on the thrust stand was video recorded.
1. Assemble the motor, motor hub, and propellers, then mount propulsion assembly to thrust stand. Inspect
2. Plug in ESC signal and power cables to the thrust stand then hook up ESC motor wires.
3. Hookup 3S test battery to the thrust stand and turn on the display. A red LED should be lit adjacent to the throttle. If it is not illuminated, check all connections and cycle power.
4. Begin recording thrust stand display.
5. When operating the thrust stand, do not stand adjacent to the propeller in case of propeller fracture. Slowly turn the throttle knob until 20 oz of thrust is observed. Target a thrust increase of 1 oz per second.
6. Upon reaching 20 oz of thrust, drive thrust input to zero then disconnect battery.</td></tr>
<tr><td>Possible Impacts</td><td colspan="2">If the motor is incapable of reaching the minimum thrust requirements, the ESCs or motors will likely need to be replaced to increase maximum power output. Otherwise, a degraded propulsion performance will have to be accepted and maneuvers must be restrained to compensate for the lower than expected thrust capability.</td></tr>
</table>

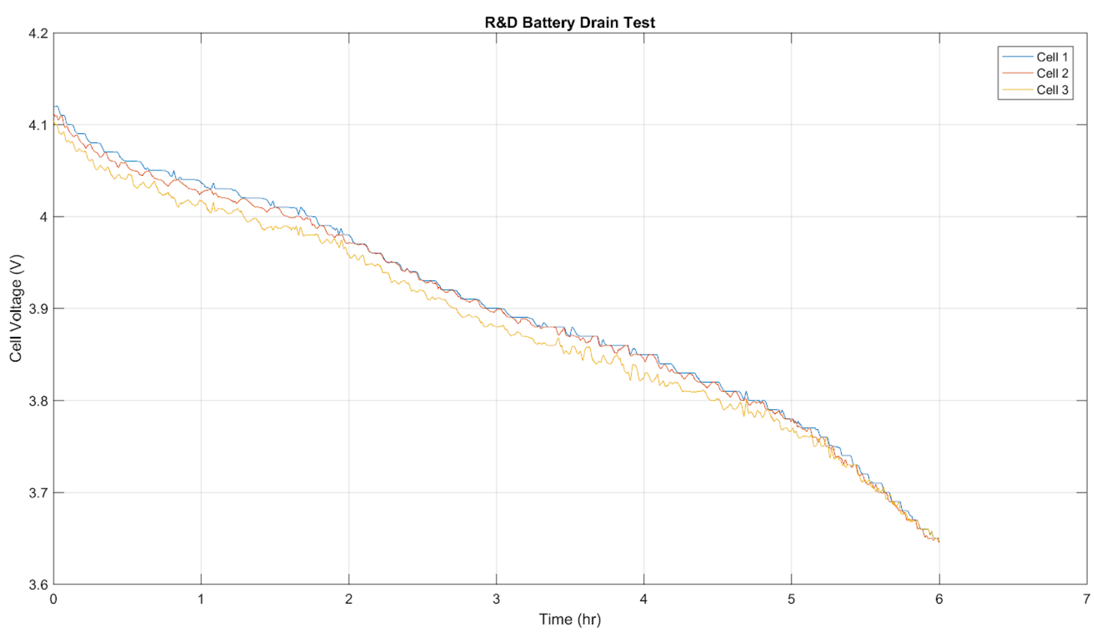
Results
Status: Complete



The data shows a nearly quadratic and x^3 regression for thrust and power respectively. These data values will be used to extrapolate to the full UAV: With a UAV weight equivalent of 40.5oz, split amongst 4 lift motors, RPMs of approximately 25,750 are required for sufficient thrust. This corresponds to a power consumption of about 60W per motor. The total power consumption during hover appears to therefore be around 240W. This produces a percent error from the expected value of power consumption of ~19.8%, which is within the decided bound for error. Therefore, the current UAV passes the thrust stand test. Additionally, the propulsion system was capable of meeting the thrust requirement of double the hover throttle.

6.4.11. Battery Drain and Power Testing - PT_07.1

Test ID: PT_07.1 **Test Name:** Battery Drain and Power Testing **Related Requirements:** T4.11 **Related Test IDs:** N/A	Objective and Tested Variables: Ensure the batteries used to power the UAV and R&D systems are capable of powering each system for a duration exceeding that of the entirety of the mission. The test variables are the UAV and R&D respective system on-times and battery cell voltages during power consumption.	Reason for Test: This test is necessary to ensure that all electrical systems on both the R&D and UAV systems have enough battery to operate throughout the entire mission timeline. This test will not only look at the energy capacity of the batteries, but also how the supplied voltage varies. The voltage difference between a fully charged and an empty LiPo battery is about 30% and it is important to make sure that all electronics and electrical actuators can operate at a reduced voltage.

	Success Criteria: This test if the R&D battery is capable of powering the system at standby for at least 4 hours. The test is successful if the UAV battery can power the UAV at hover for at least 8 minutes.
Methodology	R&D Battery Drain: 1. Wire up all R&D electrical components into their flight configuration. 2. Place a fully charged, 2,200 mAh 3S LiPo battery in the R&D bay. 3. Plug the balance connector of the R&D battery into a voltage divider circuit, such that the voltage of each cell can be continuously logged. 4. Turn on the R&D electronics with the main power switch. 5. Begin logging the voltage of each cell. 6. Turn off the system and stop logging when the overall battery voltage decreases below 9.6 V or if the test reaches 4 hours. UAV Battery Drain: 1. Put a new, 3,600 mAh 3S LiPo battery in the UAV. 2. Turn on the UAV, making sure a successful connection is made with a laptop running QGroundControl. 3. In QGroundControl, begin logging current and battery voltage. 4. Using an RC transceiver, bring the UAV to a hover. 5. Continue to hover the UAV until the battery voltage reaches 10.3 V, at which point the UAV should be manually landed on the ground.
Possible Impacts	Successful completion of this test verifies that the UAVand R&D power systems can power their respective systems well beyond the expected duration of the mission. Failure of this test indicates the need for a redesign of the power system, likely a larger capacity battery.
Results **Status:** In Progress	R&D Battery Drain:  The data above presents the decrease seen in cell voltage of the R&D battery over the course of 6 hours. As seen, the cell voltages were each measured at roughly 3.6 V after 6 hours of

	continuous power draw for the R&D system. This far exceeds the success criteria of 4 hours, thereby passing this test. This inspires confidence that the R&D system can withstand long wait times on the launchpad without concern for over-discharging the battery. UAV Battery Drain: UAV battery drain testing will be completed in the near future and will be submitted along with the rest of payload testing in the FRR Addendum.

6.4.12. Flight Reliability Confidence

As the test schedule outlined above continues to be completed in parallel with the construction of final payload components, a qualitative assessment of the payload's reliability and readiness for flight is in order.

Along with the formal testing described above, hundreds of hours have been spent performing developmental testing of various parts of the payload design. For example, while the R&D electronics were designed, many hours were spent ensuring that the embedded software controlling wireless communication between the R&D system and the GCS was free of bugs. This kind of testing usually occurs at the component level, ensuring that sub-systems and sub-system components function as they are designed. In the case of the R&D electronics, this meant rigorous testing of the wireless communication system, including hundreds of combinations of test cases. The entire payload system, with the exception of final GCS software, has been developed and tested to this level. The qualitative and quantitative data derived from this inspires a baseline level of confidence that the system is capable of performing reliably during the flight.

To achieve the maximum level of flight reliability confidence, individual subsystems and components must be integrated to demonstrate full system functionality. In the time remaining in the competition, integration testing involving the entire payload system will become the primary focus for this very reason. For example, a deployment system reliability test campaign will commence with the newly constructed payload to demonstrate and test the entire deployment sequence in environments realistic to what will be experienced during the mission. The summation of final integration testing and the verification of all payload requirements inspires confidence in the flight reliability of this design. The payload team looks forward to demonstrating these capabilities in Huntsville, Alabama in April.

6.5. Payload Construction

6.5.1. UAV Construction

The construction of the UAV involves numerous teams coming together to produce subassemblies that must fit together as one unified system. As such, the process of construction of the UAV required much communication to make sure that all components fit together as designed. In the end, the UAV's construction included very few changes; the combination of modularity as well as pre-defined tolerances in CAD allowed us to avoid fundamentally incorrect results. The UAV was built with ease of construction in mind, and a prototype had already been fit-tested earlier in the season, so the initial build process was surprisingly fast, only taking two total weeks to finish. For the rebuild of the UAV, the process was expedited to finish in under a single week, a testament to the functionality of the design and experience of the manufacturers.

6.5.1.1. Manufacturing of Components

The UAV owes its great manufacturability to its use of pre-made, modularized components, along with heavy use of 3D printed Polylactic Acid (PLA) structural members. As a break away from strategies used in previous years, the overarching usage of CAD allowed the machining of components to be universally understood and executed. The primary method of manufacturing was additive, utilizing the aforementioned PLA material. Three dimensional models are easy to convert into printable stereolithographic files on SolidWorks, and quickly printed within the same day on any accessible printer available to the team. The team extensively used printers at labs on Purdue University campus, as well as those owned by team members.

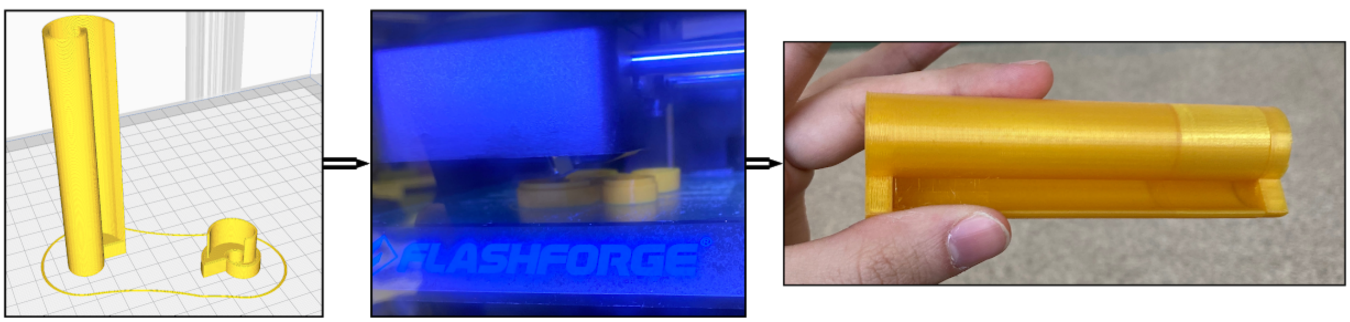


Figure 6.28: Additive Manufacturing Process, Slice (Left), Print (Mid), Assemble (Right)

Since the geometry of these computer-generated parts is pre-defined and digital, the only possible tolerance issues in manufacturing are those of the printers, which are typically within ±0.5mm. The main limitations of these parts are printability and strength. Any parts which need to be printed must have geometry which is conducive to to printing, so overhanging geometry on the build plate is avoided at all costs; as seen in Figure 6.28 above, the closed geometry of the ice mining scoop required a design that was capable of being printed without internal support material. In this case, splitting the part in two works perfectly. This comes at the cost of requiring material joints, which leads to 3D printing's next issue of yield strength. Since the printing material used is a plastic, its yield strength is typically around an order of magnitude less than most metals, so careful consideration must be used to make a part that will both print correctly and operate correctly.

For the parts, the main solutions found for this problem was an increase in wall thickness and internal infill reinforcement, as seen in the UAV design section for its legs. Additionally, to get prints to finish correctly, the designs for most parts remained as flat as possible, to allow for sufficient contact surface on the printers to maintain adhesion. An additional strategy employed was use of Carbon fiber infused filament, which increases elastic modulus (stiffness) at the cost of toughness. The majority of parts on the UAV which are intended to maintain rigidity during collision utilize this special filament, while parts intended for load-breaking use the more resilient, typical PLA.

While initial plans included use of Nylon 6 as a main structural material for both the UAV X-Wing Mechanism and central plates, the manufacturability of Nylon introduced some issues which caused a decision to be made to only Nylon for the X-Wing Mechanism. Available to PSP is Purdue University's Bechtel Innovation & Design Center, which for Nylon, had available either a waterjet method or laser cutting method. Due to time constraints and Bechtel personnel's uncertainty about Nylon in a waterjet mill, the parts were assembled 2-dimensionally in AutoCAD and cut on a laser printer. With the small design tolerances of the holes of the plates, this seemed to be a much more accurate method to prevent chipping. After machining however, it was observed that the laser cutter's ability to break all the way through the stock sheet was limited, producing only a set of UAV armatures which were in suitable condition for use. Meanwhile, the upper and lower plates were deemed unusable due to their persistent connection points with the stock sheet; the upper and lower plates have since been converted to Carbon fiber filament PLA. In the future, perhaps further experimentation can be done to find the optimal cutting settings and methods for Nylon. As an aside, multiple copies of each cut were made during this manufacturing day, which enabled the team to quickly rebuild the UAV after its destruction; this practice will be continued for logistical safety.

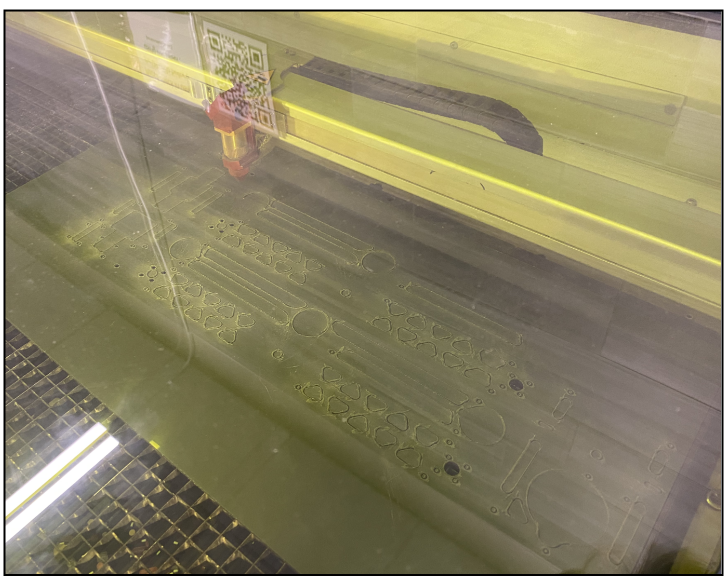


Figure 6.29: Nylon Stock Being Laser Cut at BIDC

As for the finished products, team members immediately noted the lower stiffness of Nylon versus even the simple PLA material used. However, since the UAV armatures were modeled in a 3-dimensional manner, an additional step of applying epoxy between upper and lower halves of each armature was required. Once adhered, the bending moment properties of the material increased significantly. The team concluded that, while Nylon has a much lower stiffness, it had a much higher toughness than PLA, meaning it could survive a direct impact with the ground without shattering; since the armatures are actuated far outwards from the UAV while in flight, this was deemed a beneficial feature. Through flight testing, the stiffness of the armatures was determined to be a non-issue, so the material was maintained.

6.5.1.2. Airframe Construction

Below is a description of the procedure for constructing the UAV's structural airframe. As stated before, the UAV was designed in a modular fashion, so while proper integration methods are required, the construction process may occur in a nonlinear manner. In cases where this rule is both followed or broken, it will be noted at the beginning of each subsection.

6.5.1.2.1. X-Wing Mechanism

The X-Wing Mechanism may be constructed without interaction with any electronic components other than the lift motors, so this assembly can be prepared any time before the final integration of the UAV subassemblies. The construction of the X-Wing is a fairly quick process, since most components are constrained to single axis. This assembly requires a 7/16" combination wrench and either a set of gripping pliers, or an additional crescent wrench.

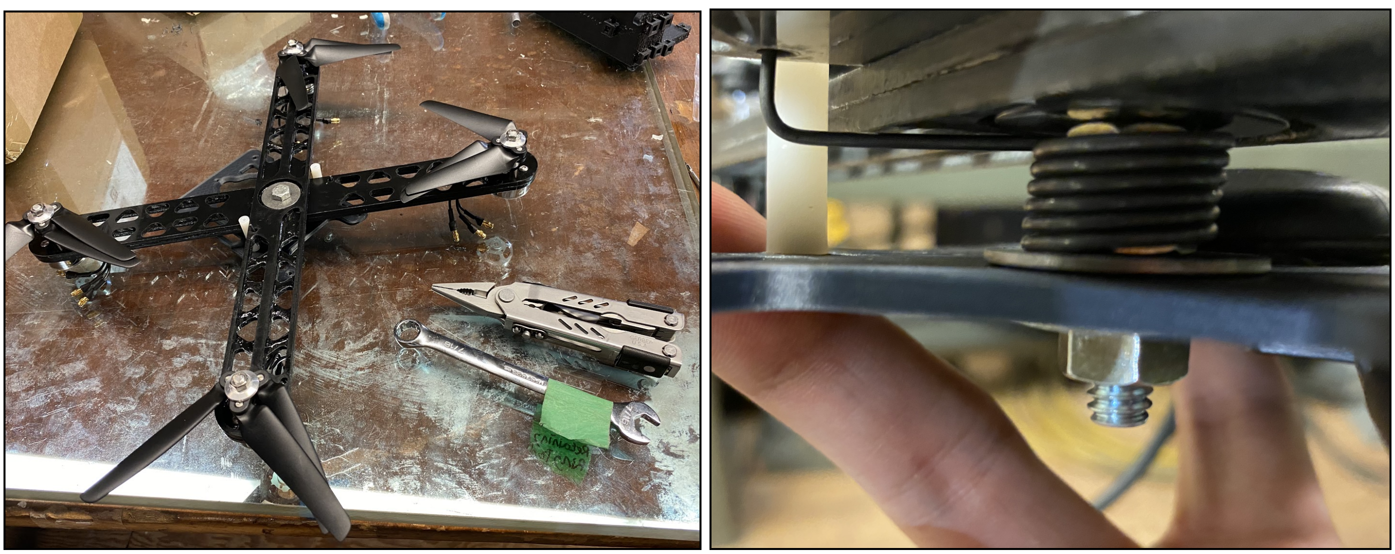


Figure 6.30: Assembled X-Wing Mechanism w/ Limiting Standoffs (Left), Axial Closeup (Right)

1. Before assembly, the 4 motors were attached at the ends of the armatures. Since the armatures are identical, it does not matter which side the motors are attached on either arm, as long as they are attached on the same side on a single arm; essentially, if both motors are attached to the top of one armature, the other two should be attached to the bottom of the other armature.

2. The X-Mechanism central ¼”-20 bolt provides the central attachment point of the assembly. First, a load distributing washer is inserted onto the bolt, followed by both armatures, oriented with their bottom sides touching.
3. The next step determines the tightness of the assembly, so it is essential that the correct desired amount of friction is found before continuing: After two buffer washers, a nut is positioned in place and tightened against the washers until play between the armatures ceases. At this point, the nut may be backed up with a second nut and counter-tightened; tightening these two nuts together makes a rigid frictional constraint that will hold its position under flight forces until removed with the right tools.
4. The following step was also executed with caution. The insertion of the torsion spring into their defined holes opens up the possibility for spontaneous injury. Surrounding team members were advised not to approach the assembly while this step was being completed. To lower the chances of this occurrence, the next washer is often loaded simultaneously.
5. The upper electronics plate may now be attached with a washer on either side for load distribution. A nylon lock nut is used and tightened against the central bolt head to its end. Since the counter-tightened nuts will not move, the force is distributed entirely through the bolt and upper plate only.
6. After aligning the X-Wing Mechanism to its proper open direction, two nylon standoffs may be attached into their slots in desired positions determined through integration testing. These are easy to untighten by hand at any time, but should not be loose enough to slide while in flight.

6.5.1.2.2. *Structural Construction*

The assembly of main structural components of the UAV mostly involves attaching electronics components to the lower plate and attachment of the legs onto the lower plate. The preparation of electronics components for assembly can be found in the UAV electronics section below. Small allen wrenches and phillips drivers will be useful for this stage, along with gripping pliers.

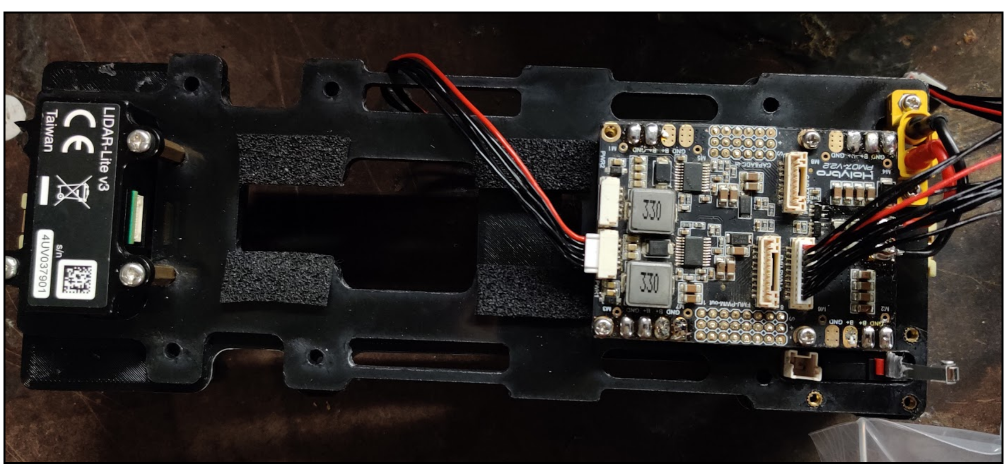


Figure 6.31: Main UAV Structural Skeleton

1. Electronics components may be attached to the lower electronics plate, including the power distribution board, Pixhawk 4, camera, and LIDAR. The pixhawk may be attached with double-faced adhesive.
2. The lower electronics plate may be attached to the lower electronics plate via two forwards connections.
3. The four aluminum standoffs may be attached to their associated positions below the upper electronics plate. The two rear standoffs will be fastened through the legs and lower plate.

6.5.1.2.3. Airframe Integration

Once the X-Wing Mechanism and Ice Mining subassemblies are complete, the remaining components of the UAV may be integrated on the finished structural frame. Special care should be taken when two subassemblies are attached, as it will likely obfuscate further adjustments to previously assembled structures. Required for this attachment procedure, once again, is a set of allen wrenches, a pair of gripping pliers, and a small combination or crescent wrench. When this integration process was completed, the UAV's mass was measured at about 40.5oz, or about 2.5lbs weight.

Figure 6.32: Overall Finished UAV Assembly

1. Assembly of the propellers includes tightly mounting them to X-Wing via screws and bolts. The stock attachment method of the lift motors was deemed insufficient, since it relied on frictional tightening which could not be adjusted without disassembly. The final UAV uses an allen screw to provide this tightening. Meanwhile, a decent amount of tightening should be applied between the propeller bushing and retaining nut.
2. After this, the ice mining system is mounted onto the legs using the screw locations that were printed for their mount. This is done with a nylon threaded rod and a small lock nut on either end. Hand tightening was deemed sufficient for this operation.
3. The Raspberry Pi can be mounted onto the upper electronics plate and connected to its associated Pixhawk and ice mining connection points. The remaining electronics components are integrated via high quality adhesives. This includes the radio and the GPS. These components should be attached and plugged in before the upper and lower plates are connected, or else their ability to be wired will be lost.
4. Once the wiring is completed and checked, the upper and lower plates are connected via bolts running through the upper aluminum standoffs.
5. The battery's wires should maintain a length that will not contact the ground before the UAV's legs. To insert the battery, feed the wire through aperture in the case first. Then, slide the battery into the case so that it fits snugly. Secure the bottom by looping zip ties through the slits on the sides of the case.

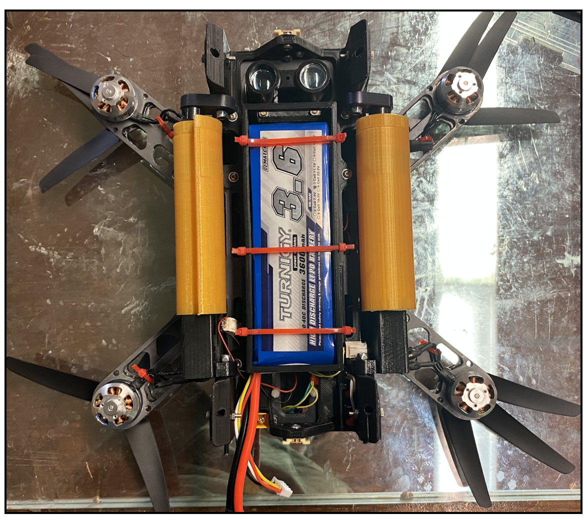


Figure 6.33: Loaded UAV Battery

6. The final step is slide over the protective Aero Package and bolt it into place. Special caution should be made in selecting the right length bolts for this connection point. While the team used available fasteners, they were long enough to create a point of danger near the battery connection hub; removing the battery wires too quickly in the vicinity of this bolt end could result in injury to either the battery wires or the user. It is suggested to use either the shortest functional bolt for this purpose and/or apply a buffer of hot glue in the area.

7. Now, the UAV is complete and may be inserted into the R&D system. See the Rocket Airframe and UAV Integration subsection of the R&D construction section for this process.

6.5.1.3. Ice Mining

Each ice mining procurement system is constructed in the same manner. This process works fairly linearly and then integrated into the UAV.

6.5.1.3.1. *Construction*

1. To begin construction for the ice mining system, several parts need to be 3D printed. These parts were the scoop, scoop cap, motor housing, mounts, and the shaft.
2. Next the scoop cap was superglued to the inside of the scoop to secure the two together
3. The rods that hold the mounts were cut to be three fourths of an inch longer than the width of the airframe legs, just enough to place the mounts and a nut on either side of the leg.

6.5.1.3.2. *Integration*

1. Integration with the airframe starts with placing the motor inside the mount mount, then connecting the mount through holes on the legs of the airframe with a rod and nuts to secure it.
2. Next, the scoop was placed on the end of the motor.
3. Then, the shaft was placed in the non motor end of the scoop and through the mount for the corresponding side. Between the scoop and the mount there is a shaft collar that is placed on the shaft and tightened to make sure that the shaft does not move.
4. The mount that doesn't have the motor is attached to the legs of the airframe with a rod and nuts to secure it together.
5. Wires were soldered to each of the DC ice mining motors and to the relevant pins on the TB6612FNG motor driver.
6. Connections between the Raspberry Pi, the motor driver, and the motors were made using a combination of metal "bullet connectors and plastic JST connectors.

6.5.2. GCS Construction

Construction of the GCS involved the installation of the three displays, wiring and mounting of the speakers, fabrication of both the CPB and PDB PCBs, mounting and wiring of all LEDs, buttons and switches, then finally the mounting of all PCB and miscellaneous hardware.

6.5.2.1. PCB Fabrication

Fabrication of the PCBs involved installation of SMD and through-hole components then checkout testing to ensure continuity. All SMD components were soldered using solder paste, while through-hole components used solder wire. Firstly, the SMD resistors/capacitors for both boards were soldered followed by installation of power electronics. Installation of power electronics was followed by installation of terminal blocks and JST connectors. Before the microcomputers and other sensitive electronics were installed, power electronics were tested to ensure correct voltage and current requirements could be met. Finally, inserts for the microcomputers were soldered such that the microcomputers may be removed and replaced. Seen below in Figure 6.34 are the fabricated GCS PCBs.

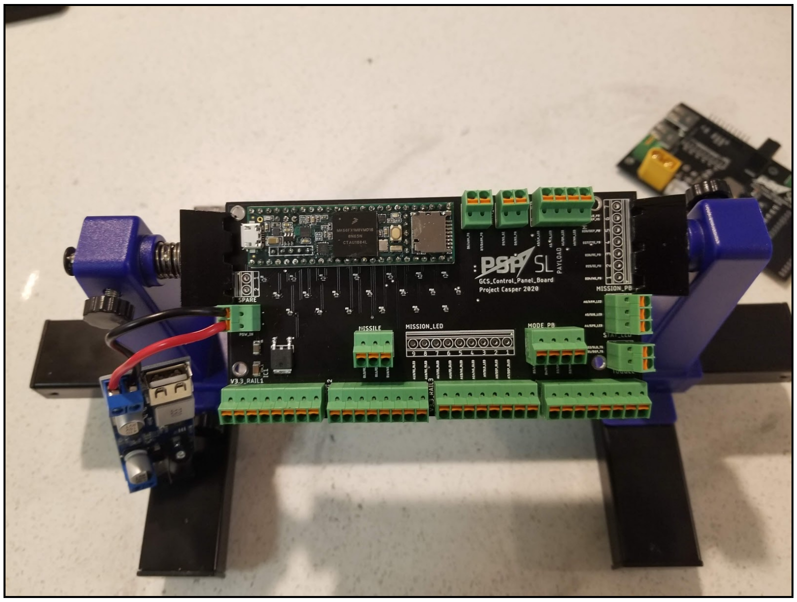


Figure 6.34: GCS Control Panel (Foreground) and Power DIstribution (Background) PCBs

6.5.2.2. GCS Hardware Construction

The majority of the GCS construction involved the mounting and wiring of LEDs, switches, buttons, and PCBs. Beyond electrical work, construction work involved panel mounting and LCD display installation. The process is detailed below.

1. Construction began with the installation of all switches, LEDs, and buttons. All LEDs were mounted with LED plastic inserts.
2. Wires were routed to and from the control panel board to any associated electrical hardware. The control panel board was then mounted to the control panel.
3. The Raspberry Pi and power distribution PCBs were mounted to the control panel.
4. The LCD panels were then installed followed by its wiring to the power distribution board and RPi 4 computer.
5. Speakers were then installed on the display panel, then wired to the amplifier on the power distribution board.
6. Finally, the control panel and display panel were installed to the protective case. The finished product (minus cable sleeving and a few miscellaneous components) can be seen below in Figure 6.35.

Figure 6.35: Finished GCS construction.

6.5.3. R&D Construction

6.5.3.1. R&D Preassembly

6.5.3.1.1. Initial Manufacturing

The first step in constructing the R&D bay is the manufacturing of the metal and 3d printed components. The two primary machined components of the system are the main parachute bulkplate, and the linear motion rods. These were each milled at Purdue's Bechtel Innovation & Design Center, as seen in figure 6.36.

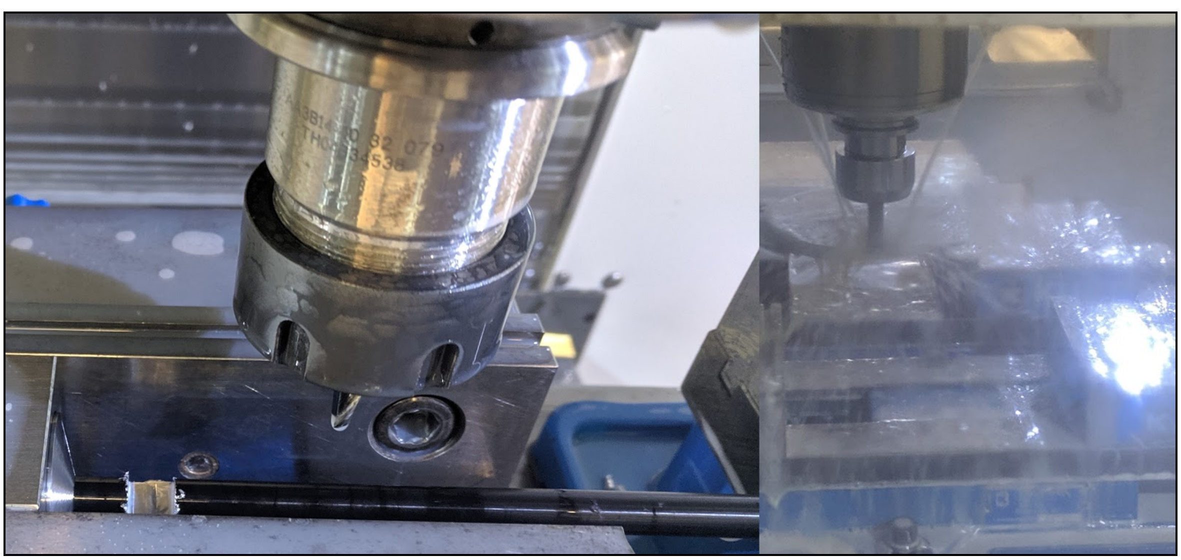


Figure 6.36: Milling the Linear Motion Rods (Left), and the Main Parachute Bulkplate (Right)

3D printed components are the following: Forward and Aft Locking Bulkheads, Forward and Aft Pivot Plates, the Lead Nut Standoff, the Payload Sled, the Airframe Hole Guides, and the Electronics and Control Housing. Some prints were post processed by tapping and drilling out certain holes. These 3d prints can be seen throughout the following pages.

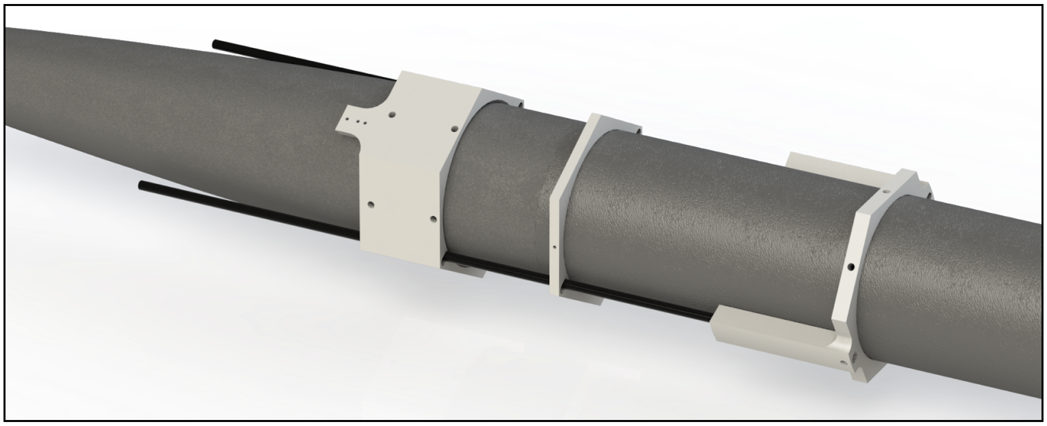


Figure 6.37. Hole Drilling Jig for Nose Cone and Upper Airframe

To integrate the payload into the rockets airframe, numerous holes were drilled into the fiberglass Nose Cone and Upper Airframe. In order to guarantee the proper placement of these critical features, 3D printed hole guides were created and attached to the airframe. The axial spacing of these guides was in turn guaranteed by reusing the linear motion rods notches.

Once all components have been manufactured, construction begins. This process is done in specific modules to allow multiple subsystems to be assembled simultaneously.

6.5.3.1.2. *Aft R&D Subsystem Assembly*

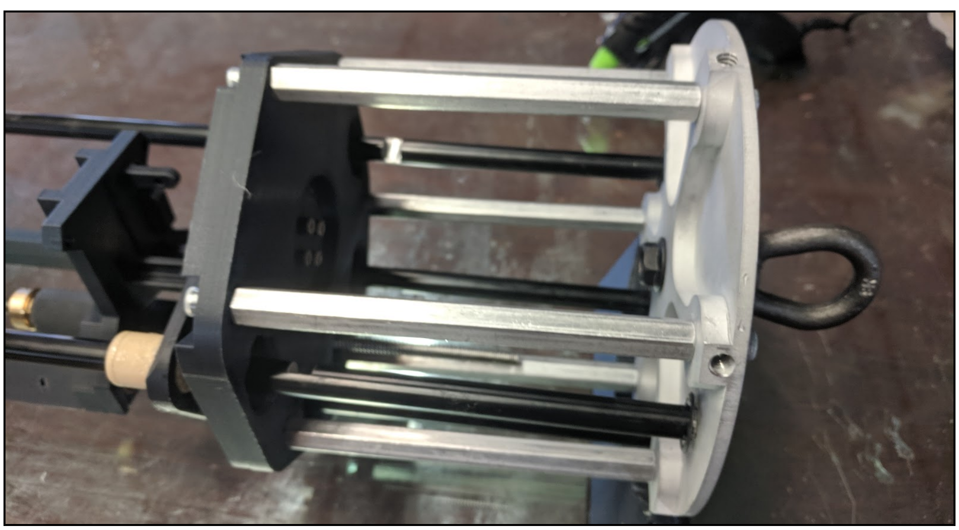


Figure 6.38: Aft R&D Subsystem

1. The 4½” aluminum standoffs and parachute eye nut/bolt are attached to the Main Parachute Bulkplate.

2. Attached Aft Locking Plate to standoffs.

   Here it was noticed during construction that the heads of the standoff screws would collide with the pivot plate in the next step, so the screws were later replaced with button head screws.

3. Using epoxy the Igus Linear Motion Bearings were adhered to the Aft Pivot Plate.

   To ensure that the bearings were straight, this step was completed simultaneously to step 4 in Forward R&D System, and the Linear Motion Rods were run through both sets of bearings. This guaranteed that the bearings would align themselves to the most aligned (therefore lowest friction) orientation.

4. The Left Handed Lead Nut was screwed into the Lead Nut Standoff, which was then screwed into the Aft Pivot Plate.
5. The Left Handed Lead Screw is then screwed into the Nut, with length later adjusted in final integration.
6. Using CA (CyanoAcrylate) adhesive the Steel Pivot Bearing was attached to the Aft Pivot Plate shaft, and into the Aft Locking Bulkhead hole.

   While the bearing is not load bearing in the axial direction, the CA adhesive prevents the system from falling apart during assembly. This was initially done using HMA (Hot Melt Adhesive), but the wicking capabilities and increased strength of CA made it a more reliable choice.

6.5.3.1.3. Forward R&D Subsystem Assembly

The Forward R&D Subsystem is the most complex part of the R&D System, so must be assembled in a very particular order. While the prediction of this order was attempted before construction began, much of it was found through trial and error.

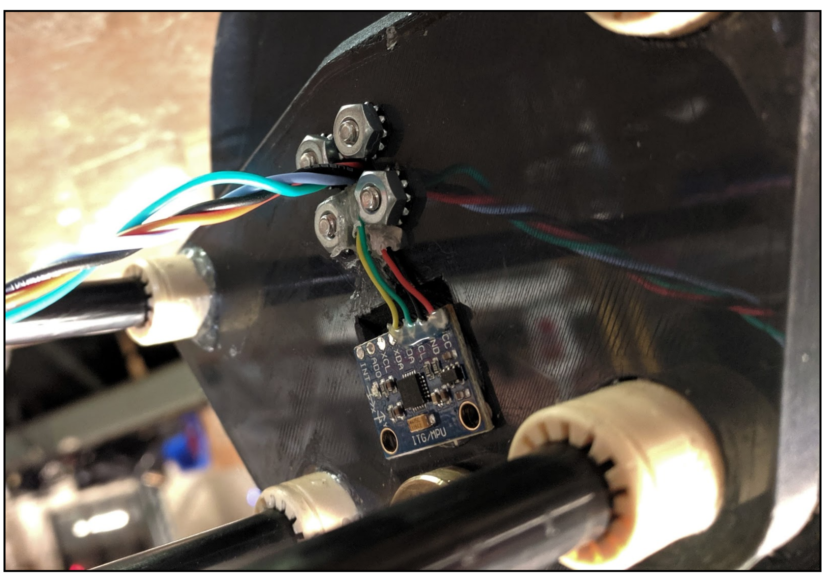


Figure 6.39: Installed GY-521 and Linear Motion Bearings

1. Using HMA, the GY-521 Gyroscope was attached to the Forward Pivot Plate, with it's wires passed through the hole in the pivot plate for later crimping.
2. Using CA Adhesive, the Steel Pivot Bearing was attached to the Forward Pivot Plate.
3. The brass worm pinion was screwed onto the Forward Pivot Plate, ensuring that the GY-521 wires pass through the center of the gear.
4. Igus Linear Motion Bearings epoxied into Forward Pivot Plate.
    Done in tandem with step 3 in the Aft R&D Subsystem.
5. Right Handed Lead Nut screwed into Forward Pivot Plate, Right Handed Lead Screw threaded through nut.
6. The limit switch was loosely screwed to the Forward Locking Bulkhead. Nuts were placed on the limit switch side of the plate to allow for easier adjustment.
7. Using HMA and screws to aid with alignment, the square ¼"-20 nuts were installed around the perimeter of the Forward Locking Bulkhead
    Originally these nuts were hexagonal, but during assembly it was discovered that they were prone to spinning inside the slots they were installed in. The additional side length of the square nuts prevents this problem.

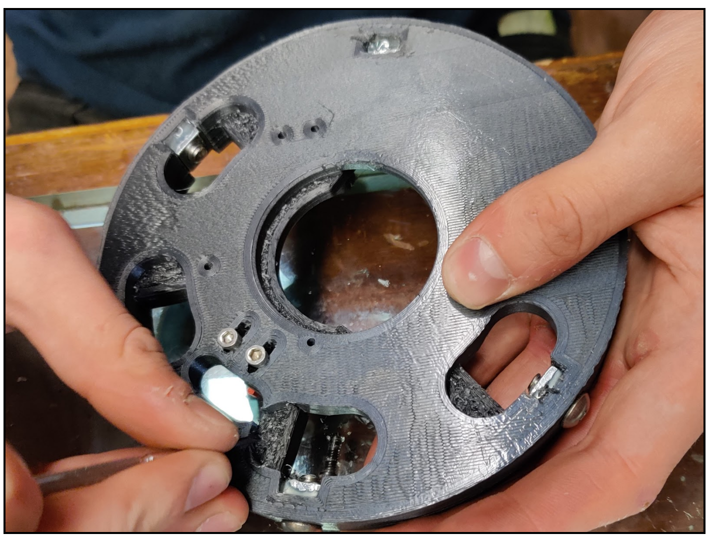


Figure 6.40: Installation of Square Nuts and cleaning of 3d print for Forward Pivot Plate

8. Toggle switch and status LED were press fit into Forward Locking Bulkhead
    Often in assembly, the mount for these components would break during assembly, so the mount is now substantially thicker and stronger to prevent these breaks.
9. Worm screw axle placed into pocket opposite the orientation servo, the worm screw is slipped over the shaft but not tightened.
10. Coupler attached to orientation servo shaft and screw orientation servo into Forward Locking Bulkhead, ensuring that the worm screw axle is inside the coupler. Screws tightened.

Various changes have been made to the Forward Locking Bulkhead, easing this assembly process. These changes include the addition of the axle pocket, the use of slots for mounting the servo and additional clearance under the servo.

11. Rotating the Aft Pivot Plate to allow for engagement in the worm gear set, the Steel Pivot Bearing was inserted into the hole in Forward Pivot Plate. This was then adhered using CA adhesive.
12. Electronics and Control Bay was prepared for installation by soldering SMDs and headers to the R&D PCB.
13. PCB and Stepper Motor Driver attached to Electronics and Control Housing.
14. Electronics and Control Housing screwed onto Forward Locking Bulkhead using ball head hex drivers.
15. All wires present cut to the appropriate lengths, then crimped with headers to attach to the board. These wires were then zip tied in place to prevent them from getting caught on the many moving parts in the forward R&D Subsystem.
16. All screws tightened.

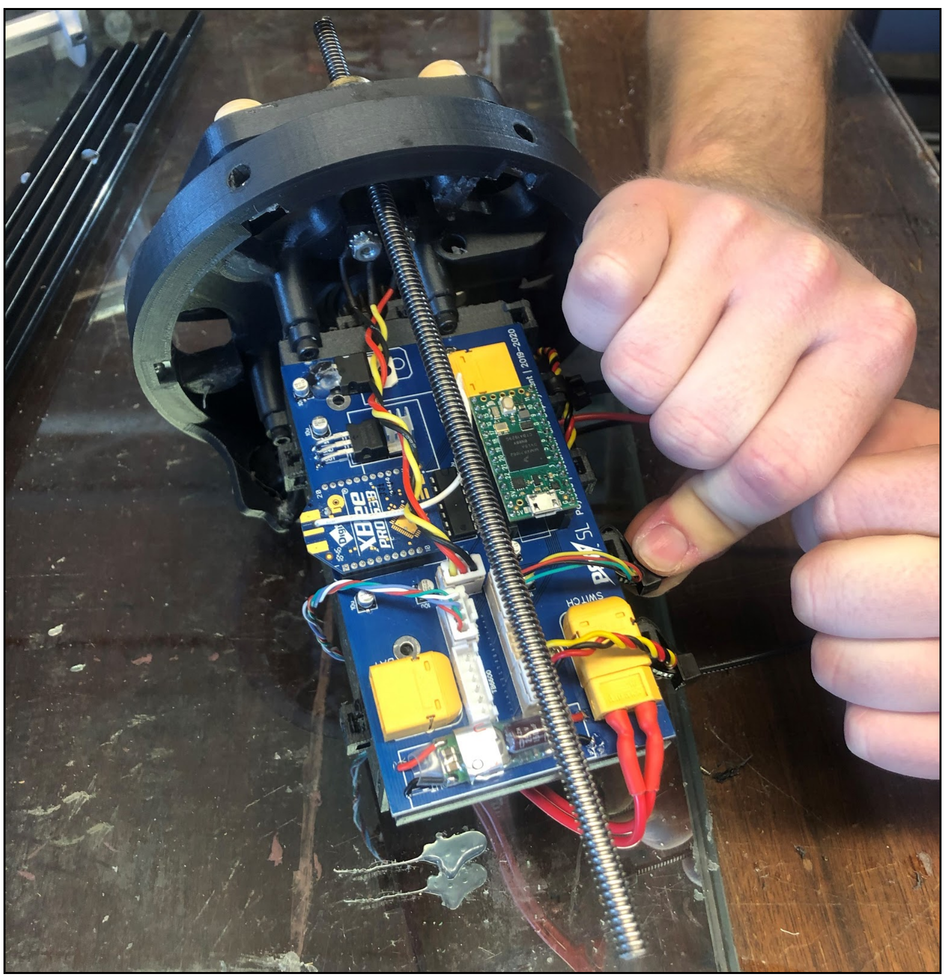


Figure 6.41: Wiring the Electronics Bay

6.5.3.1.4. Sled Subsystem Assembly

1. The Sled was assembled by first adhering Sled Shafts to End Caps with plastic bonding adhesive.
2. Brass Linear Bearings were coated in adhesive and inserted into Sled Shafts. Alignment was ensured by inserting the Linear Motion Rods through the bearings while the adhesive cured.
3. Guide Rails installed onto End Caps with CA adhesive.
4. The racks and pinions were prepared by attaching the pinions to the servo.
5. The servos and racks were all installed using fasteners, then rotated to find the maximum range. The PWM values corresponding to the upper and lower bounds were then noted to be used in programming.
6. The dual shaft stepper was installed and its rigid couplers are attached.

   The couplers have been made rigid as it was realized during construction that the flexible couplers were prone to expanding under the systems substantial loads.

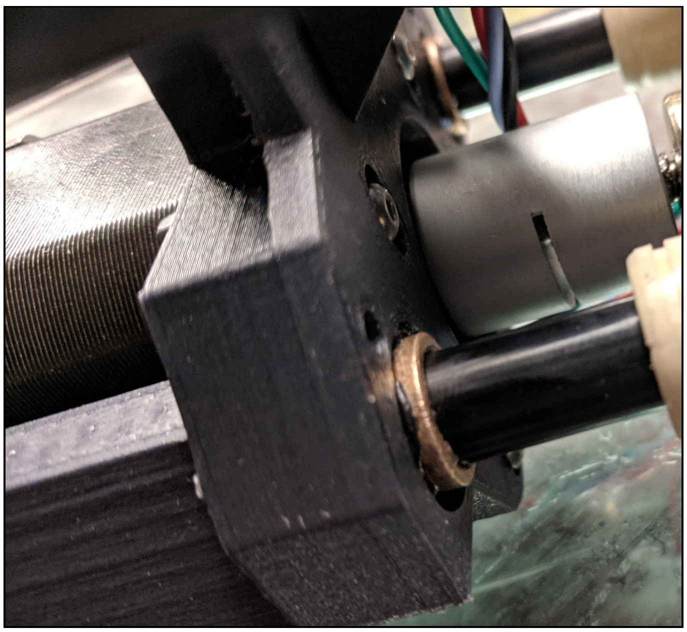


Figure 6.42: Forward end of UAV Sled installed on Linear Motion Rods, showing Stepper Motor, Rigid Coupler, and Linear Bearings

6.5.3.2. R&D Integration

1. The wires from the sled servo and stepper motors were passed through the center hole, cut to length and crimped to allow connection to the PCB.
2. Once all wires were in place, all wires were zip tied to the E&C Housing, ensuring clearance around all moving parts.
3. Lead Screws were rotated until approximately 5 inches stuck past the Aft Nut, and 1 inch past the Forward Nut. These would be adjusted to exact positions later in the process.

4. The 4 Linear Motion Rods were installed in the Forward Pivot Plate's Linear Motion Bearings. The sled was then installed on the lower two rods, ensuring that the Right Handed Lead Screw entered the stepper motor's forward rigid coupler.
5. The Aft Subsystem was integrated by sliding the Linear Motion Rods through the Aft Pivot Plate's Linear Motion Bearings, ensuring that the rods pass through the holes in the Aft Locking Bulkhead, and the lead screw enters the stepper motor's aft rigid coupler.
6. In order to ensure proper distance between subsystems, the Lead Screw stick out was determined from CAD and the physical system was adjusted to match. The process consisted of attaching the Forward Lead Screw to the stepper motor, rotating until the proper distance is reached, then detaching the lead screw and repeating for the Aft Lead Screw. These distances were: 1.37" between the Forward Pivot Plate and the Sled, and 1.6" between the Aft Pivot Plate and the Sled. The lead screws were then attached and tightened
7. Retaining rings were then attached to the ends of the Linear Motion Rods.
   The official installation tool for the rings was prohibitively expensive, so a wrench was used instead. (Figure 6.43)
8. Confirm that all screws are tightened, wires are the correct lengths, retaining rings are attached, and there appear to be no mechanical interferences.

Figure 6.43: Installing Retaining Rings at the Aft end of the Linear Motion Rods

6.5.3.3. Rocket Airframe and UAV Integration

After the R&D has passed all testing and is confirmed to be capable of performing its duties of unlocking, expansion, and orientation, preflight integration begins. This requires the completion of the UAV assembly, as described in the UAV Construction section above.

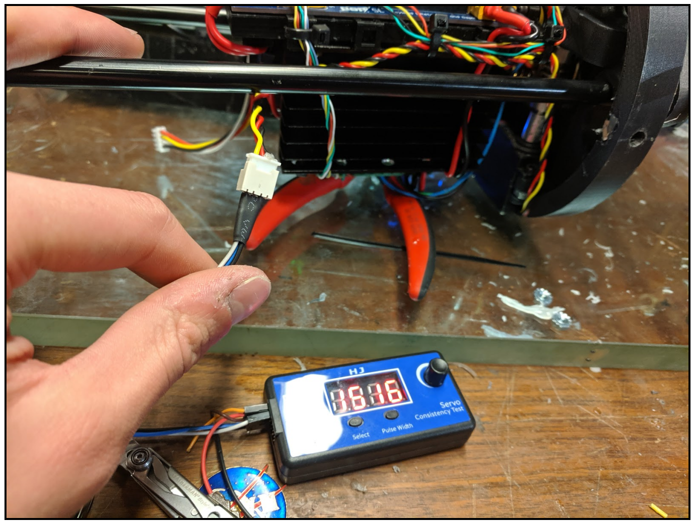


Figure 6.44: Servo controller attached to Orientation Servo Cable

1. UAV is placed on the sled, ensuring that the front of the drone (visible as the slanted face of the Aeroshell) is facing the Forward end of the R&D System. The guiding sliders at either end of the UAV should fit into the end slots in the sled.
2. While one assembler held the UAV's X-Wings in place, another rotated the retention servos ensuring proper engagement with both the X-Wing pin holes and the Aeroshell interface points. Once this step is complete, the UAV is secure within the R&D system.

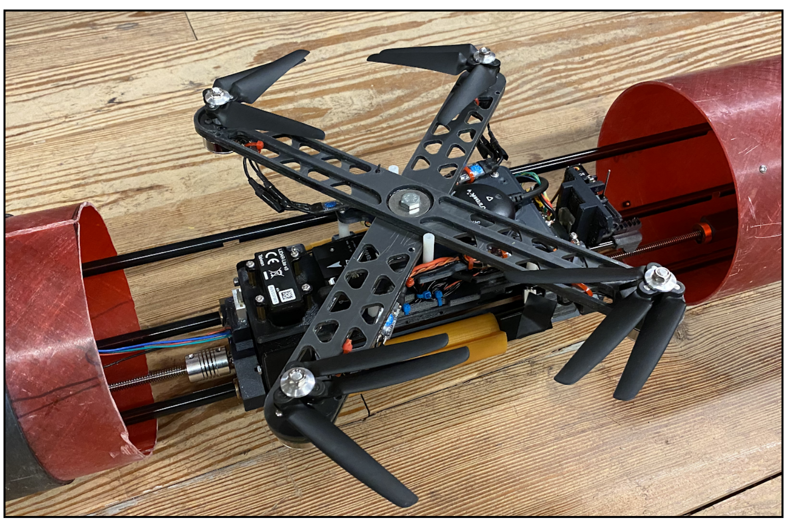


Figure 6.45: UAV Installed In R&D Sled w/ Semi-Couplers Installed

3. Using a handheld servo controller, the Orientation Servo was rotated to engage the Linear Motion Rod's notches with the Forward and Aft Locking Bulkheads.

   This task generally required multiple attempts to ensure that all notches engage simultaneously.
4. Using the servo controller, it was ensured that the Unlocking Limit Switch is properly triggered by the Right Handed Lead Screw.

If this is unsuccessful, the switch is adjusted by loosening the nuts, shifting the switch, and retightening.

5. The Integrated Payload System was then attached to the Nose cone using pre-drilled holes, ensuring that the Status Led and R&D Toggle Switch line up with their access ports.
6. After ensuring that the low profile nut lines up with the position closest to the sled, the 2 Semi-Couplers were installed.

   It was discovered that due to tolerance stack up, clearance apparent in the CAD model of the system was not present in actuality, so one of the nuts had to be ground shorter than the rest.

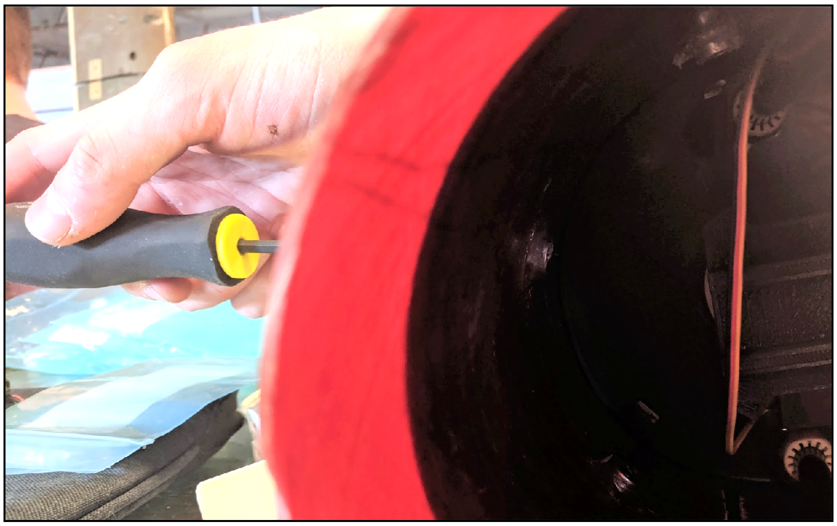


Figure 6.46: Attaching the Semi Couplers

7. After the R&D is integrated with the Nose Cone, it was partially slid into the Upper Airframe and the 2 Cam Nuts were installed.

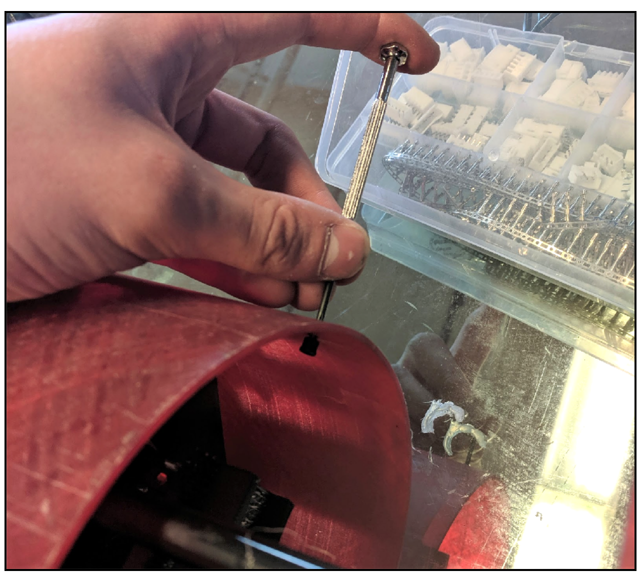


Figure 6.47: Installing a Cam Nut

8. Once the Cam Nuts are installed the Upper Airframe must be attached to R&D. This is the last time that R&D is accessible, so all assembly aids must be removed and engagement between the Aft Locking Plate must be confirmed.
9. The Upper Airframe was finally screwed into the Main Parachute Bulkplate, completing construction.

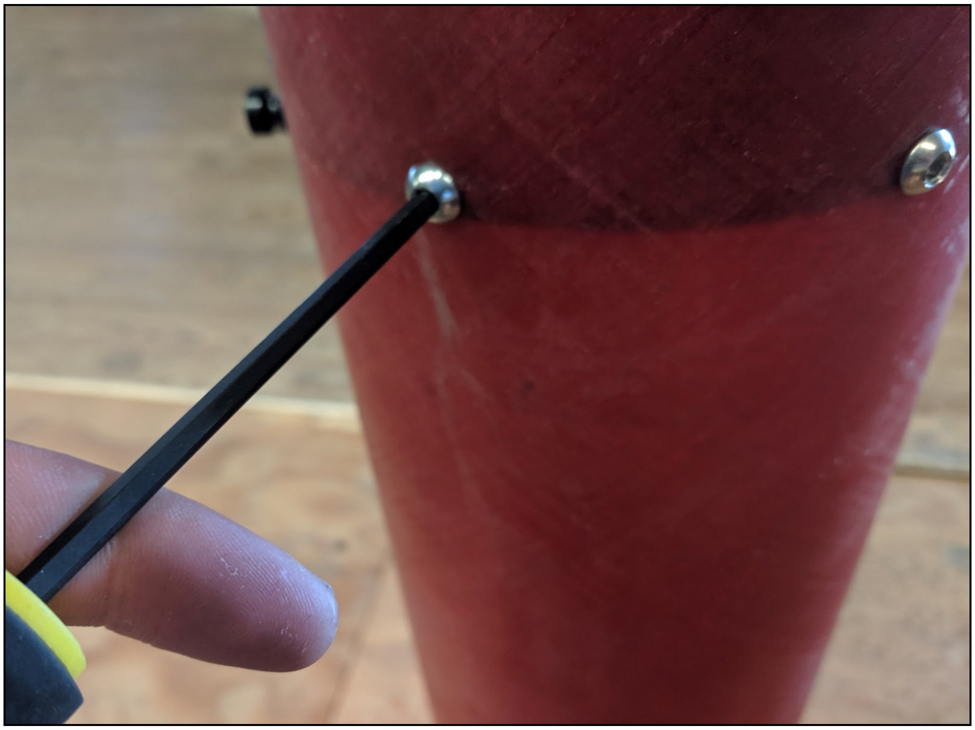


Figure 6.48: Attaching the Main Parachute Bulkplate to the Upper Airframe

6.6. Payload Demonstration Flight

The Payload Demonstration Flight was attempted on February 15, 2020. Unfortunately, due to the ballistic descent of the launch vehicle, the payload was destroyed. All indications suggest that the R&D system performed as intended up until the launch vehicle's impact with the ground. A future Payload Demonstration Flight is scheduled for March 7, 2020. A full write-up about the payload's performance during this flight will be provided in the FRR Addendum submitted in March 2020.

7. Team Safety

Critical to each successful launch is the safety and wellbeing of all involved, be they team members or passive spectators. Creating a safe launch environment consists of 3 key elements: having a consistent and predictable plan for launch, understanding the risks associated with said launch, and preparing and implementing plans to mitigate such risks. Not only do these decrease the likelihood of injury during launch, but they also increase the likelihood of a successful flight: predictability of a launch lends itself to repeatability; understanding the ways a launch can fail lends itself to preventing failure.

7.1. Operational Procedures

In preparation for actual launch procedures, checklists have been created to maintain continuity of launch operations, to alleviate possible ambiguity in launch operation, and to ensure maximum personnel safety in any contingency. Alleviation of such conditions is critical not only to an efficient launch operation, but also a safe launch: continuity means predictability, and predictability not only reduces the number of launch elements that can go awry, but also allows bystanders to recognize and prepare in the unlikely and unfortunate event that the launch does go catastrophically wrong. In addition, the creation of these checklists allows the team to create contingencies against worst case scenarios, namely misfires or unintended ballistic trajectories. While there is no way to truly abate the danger associated with the latter, preparation and the creation of a contingency is the best method for reducing the risk of tragedy.

7.1.1. Before Launch Day Checklist

Actions to be performed before travel to launch site

- Follow packing checklist to ensure all required items are brought to launch site (See Appendix B)

Actions to be performed day before launch

- Charge avionics batteries and backup batteries
- Charge payload batteries and backup batteries
- Check altimeters for continuity and operation
- Avionics preparation
  - On each threaded rod, screw on two hex nuts so that there is about one inch between the bottom of the first hex nut and the bottom of the threaded rod. Place a washer on each threaded rod.
  - Slide the drogue bulkhead facing down onto the threaded rods, then place another washer and more two hex nuts onto each one, touching the bulkhead.
  - On one threaded rod, screw on two more hex nuts so that there is about one inch between the bottom of the first hex nut and the top of the previous hex nut. On the other threaded rod, screw on two more hex nuts so that there is about 2.5in between the bottom of the first hex nut and the top of the previous hex nut.

+ Slide on the altimeter sled with the battery compartments facing up so that each side is touching the hex nuts just placed on the threaded rods. Slide on the battery guard on top of that, then the secondary payload electronics sled, then two more hex nuts onto each threaded rod so that they are touching the payload sled.
+ Cut the fingertips off of four fingers of a nitrile glove. Measure out 2, 3, 5, and 6 gram quantities of 4FG 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 cable ties.
+ Insert the 2 and 3 gram black powder charges into the corresponding black powder canisters on the drogue bulkhead and the 5 and 6 black powder charges into the corresponding black powder canisters on the main bulkhead. Pack tightly with fireproof cellulose insulation and seal with masking tape. Strip the ends of the lighters and screw them into their corresponding terminal blocks.
+ Attach the Telemetrum and RRC3+ Sport altimeters to their corresponding set of mounting posts using nylon altimeter mounting screws. Screw four wires into the the drogue and main terminals of each, but do not connect them to the terminal blocks on the exterior of the bulkheads yet.
+ Place the 3.7V LiPo battery and 9V alkaline battery with battery connector attached into their respective compartments in the altimeter sled, but do not connect them to the altimeters yet. Tape over the ends of the 9V battery connector with masking tape to prevent shorting.
+ In each shock cord, make three loops (one on each end and one in the middle). For every 10' of shock cord, make one bundle of z-folds and tape it together with masking tape. Attach large quick links to every loop. 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.

7.1.2. Launch Vehicle Preparation

General Safety

+ Ensure that at least two people are using this checklist to prep for launch
+ Ensure that a trained Range Safety Officer is present
+ Have first aid equipment and at least one phone available for use nearby
+ 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
+ Have adequate fire suppression equipment available for use nearby

- Ensure a fire blanket has been placed under the pad if conditions at launch are dry enough to require it
- Inspect personnel for Pocket Safety Document possession and ready accessibility

NOTE: Payload preparation, Launch vehicle preparation, and Avionics preparation can all be done concurrently unless otherwise stated.

QUALITY WITNESS NOTE: Quality witnesses will be responsible for a maximum of 1 witness, witnessing a completed part with which they have had no involvement in the onsite construction. Upon final assembly, they will be responsible for answering if a step has been completed and witnessed.

Payload Preparation

- **Prepare the UAV***
  - Install LiPo battery
  - Test X-Wing folding action and inspect springs for visible distortion
  - Check UAV battery level. Battery voltage shall be no less than 12.1V
  - Check RC radio battery level. Battery voltage shall be no less than 7.2V
  - Verify that valid SD card is installed in FCC and RC transmitter
  - Power vehicle on. Verify that vehicle status lights and beep codes indicate no errors when plugged in to GCS
  - Verify low accelerometer bias
  - Verify correct vehicle configuration file is loaded
  - Verify working camera stream between vehicle and GCS
  - Verify working telemetry stream between vehicle and GCS
  - Verify correct safety settings are installed on the vehicle
  - Power vehicle down
  - **QUALITY WITNESS:** Inspect UAV preparation for the following. If any of the following are missing or damaged, halt launch procedures and direct attention to the appropriate authority. NOTE: Appropriate response to any irregularities will be determined by team leads
    - Inspect for presence of:
      - Ice mining assembly
      - LiPo battery
      - Electronic component
      - FCC
      - MCU
      - PDU
      - LiDAR

            - GPS
            - 915 MHz radio
            - GSFY-10 limit switch
            - Ice mining power electronics
        - Inspect all electrical connections for exposed wire or loose connections
        - Inspect X-Wing assembly for visible or tactile cracks, scratches, or irregularities
        - Inspect propellers for visual or tactile cracks, scratches or irregularities.
        - Ensure propeller nuts are tightened.
        - Inspect airframe mechanical and electrical connections for loose leads
- **Initialize the GCS***
    - Check GCS battery level. Battery shall be no less than 75% charged
    - Power on GCS
    - Run GCS startup script. Ensure GCS command line application opens correctly
    - Run QGroundControl. Ensure application loads correctly
- **Prepare R&D***
    - Tighten all screws
    - Install a fully charged LiPo battery for the R&D electronics in the designated location in the nose cone of the rocket
    - Verify that all electrical connections between the stepper motor, servo motor, stepper driver, XBee radio, microcontroller, and electronic indicators are secure. Trace connections on schematic print-out
    - Verify that all electronics are securely mounted in place as designed, zip tied to mounting plate
    - **QUALITY WITNESS:** Inspect R&D preparation for the following. If any of the following are missing or damaged, halt launch procedures and direct attention to the appropriate authority. NOTE: Appropriate response to any irregularities will be determined by team leads
        - Test 6+ screws for tightness (random sample)
        - Verify battery presence and lightly pull test battery lead connection
        - Inspect forward and aft bulk plates for visible or tactile cracks, scratches, or irregularities
        - Inspect linear rods for visible or tactile warping, cracking, or scratches
        - Power on the R&D electronics via rocker switch, verifying that the correct LED color pattern is displayed on the LED
            - Verify that "heartbeat" message is received at the GCS

*These activities can be done concurrently

- **Record Lunar Ice Recovery Site Coordinates**
    - Walk out to the lunar ice recovery site with GPS locator and a cell phone equipped with Google Maps

- Get the GPS coordinates of the site using Google Maps on the cell phone.
- Get the GPS coordinates of the site using the GPS locator
  - Ensure the device has a GPS lock
  - Wait until the coordinates reported on the device stop changing
  - Press the button to freeze the screen. Record the coordinates on the cell phone
- Repeat the above procedure for each lunar ice recovery site
- Report the set of coordinates to payload launch day personnel

- **UAV-R&D Integration**
  - Install UAV on R&D sled. Ensure all four latches are secured to the legs of the UAV and the two guide rails are in the proper position on the forward and aft side of the UAV
  - Position lip of ice mining scoops such that they are parallel to side of the sled
  - Verify that limit switch is placed in proper position with respect to the sled
  - Fold propellers into launch configuration
  - Fold X-Wing mechanism into launch configuration. Let go of the UAV, ensuring X-Wing mechanism is locked by the two servo motors.
  - **QUALITY WITNESS:** Inspect R&D UAV integration for the following. If any of the following are missing or damaged, halt launch procedures and direct attention to the appropriate authority. NOTE: Appropriate response to any irregularities will be determined by team leads
    - Ensure 4 latches connect UAV to R&D system
    - Ensure guide rails are oriented to the proper position on forward and aft sides of the UAV
    - Ensure propellers folded to launch position
    - Ensure X-Wing mechanism is locked into launch position, and pin is visible between X-Wing bars
- **R&D Ground Test**
  - Select a team member to act as witness for R&D ground test. They MUST witness the full testing procedure, and must not be witness for any other event.
  - Lock R&D system with manual servo tester
  - Position the R&D limit switch
  - Using the GCS command line software, run test_heartbeat()
    - Expected response: 5 heartbeat signals received from system
  - Run get_bay_angle()
  - Run unlock_bay()
  - Run get_bay_angle()
    - Expected response: Roughly 10° of positive rotation from the initial angle
  - Run expand_bay()
    - Ensure system expands without obstruction
  - Run stepper_enable(0)

- Run orient_bay()
- Once the bay has oriented itself, run stop_orient(0)
- Run get_bay_angle()
  - Expected response: An angle of 0° +/- 1°
- Run unlock_UAV()
  - Ensure X-Wing mechanism unlocks and limit_switch is activated
- Power the system off
- Reset limit switch
- Install new battery in R&D electronics bay.

- **Payload - Launch Vehicle Integration**
  - Retrieve nose cone and upper airframe from construction
  - Slide nose cone over upper section of fully integrated payload bay
    - Line R&D rocker switch up with 3 corresponding linear holes on the nose cone
  - Install 6 R&D system mounting screws through nose cone into forward locking bulkhead
    - Install one screw only 2- 6 turns deep (to set alignment of bulkhead
    - Skipping 1 hole, install the next screw the same number of turns deep
    - Once all screws are loosely installed (in the same pattern described above), fully tighten all screws, torquing opposing screws around the nose cone to evenly distribute load
  - **QUALITY WITNESS:** Inspect R&D system integration into nose cone for the following. If any of the following are missing or damaged, halt launch procedures and direct attention to the appropriate authority. NOTE: Appropriate response to any irregularities will be determined by team leads
    - Inspect for the presence of the following:
      - UAV
      - R&D
      - 6 screws connecting R&D system to nosecone
    - Feel around inside of the aft end of the nose cone for any obstructions to payload bay rotation; if any are found, inform team lead for further instruction
  - Slide one semi-coupler into nose cone
    - Install all 3 screws
  - Repeat for additional semi-coupler
  - Partially slide lower end of payload bay into upper airframe
    - If R&D system must be rotated, ensure the lower R&D system does NOT rotate relative to the pivot stage
  - Install key nuts and screws into upper airframe
  - Remove rotation locks from deployment system

- Fully slide payload bay into upper airframe, aligning the key slot and key nut for orientation
- Install screws in upper airframe to lower payload bay bulk plate
- **QUALITY WITNESS:** Inspect R&D system integration to upper airframe for the following. If any of the following are missing or damaged, halt launch procedures and direct attention to the appropriate authority. NOTE: Appropriate response to any irregularities will be determined by team leads
    - Inspect for the presence of the following:
        - 6 screws connecting R&D system to nosecone
        - 6 screws connecting R&D system to upper airframe

Launch Vehicle Preparation

- **Pre-Launch Preparation**
    - Select a team member to act as witness for launch vehicle preparation. They must witness both the inspection of launch vehicle components and the installation of the motor, and must not be witness for any other event
    - Inspect all launch vehicle components for visual or tactile warping, cracks, or scratches
        - If present, report to the construction team lead. Appropriate response to any irregularities will be determined by team leads
    - Run relevant computer simulations of launch vehicle in its current construction state before launch to analyze both normal and ballistic scenarios
- **Prep and install motor** (PPE required: gloves and safety glasses)
    - 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

Avionics Preparation

- **General Preparation**
    - Fold main and drogue parachutes
    - Follow the instructions for programming the Telemetrum and RRC3+ Sport to ensure the settings are as desired

- **Avionics Bay Final Assembly**
  - Connect the batteries to their respective altimeters
  - Insert the threaded rod/sled/drogue bulkhead assembly into the avionics coupler just enough to be able to screw in the corresponding switch wires to the switch terminals of the altimeters
    - Ensure all the switches are turned OFF for now.
  - Connect the camera to the payload sled
  - **QUALITY WITNESS:** Inspect Avionics bay assembly for the following. If any of the following are missing or damaged, halt launch procedures and direct attention to the appropriate authority. NOTE: Appropriate response to any irregularities will be determined by team leads
    - Inspect for presence of:
      - One washer on each of the 2 threaded rods on the drogue bulkhead side
      - 2 nuts on each of the 2 threaded rods on the drogue bulkhead side
      - Altimeter sled
      - Battery cover
      - Secondary payload sled
      - 2 nuts on each of the 2 threaded rods securing the avionics sleds
      - Telemetrum
      - RRC3+ Sport
      - 4 wires connecting the Telemetrum to the main and drogue terminals
      - 4 wires connecting the RRC3+ Sport to the main and drogue terminals
    - Pull test each wire connecting the altimeters to the ejection charges
    - Check that the batteries are connected to their respective altimeters
      - Lipo battery connects to the Telemetrum
      - 9V battery connects to the RRC3+ Sport
  - Feed the drogue lighter connection wires though the correct holes in the drogue bulkhead and mate the bulkhead with the coupler
  - On each threaded rod, screw on two more hex nuts so that the top of the last one is slightly below the top of the coupler
  - Place a washer on each threaded rod
  - Feed the main lighter connection wires though the correct holes in the main bulkhead and mate the bulkhead with the coupler
  - Place another washer onto each threaded rod, then two more hex nuts on each to completely assemble the avionics bay together
  - Screw the lighter connection wires into their corresponding terminal blocks on the exterior of the bulkheads and tape all the wires down using masking tape

Final Vehicle Assembly

- **Lower Airframe**
  - Retrieve drogue parachute from avionics
    - Connect drogue and shock cord to lower airframe with quicklink
      - Place orange tape over closed quicklink
- **Avionics Bay/Coupler**
  - Retrieve avionics bay/coupler from avionics
  - Attach shock cord to coupler with quicklink
    - Place orange tape over closed quicklink
    - Have witnessing team member inspect quicklink and tape to ensure full link closure
  - **QUALITY WITNESS:** Inspect avionics bay integration for the following. If any of the following are missing or damaged, halt launch procedures and direct attention to the appropriate team lead
    - Inspect for the presence of the following:
      - 2 ejection charges on the aft avionics bay
      - 2 ejection charges on the fore avionics bay
      - 2 nuts on each of the 2 threaded rods on the fore and aft avionics bays.
    - Check that igniters are securely inserted into all 4 blackpowder charges
    - Check that igniters are screwed securely into terminals
      - Pull test each igniter wire lightly to check for secure connection
    - Check for orange tape over quicklink connecting drogue and shock cord to lower airframe
      - Feel tape to ensure link is fully closed and no gap is present between the threads and the link nut
    - Check for orange tape over quicklink connecting shock cord to coupler
      - Feel tape to ensure link is fully closed and no gap is present between the threads and the link nut
  - Slide avionics bay into lower airframe
  - Rotate to align proper lines on the lower airframe and coupler
  - Insert 4 shear pins into shear pin holes
- **Upper Airframe**
  - Attach shock cord ad main parachute to aft payload bay bulk plate with quicklink
    - Place orange tape over closed quicklink
    - Select person to act as quality witness for upper airframe integration. This person must check for orange tape over quicklink connecting the shock cord to aft payload bay bulk plate
      - Feel tape to ensure the link is fully closed and no gap is present between the threads and the link nut

- Insert the main parachute into the upper airframe
  - Wrap lower end of parachute and parachute cords in kevlar wrap (attached) to protect from black powder ignition
- Attach shock cord to fore avionics bay bulk plate with quicklink
  - Place orange tape over closed quicklink
- **QUALITY WITNESS:** Inspect upper airframe integration for the following. If any of the following are missing or damaged, halt launch procedures and direct attention to the appropriate team lead. NOTE: this must be the same person who performed the upper airframe integration inspection of the shock cord attachment to aft payload bay bulk plate
    - Gently slide parachute a few inches fore and aft to check for smooth movement
      - If unsure how much friction is too much between the parachute and upper airframe walls, ask a team lead
    - Check for orange tape over quicklink connecting main parachute and shock cord to forward avionics bay bulk plate
      - Feel tape to ensure the link is fully closed and no gap is present between the threads and the link nut
- Slide upper airframe onto integrated avionics bay
- Rotate to align proper lines on the upper airframe and coupler
- Insert 4 shear pins into shear pin holes
- **QUALITY WITNESS:** Inspect assembled launch vehicle for the following. If any of the following are missing, halt launch procedures and direct attention to the appropriate authority
  - Check that all fins are secure, aligned, and free from damage
  - Check that the body tube and nose cone are in good condition
  - Check that the motor tube is unobstructed (do NOT look directly down motor tube)
  - Check that 4 shear pins can be seen connecting the lower airframe to the coupler
  - Check that 4 shear pins can be seen connecting the upper airframe to the coupler
  - Look over the surface of the launch vehicle for any visible damage (cracks, scratches, etc)
    - Report any damage to appropriate team lead

- **Final Assembly Confirmation**
  - Safety team lead will call for confirmation of completion of the following actions:
    - UAV prep
    - R&D prep

        - UAV R&D integration
        - R&D ground test
        - R&D nose cone integration
        - R&D upper airframe integration
        - Launch vehicle preparation
        - Avionics bay assembly
        - Avionics bay integration
        - Upper airframe integration
        - Final launch vehicle assembly
    - If the witnessing team members declare each step as complete, proceed to launch
        - If any step is missing a witness, deconstruct the appropriate section of the launch vehicle and re-perform quality witness.
    - Determine mass of fully constructed launch vehicle
        - Re-run launch simulations to ensure proper flight path
            - If flight path is found to exceed or fall short of predicted apogee, add or remove ballast and repeat applicable quality witnesses

Launch Preparation

- RSO Inspection
- Check that weather conditions are conducive to launch
- Receive final launch clearance from RSO
- 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 1.3x the minimum safe distance from spectators based upon minimum distance table (See Appendix B)
    - 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
- Tilt launch rail and slide launch vehicle onto rail along rail buttons
- Arm the avionics system
    - Turn on every switch in avionics bay with a screwdriver to reach the switches through the switch band.
    - The Telemetrum should emit the following sets of beeps (ensure bolded events occur).
        - Beeps corresponding to the battery voltage (count to ensure the voltage is at least above 3.2V)
        - Dit, dah, dah, dit - Indicates pad mode; waiting for launch

- If only dit, dit - Indicates idle mode; ensure Telemetrum is in correct orientation (pointing up)
    - Dit, dit, dit - Continuity on both drogue and main lighters
        - If only brap - Indicates continuity on neither drogue nor main lighters
        - If only dit - Indicates continuity on only drogue lighter
        - If only dit, dit - Indicates continuity on only main lighter
        - If warble - Storage is full; need to delete extraneous flights
- The RRC3+ Sport should emit the following sets of beeps (ensure bolded events occur)
    - One 5-second beep
    - Beeps corresponding to the battery voltage (count to ensure the voltage is at least above 8.0V)
    - Beep, beep, beep - Continuity on both drogue and main lighters
        - If only long beep - Indicates continuity on neither drogue nor main lighters
        - If only short beep - Indicates continuity on only drogue lighter
        - If only beep, beep - Indicates continuity on only main lighter
- Ensure igniter clips are clean and secure them to the pad
- Install igniter to the motor
- Return to viewing area

Flight Trajectory

- Ensure the launch and the flight will not be angled towards any spectators
- 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

Avionics connection

- Assemble the Telemetrum antenna, plug it into the TeleDongle, and plug the TeleDongle into a laptop with AltOS installed.
- 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 and baud rate to what was noted when the Telemetrum was configured. Live telemetry from the Telemetrum should now be appearing on the screen
- If radio control is used for flight functions (e.g. recovery), check that the operating frequency is in the 27, 50, 53, or 72 megahertz bands. Use of 75 megahertz for flight functions is not permitted
- The avionics and recovery system should be ready for launch

Pre-Launch Safety Briefing:

- Confirm presence of trained RSO
- Designate 2 rapid response persons to administer first aid and get help, respectively

- Designate 2 spotters to track launch vehicle's flight path
  - Spotters must point to the launch vehicle at all times
- Designate 1 or more "blind men" to monitor sections of the sky not occupied by the launch vehicle for hazards during rocket descent
- Remind spectators of the appropriate reaction to a ballistic trajectory and "scatter" call

Beginning the Launch

- Shortly before the countdown, give a loud announcement that the launch vehicle will be launched; if applicable to the situation, use a PA system
- Ensure that all spectators are aware of the launch and that parents are in close contact with all children
- When launching, give a loud countdown of "5, 4, 3, 2, 1, LAUNCH!"

7.1.3. Launch Checklist

- Spotters are to follow the path of the launch vehicle 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
- Ensure all passerby and spectators are aware of the launch
- 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.
- Make sure whoever is responsible for recovery is kept fully aware of the status of the launch vehicle (failed to launch, nominal in-flight, mid air failure, returning for recovery, etc.)
- Once the vehicle has touched down, do not turn off the altimeters until data has been acquired
- Communicate launch progress effectively to NASA officials, if needed

7.1.4. 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

In the case of unintended ballistic trajectory:

- Should the launch vehicle enter 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 in attendance of the launch are to immediately turn away from the direction of the launch vehicle and run for a minimum of 10 seconds

In case of missing section of launch vehicle:

- Refer to “blind men” for indication of missing section location
- 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

NOTE: When launching through an affiliate launch day, team emergency contingencies are superseded by launch day procedures

7.1.5. Post-Launch Checklist

- Check all components of the rocket and payload for damage
    - If the payload is damaged, notify payload subteam and team leads
- Check that there are no obstacles around the landing site and that it is safe for the payload to be deployed
    - If obstructions are present, notify team leads
- Clear all personnel of launch site and return to the viewing area
- Initiate Payload Mission
    - Lock R&D system with manual servo tester
    - Position the R&D limit switch
    - Using the GCS command line software, run test_heartbeat()
        - Expected response: 5 heartbeat signals received from system
    - Run get_bay_angle()
    - Run unlock_bay()
    - Run get_bay_angle()
        - Expected response: Roughly 10° of positive rotation from the initial angle
    - Run expand_bay()
        - Ensure system expands without obstruction

- Run stepper_enable(0)
- Run orient_bay()
- Once the bay has oriented itself, run stop_orient(0)
- Run get_bay_angle()
    - Expected response: An angle of 0° +/- 1°
- Run unlock_UAV()
    - Ensure X-Wing mechanism unlocks and limit_switch is activated
- Run unlock_UAV()

7.1.6. Post-Flight Checklist

- Let NASA officials verify the results of the launch, if necessary
- Sweep the area around the touchdown site to make sure there are no potential hazards around the rocket
- Make sure there are no live wires or sharp components on the rocket before handling
- Double check that all necessary data from the avionics bay has been retrieved
    - If so, disarm the avionics
- Disarm the launch controller
- Place cap on launch rods, if necessary
- Take down the launch pad, if necessary
- Retrieve the main launch vehicle body and all components which may have landed separately
    - Check them for any failed ejection charges.
    - If there are failed ejection charges, save all ejection circuits and remove any non-discharged pyrotechnics
- Perform sweep of launch field to ensure no materials are unintentionally left behind

7.2. Hazard Analysis Methods

Critical to the success of any mission is a comprehensive understanding of the dangers involved therein. Threats to personnel, environmental factors, project dangers, and launch vehicle failure modes all contribute to the cumulative risk associated with the mission. While each team takes careful steps to minimize any such risks, and to not put team members in harm's way, the danger associated with missions such as these will likely never be fully abated. Acknowledgement of these dangers, and a thorough plan for their mitigation, is the only way to guarantee the safety of the team, and to maximize the likelihood of mission success.

For the purposes of this mission, risk analysis was broken into two categories: event probability and event severity. The respective definitions of these categories are listed below.

Category	Value	Gauge
Remote	1	Less than 3% chance of event
Unlikely	2	3-10% chance of event
Possible	3	10-25% chance of event
Probable	4	25-50% chance of event
Likely	5	Greater than 50% chance of event

Table 7.1: Event Probability Safety Matrix

In the consideration of severity, the team established several metrics for defining the associated levels, key among them being reversibility and remediation time. The highest level of severity corresponds to total irreversibility of the damage done; in various contexts, this may mean loss of life or permanent function, permanent environmental damage, or a complete scrub of the mission. Lower levels of severity are characterized by long term reversibility, and further delineated by the length of said remediation, ranging from an on-the-spot solution (first aid, consumable tool replacement, small leaks or spills) to the need for external assistance or long recovery (hospitalization, machine repair, primary environmental restoration).

Category	Value	Health and Personal Safety	Equipment	Environment	Flight Readiness
Negligible	1	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	2	Minor injury. Requires band-aid or less to treat. 5-10 minutes of recovery time required.	Minor damage. Consumable equipment element requires repair.	Minor environmental impact. Damage is focused on a small area. Little to no repair or recovery needed. Outside assistance not required.	Flight proceeds with caution.
Moderate	3	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	4	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	5	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 7.2: Event Severity Safety Matrix

In the consideration of these definitions, the team focused on establishing quantitative metrics for each level of probability and severity. The establishment of measurable standards for these categories enables the team to accurately assess the risk of every considered event (listed in the following sections). Cumulative risk for each event is found by a cross examination of the likelihood and severity of each event (performed in this case by the multiplication of the assigned values in each of these categories). A table demonstrating this is given 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

Any event categorized as 'low' or 'negligible' risks are considered acceptable by the team's standards.

Category	Negligible	Minor	Moderate	Major	Disastrous
Remote	1	2	3	4	5
Unlikely	2	4	6	8	10
Possible	3	6	9	12	15
Probable	4	8	12	16	20
Likely	5	10	15	20	25

Table 7.3: Total Event Risk Safety Matrix

Prior to a plan for risk mitigation, many of the events listed below fall outside of the acceptable tolerance. Listed alongside these events are the team's risk mitigation plans, as well as verification metrics to ensure team compliance. Post-mitigation risk is also listed, ensuring all project risks are within acceptable tolerance.

7.3. Personnel Hazard Analysis

Hazard	Likelihood (Cause)	Severity (Effect)	Risk	Mitigation	Verification	Post Mitigation Risk
Burns From Motor	2 (Proximity To Launch Pad, touching engine too soon after launch)	3 (Mild To Moderate Burns)	6, Low	Maintain minimum safe launch distances. Wait an appropriate amount of time after launch to retrieve.	200 feet border will be established after mounting of launch vehicle onto launcher as compliance to NAR safety standards.	3, Low
Contact with Airborne Chemical Debris	3 (Airborne particulate debris)	2 (Minor burns, abrasions)	6, Low	Wear appropriate PPE such as gloves, lab coats and breath masks, wash immediately with water if contact is made.	Safety Team will verify with each participating member that appropriate PPE is worn.	4. Low
Direct Contact with Hazardous Chemicals	3 (Chemical spills, improper use of chemicals)	3 (Moderate burns, abrasions)	9, Medium	Wear appropriate PPE such as gloves or lab coats, wash with water.	Safety Team will verify with each participating member that appropriate PPE is worn.	6, Low
Dust or Chemical Inhalation	3 (Airborne particulate debris)	3 (Short to long-term respiratory damage)	9, Medium	Wear appropriate PPE or respirator, work in a well ventilated area.	Safety Team will verify with each participating member that appropriate PPE is worn.	6, Low
Dehydration	3 (Failure to drink adequate amounts of water)	3 (Exhaustion and possible hospitalization)	9, Medium	Ensure all members have access to water at launch.	Mandatory water breaks will be held every hour where no work may be done during that period.	3, Low
Heatstroke	3 (High temperatures on launch day)	3 (Exhaustion and possible hospitalization)	9, Medium	Wear clothing appropriate to the weather, ensure all members have access to water at launch.	Team members must have adequate clothing, safety team will report violators to the project lead to decide if the violator should be dismissed to a colder area; water	3, Low

					will be provided.	
Hypothermia	3 (Low temperatures on launch day)	3 (Sickness and possible hospitalization)	9, Medium	Wear clothing appropriate to the weather, ensure all members have access to a warm area to rest at launch.	Team members must have adequate clothing, Safety team will report violators to the project lead to decide if the violator should be dismissed to a warmer area.	6, Low
Electrocution	2 (Improper use of equipment, static build-up)	4 (Possible explosion, destruction of electrical tools or components, possible severe harm to personnel)	8, Medium	Give labels to all high voltage equipment warning of their danger; ground oneself when working with high-voltage equipment.	Pre-operation inspection will be done by safety officer to ensure no open electrical components prior to high-voltage event. Allow only one member to work on electrical components at a time with proper PPE and student supervising.	4, Low
Entanglement with Construction Machines	4 (Loose hair, clothing, or jewelry)	5 (Severe injury, death)	20, High	Secure loose hair, clothing, and jewelry; wear appropriate PPE.	No physical contact allowed without call out before use to make sure PPE is worn. Make sure rules followed as set forth by machining rules.	5, Low
Epoxy Contact	3 (Resin Spill)	3 (Exposure to Irritant)	9, Medium	Wear appropriate PPE such as gloves or lab coats, wash with water.	Safety officer or approved safety team member will verify proper PPE is used before and during epoxy handling	6, Low
Eye Irritation	3 (Airborne particulate debris)	2 (Temporary eye irritation)	6, Low	Wear appropriate PPE or protective eyewear, wash with water if contact is made	Guaranty PPE worn at all times during manufacturing. Call out before use to make sure PPE is worn by surrounding team members	4, Low

Hearing Damage	4 (Close proximity to loud noises)	3 (Long term hearing loss)	12, Medium	Wear appropriate PPE such as ear muffs when using power tools.	PPE equipment check must be done by a safety team member before conducting construction.	6, Low
Kinetic Damage to Personnel	2 (Failure to take appropriate care around unburned fuel, post-landing launch vehicle explosion)	4 (Possible severe kinetic damage to personnel)	8, Medium	Extinguish any fires before recovering, wait for motors to burn fully before recovering, wear appropriate PPE when recovering.	Make sure the area is evacuated and designated individuals are to recover components at a designated time when determined to be safe; no contact allowed without call out before use to make sure PPE worn.	5, Low
Launch Pad Fire	2 (Dry Launch Area)	3 (Moderate Burns)	6, Low	Have fire suppression systems nearby and use a protective ground tarp.	Make sure the area is evacuated and designated individuals are to recover components at a designated time when determined to be safe; ground area will be cleared per NAR launch standard	3, Low
Injury from Ballistic Trajectory	1 (Recovery System Failure)	5 (Severe Injury, Death)	5, Low	Keep all eyes on the launch vehicle and call “heads up” if needed, limit the number of people at launch. Emphasize importance of keeping eyes on the launch vehicle during flight.	Go through safety procedures before the launch occurs. Minimum of 2 spotter will be watching rocket trajectory at all times, and have authority to call “Scatter”	5, Low
Injury from Falling Components	2 (Failure to keep all components securely attached to the launch vehicle; result of improper	5 (Severe injury, death)	10, Medium	Keep eyes on the launch vehicle at all times; make sure all team members who cannot watch the launch vehicle have spotters nearby; alert others if the launch	Go through safety procedures before the launch occurs. Minimum of 2 spotter will be watching rocket trajectory at all times, and have	5, Low

	staging constraints, part failure, or excessive vibration)			vehicle enters a ballistic trajectory.	authority to call “Scatter”	
Injury from Navigating Difficult Terrain	2 (Uneven ground, poisonous plants, fast-moving water)	4 (Broken bones, infections, drowning, etc.)	8, Medium	Do not attempt to recover the launch vehicle from atypically dangerous areas.	Set boundaries to not cross at the launch location before the launch occurs.	4, Low
Injury from Projectiles Caused by Jetblast	2 (Failure to properly clean launchpad, failure to stand an appropriate distance from the launch vehicle during launch)	3 (Moderate injury to personnel)	6, Low	Clean the launchpad before use, ensure all members are wearing proper PPE for launch, ensure all team members are an appropriate distance from the launch vehicle when launching.	Verify that the launchpad is clean and clear of debris before launch occurs. Create launch checklist to be completed before the launch vehicle can be launched.	3, Low
Physical Contact With Heat Sources	3 (Contact with launch vehicle parts which were recently worked with, improper use of soldering iron or other construction tools)	3 (Moderate to severe burns)	9, Medium	Wear appropriate PPE, turn off all construction tools when not in use, be aware of the safety hazard that parts which were recently worked with present.	Confirm that appropriate PPE is being used. Make sure that everybody is informed of the hazard.	3, Low
Physical Contact with Falling Construction Tools or Materials	3 (Materials which were not returned to a safe location after use)	5 (Bruising, cuts, lacerations, possible severe physical injury)	15, High	Brief personnel on proper clean-up procedures, wear shoes that cover the toes.	Clean workspace every time after use. Create a checklist of where to put items after use.	5, Low
Premature Ignition	2 (Short Circuit)	2 (Mild Burns)	4, Low	Prepare energetic devices only immediately prior to flight.	Place previously used materials in separate container than the unused materials.	2, Minimal
Power Lines	2 (Launch vehicle Becomes Entangled In Lines)	5 (Fatal Electrocution)	10, Medium	Call the power company and stand clear until proper personnel arrive.	Alert all team members of the hazard. Everybody is required to stand clear of the area	5, Low

					until certified personal clean up and verify that the area is safe.	
Power Tool Cuts, Lacerations, and Injuries	3 (Carelessness)	4 (Possible Hospitalization)	12, Medium	Secure loose hair, clothing, and jewelry; wear appropriate PPE; brief personnel on proper construction procedures.	No contact allowed without call out before use to make sure PPE worn. Make sure rules followed as set forth by machining rules.	4, Low
Injuries from Quadcopter payload	2 (Injury from spinning rotors)	2 (Minor cuts)	4, Low	Stay clear of quadcopter while it is in operation. Only team members familiar with the payload will handle it.	Stay minimum safe distance at launch and remain at that distance until payload and other components have landed. Have member of payload team retrieve the quadcopter.	2, Minimal
Tripping Hazards	3 (Materials which were not returned to a safe location after use, loose cords on or above the ground during construction processes)	3 (Bruising, abrasions, possible severe harm if tripping into construction equipment)	9, Medium	Brief personnel on proper clean-up procedures, tape loose cords or wires to the ground if they must cross a path which is used by personnel.	Have a clean up sheet for work space occupants to confirm everything is placed where it should be.	6, Low
Unintended Black Powder Ignition	3 (Accidental exposure to flame or sufficient electric charge)	5 (Possible severe hearing damage or other personal injury)	15, High	Label containers storing black powder, one may only handle the black powder if he/she possesses a low-explosives user permit.	Have check in/out form to confirm only those permitted to handle materials are the only ones handling the material.	5, Low
Workplace Fire	2 (Unplanned ignition of flammable substance, overheated workplace, improper use or supervision	5 (Severe burns, loss of workspace, irreversible damage to project)	10, Medium	Have fire suppression systems nearby, prohibit open flames, and store energetic devices in Type 4 magazines as stated in CFR 27 part 55.	Make sure all members are updated on the workplace fire safety protocols. Have lists of all required fire suppression system	5, Low

	of heating elements, or improper wiring)				accounted for and found near the area of work.	

Table 7.4: Personnel Hazard Analysis

7.4. Failure Modes and Effects Analysis (FMEA)

Hazard	**Likelihood (Cause)**	**Severity (Effect)**	**Risk**	**Mitigation**	**Verification**	**Post Mitigation Risk**
Airframe Failure	1 (Buckling or shearing on the airframe from poor construction or use of improper materials, faulty stress modeling)	5 (Partial or total destruction of vehicle, ballistic trajectory)	5, Low	Use appropriate materials according to extensive mathematical and physical analyses of the body tube, bulkheads, fasteners and shear pins, make use of reliable building techniques, confirm analyses with test launches.	Use a construction checklist which ensures mathematical analyses match physical analyses, if the airframe does not perform well in test launches perform another test launch with a new airframe design before converting to full-scale, and use the launch checklists to ensure both before and after launch that the airframe is in good condition.	5, Low
Failure To Launch	2 (Lack of continuity)	1 (Recycle launch pad)	2, Minimal	Check for continuity prior to attempted launch.	Include checking for continuity in launch checklist that is to be completed prior to launch.	1, Minimal
CATO	1 (Motor defect, assembly error)	5 (Partial or total destruction of vehicle)	5, Low	Inspect motor prior to assembly and closely follow assembly instructions.	Include motor inspection in pre launch checklist to verify this task is completed.	5, Low
Instability	1 (Stability margin of less than 1.00)	5 (Potentially dangerous flight path and loss of	5, Low	Measure physical center of gravity and compare to calculated center of pressure.	Have measured physical center of gravity documented and	5, Low

		vehicle)			compared prior to arriving at the launch site.	
Motor Expulsion	2 (Improper retention methods)	5 (Risk of recovery failure and low apogee)	10, Medium	Use positive retention method to secure motor.	Include motor securement into pre launch checklist to verify that this task is complete.	5, Low
Premature Ejection	2 (Altimeter programming, poor venting)	5 (Zippering)	10, Medium	Check altimeter settings prior to flight and use appropriate vent holes. Test altimeter in similar conditions to those to be experienced at launch.	Include checking altimeter settings to pre launch checklist to verify that this task is complete. Altimeter testing before launch.	5, Low
Loss of Fins or Damage	2 (Poor construction or improper materials used)	5 (Partial or total destruction of vehicle)	10, Medium	Use appropriate materials and high powered building techniques.	Conduct stress tests on fins to make sure they can withstand all forces present during flight.	5, Low
Loss of Nose Cone	2 (Poor construction or improper materials used)	5 (Partial or total destruction of vehicle)	10, Medium	Use appropriate materials and high powered building techniques.	Ensure that nose cone is secured well before ejection during test runs, otherwise alter.	5, Low
Loss of Parachute	3 (Poor attachment or improper materials used)	5 (Partial or total destruction of vehicle)	15, High	Use appropriate materials and high powered building techniques. Parachute attachment will be witnessed for quality, orange tape will be used to indicate connected quicklink	Parachute shock cord will be rated for intended use. Quick link attachment of parachute will be witnessed by 1+ additional team members and completed with orange tape around quick link.	5, Low
Ejection Charge Failure	3 (Not enough black powder, electrical failure)	5 (Ballistic trajectory, destruction of vehicle)	15, High	Ground testing will be done to ensure black powder is sufficient to separate airframe sections.	Conduct voltage test readings on power source before launch to make sure appropriate power is present	5, Low

					for launch.	
Altimeter Failure	3 (Loss of connection or improper programming, battery failure)	5 (Ballistic trajectory, destruction of vehicle)	15, High	Altimeter will be turned on only during testing and immediately before launch.	Avionics battery voltage will be checked after each testing. Record audible indication of altimeter function (beeping).	5, Low
Payload Failure	3 (Electrical failure, program errors, dead battery)	4 (Disqualified, objectives not met)	12, Medium	Test payload prior to flight, check batteries and connections.	Keep fresh batteries separate from previously used batteries. Use fresh batteries for each launch.	4, Low
Heat Damaged Recovery System	2 (Insufficient protection from ejection charge)	5 (Excessive landing velocity, potentially ballistic trajectory)	10, Medium	Use appropriate protection methods, such as Kevlar blankets.	Check that proper protection methods are securely placed before launch.	5, Low
Broken Fastener	1 (Excessive force)	5 (Ballistic trajectory)	5, Low	Use fasteners with a breaking strength safety factor of 2.	Conduct stress tests on fasteners before launch day to confirm that they meet force requirements.	5, Low
Centering Ring Failure	2 (Excessive force from motor, poor construction)	5 (Partial or total destruction of vehicle, ballistic trajectory)	10, Medium	Use appropriate centering rings according to mathematical and physical flight analyses, make use of reliable building techniques, confirm analyses with test launches.	Centering ring will be inspected prior to launch as part of launch operations	5, Low
Battery Overcharge	3 (Unsupervised /undocumented charge)	3 (Destruction of battery)	9, Medium	Ensure batteries are documented and supervised if charging.	Ensure alarms set and other individuals are aware of batteries charging.	3, Low
Premature Blackpowder Ignition	2 (Accidental exposure to flame or sufficient electric charge)	5 (Partial or complete destruction of vehicle, damage to personnel)	10, Medium	Ensure black powder is kept away from sources of heat or spark. Arm avionics only during brief testing and before launch.	Testing and pad installation will be done in accordance with launch procedures.	5, Low

Charge ignition close to motor	3 (Poor design location leads to damage)	5 (Partial or complete destruction of vehicle	15, High	Ensure black powder charge location design has sufficient distance / protection from motor and batteries.	Independently ensure design is safe; ensure by isolated testing charge may work.	5, Low
Destruction of Bulkheads	2 (Poor construction or improper bulkheads chosen which cannot withstand launch forces, faulty stress modeling)	5 (Partial or total destruction of vehicle, ballistic trajectory)	10, Medium	Use appropriate materials according to extensive high-stress mathematical and physical analyses, make use of reliable building techniques, run stability tests, confirm analyses with test launches.	Bulkheads will be visually inspected for damage prior to launch.	5, Low
Damaged Nose Cone	2 (Poor construction, damage from previous flights, poor storage, or transportation)	3 (Lower launch vehicle stability, possible deviations from flight path)	6, Low	Check the nose cone for damage before and after each launch, choose a nose cone which is strong enough to withstand launch forces according to mathematical and physical flight simulations, confirm choice of nose cone with subscale launches.	Nose cones will be inspected and repaired before and after each launch in order to make sure they are up to launch standards.	3, Low
Motor Tube Angled Incorrectly	2 (Poor construction, damage from previous flights, poor storage, or transportation)	4 (Lower launch vehicle stability, launch vehicle does not follow desired flight path well)	8, Medium	Ensure proper measurements and alignments are made during construction, ensure there is no rush to attach the motor tube, double-check the alignment of the motor before each flight, test that the desired motor alignment is correct with subscale flights.	Measurements will be made at 4 rotational points around the motor tube to ensure equal distance from edge to launch vehicle edge coupling.	4, Low
Motor Tube Comes Loose	2 (Poor construction, damage from previous flights, poor storage, or transportation, faulty motor preparation)	5 (Ballistic trajectory, catastrophic destruction of vehicle)	10, Medium	Check the motor and motor tube for damage before and after each launch, run mathematical and physical flight simulations to ensure the tube performs as planned, confirm simulations with subscale launches.	Stress test the motor tube connection to make sure it can withstand expected forces acting upon it.	5, Low

Premature Stage Separation	3 (Premature ejection, poor choice of shear pins or fasteners)	5 (Possible recovery failure and damage to or loss of vehicle, ballistic trajectory)	15, High	Check altimeter settings prior to flight, use appropriate vent holes, and run thorough analyses to determine which types of shear pins and fasteners should be used.	Redundant altimeters will be used, calibration will be checked and verified by separate individuals.	5, Low
Forgotten or Lost Components	3 (Carelessness with launch vehicle components, failure to take note of inventory before attempting to launch)	4 (Launch vehicle does not launch at the desired launch time)	12, Medium	Have spares for components which are small and easy to lose, have an inventory of all launch vehicle parts to be checked before moving the launch vehicle to a launch site.	Ensure at least two team members double check that everything in the launch vehicle inventory will be taken to the launch site and is accounted for upon arrival.	4, Low
Launch Vehicle Disconnects from the Launch Rail	2 (High wind speeds, failure to properly use the rail buttons, faulty rail buttons)	5 (Partial or total destruction of vehicle, ballistic trajectory which endangers personnel, onlookers, and property on the ground)	10, Medium	Use mathematical and physical analyses 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 by at least two separate individuals prior to launch for cracks, misalignment, or other inaccuracies.	5, Low
Flightpath Interference	2 (Wildlife in the air, unforeseen obstacles such as stray UAV's)	5 (Minor to severe change in the vehicle's flightpath, possible ballistic trajectory)	10, Medium	Ensure there are clear skies above before launching, ensure an FAA waiver has been obtained for the designated launch area.	Visually inspect the surrounding area to make sure no incoming wildlife or loose objects.	5, Low
Unplanned Amounts of Friction Between Launch Vehicle and Launch Rail	3 (Faulty setup of launch rail, faulty installation of launch vehicle on launch rail, failure to properly	2 (Launch vehicle does not follow the designated flight path well, lower than ideal apogee is	6, Low	Set up the rail using instructions which come with the product, use lubrication on the rail as needed according to weather and rail type, ensure the launch vehicle is properly installed on	Launch rails will be tested by tactile inspection to ensure proper lubrication.	2, Minimal

	lubricate launch rail as needed, weather conditions cause excess friction)	achieved)		the launch rail.		
Failure to Ignite Propellant	2 (Faulty motor preparation, poor quality of propellant, faulty igniter, faulty igniter power source, damage to motor)	5 (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)	10, Medium	Purchase propellant and motors only from reliable sources, team members who prepare the motor and igniters must be supervised by at least one other team member, determine if the igniters chosen work well during subscale testing.	Make sure igniters are well tested and are extremely reliable. If propellant does not ignite, wait at least 5 minutes before approaching the launch vehicle.	5, Low
Propellant Fails to Burn for Desired Duration	2 (Faulty motor preparation, poor quality of propellant, damage to motor)	3 (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)	6, Low	Purchase propellant and motors only from reliable sources, check the motor for damage prior to launching, team members who prepare the motor must be supervised by at least one other team member.	Team members will be designated to observe the motor preparation procedure, only approved propellant sources will be used.	3, Low
Propellant Burns Through Launch Vehicle Components	2 (Faulty motor preparation, poor quality of propellant, poor construction, damage to motor, damage to propellant	5 (Ballistic trajectory, catastrophic destruction of vehicle)	10, Medium	Purchase propellant and motors only from reliable sources, check the motor for damage prior to launching, team members who prepare the motor must be supervised by at least one other team member, test propellant casing in subscale flights.	Double check bulkhead after every flight to make sure it is in good enough condition for it to sufficiently protect launch vehicle components from propellent exhaust.	5, Low

	casing)					
Propellant Explosion	1 (Faulty motor preparation, poor quality of propellant, damage to motor)	5 (Catastrophic destruction of vehicle, possible harm to bystanders)	5, Low	Purchase propellant and motors only from reliable sources, check the motor for damage prior to launching, team members who prepare the motor must be supervised by at least one other team member.	A team member will be designated to observe the motor preparation procedure, only approved propellant sources will be used.	5, Low
Payload Computer Failure	3 (Electrical failure, program error, poor setup of wiring causes a connection to come undone, forgotten connection, battery failure)	5 (Objectives not met, loss of electronic control)	15, High	Test payload prior to flight, check batteries and connections before flight.	Ensure by design and testing that components will not fail under extreme stress.	5, Low
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)	5 (Objectives not met, failure to correctly trigger ejection charges)	15, High	Test the reliability of the wiring and batteries through subscale flights, check batteries and connections before flight.	Continuity checks will be used, visible wires will be inspected for nicks or damage prior to launch.	5, Low
Avionics Bay Fire	2 (Faulty wiring, battery failure, poor setup of wiring, adverse weather)	5 (May be disqualified if objectives are not met, possible failure to trigger ejection charges, damage to internal launch vehicle components)	10, Medium	Thermal protection of avionics bay, do not overload avionics bay with wiring, only purchase avionics and payload equipment from reliable sources, check avionics bay and payload performance with test launches.	Make sure no wires are exposed and that the avionics bay is sufficiently protected from heat.	5, Low
Human Error When Arming Avionics and	3 (Forgotten connection, forgetting to activate	5 (Disqualified, objectives not met,	15, High	Leave reminders in multiple places to check that the avionics bay and payload are armed and	All designated launch procedure observers will inspect avionics	5, Low

Payload	avionics bay components or payload prior to launch)	failure to correctly trigger ejection charges)		ready before launch, follow launch checklists closely.	for charge and activation: audible and appropriate beeps must be observed before launch.	
Arming System Failure	3 (Faulty arming system, faulty wiring, battery failure, poor setup of wiring causes a connection to come undone, forgotten connection)	5 (Disqualified, objectives not met, failure to correctly trigger ejection charges)	15, High	Ensure the avionics bay is successfully communicating with the team prior to flight, test arming system through test launches.	Ensure by design and testing that communication between components is established and reliable.	5, Low
Poor Spacing Between the Ejection Charge and the Parachute	2 (Failure to properly consider the requirements of the recovery system, poor budgeting of space in launch vehicle, failure to read instructions that come with parachute and/or ejection charges)	5 (Partial or total damage to the parachute, parachute does not launch from the launch vehicle, possible recovery failure)	10, Medium	Read all instructions which come with the parachute and ejection charges, establish clear requirements of the recovery system early in the design process, run mathematical and physical analyses on the design of the launch vehicle, ensure the parachute is spaced properly with subscale test flights.	Dual analysis will be performed to ensure no damage occurs to the parachute, ejection charge testing to ensure no parachute damage.	5, Low
Stage Fails to Separate	3 (Faulty ejection charge, excessive strength is used to hold stages together, altimeter failure)	5 (launch vehicle does not follow desired flight path, possible ballistic trajectory, lower maximum height, damage to the launch vehicle)	15, High	Any team member who loads the ejection charges must be supervised by at least one other team member, examine ejection charges for damage before launch, ensure proper functionality of the altimeters, ejection charges, and interstage joints and fasteners through test flights and mathematical and physical analyses, have a secondary ejection	Ejection charge testing will be performed to ensure charges can separate stages, dual altimeters will be employed to enable redundancy.	5, Low

				charge for each stage separation.		
Main Parachute Fails to Deploy	2 (Poor design of where parachute is located in launch vehicle, poor sealing of parachute chamber, poor loading of parachute, faulty parachute or ejection charge, altimeter failure)	5 (Main parachute does not slow down the launch vehicle, recovery failure, ballistic trajectory)	10, Medium	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, run mathematical and physical analyses as well as subscale tests to ensure parachute is in the right position in the launch vehicle, have a secondary ejection charge in case of emergency which is larger than the first.	Ejection charge testing will be done to ensure charge effectively deploys parachute. Parachute packing operation will be observed and signed off on.	5, Low
Drogue Parachute Fails to Deploy	2 (Poor design of where parachute is located in launch vehicle, poor sealing of parachute chamber, poor loading of parachute, faulty parachute or ejection charge, altimeter failure)	5 (Drogue parachute does not slow down the launch vehicle, recovery failure, ballistic trajectory)	10, Medium	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, run mathematical and physical analyses as well as subscale tests to ensure parachute is in the right position in the launch vehicle, have a secondary ejection charge in case of emergency which is larger than the first.	Ejection charge testing will be done to ensure charge effectively deploys parachute. Parachute packing operation will be observed and signed off on.	5. Low
Parachute Canopy Breaks or Tears	1 (Poor canopy materials, improper ejection of recovery system, damage from previous flights or transportation)	5 (Possible recovery failure, ballistic trajectory)	5, Low	Only buy parachutes from reliable sources, remove threats to parachute integrity from the parachute housing, test the recovery system through mathematical and physical analyses as well as subscale flights, check the recovery system for damage before launch.	Run simulations and mathematical analysis to ensure the acquired parachute is capable of withstanding forces to safely descend the launch vehicle. Visually inspect parachute for	5, Low

					damage prior to packing.	
Parachute Shroud Lines Break	1 (Poor shroud line materials, improper ejection of recovery system, damage from previous flights or transportation)	5 (Possible recovery failure, ballistic trajectory)	5, Low	Only buy parachutes from reliable sources, remove threats to parachute integrity from the parachute housing, test the recovery system through mathematical and physical analyses as well as subscale flights, check the recovery system for damage before launch.	Ensure by design and testing that the shroud lines are strong enough to handle expected forces.Visually inspect parachute for damage prior to packing.	5, Low
Complete airframe separation	1 (Faulty shock cord, damage to shock cord, faulty eyebolt, failure to properly connect shock cord to eyebolt)	5 (Parachute disconnect from the launch vehicle, recovery failure, ballistic trajectory)	5, Low	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.	Test the shock cord to ensure it can withstand the forces acting upon it during descent. Quick links used to connect shock cord will be taped over when connection is complete.	5, Low
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)	5 (Shock cord or parachutes may not fully achieve their goal, possible ballistic trajectory, possible failed recovery)	10, Medium	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 shock cord in test flights, appropriately follow recommended sizings for shock cord and parachutes.	Designated parachute packing observer will record the packing and make notes on operation, and have the right to demand repacking.	5, Low
Parachute Comes Loose from launch vehicle	2 (Failure of recovery system mount on the launch vehicle body,	5 (Recovery failure, ballistic trajectory)	10, Medium	Only buy parachutes from reliable sources, test the recovery system through mathematical and physical analyses as	Ensure by design and testing that the parachute is attached well. Quick links used	5, Low

	poor shroud line materials, improper ejection of recovery system, damage from previous flights or transportation)			well as subscale flights, check the recovery system for damage before launch, double check that the recovery system is properly mounted before launch.	to connect shock cord will be taped over when connection is complete.	
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)	5 (Shock cord or parachutes do not fully achieve their goal, possible ballistic trajectory, possible failed recovery, damage to internal launch vehicle components)	10, Medium	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. Only flame resistant materials are to be used for shock cords and parachutes.	Designated packing operation observer will document the packing process to ensure proper placement.	5, Low
Destruction Due To Drag Forces	1 (Poor construction or improper materials used)	5 (Partial or total destruction of vehicle)	5, Low	Use appropriate materials and high powered building techniques.	Test in simulation to find coefficient of drag to estimate drag on full scale.	5, Low
Airframe Zipper	2 (Excessive deployment velocity)	5 (Partial destruction of vehicle)	10, Medium	Properly time ejection charges and use an appropriately long tether.	Test and observe at full scale launch prior to Huntsville.	5, Low
GPS Lock Failure	2 (Interference or dead battery)	5 (Loss of vehicle)	10, Medium	Ensure proper GPS lock and battery charge before flight.	Check battery charge before flight to ensure it is capable of providing power during the duration of flight.	5, Low
Insufficient Landing Speed	3 (Improper load, higher coefficient of drag for the parachutes than needed, higher surface area of the	2 (Unexpected changes in flightpath and landing area, increased potential for	6, Low	Use subscale flights to determine if the subscale parachutes were accurately sized, use recommended and proven-to-work parachute sizing techniques.	Dual simulations will validate theoretical parachute performance.	2, Minimal

	parachutes than needed)	drift)				
Excessive Landing Speed	3 (Parachute damage or entanglement, improper load)	5 (Partial or total destruction of vehicle)	15, High	Properly size, pack, and protect parachute.	Test and observe at full scale launch prior to Huntsville.	5, Low
Battery Leakage/ Combustion	2 (Battery compartment becomes punctured)	5 (Potential for ballistic trajectory)	10, Medium	Check battery integrity before each launch.	Include checking battery condition in pre launch checklist.	5, Low
Payload Retention System Failure	3 (Bulkplate failure, screw sheer, connecting rod failure)	4 (Loss of payload, damage to payload, damage to payload orientation system)	12, Medium	Material strength will be tested before flight, all retention system components will be inspected for damage before installation.	Inspection will be documented in flight preparation checklists.	4, Low
Payload Damaged on Landing	3 (Excessive landing speed)	4 (Loss of payload, inability to complete mission)	12, Medium	Landing velocity will be calculated before launch (and parachutes sized accordingly) to reduce the chance of damage on landing.	2 forms of simulation will be used on the launch field to calculated predicted landing speed in current conditions	4, Low
Payload Bay Unable to Extend	4 (Improper landing, exceedingly uneven terrain)	4 (Unable to complete mission)	16, High	Payload extension will be tested in a variety of landing configurations and ground materials	Testing will be documented by payload team lead. (See PT_04.1)	
Payload unable to orient	2 (Damage to seromotor, damage to gyroscope, obstruction in upper airframe)	4 (Unable to complete mission)	8, Medium	Payload bay will be inspected for obstructions and the retention system tested for free rotation prior to integration into airframe.	Testing will be documented by payload team lead. (See PT_04.1)	
Loose Payload in Payload Bay	3 (Damage to payload retention system, improper payload installation)	4 (Improper orientation at payload deployment, possible mass shift affecting flight trajectory)	12, Medium	Payload retention system will be checked for cracks before sealing of launch vehicle, payload installation will be inspected as part of pre-launch procedure.	Inspection steps will be listed in pre-flight checklist.	4, Low

Improper Payload Orientation	4 (Damage to orientation system, system unable to read payload orientation)	4 (Failure to perform payload mission)	16, High	Payload bay will be visually inspected before sealing of launch vehicle for damage to orientation motors and physical obstructions.	Inspection steps will be listed in pre-flight checklist.	4, Low
Payload Rotor Arm Deployment Failure	2 (Damage to payload deployment springs, payload deployment obstruction)	4 (Failure to perform payload mission)	8, Medium	Payload spring systems will be inspected for damage and replaced as necessary.	Payload team lead will be responsible for final payload inspection prior to launch day.	4, Low

Table 7.5: Failure Modes and Effects Analysis

7.5. Environmental Hazard Analysis

Hazard	Likelihood (Cause)	Severity (Effect)	Risk	Mitigation	Verification	Post Mitigation Risk
Landscape	3 (Trees, brush, water, power lines, wildlife)	5 (Inability to recover launch vehicle, payload UAV crash)	15, High	Angle launch vehicle into wind as necessary to reduce drift and avoid hazards.	Inspect launch site before launch to verify that it is a suitable area to launch.	5, Low
Humidity	3 (Climate, poor forecast)	1 (Rust on metallic components)	3, Low	Use as little metal as possible. Store indoors.	Check weather beforehand for ideal launch time.	1, Minimal
Winds	3 (Poor forecast)	4 (Inability to launch, excessive drift, payload UAV drift/control issues)	12, Medium	Angle into wind as necessary and abort if wind exceeds 20 mph.	Check weather beforehand for ideal launch time.	4, Low
Rain/Storms	3 (Poor forecast)	3 (Damage to electrical components)	9, Medium	Keep launch vehicle away from moisture/elements prior to launch. Cover any exposed electrical components.	Visual inspection of electrical components to ensure dry surface.	3, Low
Low Visibility	2 (Fog)	4 (Inability to maintain visual contact with the launch vehicle)	8, Medium	Postpone launch if horizontal visibility is less than 5 miles, or if there is a cloud ceiling below the	Check weather forecast for visibility conditions.	4, Low

				expected apogee with a 20% safety factor.		
High Temperatures	3 (Poor forecast)	3 (Heat stroke or damage to electrical components)	9, Medium	Keep launch vehicle in shaded area until before launch. Provide shaded area to team members as needed.	Check weather beforehand for ideal launch time. Contact will be made with launch site ahead of time to ensure presence of shaded structure, or some structure will be brought by the team.	3, Low
Low Temperatures	3 (Poor forecast)	3 (Frostbite, frost on ground, ice on vehicle, clogging of vehicle ventilation, change in launch vehicle rigidity and mass, higher drag force on launch vehicle)	9, Medium	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. Provide team members with warm environment above 60°F.	Ensure team is notified through email or instant message of all weather on day of launch or manufacturing to wear proper clothing. Do not launch if weather is below designed intent of launch vehicle. Team members exhibiting signs of frostbite will be escorted to designated warm space (heated interior space or vehicle)	3, Low
Pollution From Exhaust	5 (Combustion of APCP motors)	1 (Small amounts of greenhouse gasses emitted)	5, Low	Use only launch vehicle motors approved for use by the National Association of launch vehicle, Canadian Association of launch vehicle, or Tripoli Rocketry Association.	Launch vehicle motors in consideration will be checked by a safety team member to ensure compliance.	5, Low
Pollution From vehicle	2 (Loss of components from vehicle)	3 (Materials degrade extremely slowly, possible harm to wildlife or water contamination)	6, Medium	Properly fasten all components. Scavenge for fallen parts after launch is completed.	Inspect the securements of components before launch. Have designated clean up team for each launch.	3, Low

Pollution from Team Members	2 (Failed disposal of litter, improper cleanup procedures, members walk through important plantlife, farming fields, sod, etc.)	4 (Litter may degrade extremely slowly, wildlife may consume harmful litter)	8, 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, designated waste disposal will be provided.	4, Low
Collisions with Man-made Structures	2 (Failure to properly predict trajectory, failure to choose an appropriate launch area)	5 (Damage to public property or private property not owned by the team, damage to team equipment)	10, Medium	Do not launch under adverse conditions which may affect the course of the launch vehicle (See Wind). Run a large number of tests which analyze the launch vehicle's trajectory mathematically and physically. Choose a launch area which is not close to civilization. Follow launch procedures closely.	Run tests to analyze and estimate the launch vehicle's trajectory so that the launch vehicle's path is known to the team. Do not launch under adverse weather conditions (See Wind) and choose a launch location which allows for open space to avoid accidents.	5, Low
Wildlife Contact with Launch Vehicle	1 (Failure to accurately predict trajectory, unexpected appearance of wildlife, poor choice of launch area)	4 (Damage to vehicle components, damage to wildlife)	4, Low	Launch in an open area with high visibility. Be aware of the surroundings when choosing a launch area and launching.	Perform visual sweep of launch field to ensure no wildlife is present. Gently encourage wildlife displacement if any is present: if cannot be displaced, relocate launch location.	4, Low
Wildlife Contact with Launch Pad	1 (Failure to monitor the launch pad, poor choice of launch area)	4 (Possible inability to launch the launch vehicle, unpredictable launch behavior or trajectory)	4, Low	Have at least one team member monitoring the launch pad at all times. Launch in an open area with high visibility. Be aware of the surroundings when choosing a launch area and	Perform visual sweep of launch field to ensure no wildlife is present. Gently encourage wildlife displacement if any is present: if cannot be displaced, relocate launch location.	4, Low

				launching. If animals tamper with the launchpad do not launch.		
Battery Leakage	3 (Absence of -or damage to - battery casing causing puncture or cracking)	4 (Possible toxic acid leak, heavy metal contamination)	12, 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.	Inspect battery casing prior to launch to ensure the battery is properly protected and unlikely to become punctured.	4, Low
Fire	5 (Exhaust caused by launch vehicle engine)	5 (Possible spread of wildfire, burns to personnel)	25, Very High	Ground will be cleared per NAR standard. Fire extinguishers will be on hand. Flame retardant tarp will be deployed to prevent catching fire. Launch will not be performed on dry brush.	Inspection by safety officer will be performed to ensure compliance with NAR safety standard on minimum clear area. Launch site will be sprayed with water as necessary.	5, Low
Kinetic Damage to Buildings	2 (launch vehicle veers off trajectory causing landing in occupied area)	4 (Repairable destruction to building)	8, Medium	Choose launch site that is remote enough to make this risk negligible.	Ensure minimum distance from significant buildings/structures exceeds minimum personnel distance as established by NAR safety standard by a factor of at least 3.	4, Low
Kinetic Damage to Terrain	5 (launch vehicle has excessive landing speed)	1 (Creation of small ground divots, mild inconvenience to wildlife and flora)	5, Low	Simulate landing conditions to ensure parachute generates sufficient drag to slow launch vehicle to acceptable parameters.	Dual simulations will be performed to ensure proper parachute performance.	2, Minimal
Unstable Ground	2 (Poor choice of launch site, inclement weather creating mud or softening the ground)	3 (Personnel may slip or fall and damage equipment or themselves, launch pad may sink into the ground and cause an	6, Low	A rigid system which can be used to support the launch pad, such as wooden planks (if needed to reduce their flammability, they may be wetted directly underneath	Use designated launch areas as designated to which must strictly follow this rule to be approved.	3, Low

		unexpected trajectory)		the rocket), choice of a launch site which has rigid ground, observation of launch pad condition shortly before launch.		
Obstructions on Launch Field	4 (Rocky terrain, soft/uneven dirt, scrub, sand)	3 (Payload deployment failure)	12, Medium	Payload deployment will be tested on terrains including loose rocks, sand, and dirt ruts.	Testing will be documented by payload team lead. (See PT_04.1)	3, Low

Table 7.6: Environmental Hazard Analysis

7.6. Project Risks Analysis

Hazard	Likelihood (Cause)	Severity (Effect)	Risk	Mitigation	Verification	Post Mitigation Risk
Landscape	3 (Trees, brush, water, power lines, wildlife)	5 (Inability to recover launch vehicle, payload UAV crash)	15, High	Angle launch vehicle into wind as necessary to reduce drift and avoid hazards.	Inspect launch site before launch to verify that it is a suitable area to launch.	5, Low
Humidity	3 (Climate, poor forecast)	1 (Rust on metallic components)	3, Low	Use as little metal as possible. Store indoors.	Check weather beforehand for ideal launch time.	1, Minimal
Winds	3 (Poor forecast)	4 (Inability to launch, excessive drift, payload UAV drift/control issues)	12, Medium	Angle into wind as necessary and abort if wind exceeds 20 mph.	Check weather beforehand for ideal launch time.	4, Low
Rain/Storms	3 (Poor forecast)	3 (Damage to electrical components)	9, Medium	Keep launch vehicle away from moisture/elements prior to launch. Cover any exposed electrical components.	Visual inspection of electrical components to ensure dry surface.	3, Low
Low Visibility	2 (Fog)	4 (Inability to maintain visual contact with the launch vehicle)	8, Medium	Postpone launch if horizontal visibility is less than 5 miles, or if there is a cloud ceiling below the expected apogee with a 20% safety factor.	Check weather forecast for visibility conditions.	4, Low

High Temperatures	3 (Poor forecast)	3 (Heat stroke or damage to electrical components)	9, Medium	Keep launch vehicle in shaded area until before launch. Provide shaded area to team members as needed.	Check weather beforehand for ideal launch time. Contact will be made with launch site ahead of time to ensure presence of shaded structure, or some structure will be brought by the team.	3, Low
Low Temperatures	3 (Poor forecast)	3 (Frostbite, frost on ground, ice on vehicle, clogging of vehicle ventilation, change in launch vehicle rigidity and mass, higher drag force on launch vehicle)	9, Medium	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. Provide team members with warm environment above 60°F.	Ensure team is notified through email or instant message of all weather on day of launch or manufacturing to wear proper clothing. Do not launch if weather is below designed intent of launch vehicle. Team members exhibiting signs of frostbite will be escorted to designated warm space (heated interior space or vehicle)	3, Low
Pollution From Exhaust	5 (Combustion of APCP motors)	1 (Small amounts of greenhouse gasses emitted)	5, Low	Use only launch vehicle motors approved for use by the National Association of launch vehicle, Canadian Association of launch vehicle, or Tripoli Rocketry Association.	Launch vehicle motors in consideration will be checked by a safety team member to ensure compliance.	5, Low
Pollution From vehicle	2 (Loss of components from vehicle)	3 (Materials degrade extremely slowly, possible harm to wildlife or water contamination)	6, Medium	Properly fasten all components. Scavenge for fallen parts after launch is completed.	Inspect the securements of components before launch. Have designated clean up team for each launch.	3, Low
Pollution from Team Members	2 (Failed disposal of litter,	4 (Litter may degrade extremely	8, Medium	Brief team members on proper cleanup procedures. Foster a	Follow societal standards and leave site cleaner than was	4, Low

	improper cleanup procedures, members walk through important plantlife, farming fields, sod, etc.)	slowly, wildlife may consume harmful litter)		mindset of leaving no trace at launch sites. Only the minimum number of required team members should retrieve the launch vehicle.	found. Make sure disposable equipment is kept track of and guaranteed to remain at designated locations, designated waste disposal will be provided.	
Collisions with Man-made Structures	2 (Failure to properly predict trajectory, failure to choose an appropriate launch area)	5 (Damage to public property or private property not owned by the team, damage to team equipment)	10, Medium	Do not launch under adverse conditions which may affect the course of the launch vehicle (See Wind). Run a large number of tests which analyze the launch vehicle's trajectory mathematically and physically. Choose a launch area which is not close to civilization. Follow launch procedures closely.	Run tests to analyze and estimate the launch vehicle's trajectory so that the launch vehicle's path is known to the team. Do not launch under adverse weather conditions (See Wind) and choose a launch location which allows for open space to avoid accidents.	5, Low
Wildlife Contact with Launch Vehicle	1 (Failure to accurately predict trajectory, unexpected appearance of wildlife, poor choice of launch area)	4 (Damage to vehicle components, damage to wildlife)	4, Low	Launch in an open area with high visibility. Be aware of the surroundings when choosing a launch area and launching.	Perform visual sweep of launch field to ensure no wildlife is present. Gently encourage wildlife displacement if any is present: if cannot be displaced, relocate launch location.	4, Low
Wildlife Contact with Launch Pad	1 (Failure to monitor the launch pad, poor choice of launch area)	4 (Possible inability to launch the launch vehicle, unpredictable launch behavior or trajectory)	4, Low	Have at least one team member monitoring the launch pad at all times. 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	Perform visual sweep of launch field to ensure no wildlife is present. Gently encourage wildlife displacement if any is present: if cannot be displaced, relocate launch location.	4, Low

				launch.		
Battery Leakage	3 (Absence of -or damage to - battery casing causing puncture or cracking)	4 (Possible toxic acid leak, heavy metal contamination)	12, 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.	Inspect battery casing prior to launch to ensure the battery is properly protected and unlikely to become punctured.	4, Low
Fire	5 (Exhaust caused by launch vehicle engine)	5 (Possible spread of wildfire, burns to personnel)	25, Very High	Ground will be cleared per NAR standard. Fire extinguishers will be on hand. Flame retardant tarp will be deployed to prevent catching fire. Launch will not be performed on dry brush.	Inspection by safety officer will be performed to ensure compliance with NAR safety standard on minimum clear area. Launch site will be sprayed with water as necessary.	5, Low
Kinetic Damage to Buildings	2 (launch vehicle veers off trajectory causing landing in occupied area)	4 (Repairable destruction to building)	8, Medium	Choose launch site that is remote enough to make this risk negligible.	Ensure minimum distance from significant buildings/structures exceeds minimum personnel distance as established by NAR safety standard by a factor of at least 3.	4, Low
Kinetic Damage to Terrain	5 (launch vehicle has excessive landing speed)	1 (Creation of small ground divots, mild inconvenience to wildlife and flora)	5, Low	Simulate landing conditions to ensure parachute generates sufficient drag to slow launch vehicle to acceptable parameters.	Dual simulations will be performed to ensure proper parachute performance.	2, Minimal
Unstable Ground	2 (Poor choice of launch site, inclement weather creating mud or softening the ground)	3 (Personnel may slip or fall and damage equipment or themselves, launch pad may sink into the ground and cause an unexpected trajectory)	6, Low	A rigid system which can be used to support the launch pad, such as wooden planks (if needed to reduce their flammability, they may be wetted directly underneath the rocket), choice of a launch site which has rigid ground,	Use designated launch areas as designated to which must strictly follow this rule to be approved.	3, Low

				observation of launch pad condition shortly before launch.		
Obstructions on Launch Field	4 (Rocky terrain, soft/uneven dirt, scrub, sand)	3 (Payload deployment failure)	12, Medium	Payload deployment will be tested on terrains including loose rocks, sand, and dirt ruts.	Testing will be documented by payload team lead. (See PT_04.1)	3, Low

Table 7.7 Project Risks Analysis

7.7. Considerations for Application

As demonstrated above, there are numerous ways in which a launch could go wrong. The goal of identifying these hazards and constructing launch preparation procedures is of course to minimize the risk of a launch failure, but no amount of preparation can reduce that chance to zero. As such, several considerations must be made to ensure that not only are the odds of failure as low as possible, but that the team and all spectators are prepared in the event of any foreseeable failure.

In terms of reducing risk, there are two key aspects of preparation which most impact launch safety: process and verification. A good launch runs like a well maintained engine: each component operating in accordance with a predefined process, handing off needed materials and completing operations at such a time as the next step of the process is ready for such a handoff. Construction is ready to perform final assembly as soon as avionics and payload have completed their construction and test. The launch rail is constructed as soon as final assembly has occurred. Of course, each team has a different number of operations it must respectively perform before launch can commence, and as such some teams may have to wait before they become needed for further operations. The goal of predefining launch day operations is to ensure these lapses in action are as small as possible, and to show each team where they fall in the larger assembly; give them a systems view of the process, rather than a subsystems view.

As important as the process is to a safe launch, equally so is verification. The longer one spends looking at their own work, the less likely they are to be able to spot the flaws in it. As such, it is imperative that it not only be encouraged but insisted that there be time set aside for inspection of work by fresh eyes, people not previously involved in the process. These quality witness steps must be done in accordance with a clear and concise list of failure criteria, otherwise the inspector is simply looking at work rather than truly inspecting it.

If enough attention has been paid to the writing of launch day operation checklists, launch preparation will go as smoothly as possible and have the highest likelihood of successful launch. If not, launch operations will grind slowly on, and the chance for small errors to compile will grow dramatically. Investing a decent amount of time to properly prepare for launch will save the team incalculably in terms of time on the launch field and risk of failure.

Finally, as launch day approaches, the team must not only consider its own efforts, but the impact those efforts may have; for this team specifically (and others in the area), launches take place thanks to the generosity of farmers who allow teams to launch from their fields. As such,their land must be treated with respect; all waste generated by the team should be properly disposed of, be it launch essential or superfluous. When operating on or around equipment not owned by the team, the utmost of care and respect should be given to it. When leaving the launch field, one should not be able to tell the team had been there at all.

8. Project Plan

8.1. Derived Requirements & Verification Plans

8.1.1. NASA-Derived R&VP

The following list of requirements are derived by the NASA Student Launch team and need to be completed and followed in order to ensure that the PSP-SL team is constantly meeting the safety standards of high powered flight and completing the goals set by the Student Launch team. The PSP-SL team has looked at all requirements and broken each into several sections to ensure that the team is meeting / exceeding each NASA derived requirement. The sections are as follows: General Requirements & Verification Plans (R&VP), Vehicle R&VP, Avionics & Recovery R&VP, Payload R&VP, and Safety R&VP. Each of the above sections will be broken into individual requirements and will be verified via one of 4 ways: Inspection, Demonstration, Test, and / or Analysis.

1. Inspection: Thorough examination of the system or process using physical manipulation, measurements, or observation via the five human senses.
2. Demonstration: Manipulation of a given system or process intended to verify that the results match the expected results.
3. Test: Verification of a given system or process through the use of a procedure, given relevant inputs, to ensure that the system or process meets and exceeds expected results specified in the requirements.
4. Analysis: Verification of a given system or process through utilizing calculations, academic theory, and system models.

Each of the following requirements, both team derived and NASA derived, has been given a unique ID number which references the requirements from the NASA Student Launch Handbook, written by the NASA Student Launch team.

Additionally, the PSP-SL team has generated a table format which organizes R&VP for each requirement. Each table lists requirement ID, the requirement's description, the team's verification plan for the requirement, additional comments for the requirement (if applicable), the ID for the test which verifies the requirement (if applicable), the status of the requirement (complete or incomplete), and one of four colors which indicates the type of verification. These colors are shown along the left side of each table, and multiple colors means multiple methods of verification. For requirements which are not applicable to the PSP-SL team, these colors were left as white, as was the coloration of the verification status box. A guide to which color corresponds to each verification method follows:

Inspection	**Demonstration**
Analysis	**Test**

Table 8.1: Verification Method Color Key

8.1.1.1. General R&VP

D	**Requirement ID:** 1.1 **Description:** Students on the team will do 100% of the project, including design, construction, written reports, presentations, and flight preparation with the exception of assembling the motors and handling black powder or any variant of ejection charges, or preparing and installing electric matches (to be done by the team's mentor). Teams will submit new work. Excessive use of past work will merit penalties.	**Verification Plan:** PSP-SL members shall demonstrate the new work they have completed by submitting milestone documents and shall demonstrate the understanding they have gained by doing the work themselves during PowerPoint presentations. **Comments:** This requirement will be verified after submission of PLAR.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.2 **Description:** The team will provide and maintain a project plan to include, but not be limited to, the following items: project milestones, budget and community support, checklists, personnel assignments, Science, Technology, Engineering and Math (STEM) engagement events, and risks and mitigations.	**Verification Plan:** Project plan completion shall be demonstrated by turning in the milestone reports which contain it. **Comments:** This requirement is addressed by sections 7 (Safety) and 8 (Project Plan).
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.3 **Description:** Foreign National (FN) team members must be identified by the Preliminary Design Review (PDR) and may or may not have access to certain activities during launch week due to security restrictions. In addition, FN's may be separated from their team during certain activities on site at Marshall Space Flight Center.	**Verification Plan:** Foreign national team members' contact information shall be demonstrated when it is submitted alongside PDR documentation. **Comments:** All PSP-SL FN have been submitted to the board for approval.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.4 **Description:** The team must identify all team members attending launch week activities by the Critical Design Review (CDR). Team members will include:	**Verification Plan:** PSP-SL member contact information shall be demonstrated when it is submitted alongside CDR documentation.

	• Students actively engaged in the project throughout the entire year. • One mentor (see requirement 1.13). • No more than two adult educators.	**Comments:** The team submitted its launch week team member list concurrently with all CDR documents.
Status: *Complete*		**Verification Test ID:** N/A

D	**Requirement ID:** 1.5 **Description:** The team will engage a minimum of 200 participants in educational, hands-on Science, Technology, Engineering, and Mathematics (STEM) activities, as defined in the STEM Engagement Activity Report, by FRR. To satisfy this requirement, all events must occur between project acceptance and the FRR due date and the STEM Engagement Activity Report must be submitted via email within two weeks of the completion of the event.	**Verification Plan:** STEM Engagement Activity Reports shall be completed and demonstrated to the NASA Student Launch team via email throughout the course of the project. Activity Reports shall be submitted within a week of each event occurring so documentation can be written accurately.
		Comments: As of FRR the team has engaged with 1,219 students and is continually planning more events. This requirement has more discussion within section 8.
Status: *Complete*		**Verification Test ID:** N/A

D	**Requirement ID:** 1.6 **Description:** The team will establish a social media presence to inform the public about team activities.	**Verification Plan:** PSP-SL's social media information shall be publicly available online and links to each social media outlet of the team shall be provided to the NASA Student Launch team.
		Comments: The team has a social media presence on Twitter, Facebook, Instagram, and a personal website, which it has informed the NASA Student Launch Team about.
Status: *Complete*		**Verification Test ID:** N/A

D	**Requirement ID:** 1.7 **Description:** Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large	**Verification Plan:** All deliverables shall be demonstrated to the NASA project management via email or link by the deadlines listed in the Project Plan section. All milestone deliverables will be completed at least a week in advance so they can be reviewed and submitted on time.

	to attach to an email, inclusion of a link to download the file will be sufficient.	**Comments**: The team will attempt to deliver all deliverables the day before they are due. This requirement has been completed for all deliverables submitted to the NASA Student Launch Team as of FRR with the exception of social media forms which experienced an email delay and arrived a minute late.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.8 **Description:** All deliverables must be in PDF format.	**Verification Plan:** Each deliverable shall be downloaded from the team's Google Drive folder in a PDF format before being sent, and shall be stored in the drive if needed again in the future.
		Comments: This requirement has been completed for all deliverables submitted to the NASA Student Launch Team as of FRR.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.9 **Description:** In every report, teams will provide a table of contents including major sections and their respective sub-sections.	**Verification Plan:** Tables of contents shall be included at the beginning of each milestone report and will be included when the report is submitted to the NASA Student Launch Team.
		Comments: This requirement has been completed for all milestone reports submitted to the NASA Student Launch Team as of FRR.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.10 **Description:** In every report, the team will include the page number at the bottom of the page.	**Verification Plan:** Each milestone report submitted to the NASA Student Launch team shall have a page number visible at the bottom-right corner of each page.
		Comments: This requirement has been completed for all milestone reports submitted to the NASA Student Launch Team as of FRR.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.11 **Description:** The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.	**Verification Plan:** PSP-SL shall demonstrate its capability to conduct video teleconferences by participating in all milestone presentation conferences with the NASA Student Launch team, and will only use speakerphones if there is no device available which can transmit better audio quality. **Comments:** This requirement has been verified via participation in PDR and CDR presentations.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.12 **Description:** All teams will be required to use the launch pads provided by Student Launch's launch services provider. No custom pads will be permitted on the launch field. At launch, 8' 1010 rails and 12' 1515 rails will be provided. The launch rails will be canted 5 to 10° away from the crowd on launch day. The exact cant will depend on launch day wind conditions.	**Verification Plan:** PSP-SL shall demonstrate its full scale vehicle's compatibility with the launch pads provided by the launch services provider by launching its full scale vehicle demonstration flight on a 12' 1515 launch rail. **Comments:** The team has chosen to use a 12' 1515 launch rail on launch day and at its full-scale demonstration flights.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 1.13 **Description:** Each team must identify a "mentor." A mentor is defined as an adult who is included as a team member, who will be supporting the team (or multiple teams) throughout the project year, and may or may not be affiliated with the school, institution, or organization. The mentor must maintain a current certification and be in good standing through the National Association of Rocketry (NAR) or Tripoli Rocketry Association (TRA) for the motor impulse of the launch vehicle and must have flown and successfully recovered (using electronic, staged recovery) a minimum of 2 flights in this or a higher impulse class, prior to PDR. The mentor is designated as the individual owner of the launch vehicle for liability purposes and must travel with the team to launch	**Verification Plan:** Information on PSP-SL's mentor shall be provided within project milestone documentation, which will be supplied to the NASA Student Launch team via email. This information will include the mentor's affiliation with NAR and TRA and the mentor's number of level 1, 2, and 3, high-power rocketry flights, as defined by NAR.

	week. One travel stipend will be provided per mentor regardless of the number of teams he or she supports. The stipend will only be provided if the team passes FRR and the team and mentor attend launch week in April.	**Comments:** The PSP-SL mentor for the 2019-2020 competition is Victor Barlow.
	Status: *Complete*	**Verification Test ID:** N/A

8.1.1.2. Vehicle R&VP

A	**Requirement ID:** 2.1 **Description:** The vehicle will deliver the payload to an apogee altitude between 3,500’ and 5,500’ above ground level. Teams flying below 3,000’ or above 6,000’ on Launch Day will be disqualified and receive zero altitude points towards their overall project score.	**Verification Plan:** The altitude shall be determined through OpenRocket simulations, RASAero, and MATLAB code of the launch vehicle trajectory. **Comments:** The team has chosen a target altitude between 3,500’ and 5,500’. Capability to launch within this range was proven during the first full-scale demonstration flight and will be reverified at the second full-scale demonstration flight.
	Status: *Complete*	**Verification Test ID:** N/A

A	**Requirement ID:** 2.2 **Description:** Teams shall identify their target altitude goal at the PDR milestone. The declared target altitude will be used to determine the team’s altitude score during Launch Week.	**Verification Plan:** The team shall use OpenRocket simulations, RASAero, and MATLAB code to predict the target altitude. **Comments:** The team has chosen its target altitude to be 4325’.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 2.3 **Description:** The vehicle will carry one commercially available, barometric altimeter for recording the official altitude used in determining the Altitude Award winner. The Altitude Award will be given to the team with the smallest difference between their measured apogee and their official target altitude on launch day. This altimeter may also be used for deployment purposes (see Requirement 3.4).	**Verification Plan:** The existence of a commercial altimeter in the launch vehicle shall be verified through inspection. **Comments:** A redundant set of commercially available altimeters are included in the launch vehicle and used to verify its apogee.

Status: *Complete*	**Verification Test ID:** N/A

T	**Requirement ID:** 2.4 **Description:** The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.	**Verification Plan:** The team shall reuse the launch vehicle in subscale and full scale test flights. **Comments:** This requirement will be verified via a successful full-scale demonstration flight which results in no damages to the launch vehicle.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.5 **Description:** The launch vehicle will have a maximum of four (4) independent sections. An independent section is defined as a section that is either tethered to the main vehicle or is recovered separately from the main vehicle using its own parachute.	**Verification Plan:** The team shall demonstrate that there are no more than 4 independent sections via documentation in CDR. **Comments:** The team's current design consists of three tethered sections.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 2.5.1 **Description:** Coupler/airframe shoulders which are located at in-flight separation points will be at least 1 body diameter in length.	**Verification Plan:** The team shall measure to make sure the coupler/airframe shoulders that are located at in-flight separation points are at least 1 body diameter (6") in length. **Comments:** The avionics bay is the only section located on an in-flight separation point, and the upper and lower airframe each overlay with the coupler by 6" (1 diameter).
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.5.2 **Description:** Nosecone shoulders which are located at in-flight separation points will be at least ½ body diameter in length.	**Verification Plan:** The team shall verify via demonstration in the CDR documentation that there are no in-flight separation points which need to be at least ½ body diameter (3") in length. **Comments:** The team's current design does not have an in-flight separation point at the nosecone shoulder.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.6 **Description:** The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens.	**Verification Plan:** The preparation time of the launch vehicle shall be verified through testing at both full scale launch vehicle and payload demonstration flights. **Comments:** The team has made it a priority to prepare the night prior to ALL launch days. The vehicle, excluding prior on-site testing of payload and avionics systems, was able to be assembled within a two-hour time frame at the first full-scale demonstration flight, validating this requirement.
	Status: Complete	**Verification Test ID:** N/A

T	**Requirement ID**: 2.7 **Description:** The launch vehicle and payload will be capable of remaining in launch-ready configuration on the pad for a minimum of 2 hours without losing the functionality of any critical on-board components, although the capability to withstand longer delays is highly encouraged.	**Verification Plan**: Ability of the vehicle and payload to remain in launch-ready configuration shall be verified by ground testing. **Comments:** Payload testing has confirmed the payload system can be powered for at least six hours, and avionics testing has confirmed the avionics can be powered for at least three hours.
	Status: Complete	**Verification Test ID**: A_04 AND PT_07.1

D	**Requirement ID:** 2.8 **Description:** The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider.	**Verification Plan:** The team shall use a standard 12-volt direct current firing system during its full-scale test launches to ensure successful integration with such a system can be achieved. **Comments:** This requirement was verified by a successful takeoff from a 12-volt DC firing system at the first full-scale demonstration flight.
	Status: Complete	**Verification Test ID:** N/A

D	**Requirement ID:** 2.9 **Description:** The launch vehicle will require no external circuitry or special ground support equipment to initiate launch (other than what is provided by the launch services provider).	**Verification Plan:** Ability to launch without external circuitry or special ground support shall be demonstrated in designs presented for PDR and CDR and proven in flight testing. **Comments:** This requirement was verified by the sub-scale and full-scale demonstration flights.
	Status: Complete	**Verification Test ID:** N/A

<table>
<tr><td>I</td><td rowspan="2">Requirement ID: 2.10

Description:
The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli RocketryAssociation (TRA), and/or the Canadian Association of Rocketry (CAR).</td><td>Verification Plan: Use of required solid motor propulsion system shall be verified by inspection of the launch vehicle and demonstration during flights.</td></tr>
<tr><td>D</td><td>Comments: The team decided to use the CTI L1115 4 grain SRM. This motor is compliant with NAR, TRA, and CAR.</td></tr>
<tr><td colspan="2">Status: Complete</td><td>Verification Test ID: N/A</td></tr>
</table>

<table>
<tr><td rowspan="2">D</td><td rowspan="2">Requirement ID: 2.10.1

Description:
Final motor choice will be declared by the Critical Design Review (CDR) milestone.</td><td>Verification Plan: The team shall demonstrate that a final motor was chosen by showing its motor choice in CDR.</td></tr>
<tr><td>Comments: The team decided, as of CDR, to use the CTI L1115 4 grain SRM. This motor is compliant with NAR, TRA, and CAR.</td></tr>
<tr><td colspan="2">Status: Complete</td><td>Verification Test ID: N/A</td></tr>
</table>

<table>
<tr><td rowspan="2">D</td><td rowspan="2">Requirement ID: 2.10.2

Description:
Any motor change after CDR must be approved by the NASA Range Safety Officer (RSO) and will only be approved if the change is for the sole purpose of increasing the safety margin. A penalty against the team's overall score will be incurred when a motor change is made after the CDR milestone, regardless of the reason.</td><td>Verification Plan: If the team must use another motor, the team shall document the motor change after approval from the NASA RSO.</td></tr>
<tr><td>Comments: The team purchased three motors for use with full-scale flights and does not anticipate any need to change. This requirement will be verified after either PLAR is completed or a motor change is conducted and verified by the NASA RSO.</td></tr>
<tr><td colspan="2">Status: In Progress</td><td>Verification Test ID: N/A</td></tr>
</table>

<table>
<tr><td>I</td><td rowspan="2">Requirement ID: 2.11

Description:
The launch vehicle will be limited to a single stage.</td><td>Verification Plan: Limitation of a single stage in launch vehicle shall be verified by inspection and demonstrated in design documentation for CDR.</td></tr>
<tr><td>D</td><td>Comments: This requirement has been verified by CDR documentation.</td></tr>
<tr><td colspan="2">Status: Complete</td><td>Verification Test ID: N/A</td></tr>
</table>

I	**Requirement ID:** 2.12 **Description:** The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class). The total impulse provided by a High School or Middle School launch vehicle will not exceed 2,560 Newton-seconds (K-class).	**Verification Plan:** Total impulse shall be verified by consulting the specifications provided by the manufacturer of the solid rocket motor used onboard the launch vehicle. **Comments:** The chosen motor, the CTI L1115 4 grain, meets this requirement with a total impulse of 5015 N-s.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 2.13 **Description:** Pressure vessels on the vehicle will be approved by the RSO and will meet requirements 2.13.1, 2.13.2, and 2.13.3	**Verification Plan:** See respective verifications for 2.13.1, 2.13.2, and 2.13.3. The vehicle shall also be presented to the RSO for hands on inspection. **Comments:** Requirements 2.13.1, 2.13.2, and 2.13.3 have either been completed or are not applicable because the launch vehicle has no pressure vessels. This requirement will be completed after the RSO inspects the launch vehicle during launch week.
	Status: *In Progress*	**Verification Test ID:** N/A

T A	**Requirement ID:** 2.13.1 **Description:** The minimum factor of safety (Burst or Ultimate pressure versus Max Expected Operating Pressure) will be 4:1 with supporting design documentation included in all milestone reviews.	**Verification Plan:** Use of minimum 4:1 safety factor shall be verified through inspection (safety factor will appear in the calculation to determine max expected altitude. **Comments:** FEA and an avionics ejection test was successfully conducted to provide verification for this requirement as it applies to launch vehicle section separation via black powder charge.
	Status: *Complete*	**Verification Test ID:** A_03

	Requirement ID: 2.13.2 **Description:** Each pressure vessel will include a pressure relief valve that sees the full pressure of the tank and is capable of withstanding the maximum pressure and flow rate of the tank.	**Verification Plan:** N/A **Comments:** There is no pressure tank in the current design of the vehicle, therefore this requirement does not apply.

	Status: N/A	**Verification Test ID:** N/A

	Requirement ID: 2.13.3 **Description:** The full pedigree of the tank will be described, including the application for which the tank was designed and the history of the tank. This will include the number of pressure cycles put on the tank, the dates of pressurization/depressurization, and the name of the person or entity administering each pressure event.	**Verification Plan:** N/A **Comments:** There is no pressure tank in the current design of the vehicle, therefore this requirement does not apply.
	Status: N/A	**Verification Test ID:** N/A

I	**Requirement ID:** 2.14 **Description:** The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	**Verification Plan:** The minimum static stability shall be verified by measuring the axial distance between the center of gravity and the center of pressure of the vehicle. **Comments:** The team used verification off of the rail stability through the use of OpenRocket, RASAero, and an in-house stability code. The team has also verified the rocket is stable coming off the rail during the first vehicle demonstration flight.
	Status: Complete	**Verification Test ID:** N/A

A	**Requirement ID:** 2.15 **Description:** Any structural protuberance on the launch vehicle will be located aft of the burnout center of gravity.	**Verification Plan:** If structural protuberances exist on the launch vehicle, the burnout center of gravity shall be found via analysis and simulation and marked on the launch vehicle to ensure there are no protuberances in the fore direction. **Comments:** The team's launch vehicle does not have any structural protuberances.
	Status: N/A	**Verification Test ID:** N/A

D	**Requirement ID:** 2.16 **Description:** The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	**Verification Plan:** The minimum velocity shall be verified through OpenRocket simulations and the vehicle demonstration test flight. **Comments:** The team verified rail exit velocity through the use of OpenRocket, RASAero, and an in-house trajectory code. Additionally, the full-scale demonstration flight rail exit velocity was greater than 52 fps.

Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.17 **Description:** All teams will successfully launch and recover a subscale model of their launch vehicle prior to CDR. Subscales are not required to be high power launch vehicles.	**Verification Plan:** The team shall demonstrate that the team completed a launch successfully by showing proof in CDR. **Comments:** The team completed a successful subscale launch on 11/24/2019.
	Status: *Complete*	**Verification Test ID:** N/A

A	**Requirement ID:** 2.17.1 **Description:** The subscale model should resemble and perform as similarly as possible to the full-scale model, however, the full-scale will not be used as the subscale model.	**Verification Plan:** The team shall analyze major dimensions and weights of the full-scale and halved them to aptly resemble the full-scale model. **Comments:** The team completed a successful subscale launch on 11/24/2019. This vehicle closely resembled the team's 2020 full scale launch vehicle.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 2.17.2 **Description:** The subscale model will carry an altimeter capable of recording the model's apogee altitude.	**Verification Plan:** The team shall inspect the subscale model before launch to make sure a capable altimeter is installed. **Comments:** The team used a MissileWorks RRC3+ Sport altimeter as a primary source for collecting telemetry. The team also used a redundant altimeter, JollyLogic AltimeterOne, to verify the apogee.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.17.3 **Description:** The subscale launch vehicle must be a newly constructed launch vehicle, designed and built specifically for this year's project.	**Verification Plan:** Documented new construction processes and changes in design to the 2019-2020 subscale shall be included in the CDR report. **Comments:** The subscale launch vehicle resembles the 2020 PSP-SL full scale launch vehicle and was constructed in the Fall 2019.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.17.4 **Description:** Proof of a successful subscale flight shall be supplied in the CDR report. Altimeter data output may be used to meet this requirement.	**Verification Plan:** The team shall demonstrate that the team made a successful subscale flight via documentation in CDR. **Comments:** The team has attached the results showing the subscale flight has been completed in Section 3.2.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.18.1 **Description:** All teams will successfully launch and recover their full-scale launch vehicle prior to FRR in its final flight configuration. The launch vehicle flown must be the same launch vehicle to be flown on launch day.	**Verification Plan:** The team shall demonstrate and make sure the launch vehicle meets the requirements. **Comments:** The team conducted their first demonstration flight which was unsuccessful. The team will be conducting a reflight in early March, after which this requirement will be completed. The launch vehicle is currently under construction and all necessary flight tests will be reconducted prior to flight.
	Status: *In Progress*	**Verification Test ID:** N/A

T	**Requirement ID:** 2.18.1.1 **Description:** The vehicle and recovery system will have functioned as designed.	**Verification Plan:** The team shall verify the functions of the launch vehicle and recovery system through testing and full-scale demonstration flight. **Comments:** This requirement will be completed when all verification tests listed are completed and the full-scale demonstration flight results in a successful recovery.
	Status: *In Progress*	**Verification Test ID:** A_01, A_02, A_03, A_41, A_05

D	**Requirement ID:** 2.18.1.2 **Description:** The full-scale launch vehicle must be a newly constructed launch vehicle, designed and built specifically for this year's project.	**Verification Plan:** The team shall demonstrate via milestone report documentation that the full-scale launch vehicle is newly designed and built. **Comments:** The full-scale launch vehicle which is currently under construction matches the new 2020 design discussed in all 2019-2020 milestone reports until this point.
	Status: *Complete*	**Verification Test ID:** N/A

	Requirement ID: 2.18.1.3 **Description:**	**Verification Plan:** N/A

	The payload does not have to be flown during the full-scale Vehicle Demonstration Flight.	**Comments:** The team's current design requires the payload Retention & Deployment system, regardless if the drone is being flown. There are no plans to fly the full-scale launch vehicle without the payload inside.
Status: N/A		**Verification Test ID:** N/A

I	**Requirement ID:** 2.18.1.3.1 **Description:** If the payload is not flown, mass simulators will be used to simulate the payload mass.	**Verification Plan:** The team shall inspect to make sure a mass simulator is used in the case that the payload is not configured properly to be inserted to the vehicle. Alternatively, the team will inspect to make sure the payload is being flown.
		Comments: The team's current design requires the payload Retention & Deployment system, regardless of if the drone is being flown. There are no plans to fly the full-scale launch vehicle without the payload inside.
Status: N/A		**Verification Test ID:** N/A

A	**Requirement ID:** 2.18.1.3.2 **Description:** The mass simulators will be located in the same approximate location on the launch vehicle as the missing payload mass.	**Verification Plan:** The team shall analyze and verify that any mass simulators do not change the location of the vehicle's center of mass.
		Comments: The team will use the overall payload weight and system center of gravity as verification for the location for the mass simulator, in the case that mass simulators are used. There are no plans to fly the full-scale launch vehicle without the payload inside.
Status: N/A		**Verification Test ID:** N/A

I	**Requirement ID:** 2.18.1.4 **Description:** If the payload changes the external surfaces of the launch vehicle (such as with camera housings or external probes) or manages the total energy of the vehicle, those systems will be active during the full-scale Vehicle Demonstration Flight.	**Verification Plan:** The team shall inspect and make sure any external or energy-modifying payload systems are active during demonstration flight.
		Comments: The team's 2020 design currently does not have any external or energy-modifying payload systems.
Status: N/A		**Verification Test ID:** N/A

I	**Requirement ID:** 2.18.1.5 **Description:** Teams shall fly the launch day motor for the Vehicle Demonstration Flight. The team may request a waiver for the use of an alternative motor in advance if the home launch field cannot support the full impulse of the launch day motor or in other extenuating circumstances (such as weather).	**Verification Plan:** The team shall make sure the motor used for demonstration flights is the launch day motor by inspecting the motor.
		Comments: The team currently has all three motors it plans to use on hand, and they are all the same motor. The team does not anticipate any need for this to change.

Status: Complete	Verification Test ID: N/A

A	**Requirement ID:** 2.18.1.6 **Description:** The vehicle must be flown in its fully ballasted configuration during the full-scale test flight. Fully ballasted refers to the same amount of ballast that will be flown during the launch day flight. Additional ballast may not be added without a re-flight of the full-scale launch vehicle.	**Verification Plan:** The team shall inspect the vehicle to make sure it is flown in its fully ballasted configuration during the full-scale demonstration flight. **Comments:** As of FRR, the team added a few pounds of ballast to the launch vehicle after running several simulations to confirm.
	Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** 2.18.1.7 **Description:** After successfully completing the full-scale demonstration flight, the launch vehicle or any of its components will not be modified without the concurrence of the NASA Range Safety Officer (RSO).	**Verification Plan:** The team shall demonstrate that the launch vehicle has not changed since FRR addendum submission by bringing a launch vehicle to Huntsville which matches the design described in the FRR addendum. **Comments:** This requirement will be verified when a vehicle which matches the same configuration as that used in the vehicle demonstration flight is flown in Huntsville.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.18.1.8 **Description:** Proof of a successful flight shall be supplied in the FRR report. Altimeter data output is required to meet this requirement.	**Verification Plan:** The team will demonstrate that a successful flight occurred by showing altimeter data output in the FRR report (or the FRR report addendum, in case of a launch failure). **Comments:** AltusMetrum Telemetrum, MissileWorks, and JollyLogic AltimeterOne will all be flown to ensure that an apogee is successfully collected. This information will be supplied in the FRR report addendum. The telemetry data from the first vehicle demonstration flight has been provided in section 3.2.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.18.1.9 **Description:** Vehicle Demonstration flights must be completed by the FRR submission deadline. No exceptions will be made. If the Student Launch office determines that a Vehicle Demonstration Re-flight is necessary, then an extension may be granted. THIS EXTENSION IS	**Verification Plan:** The team will demonstrate that a successful flight has occurred via documentation included in a milestone report. **Comments:** The team conducted the first vehicle demonstration flight on February

	ONLY VALID FOR RE-FLIGHTS, NOT FIRST TIME FLIGHTS. Teams completing a required re-flight must submit an FRR Addendum by the FRR Addendum deadline.	15th 2020. The flight was unsuccessful and the team was given permission to refly the launch vehicle, so this requirement will be complete when the FRR addendum is submitted.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.18.2 **Description:** Payload Demonstration Flight - All teams will successfully launch and recover their full-scale launch vehicle containing the completed payload prior to the Payload Demonstration Flight deadline. The launch vehicle flown must be the same launch vehicle to be flown on launch day. The purpose of the Payload Demonstration Flight is to prove the launch vehicle's ability to safely retain the constructed payload during flight and to show that all aspects of the payload perform as designed. A successful flight is defined as a launch in which the launch vehicle experiences stable ascent and the payload is fully retained until it is deployed (if applicable) as designed.	**Verification Plan:** The team shall demonstrate that the vehicle can be successfully flown with the completed payload. **Comments:** The R&D system had no identified problems during the first vehicle demonstration flight, but the flight was unsuccessful. This requirement will be completed with the completion of a successful full-scale demonstration flight.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.18.2.1 **Description:** The payload must be fully retained until the intended point of deployment (if applicable), all retention mechanisms must function as designed, and the retention mechanism must not sustain damage requiring repair.	**Verification Plan:** The team shall verify that the R&D system is functional during flight via demonstrating its performance in a demonstration flight. **Comments:** The payload retention and deployment mechanisms functioned as designed during the full-scale demonstration flight, but sustained damage upon landing. This requirement will be completed upon a successful payload demonstration flight.
	Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** 2.18.2.2 **Description:** The payload flown must be the final, active version.	**Verification Plan:** The team shall verify that the payload flown is the final version by inspecting the payload.

		Comments: This requirement shall be completed upon a successful payload demonstration flight.
	Status: *In Progress*	**Verification Test ID:** N/A

	Requirement ID: 2.18.2.3 **Description:** If requirements 2.18.2.1 and 2.18.2.2 are met during the original Vehicle Demonstration Flight, occurring prior to the FRR deadline and the information is included in the FRR package, the additional flight and FRR Addendum are not required.	**Verification Plan:** N/A **Comments:** N/A
	Status: N/A	**Verification Test ID:** N/A

D	**Requirement ID:** 2.18.2.4 **Description:** Payload Demonstration Flights must be completed by the FRR Addendum deadline. NO EXTENSIONS WILL BE GRANTED.	**Verification Plan:** The team shall verify that the payload demonstration flight is complete by the FRR Addendum by including information demonstrating its completion in the FRR Addendum deadline. **Comments:** This requirement shall be completed upon submission of the FRR Addendum.
	Status: *Incomplete*	**Verification Test ID:** N/A

D	**Requirement ID:** 2.19 **Description:** An FRR Addendum will be required for any team completing a Payload Demonstration Flight or NASA required Vehicle Demonstration Re-flight after the submission of the FRR Report.	**Verification Plan:** The team shall verify the FRR addendum has been completed by downloading it as a PDF and submitting it to the NASA Student Launch Team. **Comments:** The team will submit an FRR Addendum to verify its payload demonstration flight has been completed after submitting FRR report.
	Status: *Incomplete*	**Verification Test ID:** N/A

	Requirement ID: 2.19.1 **Description:**	**Verification Plan:** N/A

	Teams required to complete a Vehicle Demonstration Re-Flight and failing to submit the FRR Addendum by the deadline will not be permitted to fly the vehicle at launch week.	**Comments:** N/A
Status: N/A		**Verification Test ID:** N/A

	Requirement ID: 2.19.2 **Description:** Teams who successfully complete a Vehicle Demonstration Flight but fail to qualify the payload by satisfactorily completing the Payload Demonstration Flight requirement will not be permitted to fly the payload at launch week.	**Verification Plan:** N/A **Comments:** N/A
Status: N/A		**Verification Test ID:** N/A

	Requirement ID: 2.19.3 **Description:** Teams who complete a Payload Demonstration Flight which is not fully successful may petition the NASA RSO for permission to fly the payload at launch week. Permission will not be granted if the RSO or the Review Panel have any safety concerns.	**Verification Plan:** N/A **Comments:** N/A
Status: N/A		**Verification Test ID:** N/A

I	**Requirement ID:** 2.20 **Description:** The team's name and launch day contact information shall be in or on the launch vehicle airframe as well as in or on any section of the vehicle that separates during flight and is not tethered to the main airframe. This information shall be included in a manner that allows the information to be retrieved without the need to open or separate the vehicle.	**Verification Plan:** The team shall inspect the launch vehicle and make sure all required information exists on each separate part. **Comments:** The team plans on attaching a note on each section with the team contact information and name after the full-scale vehicle has finished construction. This requirement will be completed at that time.
Status: Incomplete		**Verification Test ID:** N/A

I	**Requirement ID:** 2.21 **Description:**	**Verification Plan:** The team shall inspect the placement and visuals of lithium polymer batteries to ensure this requirement is met. The team

	All Lithium Polymer batteries will be sufficiently protected from impact with the ground and will be brightly colored, clearly marked as a fire hazard, and easily distinguishable from other payload hardware.	will wrap all LiPo batteries in bright orange duct tape to ensure that the batteries are clearly marked. **Comments:** This requirement will be completed after the final flight of the launch vehicle in Huntsville.
	Status: *In Progress*	**Verification Test ID:** N/A

I D	**Requirement ID:** 2.22.1 **Description:** The launch vehicle will not utilize forward canards. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the launch vehicle's stability.	**Verification Plan:** The team shall verify the absence of forward canards through inspection of the vehicle and demonstration of the design in milestone reports. **Comments:** The team's 2020 design does not and will not use any canards or external camera housings.
	Status: Complete	**Verification Test ID:** N/A

I D	**Requirement ID:** 2.22.2 **Description:** The launch vehicle will not utilize forward firing motors.	**Verification Plan:** The team shall verify the absence of forward firing motors through inspection of the launch vehicle and demonstration at the vehicle demonstration flight.. **Comments:** The team's 2020 design does not and will not use any forward firing motors.
	Status: Complete	**Verification Test ID:** N/A

D	**Requirement ID:** 2.22.3 **Description:** The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, Metal-Storm, etc.)	**Verification Plan:** The team shall verify the absence of prohibited motors through demonstration at the vehicle demonstration flight. **Comments:** The team's 2020 design does not and will not use any motors that expel titanium sponges.
	Status: Complete	**Verification Test ID:** N/A

D	**Requirement ID:** 2.22.4 **Description:** The launch vehicle will not utilize hybrid motors.	**Verification Plan:** The team shall verify the absence of hybrid motors through demonstration at the vehicle demonstration flight.

		Comments: The team's 2020 design does not and will not use any hybrid motors.
Status: Complete		**Verification Test ID:** N/A

I D	**Requirement ID**: 2.22.5 **Description**: The launch vehicle will not utilize a cluster of motors.	**Verification Plan:** The team shall verify the absence of a cluster of motors through inspection of the vehicle and demonstration at the vehicle demonstration flight.
		Comments: The team's 2020 design does not and will not utilize a cluster of motors.
Status: Complete		**Verification Test ID:** N/A

I	**Requirement ID:** 2.22.6 **Description:** The launch vehicle will not utilize friction fitting for motors.	**Verification Plan:** The team shall verify the absence of friction fitting through inspection of the launch vehicle.
		Comments: The team's 2020 design does not and will not use any friction fitting for motors..
Status: Complete		**Verification Test ID:** N/A

A	**Requirement ID:** 2.22.7 **Description:** The launch vehicle will not exceed Mach 1 at any point during flight.	**Verification Plan:** The team shall use calculations and OpenRocket launch vehicle simulations to verify the max speed does not exceed Mach 1.
		Comments: This requirement was verified through OpenRocket, RASAero, and in-house trajectory MATLAB code.
Status: Complete		**Verification Test ID:** N/A

A	**Requirement ID:** 2.22.8 **Description:** Vehicle ballast will not exceed 10% of the total unballasted weight of the launch vehicle as it would sit on the pad (i.e. a launch vehicle with an unballasted weight of 40lbm. on the pad may contain a maximum of 4lbm. of ballast).	**Verification Plan:** The team shall verify the percent of unballasted weight the ballast represents by analyzing the full-scale vehicle's mass margins and the expected amount of ballast needed to reach the desired apogee.
		Comments: As of FRR, the launch vehicle is underweight, and the team has incorporated ballast which is under 10% of that weight on the vehicle which will be flown at the second vehicle demonstration flight.
Status: Complete		**Verification Test ID:** N/A

	Requirement	Verification
A	**Requirement ID:** 2.22.9 **Description:** Transmissions from onboard transmitters will not exceed 250 mW of power (per transmitter).	**Verification Plan:** The team shall calculate power transmitted by each transmitter and make sure it does not exceed 250mW. **Comments:** The team does not utilize any transmitters that exceed 250 mW.
	Status: *Complete*	**Verification Test ID:** N/A

	Requirement	Verification
T A	**Requirement ID:** 2.22.10 **Description:** Transmitters will not create excessive interference. Teams will utilize unique frequencies, hand- shake/passcode systems, or other means to mitigate interference caused to or received from other teams.	**Verification Plan:** The team shall test whether or not the transmitter does not create excessive interference after hypothesizing whether it might via calculation. **Comments:** The team will ensure that proper transmission procedures are used during any and all transmissions. This requirement will be completed after the final full-scale flight in Huntsville.
	Status: *In Progress*	**Verification Test ID:** N/A

	Requirement	Verification
I A	**Requirement ID:** 2.22.11 **Description:** Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses.	**Verification Plan**: The team shall inspect the metal used and its properties to find if it meets this requirement and shall analyze how the metal deals with airframe structural integrity. **Comments:** The team utilizes lightweight metal in the construction of the payload R&D system and at the tip of the nose cone.
	Status: *Complete*	**Verification Test ID:** N/A

8.1.1.3. Avionics and Recovery R&VP

I	**Requirement ID:** 3.1 **Description:** The launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee, and a main parachute is deployed at a lower altitude. Tumble or streamer recovery from apogee to main parachute deployment is also permissible, provided that kinetic energy during drogue stage descent is reasonable, as deemed by the RSO.	**Verification Plan:** The team shall design the recovery system in accordance with the requirement and it will be documented within the vehicle design section of FRR. **Comments:** The team has thoroughly inspected the vehicle design ensuring that it meets this requirement.
	Status: *Complete*	**Verification Test ID:** N/A

T	**Requirement ID:** 3.1.1 **Description:** The main parachute shall be deployed no lower than 500'.	**Verification Plan:** The main parachute shall be programmed to deploy at 800' to ensure that by the time it reaches 500', it is fully open. **Comments:** This was verified on the 2nd of February when the success criteria was met for the Parachute Drop Test (A_05).
	Status: *Complete*	**Verification Test ID:** A_05

D	**Requirement ID:** 3.1.2 **Description:** The apogee event may contain a delay of no more than 2 seconds.	**Verification Plan:** The team shall verify this requirement by ensuring that the primary charge deploys no more than 2 seconds after apogee during the subscale and both full scale demonstration launches. **Comments:** This was completed on the 24th of November as part of the subscale launch and also on the 15th of February as part of the vehicle demonstration flight.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 3.1.3 **Description:** Motor ejection is not a permissible form of primary or secondary deployment.	**Verification Plan:** The team shall deploy the main and drogue parachutes via charges contained on either side of the avionics bay. This is verified throughout the entire design and during both of the full-scale demonstration flights. **Comments:** This was completed during the vehicle demonstration flight on the 15th of February and will be proven again during the secondary vehicle demonstration reflight.

Status: *Complete*	**Verification Test ID:** N/A

T	**Requirement ID:** 3.2 **Description:** Each team must perform a successful ground ejection test for both the drogue and main parachutes prior to the initial subscale and full-scale launches.	**Verification Plan:** The team shall ensure that the avionics bay separates at least 6" from the corresponding airframe with respect to its respective black powder charge. **Comments:** This was completed after conducting test A_03 on the 26th of January, and all success criteria were met.
	Status: *Complete*	**Verification Test ID:** A_03

A	**Requirement ID:** 3.3 **Description:** Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.	**Verification Plan:** The team shall ensure the landing kinetic energy does not exceed the maximum limit. This shall be verified through MATLAB landing kinetic energy code, ensuring that a proper main parachute is chosen. **Comments:** This was completed through a parachute literature review and study of a wide array of parachutes that fit within the competitions order or magnitude.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 3.4 **Description:** The recovery system will contain redundant, commercially available altimeters. The term "altimeters" includes both simple altimeters and more sophisticated flight computers.	**Verification Plan:** The team shall ensure that the avionics design consists of two commercially available altimeters. The team will also ensure that the two altimeters are not from the same company. **Comments:** The team has chosen to use the Altus Metrum Telemetrum as the primary altimeter and the Missile Works RRC3+ Sport as the redundant altimeter.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 3.5 **Description:** Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.	**Verification Plan:** The team will design the avionics section such that each commercially available altimeter has its own source of power. **Comments:** The two altimeter-battery systems are completely separated as discussed in Section 4.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 3.6 **Description:** Each altimeter will be armed by a dedicated mechanical arming switch that is accessible from the exterior of the launch vehicle airframe when the launch vehicle is in the launch configuration on the launch pad.	**Verification Plan:** The team shall design the avionics bay such that each altimeter has its own switch that is readily accessible. **Comments:** The team has designed interior switch mounts for the rocker switches that are epoxied inside the avionics coupler and are accessible from the exterior of the vehicle. These can be referenced in Section 4.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 3.7 **Description:** Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).	**Verification Plan:** This has been verified via the subscale and full scale launches. **Comments:** The rocker switch is mounted to the interior of the avionics coupler and cannot be disarmed due to flight forces.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 3.8 **Description:** The recovery system electrical circuits will be completely independent of any payload electrical circuits.	**Verification Plan:** Independence has been verified via inspection. **Comments:** The altimeter-ejection systems are not wired to the secondary payload (camera) system in the avionics bay in any way, nor to the primary payload system.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 3.9 **Description:** Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	**Verification Plan:** The use of shear pins has been verified through inspection. **Comments:** The team's 2020 design utilizes shear pins for both the main and drogue parachute compartments.
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** 3.10 **Description:** The recovery area will be limited to 2,500 ft. radius from the launch pads.	**Verification Plan:** This was partially verified via the vehicle demonstration flight. More specifically, the drift data from the vehicle demonstration flight will be used to assist the team in determining the ideal altitude to deploy the main parachute in the reflight and on launch day.

		Comments: This has also been verified via OpenRocket, RASAero, and MATLAB trajectory code.
Status: *In Progress*		**Verification Test ID**: N/A

D	**Requirement ID:** 3.11 **Description:** Descent time will be limited to 90 seconds (apogee to touch down).	**Verification Plan:** This is verified through the subscale and full scale launches. **Comments:** This is also verified via OpenRocket, RASAero, and MATLAB trajectory code, but the simulations are currently concluding that the descent time will be about 10 seconds longer than the requirement. This will continue to be addressed by the team.
Status: *In Progress*		**Verification Test ID:** N/A

D	**Requirement ID:** 3.12 **Description:** An electronic tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver.	**Verification Plan:** This has been verified via the vehicle demonstration flight. **Comments:** The Altus Metrum Telemetrum is able to transmit telemetry and GPS coordinates to the team during flight.
Status: Complete		**Verification Test ID:** N/A

I	**Requirement ID:** 3.12.1 **Description:** Any launch vehicle section or payload component, which lands untethered to the launch vehicle, will contain an active electronic tracking device.	**Verification Plan:** Having these components is verified via inspection. **Comments:** The team's design does not include any launch vehicle section or payload component that lands untethered to the launch vehicle. Unfortunately, the lower airframe landed untethered to the vehicle during the vehicle demonstration flight, so this requirement has not yet been verified.
Status: *In Progress*		**Verification Test ID:** N/A

T	**Requirement ID:** 3.12.2 **Description:** The electronic tracking device(s) will be fully functional during the official flight on launch day.	**Verification Plan:** The functionality of the tracking devices has been verified through individually testing each major electronic system within the avionics bay. **Comments:** This was completed after conducting and meeting the success criteria for tests A_01 and A_04 on the 19th and 25th of January, respectively.

Status: *Complete*	**Verification Test ID:** A_01, A_04

D	**Requirement ID:** 3.13 **Description:** The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	**Verification Plan:** This has been verified via demonstration during the full scale launch. **Comments:** This was completed after the full scale launch on the 15th of February.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 3.13.1 **Description:** The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.	**Verification Plan:** This has been verified via inspection. **Comments:** No other radio frequency transmitting device and/or magnetic wave producing device is placed in the avionics bay with the altimeters.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 3.13.2 **Description:** The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.	**Verification Plan:** This has been verified via inspection. **Comments:** The team's 2020 design includes shielding between the recovery system electronics and the payload transmitters.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 3.13.3 **Description:** The recovery system electronics will be shielded from all onboard devices which may generate magnetic waves (such as generators, solenoid valves, and Tesla coils) to avoid inadvertent excitation of the recovery system.	**Verification Plan:** This has been verified via inspection. **Comments:** The team's 2020 design does not include onboard devices which may generate magnetic waves.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 3.13.4 **Description:**	**Verification Plan:** This has been verified via inspection.

	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.	**Comments:** The team's 2020 design does not include any other onboard devices which may adversely affect the proper operation of the recovery system electronics.
	Status: *Complete*	**Verification Test ID:** N/A

8.1.1.4. Payload R&VP

D A	**Requirement ID:** 4.2 **Description:** The team will design a UAV payload that will safely be carried by a high powered rocket. The UAV will deploy from the launch vehicle and recover simulated lunar ice. The UAV will be designed to be safe and follow all rules and regulations.	**Verification Plan:** The UAV will undergo a series of developmental and operational testing and simulations that will validate the capability of the UAV to complete a successful ice sample recovery. These tests will validate that the UAV can functionally perform every mission function on its own as well as in sequence. In addition, all safety critical structural components used on the UAV and UAV retention system will be designed to have a safety factor of at least two using FEA. **Comments:** The UAV is currently being tested in simulation to verify its ice mining and recovery capability. Demonstration of a safe payload flight and ice sample recovery is set to be complete during the full-scale demonstration flight. This requirement will be verified upon successful demonstration in simulation and during the full-scale flight.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** 4.3.1 **Description:** The launch vehicle will be launched from the NASA-designated launch area using the provided launch pad. All hardware utilized at the recovery must launch on the vehicle.	**Verification Plan:** The payload on the launch vehicle will be designed to contain all the hardware necessary for mission completion, All manipulation and control of the payload post recovery will be done through wireless commands issued from the GCS. **Comments:** The payload has been designed to contain all necessary hardware on the launch vehicle. This requirement will be verified through flight demonstration at competition.
	Status: *Incomplete*	**Verification Test ID:** N/A

A T	**Requirement ID:** 4.3.2 **Description:** The team will be able to recover ice samples from five different recovery areas with each recovery site being 3' in diameter and contain	**Verification Plan:** The UAV and ice mining system will be tested in simulation and in a makeshift sampling area to confirm that the UAV will be able to detect, track, and extract an ice sample from a recovery area. **Comments:** Payload tests PT_01.1 and PT_01.2 are in the process of being completed. Requirement will be verified upon

	sample material extending to at least 2" below the surface.	completion of these two tests showing successful ice sample recovery capability.
	Status: *In Progress*	**Verification Test ID:** PT_01.1, PT_01.2

D	**Requirement ID:** 4.3.3 **Description:** The recovered ice sample will be a minimum of 10 milliliters (mL).	**Verification Plan:** The UAV ice mining and procurement system will be tested to mine and contain at least 10mL of ice both on a test stand and during a mission. This capability will be demonstrated during both PT_01.1 and PT_02.1. **Comments:** The ice mining system has been designed to recover more than 10ml of ice. This requirement will be verified upon demonstration of recovery capability during PT_01.1 and PT_01.2, which are currently in progress.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** 4.3.4 **Description:** Once the sample is recovered, it must be stored and transported at least 10' linearly from the recovery area.	**Verification Plan:** The UAV will be programmed to fly at least 10' linearly away from the recovery site at full ice capacity. **Comments:** Requirement will be verified during the payload demonstration flight.
	Status: *Incomplete*	**Verification Test ID:** N/A

I D	**Requirement ID:** 4.3.5 **Description:** The team must abide by all FAA and NAR rules and regulations.	**Verification Plan:** The operation of the UAV will abide by any and all rules and regulations from the FAA and NAR applicable to the operation of model aircraft. In addition, the operation of the UAV will follow any rules regulations issued by state and other local governments. **Comments**: All FAA and NAR rules and regulations have been reviewed and are being complied with. Checklists and testing procedures have been written using these rules and regulations as a guideline.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 4.3.6 **Description:** Black Powder and/or similar energetics are only permitted for deployment of in-flight recovery	**Verification Plan:** The deployment used for the payload has been designed to strictly employ the use of mechanical systems instead of energetics. **Comments:** Requirement has been verified as the payload strictly makes use of a mechanical deployment system.

	systems. And ground systems must employ mechanical systems.	
Status: *Complete*		**Verification Test ID:** N/A

I	**Requirement ID:** 4.3.7 **Description:** Any part of the payload or vehicle that is designed to be deployed, whether on the ground or in the air, must be fully retained until it is deployed as designed.	**Verification Plan:** The ground-deployed payload will be retained and locked in the vehicle until a signal is sent from the GCS. **Comments:** Requirement has been verified as the payload has been designed to be locked until a signal is sent from the GCS to initiate the payload deployment procedure.
Status: *Complete*		**Verification Test ID:** N/A

I	**Requirement ID:** 4.3.7.1 **Description:** A mechanical retention system will be designed to prohibit premature deployment.	**Verification Plan:** The retention and deployment system will strictly make use of a mechanical system to retain and deploy the UAV. **Comments:** Requirement has been verified as deployment can only be signaled by the GCS, and the design makes use of only mechanical systems by design.
Status: *Complete*		**Verification Test ID:** N/A

D A	**Requirement ID:** 4.3.7.2 **Description:** The retention system will be robust enough to successfully endure flight forces experienced during both typical and atypical flights.	**Verification Plan:** All structural components in the retention system will be designed with a factor of safety of at least 2 and functionality of the retention system will be demonstrated during the full-scale demonstration flight. **Comments:** FEA simulations of all structural components have been completed showing a minimum factor of safety of 2. Requirement will be verified upon successful completion of the full-scale demonstration flight.
Status: *In Progress*		**Verification Test ID:** N/A

I	**Requirement ID:** 4.3.7.3 **Description:** The designed system will be fail-safe.	**Verification Plan:** The mechanical system employed to retain the payload in-flight has been designed to be fail-safe and will function regardless of power delivery. **Comments:** Requirement has been verified as all mechanical retention systems make use of strictly fail-safe locking mechanisms by design.

Status: Complete	**Verification Test ID:** N/A

I	**Requirement ID:** 4.3.7.4 **Description:** Exclusive use of shear pins will not meet requirement 4.3.7.	**Verification Plan:** Shear pins will not be used for the retention of the payload. **Comments:** Requirement has been verified as the payload does not make use of shear pins in its design.
	Status: Complete	**Verification Test ID:** N/A

	Requirement ID: 4.4.1 **Description:** Any experiment element that is jettisoned during the recovery phase will receive real-time RSO permission prior to initiating the jettison event.	**Verification Plan:** No payload components will be jettisoned during the recovery phase by design in accordance with requirements 4.3.7.3 and 4.3.7.2.fds **Comments:** The UAV will not be jettisoned during the recovery phase and will not require real-time RSO permission.
	Status: N/A	**Verification Test ID:** N/A

	Requirement ID: 4.4.2 **Description:** The UAV, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAV.	**Verification Plan:** The UAV is not designed to be deployed during flight and therefore will not require a remotely controlled release mechanism that will be triggered during descent. **Comments:** The UAV will not be deployed during descent.
	Status: N/A	**Verification Test ID:** N/A

I	**Requirement ID:** 4.4.3 **Description:** Teams flying UAVs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft.	**Verification Plan:** The operation of the UAV shall follow all laws laid out by the FAA pertaining to the operation of rotorcraft and model aircraft. **Comments:** FAA rules and regulations have been reviewed and are being complied with. This includes rules included in the FAA's Special Rule for Model Aircraft and the FAA Part 107.
	Status: Complete	**Verification Test ID:** N/A

I	**Requirement ID:** 4.4.4 **Description:** Any UAV weighing more than .55lbs will be registered with the FAA and the registration number marked on the vehicle.	**Verification Plan:** The UAV will be registered with the FAA and its registration number is clearly marked on the outside of the vehicle. **Comments:** Requirement has been verified as the UAV has been registered with the FAA (Certificate Number FA3EXNERX4) and is clearly marked on the outside of the vehicle.
	Status: *Complete*	**Verification Test ID:** N/A

8.1.1.5. Safety R&VP

I	**Requirement ID:** 5.1 **Description:** Each team will use a launch and safety checklist. The final checklists will be included in the FRR report and used during the Launch Readiness Review (LRR) and any launch day operations.	**Verification Plan:** Design review documents will be inspected to contain a launch checklist encompassing at least Pre-Launch, Launch, and Post Launch operations. **Comments:** Checklists have been created to maintain continuity in launch procedures. Quality witness stops ensure the quality of work done in previous steps, as well as provide future verification of step completion.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 5.2 **Description:** Each team must identify a student safety officer who will be responsible for all items in section 5.3.	**Verification Plan:** A safety officer will be voted on before the competition season. **Comments:** The team safety officer for 2019-2020 is Noah Stover. This requirement was fulfilled before the beginning of the competition season.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 5.3.1 **Description:** Monitor team activities with an emphasis on safety during the design of vehicle and payload, the construction of vehicle and payload components, the assembly of vehicle and payload, the ground testing of vehicle and payload, the subscale launch test(s), the full-scale launch test(s), the launch day, the recovery activities, and the STEM engagement activities.	**Verification Plan:** The safety officer will be held accountable by record of attendance by the heads of operations for construction and testing procedures, and the project manager for launch operations. **Comments:** Safety officer presence at launch day, construction days, and engagement activities encourages a focus on safe processes and operations. This requirement shall be completed upon completion of launch operations.
	Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** 5.3.2 **Description:** Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	**Verification Plan:** Safety plans will be put in place for the operations of construction (machine operations, epoxy application, etc), launch (see 5.1), and vehicle recovery. **Comments:** Safety steps and procedures have been integrated in construction and launch day activities to ensure operational efficiency and team wellbeing. This requirement was completed upon the completion of launch day procedures and operations safety briefings.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 5.3.3 **Description:** Manage and maintain current revisions of the team's hazard analyses, failure modes analysis, procedures, and MSDS/chemical inventory data.	**Verification Plan:** Safety data will be reviewed before each milestone document submission and be updated accordingly. **Comments:** Analysis of project hazards allows for the mitigation of possible threats and the creation of a safe work environment. This requirement shall be completed upon the completion of hazardous team activities.
	Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** 5.3.4 Description: Assist in the writing and development of the team's hazard analyses, failure modes analysis, and procedures.	**Verification Plan:** Hazard analysis will be present in PDR document, and presence will be confirmed by Safety Officer and Project Manager **Comments:** Safety officer participation in the creation of hazard analysis encourages a focus on the comprehensive wellbeing of the launch vehicle, project, and team members. This requirement was completed upon completion of the FRR document
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** 5.4 **Description:** During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's	**Verification Plan:** Inform RSO and club president of launch in a reasonable time prior. Obtain permission to use payload in launch if payload is to be used. **Comments:** In order to organize launches the team will contact necessary administrative heads to ensure the team's launch requirements are within the safety standards they hold for launches. Verification shall occur upon completion of test launch.

	President or Prefect and RSO before attending any NAR or TRA launch.	
Status: *In Progress*		**Verification Test ID:** N/A

I	**Requirement ID:** 5.5 **Description:** Teams will abide by all rules set forth by the FAA.	**Verification Plan:** An extensive review of FAA guidelines and regulations and checked in order to make sure that all subteams follow and stay within the given regulations.
		Comments: The team has reviewed FAA guidelines in order to analyze possible risks and their mitigations. Before constructions or launches,the guidelines will be reviewed again to make sure they are followed. Verification shall occur upon completion of test launch.
Status: *In Progress*		**Verification Test ID:** N/A

8.1.2. Team-Derived R&VP

8.1.2.1. Team-Derived General R&VP

D	**Requirement ID:** T1.1 **Description:** All milestone documents will be finished by the team at least three days ahead of the required deadline; this ensures that the executive board may review and make edits prior to milestone submission.	**Verification Plan:** Subteam leads will ensure that each subteam finishes their respective section prior to this deadline.
		Comments: FRR was completed by the 28th of February 2020 so that the project manager and assistant project manager could review, refine, and finalize. This requirement will be completed after PLAR is submitted.
Status: *In Progress*		**Verification Test ID:** N/A

I	**Requirement ID:** T1.2 **Description:** Each team member, regardless of position, will miss no more than five (5) meetings throughout the entirety of the competition; this ensures that team members stay actively engaged and are making meaningful contributions to the team's design.	**Verification Plan:** Team will take attendance prior to the start of each meeting
		Comments: As of CDR, the team has had to remove several members due to inconsistent attendance and missing more than the five (5) allowed meetings. This requirement will be completed after PLAR is submitted.
Status: *In Progress*		**Verification Test ID:** N/A

D	**Requirement ID:** T1.3 **Description:** STEM engagement activity reports will be submitted within a week of the activity date so that documentation of even can be properly written.	**Verification Plan:** The Social / Outreach team lead will bring activity reports to all outreach events to ensure that team members fill out reports at the event's completion. **Comments:** The team has been working on refining the process for STEM engagement activity reports and is on track to meet this requirement. Verification will occur upon submission of the final activity report.
Status: *In Progress*		**Verification Test ID:** N/A

I	**Requirement ID:** T1.4 **Description:** In order to be eligible to attend launch week, each team member will be required to attend a minimum of three STEM educational outreach events.	**Verification Plan**: Attendance will be taken and inspected prior to the start of each STEM outreach event. **Comments:** This requirement shall be verified upon the week before launch week.
Status: *In Progress*		**Verification Test ID:** N/A

8.1.2.2. Team-Derived Vehicle R&VP

D A	**Requirement ID:** T2.1 **Description:** The vehicle will carry the payload to an apogee altitude of 4325 +/- 100' AGL.	**Verification Plan:** Verification analysis will be performed in OpenRocket, secondary analysis will be performed in RASAero, tertiary analysis will be performed in avionics and recovery trajectory code, and final verification will be gathered from full scale launch altimeter data. **Comments:** This requirement shall be verified upon successful launch, as determined by final apogee retrieved from avionics' altimeters.
Status: *In Progress*		**Verification Test ID:** N/A

A	**Requirement ID:** T2.2 **Description:** The vehicle will be capable of carrying the payload to apogee with a 12.5 pound or less payload.	**Verification Plan:** 12.5 pounds will be included in the mass of simulations performed to account for the mass of the payload. Further verification will be performed from the gathering of altimeter data during final launch. **Comments:** This requirement was verified by simulation given the known weights of other sections, and the known capabilities of the motor.
Status: Complete		**Verification Test ID:** N/A

D	**Requirement ID:** T2.3 **Description:** The flight path of the launch vehicle shall not differ from the vertical axis by an observable amount under any circumstances or launch conditions with the exception of the flight path at apogee.	**Verification Plan:** Visual inspection of all launch vehicle test flights during ascent will verify the vehicle's flight path does not vary from the vertical direction by unreasonable amounts. **Comments:** This requirement shall be verified by visual inspection at demonstration flight.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** T2.4 **Description:** The vehicle will be capable of successfully deploying the payload system's UAV after successfully landing.	**Verification Plan:** This requirement shall be verified by demonstrating payload deployment capabilities of the launch vehicle during the full scale flight or the payload demonstration flight. **Comments:** This requirement shall be verified via a successful landing and deployment of the UAV at test flight.
	Status: *In Progress*	**Verification Test ID:** N/A

D	**Requirement ID:** T2.5 **Description:** The full-scale launch vehicle will be successfully launched in a test flight before March 2, 2020, configured in the same configuration that will be used on the final launch day	**Verification Plan:** Full scale flight launch data shall be recorded and included in milestone documentation to prove a full scale flight has occurred by the specified date and in the desired configuration. **Comments:** Launch was completed on the 15th of February. Successful recovery was not demonstrated; reflight shall be needed.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** T2.6 **Description:** If the launch day motor is not capable of being flown during the full-scale test flight, the replacement motor shall simulate as closely as possible the predicted maximum velocity and maximum acceleration of the launch day flight.	**Verification Plan:** The motor which is used to simulate the final motor to be used shall be the closest allowable motor impulse level and shall retain a size and mass which differs by no more than 10% than the motor to be used. **Comments**: Replacement motors are identical to the primary motor, and are transported separate from the primary motor in case of accident. Motor performance specifications are verified by producer specifications
	Status: *Complete*	**Verification Test ID:** N/A

D	**Requirement ID:** T2.7 **Description:** If the Student Launch office determines that a re-flight is necessary, then another flight of the full-scale vehicle will be conducted before March 20, 2020.	**Verification Plan:** Full scale re-flight launch data will be recorded and included in milestone documentation to prove a re-flight has occurred by the specified date. **Comments:** Due to the failure of the team's first launch, this requirement will be verified upon completion of the team's reflight.
	Status: *In Progress*	**Verification Test ID:** N/A

8.1.2.3. Team-Derived Avionics and Recovery R&VP

T	**Requirement ID:** T3.1 **Description:** The drogue parachute needs to be able to open within a consistent time frame after being ejected in order to fulfill the design requirements. The main parachute also needs to open within 300' of deployment, as it has been programmed to deploy at 800' and needs to be fully open by 500' as stated in the competition requirements.	**Verification Plan:** After each trial the drogue parachute was dropped, the amount of time it took for it to come to a fully opened state was measured. It passed this test if the times measured in the three trials were all within 0.50 seconds of each other. The main parachute passed this test if it was at least 17% open after falling 50' for all three trials (extrapolating this value ensures that the parachute would be 100% open after falling 300'). **Comments:** This was completed after conducting and meeting all success criteria for test A_05 on the 2nd of February.
	Status: *Complete*	**Verification Test ID:** A_05

T	**Requirement ID:** T3.2 **Description:** Each battery of both the 3.7V LiPo and 9V alkaline variety needs to be able to supply sufficient voltage to its corresponding altimeter for 1 hour more than the required amount of time (2 hours) while not dropping below 3.2V for the LiPo battery or 8.0V for the alkaline battery.	**Verification Plan:** Each battery is verified if, connected to its corresponding altimeter, the battery is able to keep it powered on for 3 hours as well as not drop below 3.2V for the LiPo battery or 8.0V for the alkaline battery (voltage was measured every 0.5 hours). **Comments:** This was completed after conducting and meeting all success criteria for test A_04 on the 25th of January.
	Status: *Complete*	**Verification Test ID:** A_04

	Requirement	Verification
T / A	**Requirement ID:** T3.3 **Description:** For ground testing, the black powder ejection system must create at least 6' of separation between the avionics bay and each airframe for at least one amount of black powder equal to or greater than 5 grams for the main ejection charge and 2 grams for the drogue ejection charge.	**Verification Plan:** Ejection charge sizing analysis was performed using hand calculations to estimate a target amount of black powder to be used. Then the distance between the avionics bay and each airframe was measured after test ejection, ultimately allowing the team to determine the most efficient amount of black powder to use. **Comments:** The required analysis was completed prior to CDR. This requirement was verified after conducting and meeting all success criteria for test A_03 on the 26th of January.
	Status: Complete	**Verification Test ID:** A_03

	Requirement	Verification
T	**Requirement ID:** T3.4 **Description:** Both altimeters must be able to consistently ignite both ejection charges at the appropriate times.	**Verification Plan:** Altimeter functionality has been verified through simulating a flight via a vacuum chamber. **Comments:** This was completed after conducting and meeting all success criteria for test A_02 on the 20th of January.
	Status: Complete	**Verification Test ID:** A_02

	Requirement	Verification
T	**Requirement ID:** T3.4.1 **Description:** The primary drogue ejection charge will ignite within +/- 500' of apogee.	**Verification Plan:** Recorded drogue ignition altitude has been compared against apogee altitude in the Altimeter Ejection Vacuum Test. **Comments:** This was completed after conducting and meeting all success criteria for test A_02 on the 20th of January.
	Status: Complete	**Verification Test ID:** A_02

	Requirement	Verification
T	**Requirement ID:** T3.4.2 **Description:** The redundant drogue ejection charge will have a drogue delay between 0.75 and 1.75 seconds.	**Verification Plan:** The duration of time between apogee and drogue ignition has been measured in the Altimeter Ejection Vacuum Test. **Comments:** This was completed after conducting and meeting all success criteria for test A_02 on the 20th of January.
	Status: Complete	**Verification Test ID:** A_02

T	**Requirement ID:** T3.4.3 **Description:** The primary and redundant main ejection charges will ignite within +/- 50' of their programmed deployment altitudes (800' AGL for the primary altimeter and 700' AGL for the redundant altimeter).	**Verification Plan:** Recorded main ignition altitudes have been compared against programmed deployment altitudes for each altimeter in the Altimeter Ejection Vacuum Test. **Comments:** This was completed after conducting and meeting all success criteria for test A_02 on the 20th of January.
	Status: Complete	**Verification Test ID:** A_02

T	**Requirement ID:** T3.5 **Description:** The altimeter firing sequence will be consistent across temperature extremes.	**Verification Plan:** Each altimeter is verified if it emits three beeps every five seconds after the initialization routine in both temperature extremes, indicating successful continuity for a dual deploy configuration. **Comments:** This was completed after finishing the procedure and meeting all success criteria for test A_01 on the 19th of January.
	Status: Complete	**Verification Test ID:** A_01

I	**Requirement ID:** T3.6 **Description:** The parachute will be rolled in a loosely packed cylindrical shape before it is placed into the launch vehicle.	**Verification Plan:** This is verified via inspection while assembling the launch vehicle before flight. **Comments:** The parachute was folded in a triangular pattern for the full scale test flight. It is believed that this folding pattern contributed to the main parachute not opening properly. This will therefore be verified at the second full scale test flight.
	Status: *In Progress*	**Verification Test ID:** N/A

8.1.2.4. Team-Derived Payload R&VP

I	**Requirement ID:** T4.1 **Description:** The vehicle shall not pose a significant safety risk to its surroundings during operation.	**Verification Plan:** Operation of the UAV will strictly adhere to predetermined flight paths. Any and all safety risks will be identified and addressed prior to flight, and proper documentation of emergency procedures will be available at hand. **Comments:** Each UAV flight is currently requiring the use of a flight test document that contains information relating to the safe operation of the UAV as well as all rules and regulations, both FAA and local, that must be complied with. This flight test

		document also contains a pre-flight checklist that ensures the operation of the UAV is safe and predictable.
Status: Complete		**Verification Test ID:** N/A

I	**Requirement ID:** T4.2 **Description:** Autonomous operation of the UAV shall require a designated Pilot-in-Command (PIC) monitoring UAV telemetry and status, and an observer that maintains visual line of sight with the UAV at all times.	**Verification Plan:** Every flight of the UAV will require a designated pilot-in-command (PIC) and observer, both with proper training and equipment. This information will be documented in a preflight checklist and a flight maintenance document.
		Comments: A PIC and observer are being designated and briefed prior to each flight.
Status: Complete		**Verification Test ID:** N/A

I D	**Requirement ID:** T4.3 **Description:** Control of the UAV with computer vision algorithms shall be minimally accompanied with real-time imaging data and a kill-switch.	**Verification Plan:** Testing of computer vision algorithms on a UAV in-flight will require imaging data to be transmitted and monitored by the PIC. A kill-switch must be easily accessible at all times by the PIC, and the PIC shall remain in constant contact with the observer.
		Comments: Flight testing of the UAV with offboard control is not taking place until the GCS construction has been completed and its functionality verified. Testing is also contingent upon successful tuning of the UAV.
Status: *In Progress*		**Verification Test ID:** N/A

D	**Requirement ID:** T4.4 **Description:** Switches on the GCS that alter the operation or flight mode of the UAV, that are mission critical, or are essential for the safe operation of the UAV will require checkout testing.	**Verification Plan:** Switches will be tested in simulation and using flight hardware (assuming the test will not risk the safety of the vehicle nor its surroundings) to ensure expected behavior is met.
		Comments: Demonstration of GCS switch functionality will be completed during PT_04.1 in simulation and PT_03.1/PT_04.2 with UAV hardware.
Status: *In Progress*		**Verification Test ID:** N/A

I	**Requirement ID:** T4.5 **Description:**	**Verification Plan:** The operation of the UAV shall follow all rules laid out by Purdue University pertaining to the operation of UAVs.

	The operation of the UAS shall adhere to Purdue's Operating Procedures For Use of UAS and Model Aircraft.	**Comments:** All rules laid out by Purdue University regarding the operation of UAVs have been reviewed and the payload team is in full compliance.
	Status: *Complete*	**Verification Test ID:** N/A

T	**Requirement ID:** T4.6 **Description:** The UAV shall be able to deploy from different landing orientations and conditions.	**Verification Plan:** UAV deployment will be tested with varying landing orientations of the payload bay to identify worst-case deployment scenarios. Additionally, UAV deployment will be tested with various angles of the UAV sled to identify worst-case sled orientations that still allow for successful deployment of the UAV.
		Comments: Tests PT_02.1 and PT_02.2 were both completed successfully, demonstrating that the UAV can deploy from the R&D system in a variety of launch vehicle landing orientations.
	Status: *Complete*	**Verification Test ID:** PT_02.1, PT_02.2

T	**Requirement ID:** T4.7 **Description:** The UAV shall have smooth, safe, and stable flight throughout the entirety of its mission.	**Verification Plan:** Low-level control loop gains will be tuned, utilizing standard PID tuning procedures, to ensure safe and stable flight of the UAV.
		Comments: Flight controller tuning will take place during test PT_03.1. Development of automatic tuning methods is in progress such that this requirement will be verified in the near future.
	Status: *In Progress*	**Verification Test ID:** PT_03.1

T	**Requirement ID:** T4.8 **Description:** The UAV's computer-vision and imaging system shall identify ice mining recovery areas and facilitate guided-descent of the UAV at such locations.	**Verification Plan:** Recovery area identification performance will be tested with a sample data set of recovery area images. Guided descent of the UAV will be tested in computer simulations as well as UAV test flights with sample recovery area test articles.
		Comments: The computer-vision software and navigational software will be tested in PT_04.1 and PT_04.2. Requirement will be verified upon completion of these tests.
	Status: *In Progress*	**Verification Test ID:** PT_04.1, PT_04.2

T	**Requirement ID:** T4.9 **Description:**	**Verification Plan:** Key metrics quantifying the performance of data links within the system will be analyzed under various

	Communication and data links within the payload system will maintain a strong connection throughout the course of the mission with a minimum operational range of 1 mile.	simulated mission conditions. Examples of such metrics include packet loss and wireless signal strength. **Comments:** All payload wireless data links will undergo range testing in PT_05.1. Requirement will be verified upon completion of this test. Developmental testing of the wireless communication systems indicates successful operation of such systems at short range.
	Status: *In Progress*	**Verification Test ID:** PT_05.1

T	**Requirement ID:** T4.10 **Description:** The motors of the UAV must be able to minimally generate double the hover thrust, and motor power usage at throttle enables UAV flight time within ±20% of the expected flight time.	**Verification Plan:** A thrust stand will be employed to quantify the maximum amount of force the UAV can exert. Power and RPM data will also be mapped as a function of thrust. **Comments:** The UAV has undergone thrust stand testing and it has been verified that the maximum expected flight time is 9.6 min compared to the initial estimate of 10.1 min, still meeting our requirement.
	Status: Complete	**Verification Test ID:** PT_06.1

T	**Requirement ID:** T4.11 **Description:** Batteries for the R&D system shall minimally allow system operation for at least 4 hours under normal operation. UAV batteries shall provide enough energy to hover the UAV for at least 8 minutes.	**Verification Plan:** All batteries used on these systems will undergo drain testing to determine how long the battery is expected to last and how certain mission phases and system actions impact battery characteristics. **Comments:** Test PT_07.1 has been completed. Both the UAV and the R&D power systems surpassed their respective minimum power capacity requirements.
	Status: Complete	**Verification Test ID:** PT_07.1

8.1.2.5. Team-Derived Safety R&VP

I	**Requirement ID:** T5.1 **Description:** Every team member must have a Pocket Safety Document on their person for all launch day, construction, assembly, or test operation.	**Verification Plan:** Team members will be asked to display Pocket Safety Documents before operation occurs. **Comments:** Separate pocket safety documents have been written for the operations of testing, machining, construction, and launch day. Will be in progress until the end of launch proceedings.

Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** T5.2.1 **Description:** Team members must be briefed on machine operations and operational hazards prior to construction operations.	**Verification Plan:** All team members performing machining or other construction operations will be present for a pre-operation briefing presentation covering PPE, machine operation, and other safety hazards approved by the safety officer. **Comments:** Pocket Safety Documents (See T5.1) will contain a condensed version of pre-operation briefing for on-site reference. Completion verified by the end of launch vehicle construction.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** T5.2.2 **Description:** Team members must be briefed on testing operations and operational hazards prior to tests.	**Verification Plan:** All team members performing testing will be present for a pre-test briefing presentation covering safety procedure, material hazards, and necessary PPE approved by the safety officer. **Comments:** Pocket Safety Documents (See T5.1) will contain a condensed version of pre-test briefing for on-site reference. Completion verified by the end of avionics and retention testing.
	Status: *Complete*	**Verification Test ID:** N/A

I	**Requirement ID:** T5.2.3 **Description:** Team members must be briefed on launch operations and procedures prior to any sub-scale or full-scale launch.	**Verification Plan:** All team members performing launch procedures will be present for a pre-launch briefing presentation covering PPE, launch hazards, and proper launch procedure. **Comments:** Pocket Safety Documents (See T5.1) will contain a condensed version of launch briefing for on-site reference. Will be in progress until all launch proceedings are complete.
	Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** T5.3 **Description:** All students working with powered machinery must demonstrate a clear and comprehensive knowledge of the machine and its requisite safety standards per the standards of the machining location.	**Verification Plan:** Before operation, students must present verification of completion of requisite safety briefings, courses, or other material provided by the machine's holding group (Purdue Bechtel Innovation Design Center, Zucrow Labs, Purdue Aerospace Science Laboratory, etc). **Comments:** The Purdue Bechtel Innovation Design Center requires online quizzes going over machine safety before the location is accessible to the student. All students performing machining operations have demonstrated proficiency prior to operation. Completion verified by the end of launch vehicle construction.

Status: Complete	**Verification Test ID:** N/A

I	**Requirement ID:** T5.4 **Description:** First aid equipment will be available and accessible at all launch day, construction, assembly, or test operations.	**Verification Plan:** Safety officer will be responsible for the upkeep and presentation of first aid kit. Kit's presence will be logged by a safety officer, and initiated and dated by one witnessing team member. **Comments:** First aid kit contains multi-sized bandages, antibiotics, anti-inflammatories, anti-itch cream, pain killers, gauze, and an instant ice pack. Will be in progress until all launch proceedings are complete.
	Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** T5.5 **Description:** A clear walking path free of hazards or pitfalls must be marked for use by team members on the launch field from the launch pad to observation area	**Verification Plan:** Safety team members will perform sweep of surroundings before rocket setup. A clear path will be denoted by two rows of flags containing the cleared path. **Comments:** Flags will be counted upon placement and recounted upon removal to ensure all flags are collected and accounted for. Will be in progress until all launch proceedings are complete.
	Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** T5.6 **Description:** Completion of critical steps in the process of launch vehicle construction (payload assembly, R&D ground test, final vehicle assembly, etc) must be overseen by a quality witness to confirm satisfactory quality and full step completion	**Verification Plan:** Witnesses will bear responsibility for respective step completion: see requirement T5.6.1 **Comments:** Quality witnesses ensure completion of critical steps, quality of work, and absence of component damage. Will be in progress until all launch proceedings are complete.
	Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** T5.6.1 **Description:** Before launch vehicle is to be deemed complete, quality witnesses must confirm the completion of their respective steps.	**Verification Plan:** The safety team lead will read a list of all quality witness steps upon construction completion. Each witness will confirm the completion of their respective step.

	Comments: If any step lacks a witness who can confirm its completion, the vehicle will be deconstructed to confirm step completion, and any affected quality witnesses repeated. Will be in progress until all launch proceedings are complete.
Status: *In Progress*	**Verification Test ID:** N/A

I	**Requirement ID:** T5.6.2 **Description:** Quality witnesses must witness no more than one witness step.	**Verification Plan:** Any steps with repeating quality witnesses (as determined by safety team lead list) will be deconstructed to confirm completion, and any affected quality witnesses will be repeated
		Comments: Will be in progress until all launch proceedings are complete.
	Status: *In Progress*	**Verification Test ID:** N/A

8.2. Budgeting

This section outlines the team's purchases as well as the overall budget for the team. There are details included about specific items purchased and the plan to obtain funding for the project.

8.2.1. Line Item Budget

The line item budget as of FRR has been updated to include parts which had to be re-purchased following the failed first vehicle demonstration flight. Applicable taxes and shipping/handling fees have been accounted for in the totals within the Allocation of Funds (Table 8.3) and Funding Sources and Remaining Finances (Table 8.4) tables.

Subteam	Item	Merchant	Quantity	Unit Cost	Total Cost
Payload Retention and Deployment					
Payload	Leveling servo	Servocity	1	$32.90	$32.90
Payload	Leveling clamp	Servocity	1	$6.99	$6.99
Payload	Servo-worm coupler	Servocity	1	$6.99	$6.99
Payload	Power Transmission shaft	Servocity	2	$1.09	$2.18
Payload	Linear motion shafts	McMaster-Carr	4	$28.80	$115.20
Payload	Retaining rings	McMaster-Carr	1	$8.69	$8.69
Payload	Bushings	McMaster-Carr	12	$0.86	$10.32
Payload	turntable	McMaster-Carr	2	$3.11	$6.22
Payload	RH Leadscrew	McMaster-Carr	1	$16.60	$16.60
Payload	LH Leadscrew	McMaster-Carr	1	$20.24	$20.24
Payload	Leadscrew Couplers	Amazon	1	$8.69	$8.69
Payload	Eye nut	McMaster-Carr	1	$14.35	$14.35
Payload	Standoffs	McMaster-Carr	6	$2.60	$15.60

Payload	Right handed nuts	McMaster-Carr	1	$31.42	$31.42
Payload	Left handed nut	McMaster-Carr	1	$31.42	$31.42
Payload	Dual shaft stepper	Amazon	1	$21.50	$21.50
Payload	Eye nut bolt	McMaster-Carr	1	$5.29	$5.29
Payload	Xbee RF Module Kit	Digikey	1	$99.00	$99.00
Payload	Teensy 4.0 Microcontroller	PJRC	2	$19.95	$39.90
Payload	LiPo Battery	Amazon	1	$21.00	$21.00
Payload	Gyroscope	Amazon	1	$4.99	$4.99
Payload	Worm Set	Servocity	1	$21.99	$21.99
Payload	Bulk plate stock	McMaster-Carr	2	$16.78	$33.56
Payload	Stepper encoder	Digikey	1	$23.63	$23.63
Payload	50 ¼”-20 screws	McMaster-Carr	1	$5.08	$5.08
Payload	100 4-40 screws	McMaster-Carr	1	$8.96	$8.96
Payload	100 6-32 screws	McMaster-Carr	1	$8.96	$8.96
Payload	100 6-32 nuts	McMaster-Carr	1	$3.01	$3.01
Payload	Retaining ring pliers	McMaster-Carr	1	$16.12	$16.12
Payload	Pcb standoffs	McMaster-Carr	4	$2.86	$11.44
Payload	Activation switch	Digikey	1	$1.13	$1.13
Payload	100 push on retaining rings	McMaster-Carr	1	$7.63	$7.63
Payload	Eye nut	McMaster-Carr	1	$11.32	$11.32
Payload	Allen key set	McMaster-Carr	2	$6.79	$13.58
Payload	100 6/32 socket head screw	McMaster-Carr	1	$6.08	$6.08
Payload	TO-220 clip on heatsink	Adafruit	2	$1.25	$2.50
Payload	UBEC 5V @3A	Adafruit	2	$9.95	$19.90
Payload	JST- XHP connectors pack	Amazon	1	$8.99	$8.99
Payload	L7805 Voltage Regulator -5V	Sparkfun	4	$0.95	$3.80
Payload	Bushings	McMaster-Carr	10	$0.86	$8.60
Payload	Ball Bearings	McMaster-Carr	2	$6.48	$12.96
Payload	100 4-40 Screws 1/2"	McMaster-Carr	1	$9.20	$9.20
Payload	100 1/4"-20 Nuts	McMaster-Carr	1	$3.90	$3.90
Payload	100 1/4"-20 Screws	McMaster-Carr	1	$4.38	$4.38
Payload	10 6-32 Screws	McMaster-Carr	1	$4.00	$4.00
Payload	Ball Bearings	McMaster-Carr	2	$12.34	$24.68
Payload	Stepper Motor Driver	Robotshop	1	$18.00	$18.00
Payload	Teensy 4.0 Replacement	PJRC	1	$19.95	$19.95
Payload	3.3V to 5V Level shifter	Amazon	1	$3.98	$3.98
Payload	10 Socket Nuts	McMaster-Carr	1	$11.27	$11.27
Payload	100 4-40 Button Heads	McMaster-Carr	1	$3.02	$3.02
Payload	Self Aligning Bushing	igus	4	$5.22	$20.88
Payload	Fixed Alignment Bushing	igus	4	$5.83	$23.32
Payload	25 Press Fit Nuts	McMaster-Carr	1	$8.76	$8.76
Payload	100 Thin Nylock Nuts	McMaster-Carr	1	$3.71	$3.71
Payload Electronics and Controls					
Payload	Pixhawk 4 Kit	Sparkfun	1	$249.99	$249.99
Payload	ReadyToSky 915MHz 500mw	Amazon	1	$23.99	$23.99

Payload	FrSky R-XSR RC Receiver	Amazon	1	$26.99	$26.99
Payload	Raspberry Pi Zero W	Adafruit	2	$5.00	$10.00
Payload	Nylon 6 Standoffs	McMaster-Carr	8	$2.00	$16.00
Payload	3600mAh 3S 30 Turnigy Battery	Hobbyking	2	$27.65	$55.30
Payload	Toggle Switch and Cover	Sparkfun	4	$2.95	$11.80
Payload	15.6" Display	Amazon	1	$61.00	$61.00
Payload	15.6" Display Controller	Amazon	1	$26.68	$26.68
Payload	5mm LED Holder	Sparkfun	20	$0.50	$10.00
Payload	5mm LED Pack	Amazon	1	$10.99	$10.99
Payload	Momentary Push Button Switch x5	Amazon	2	$11.69	$23.38
Payload	LED Push Button Switch x5	Amazon	1	$11.97	$11.97
Payload	3Pin Toggle Switch x10	Amazon	1	$7.99	$7.99
Payload	Rocker Switch x15	Amazon	1	$6.99	$6.99
Payload	Raspberry Pi 4 2GB	Adafruit	1	$45.00	$45.00
Payload	Taranis Q X7	Banggood	1	$97.99	$97.99
Payload	3.2" LCD Display	Banggood	1	$6.99	$6.99
Payload	Raspberry Pi Zero Camera	Amazon	1	$24.83	$24.83
Payload Ice Mining					
Payload	DC 6V Gear Motor High Torque	Amazon	2	$10.99	$21.98
Payload	Low-Strength Steel Nylon-Insert Locknut: Zinc-Plated, 4-40 Thread Size	McMaster-Carr	1	$2.79	$2.79
Payload	Set Screw Shaft Collar: for 1/4" Diameter, Black-Oxide 1215 Carbon Steel	McMaster-Carr	2	$1.15	$2.30
Payload	12" D-Profile Rotary Shaft	McMaster-Carr	1	$9.40	$9.40
Payload	torsion spring: 270 Degree Angle, Right-Hand Wound, 0.171" OD	McMaster-Carr	2	$5.22	$10.44
Payload	Nylon Threaded Rod: 4-40 Thread Size, 2' Long, Black	McMaster-Carr	1	$7.15	$7.15
Payload Airframe					
Payload	Turnigy Multistar 21A ESC	Hobbyking	6	$9.81	$58.86
Payload	Luminier 6.7x3x3 Folding Prop, 4 Pack	Amazon	2	$11.99	$23.98
Payload	Turnigy Aerodrive SK3 1740Kv	HobbyKing	5	$18.03	$90.15
Payload	Nylon Sheet				$0.00
Payload	Torsion Spring 5 Pack (180 Degree Right-Hand Wound, 0.556" OD)	McMaster-Carr	1	$1.00	$1.00
Payload	Female Threaded Hex Standoff (18-8 Nylon, 1/4" Hex, 1" Long, 4-40 Thread)	McMaster-Carr	8	$2.23	$17.84
Payload	18-8 Stainless Steel Hex Head Screws 100 Pack (6-32 Thread Size, 1/2" Long)	McMaster-Carr	1	$9.58	$9.58
Payload	316 Stainless Steel Washer 25 Pack (Oversized, Number 12 Screw Size, 0.25" ID, 1" OD)	Menards	2	$0.49	$0.98
Payload	Zinc Yellow-Chromate Plated Hex Head Screw 25 Pack (Grade 8 Steel, 1/4"-20 Thread Size, 1-1/2" Long, Fully Threaded)	Menards	2	$0.89	$1.78
Payload	Extreme-Strength Steel Extra-in HeWide	Menards	2	$0.49	$0.98

	Thx Nut 2 Pack (Grade 2H, Zinc-Plated, 1/4"-20 Thread Size)				
Payload Secondary Camera					
Payload	ELP 5MP Camera	Not Purchased Yet	1	$48.00	$48.00
Payload	Pimironi LiPo Sheet	Not Purchased Yet	1	$9.95	$9.95
Payload	LiPo Battery 3.7v 2000mAh	Not Purchased Yet	1	$12.95	$12.95
Payload	RPi Zero	Not Purchased Yet	1	$10.00	$10.00
Construction					
Construction	G12 Fiberglass Coupler Tubes (6" Dia. x 27" Len)	Wildman Rocketry	27	$4.89	$132.03
Construction	G12 Fiberglass Airframe (6" Dia x 60" Len)	Wildman Rocketry	1	$231.50	$231.50
Construction	G12 Fiberglass Airframe (6" Dia x 48" Len)	Wildman Rocketry	2	$185.00	$370.00
Construction	G12 Fiberglass 5:1 Von Karman Nosecone w/ Metal Tip (6" Dia.)	Wildman Rocketry	1	$129.00	$129.00
Construction	G10 Fiberglass Airframe Bulkplate (6" Dia. x 0125")	Wildman Rocketry	6	$9.00	$54.00
Construction	G10 Fiberglass Coupler Bulkplate (5.775" Dia. x 0125")	Wildman Rocketry	6	$9.00	$54.00
Construction	G12 Fiberglass Coupler Tubes (6" Dia. x 3" Len)	Wildman Rocketry	3	$4.89	$14.67
Construction	G12 Fiberglass Switch Band (6" Dia. x 3" Len)	Wildman Rocketry	2	$10.00	$20.00
Construction	Cesaroni (CTI) L1115 Classic High Power Rocket Motor	Wildman Rocketry	1	$292.99	$292.99
Construction	75mm Motor Retainer (need to check connection (flange))	Wildman Rocketry	1	$51.00	$51.00
Construction	G12 Fiberglass Centering Rings (6" OD x 75mm ID)	Wildman Rocketry	3	$10.00	$30.00
Construction	G12 Fiberglass Motor Tube (75mm Dia.)	Wildman Rocketry	1	$41.02	$41.02
Construction	Cesaroni (CTI) L1115 Classic High Power Rocket Motor	Wildman Rocketry	2	$292.99	$585.98
Construction	Structural Adhesive, Epoxy, Loctite 1C-Lv, 1.69 oz. Cartridge	McMaster-Carr	10	$17.78	$177.80
Construction	5.9" Long Taper Tip Nozzle with Bayonet Connection for Two-Part Cartridge	McMaster-Carr	40	$1.30	$52.00
Construction	Dispensing Gun for Two-Part Cartridge	McMaster-Carr	1	$23.76	$23.76
Avionics					
Avionics	9V Battery Connectors	Amazon	1	$3.40	$3.40
Avionics/ Construction	Latex Gloves	Amazon	1	$10.65	$10.65
Avionics	Hex Wrench Set	Amazon	1	$16.26	$16.26
Avionics	Terminal Blocks	Apogee Rockets	2	$5.20	$10.40
Avionics	Altimeter Mounting Posts	Apogee Rockets	4	$5.48	$21.92
Avionics	3.7V 900 mAh LiPo Battery	Apogee Rockets	1	$13.20	$13.20
Avionics	FFFFG Black Powder (1 lb)	Graf & Sons	4	$48.33	$193.32
Avionics	1' Lighters (80 ct)	Electric Match	1	$53.98	$53.98
Avionics	3' Lighters (10 ct)	Electric Match	1	$25.48	$25.48

Avionics	Red 28 Gauge Stranded Wire (90 ft)	Pololu Robotics & Electronics	1	$7.46	$7.46
Avionics	Black 28 Gauge Stranded Wire (90 ft)	Pololu Robotics & Electronics	1	$7.47	$7.47
Avionics	Rocker Switches	Digikey	4	$6.14	$9.59
Avionics	USB A to USB Micro B Cable	Amazon	1	$2.68	$2.68
Avionics	Terminal Blocks for Telemetrum	Digikey	2	$10.72	$15.44
Avionics	Terminal Blocks	Apogee Rockets	2	$9.36	$12.91
Avionics	Rocker Switches	Digikey	3	$7.20	$9.50
Rebuild items					
Avionics	24" Classic Elliptical Parachute / CFC-24	Fruit Chutes	1	$64.00	$64.00
Construction	4 foot G12 fiberglass airframe (6 in. ID, 6.17 in. OD)	Wildman Rocketry	1	$185.00	$185.00
Construction	75mm 4 grain motor casing	Wildman Rocketry	1	$590.00	$590.00
Construction	6" 75 mm fiberglass centering rings	Wildman Rocketry	3	$10.00	$30.00
Construction	75 mm motor retainer	Wildman Rocketry	1	$51.00	$51.00
Construction	3/8" thick shock cord, sold by the yard	Wildman Rocketry	20	$2.50	$50.00
Construction	5:1 Von Karman 6" dia. Nose cone	Wildman Rocketry	1	$129.00	$129.00
Construction	18"x18" Square Nomex Heat Shield	Wildman Rocketry	1	$10.95	$10.95
Avionics	Eggfinder TX Transmitter	Eggtimer Rocketry	2	$70.00	$140.00
Avionics	Eggfinder RX “Dongle” receiver	Eggtimer Rocketry	2	$25.00	$50.00
Avionics	Telemetrum v3.0	Altus Metrum	1	$300.00	$300.00
Construction	G12-6.0 x1 Fiberglass Sheet	Wildman Rocketry	1	$138.75	$138.75
Construction	Fiberglass F12 6.0” 5:1 Von Karman Nose Cone Motor Retainer 75mm (FNC 6.0 -5-1VK_FW_MT)	Wildman Rocketry	1	$96.75	$96.75
Construction	Motor Retainer 75mm (RA75P)	Wildman Rocketry	1	$45.90	$45.90
Construction	3/8” Tubular Kevlar Shock cord	Wildman Rocketry	20	$37.50	$37.50
Construction	AeroTech 75mm 5120 4 Grain Motor Case (755120M)	Wildman Rocketry	1	$295.00	$295.00
Construction	G10 Fiberglass Centering Rings 6.0”-75mm (FCR6.0-3.0)	Wildman Rocketry	3	$7.00	$7.00
Construction	18”x18” Nomex Heat Resistance Shield	Wildman Rocketry	1	$6.57	$6.57

	(FCP18X18)				
Payload	Linear Motion Shaft	McMaster-Carr	4	$28.80	$115.20
Payload	Ball Bearing	McMaster-Carr	1	$12.34	$12.34
Payload	RH Leadscrew	McMaster-Carr	1	$16.60	$16.60
Payload	LH Leadscrew	McMaster-Carr	1	$20.24	$20.24
Payload	Stepper Driver	Amazon	1	$12.59	$12.59
Payload	Teensy 4.0	PJRC	1	$19.95	$19.95
Payload	100 Square 1/4"-20 Nut	McMaster-Carr	1	$4.71	$4.71
Payload	25 1/4"-20 x 1in Screw	McMaster-Carr	1	$6.37	$6.37
Payload	50 1/4"-20 x .5in Screw	McMaster-Carr	1	$5.65	$5.65
Payload	Flex coupling	Amazon	2		
Payload	XT60PW Connectors	Amazon	1	$8.99	$8.99
Payload	Heatsink Assortment	Amazon	1	$8.99	$8.99
Payload	5V Buck Converter	Adafruit	1	$9.99	$9.99
Payload	3.3 to 5V Level shifter	Adafruit	1	$1.50	$1.50
Payload	5V Linear regulator	Adafruit	1	$0.75	$0.75
Payload	2mm Female Headers	Adafruit	1	$3.95	$3.95
Payload	25 10-32 - 1/2"	McMaster-Carr	1	$5.41	$5.41
Payload	Better Leadscrew Couplers	Amazon	2	$6.04	$12.08
Payload	Turnigy 3600mAh Battery	Hobby King	2	$27.14	$54.28
Payload	Nylon Threaded Rod: 4-40 Thread Size, 2 Feet Long, Black	McMaster-Carr	1	$7.15	$7.15
Payload	Pixhawk 4 Kit	Amazon	1	$234.95	$234.95
Payload	Luminier 6.7x3x3 Prop 4 Pack	getfpv	2	$9.99	$19.98
Payload	Turnigy Aerodrive Motor	Hobby Kind	5	$17.99	$89.95
Payload	10 4-40 x .5in Flanged Cap Screw	McMaster-Carr	1	$7.50	$7.50

Payload	4-40 Round Nylon Standoff 1in	McMaster-Carr	2	$1.67	$3.34
Payload	4-40 Hex Aluminum Standoff 1in	McMaster-Carr	6	$0.81	$4.86
Payload	Turnigy 21A ESC	Hobby King	2	$9.81	$19.62
Payload	Raspberry Pi Zero W	Adafruit	1	$10.00	$10.00
Payload	CF PLA	Amazon	2	$27.99	$55.98

Table 8.2: Line Item Budget

8.2.2. Funding Plan

8.2.2.1. Sources of Funding

At the beginning of the competition, the overall budget was $11,050, and up until the first unsuccessful launch, the team was on budget. Although Payload had gone over budget by about $100, the money was reallocated from the branding team. The branding team shifted from paying for the team's apparel out of the budget to having individual team members pay for their apparel, which provided $157 in profit. Unfortunately, the first unsuccessful launch set back the budget significantly. The damage to the vehicle and the payload had a loss of $2,717.87 of materials. Fortunately, the Aeronautical and Astronautical Engineering Department funded $2000 of this deficit. Additionally, Zucrow Propulsion Labs purchased $1500 of materials for the team and Wildman Rocketry gave the team a 40% discount on personal team purchases. A current travel grant is pending in the AAE department for $2000 which would help fund 10 member's travel to the competition. Additionally, there has been outreach to the Women in Engineering for the sponsorship of the five female team members who are traveling to the event; a total of $1000. Furthermore, the team has reached out for additional funding from the Mechanical Engineering Department, Electrical and Computer Engineering Department, and Polytechnic Department for additional funds. There have been $6000 of requests for funding made that the team has high certainty of obtaining. Finally, the team is doing further crowdfunding campaigns within the nearby rocketry community and through social media platforms. Through crowdfunding after the unsuccessful launch, the team has raised $1,250 for the team. The team will continue to fundraise to ensure there are funds for any unseen circumstances that may occur this year, and the team will have any additional funds roll over to the team for next year, but currently it is likely that the team has overestimated the total needed for the budget this year, and will not need the funds originally thought to be needed. There are sections of the budget that have allocations larger than the anticipated costs such as the branding budget which has a remaining $450.00 to spend, but will likely spend less than $100 on the team's display for the rocket fair. Additionally, the team is spending less than anticipating on housing, so the the travel budget is likely closer $3000, saving the team $1000, but the budget will remain the same to account for unseen circumstances which may arise.

8.2.2.2. Allocation of Funds

Section	Estimated Cost
Construction	$3000.00
Avionics	$900.00
Payload	$2000.00
Outreach	$100.00
Safety	$250.00
Branding	$450.00
Travel	$4000.00
Rebuild	$2717.87
Total	$13417.87

Table 8.3: Allocation of Funds

8.2.2.3. Funding Sources and Remaining Finances

Source	Estimated Cost
Aerojet Rocketdyne	$1600
Crowdfunding	$5266.96
Purdue Propulsion	$1315.02
ECE Department	$2000.00
ME Department	$1000.00
AAE Department	$2000.00
Money From Apparel Sales	$157.00
Total Raised	$13338.98
Total Remaining to be Fundraised	$78.89
Total Remaining in Bank Account	$7104.54

Table 8.4: Funding Sources and Remaining Finances

8.3. Completed STEM Engagement Events Since December

Event	Date of Event	Direct Interactions	Indirect Interactions
Purdue Space Day Ambassadors	1/24/2020	50	2
College Mentors for Kids	2/26/2020	24	0
Imagination Station	3/1/2020	9	5
FRR Total		83	7
Entire Competition Total		1,219	282

Table 8.5: STEM Engagement Events from CDR to FRR

8.3.1. Purdue Space Day Ambassadors - 1/24/2020

8.3.1.1. Description

The activity was to make straw rockets and test them at different angles to see what would produce the best result.

8.3.1.2. Activity Educational Goal

The goal of this activity was to teach the children about momentum and how rockets work. They were also able to learn about how the shape of their fins and the weight of their nose cones would affect how their rockets fly.

8.3.1.3. Outcome

The students were able to learn about the basic design of rockets as well as how to make the best rocket to go the farthest that it could.

8.3.2. College Mentors for Kids - 2/26/2020

8.3.2.1. Description

College Mentors for Kids is a program that Purdue University offers that brings in local students once a week and pairs them with a Purdue student. The team led the activity with groups of 1st and 2nd graders. The activity was to make paper rockets powered by blowing into a straw.

8.3.2.2. Activity Educational Goal

The goal of this activity was to teach the students how rockets work and why it is important to have fins and stability within a rocket design.

8.3.2.3. Outcome

The students were able to learn all of the best ways to make their rocket the most efficient that it could be. They learned the difference between having fins on their rocket and having wings on their rocket and which one was more efficient and why.

8.3.3. Imagination Station- 3/1/2020

8.3.3.1. Description

Imagination Station is a local children's science museum that has events throughout the year. The team made foam rockets with the children in attendance.

8.3.3.2. Activity Educational Goal

The goal of this activity was for the students to learn about energy and how it works in rockets. The students were tasked to make their rocket travel as far as it could and go as high as possible.

8.3.3.3. Outcome

The students were able to learn the basic design of rockets and how the rubber bands would launch them into the air. They also learned the importance of launch angles for their rockets to go the highest or farthest that they could go.

8.4. Plans for Future STEM Engagement

The deadline for STEM Engagement to count towards the team's score is FRR. Regardless of that, the team will continue to do events with College Mentors for Kids, Imagination Station, and Purdue Space Day Ambassadors. The team values STEM outreach and has made it one of the requirements to join the team in Huntsville for launch week.

8.5. Project Timeline

The timeline the PSP-SL team will be following is shown below. The timeline outlines the following events: deadlines, launch opportunities, meetings or teleconferences with NASA officials, general team meetings, and miscellaneous events.

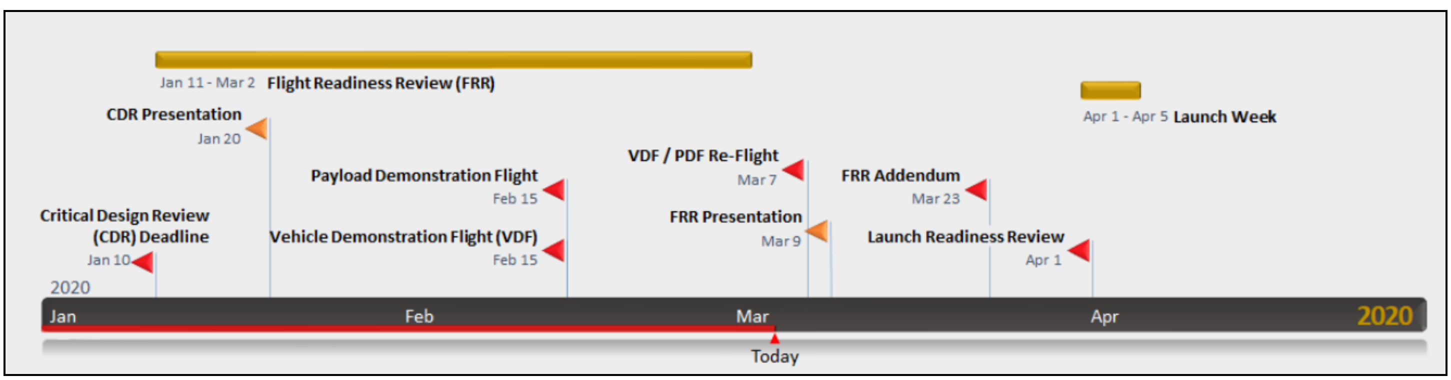


Figure 8.6: Major Milestone Project Timeline

Date	Event	Date	Event
08/22/2019	NASA Releases 2020 Student Launch Handbook	01/13/2020	CDR video teleconferences start
09/01/2019	Purdue SL general meeting	01/11/2020-01/12/2020	Tentative Indiana Rocketry Launch
09/02/2019	LABOR DAY	01/19/2020	Purdue SL general meeting
09/07/2019-09/08/2019	Indiana Rocketry Launch	01/20/2020	MARTIN LUTHER KING JR. DAY

09/08/2019	Purdue SL general meeting	01/22/2020	CDR video teleconferences end
09/15/2019	Purdue SL general meeting	01/26/2020	Purdue SL general meeting
09/18/2019	Proposal due to project office by 3PM CDT	01/31/2020	FRR Q&A
09/22/2019	Purdue SL general meeting	02/02/2020	Purdue SL general meeting
09/29/2019	Purdue SL general meeting	02/09/2020	Purdue SL general meeting
10/03/2019	Awarded proposals announced	02/08/2020-02/09/2020	Tentative Indiana Rocketry Launch
10/06/2019	Purdue SL general meeting	02/16/2020	Purdue SL general meeting
10/07/2019-10/08/2019	OCTOBER BREAK	02/23/2020	Purdue SL general meeting
10/09/2019	Kickoff, PDR Q&A	03/01/2020	Purdue SL general meeting
10/12/2019-10/13/2019	Indiana Rocketry Launch @ Tab, Indiana	03/01/2020	Final day for full scale launch/Vehicle Demonstration Flight
10/13/2019	Purdue SL general meeting	03/02/2020	Vehicle Demonstration Flight data reported to NASA
10/20/2019	Purdue SL general meeting	03/02/2020	FRR report, slides, and flysheet posted online by 8AM CDT
10/25/2019	Web presence established, URLs sent to project office by 8AM CDT	03/06/2020	FRR video teleconferences start
10/27/2019	Purdue SL general meeting	03/08/2020	Purdue SL general meeting
11/01/2019	PDR report, slides, and flysheet posted online by 8AM CDT	03/14/2020-03/15/2020	Tentative Indiana Rocketry Launch
11/03/2019	Purdue SL general meeting	03/15/2020	Possible Purdue SL general meeting
11/04/2019	PDR video teleconferences start	03/16/2020-03/21/2020	SPRING BREAK
11/07/2019-11/10/2019	SEDS SpaceVision in Tempe, Arizona	03/19/2020	FRR video teleconferences end
11/09/2019-11/10/2019	Tentative Indiana Rocketry Launch	03/22/2020	Purdue SL general meeting
11/10/2019	Purdue SL general meeting	03/23/2020	Payload Demo Flight/Vehicle Demonstration Re-flight deadlines
11/15/2019-11/17/2019	Midwest Power Launch @ Princeton, Illinois	03/23/2020	FRR Addendum submitted to NASA by 8:00 AM CDT (if needed)
11/17/2019	Purdue SL general meeting	03/26/2020	Launch Week Q&A
11/20/2019	PDR video teleconferences end	03/29/2020	Purdue SL general meeting
11/24/2019	PSP-SL Subscale Launch	04/01/2020	Travel to Huntsville, Alabama
11/25/2019	CDR Q&A	04/01/2020	OPTIONAL – LRR for teams arriving early
11/27/2019-	THANKSGIVING BREAK	04/02/2020	Official launch week kickoff and activities

11/30/2019			
12/01/2019	Purdue SL general meeting	04/02/2020	LRR (If not done on 04/01)
12/07/2019-12/08/2019	Tentative Indiana Rocketry Launch	04/03/2020	Launch week activities
12/08/2019	Purdue SL general meeting	04/04/2020	Launch day
12/14/2019-01/13/2020	WINTER BREAK	04/04/2020	Awards Ceremony
01/10/2020	Final day for subscale launch	04/05/2020	Backup launch day
01/10/2020	Final motor choice made for launch	04/05/2020	Possible Purdue SL general meeting
01/12/2020	Possible Purdue SL general meeting	04/12/2020	Purdue SL general meeting
01/10/2020	CDR report, slides, and flysheet posted online by 8AM CDT	04/19/2020	Purdue SL general meeting
01/12/2020	Purdue SL general meeting	04/27/2020	PLAR posted online by 8AM CDT

Table 8.7: Project Timeline