WASHINGTON UNIVERSITY IN ST. LOUIS

2022-2023 NASA USLI Team

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St. Louis, MO 63105

Behnken 1

FLIGHT READINESS REVIEW

MARCH 6, 2022

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1 Summary of Flight Readiness Review Report

1.1 Team Summary

The team name of Washington University in St. Louis's NASA Student Launch team is WURocketry. The mailing address of WURocketry is: Lopata 303, 1 Brookings Drive St. Louis, MO 63105. The team will participate in the launch week held in Huntsville, AL, between April 12th-16th, 2022. WURocketry will complete the final launch during launch day. The team mentor is Mike Walsh (TRA: 09969, NAR: 85317, Certification Level 3), an Engineering Analyst - Casting for Toyota Motor Manufacturing. Mike's contact information is Michael.Walsh@toyota.com or (636)-358-2490.

1.1.1 Time Spent on Flight Readiness Review

Table 1: Time Spent on Flight Readiness Review Broken Down by Group

Group	Avionics	Payload	Structures	R & P	Aero	Business/ Funding	STEM Engagement	Executive Team	**Total**
Time (Hours)	30	118	187	50	17	10	15	71	**498**

1.1.2 STEM Engagement Summary

Eight total events reaching 415 student were held by WURocketry over the course of the competition season. The events consisted of a Fling Flyer design activity, where students designed an airplane with different materials, and then tested the plane for distance, as well as a Q&A session regarding general aerospace concepts provided to middle school students. A stomp rocket activity was conducted with K-5 students that taught the design process as it relates to rocket design. Rocket components and subsystems were explained at a local STEAM fair, and a straw rocket activity was conducted with K-5 students to introduce them to the engineering design process.

1.2 Launch Vehicle Summary

Table 2: Launch Vehicle Summary

Target Altitude – 4650 ft	**Final Motor Choice** – Aerotech L1390G-P
Individual Sections: Forward – 64.725 in, 17.95 lb Mid – 14.75 in, 5.32 lb Aft – 31.525 in, 19.84 lb wet (15.48 lb dry)	**Recovery System** – 18 in Elliptical drogue parachute released at apogee, 120 in Iris Ultra Standard parachute released at 600 ft, 5/8 in tubular nylon shock cords of 15, 30, 15, 25 ft in respective order from forward to aft eyebolts
Wet Mass – 43.1 lb	**Burnout Mass -** 38.75 lb
Landing Mass – 38.75 lb	**Dry Mass without Ballast** – 38.75 lb
Rail size – 1515 Rail, 144 in	**Dry Mass with Ballast -** N/A

1.3 Payload Summary

The VISiON (Virtual Interactive Snapshot in Operational eNvironment) payload experiment is an imaging system designed for use in the WURocketry 2022-2023 mission. It is capable of receiving radio frequency commands over an automatic packet reporting system to capture images of the landing site of the vehicle it is on. The mechanical design of the system includes mechanisms for retention, self-righting, and deployment, while the electrical design covers power distribution, control, and imaging capabilities. The entire system weighs 4.67 lbs and has a length of 12.4 in. VISiON is located within the payload bay in the forward section of the rocket, situated behind the nosecone.

2 Changes Made Since CDR

2.1 Changes Made to Vehicle Criteria

2.1.1 Structures

Two major structural changes occurred since the CDR submission. When weighing the launch vehicle on the pad, the rocket was found to be about 2 pounds heavier than expected. The team believes that the fasteners, wires, epoxy, and recovery hardware such as eye bolts, quick links, and swivel joints collectively add a significant amount of weight (2-3 lb) to the launch vehicle. The fin shells were designed and 3D printed to be smaller and lighter to reduce overall weight. Additionally, the bulkheads were CNC machined to remove a substantial amount of aluminum material. The bulkheads were re-designed on SolidWorks, analyzed with the snatch force using Finite Element Analysis, and machined using a 3-axis CNC vertical mill. Just over 1 lb was removed from the bulkheads, which weighed 3 lbs collectively before any mass optimization. Many of the expected weights of components differed from the actual weights, so the team individually measured each component once construction had finished to ensure that the accurate masses had been found.

2.1.2 Avionics

The majority of the avionics bay has remained consistent with the design it held in the CDR document; however, considering the shortfall in the full scale test flight to reach the team's apogee goal, non-mission critical sensors on the avionics bay will be omitted in the final competition launch. The purpose of this designation is to provide a potential 0.5 lb weight reduction to the rocket if future test flights indicate that the altitude undershoot for the full scale rocket is a persistent issue.

2.1.3 Recovery Subsystem

Two major changes occurred in the recovery subsystem since the CDR submission. To ensure deployment of the drogue parachute, the recovery harness layout has been adjusted and finalized as seen in Section 3.3.3. The 25 ft shock cord that used to connect the aft section to the aft avionics bay bulkhead, has been relocated to connect the aft section to the drogue parachute. This reduces the changes of the drogue parachute getting stuck in the body tubes during seperation. Additionally, changes have been made to the shock cord protection method and recovery packing. Due to the diameter of the body tubes and a large pressure chamber relative to the hardware and recovery harness within, the shock cords were not aptly covered from heat during black power ignition. Due to this, Nomex blankets are now used to wrap all of the shock cords to protect the cords from flames from black powder detonation. This can also be seen in Section 3.3.3.

2.2 Changes Made to Payload Criteria

2.2.1 Payload Mechanical Changes

1. **Strengthened Motor Axle** The use of a new and more robust axle design was implemented during the construction of the separation mechanism. The mechanism

no longer relies on the use of an axle bearing to support the motor axle in favor of a more sturdy axle.

2. **Electronics Board Support Rods** Previously, the electronics board was mounted on top of 3-D printed telescoping rods. The design now utilizes aluminum rods which are screwed into the rotating tracks on the aft end and pass through the rotating tracks on the forward end. The aluminum rods are lighter, increase stability, and replace the additional solenoid used to stop payload rotation during flight.

3. **Key-Slot Rack and Pinion** In addition to the original separation method that used a rack and pinion, the design has been improved through the use of a "key and slot" that provides better support of the rack while maintaining contact with the pinon gears.

4. **Optimized Mass and Board Layout** The original board has been replaced with a basswood board in response to temperature and structural concerns with regards to mounting components via screws. The board components have also been rearranged and stripped to optimize volume and mass constraints.

5. **Shortened Scissor Lift** The originally designed lift has been shortened by removing a layer within the scissoring mechanism to allow for the lift to fit within the bay. With the new scissor lift placed upon the electronics basswood board and the camera components on top, the entire mechanism remains about 0.2" below the body tube when retracted.

2.2.2 Payload Electrical Changes

1. **Lightweight Imaging Software Library** After multiple tests with regards to runtime and program performance, a new lightweight image transform library was used to implement the image transform function. The new library uses less memory and performed equally as well in terms of image quality and runtime.

2. **Motive Voltage Regulator** To better supply power to the camera subsystem servos on-board the vehicle, a new voltage regulator was implemented to meet the rated operational voltage as needed. With the increased power supplied, the servos are capable of achieving greater precision and torque of its rotation.

2.3 Changes Made to Project Plan

A couple of changes were made to the project plan since the Critical Design Review. Additions to the budget included extra nomex blankets for shock cord protection, extra hardware for payload construction, and travel funds. These additions are included in the budget in section 8.2.1. Since the CDR, a sponsorship brochure has been developed that is currently in the process of being cleared by the school to send out to companies in order to begin acquiring funds for next school year.

Few updates have been made to the timeline with regards to WURocketry's project plan. Minor changes to the project plan include scheduled STEM Engagement events and launch opportunities. Multiple STEM Engagements have been added to the schedule and will continue to be added as opportunities arise in the St.Louis region. Since the CDR, WURocketry has also successfully attempted one full scale launch and has scheduled a payload demonstration flight for March 11, 2023.

3 Vehicle Criteria

3.1 Design of Vehicle

3.1.1 Mission Statement

WURocketry aims to design, manufacture, test, assemble, document, present, and launch a recoverable and reusable rocket attaining an apogee of 4650 ft while carrying a functioning payload for the 2022-2023 NASA Student Launch.

3.1.2 Mission Success Criteria

The mission will be considered successful if it meets all requirements and specifications (vehicle, recovery, safety, and payload) outlined in the 2022-2023 Student Launch Handbook as well as all team derived requirements listed in Section 8.1.

3.1.3 Launch Vehicle Overview

The launch vehicle is designed to be 111 in long with an outer diameter of 6.17 in. The wet weight of the vehicle is 43.1 lb and the dry weight is 38.75 lb. The primary motor will be the Aerotech L1390G-P motor with a wet weight of 8.55 lb. Figure 1 displays a layout of the rocket with the Forward, Mid, and Aft Sections labeled with dimensions. These sections have been divided based on the proposed in-flight separation points necessary for the deployment of the main and drogue parachutes, as well as the ease of manufacturing, assembly, and transportation of the rocket. Figure 2 consists of the key corresponding with Figure 1. It labels the parts of the rocket in the current vehicle design layout.

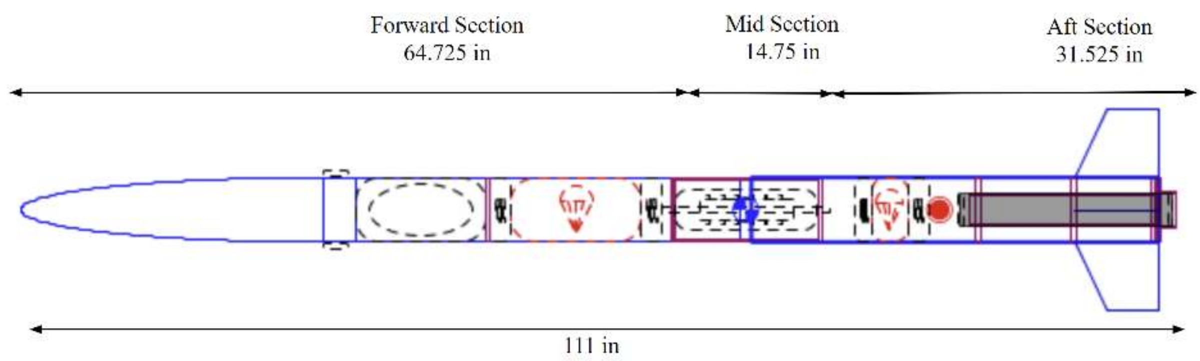


Figure 1: Current Vehicle Design Layout

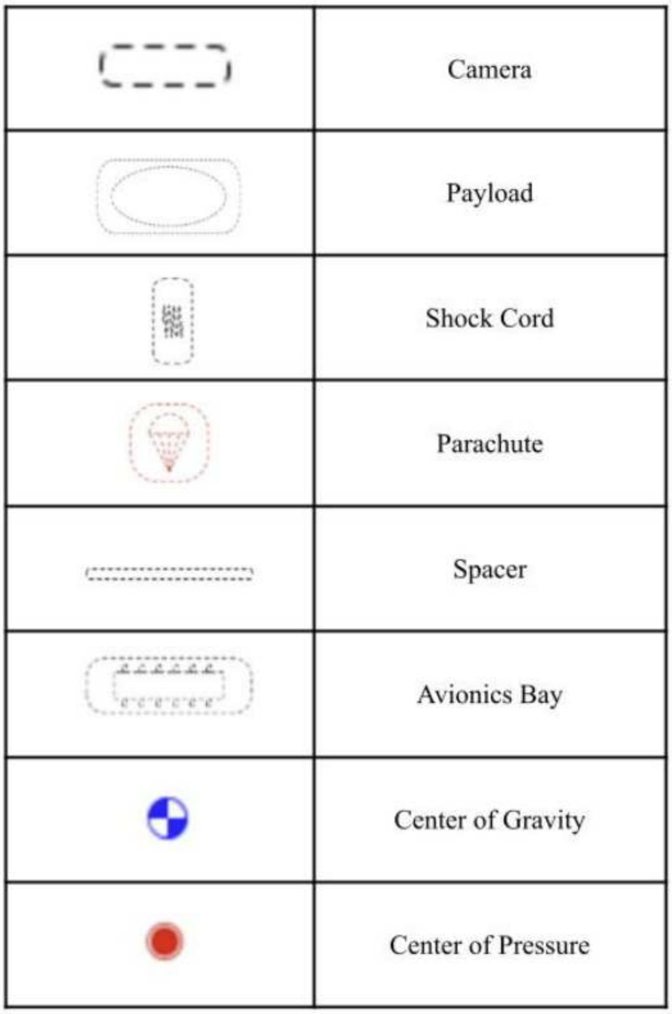


Figure 2: Launch Vehicle Component Layout.

The forward section of the rocket is made up of a 5:1 elliptical nose cone, cameras, payload, main parachute, shock cords, and a bulkhead. The main parachute is to be released from the in-flight separation point located between the forward and mid sections. These sections combine to come to a length of 64.725 in. and a weight of 17.95 lb with the payload, and 12.95 lb without payload.

The mid-section is made up of the avionics bay, a coupler connecting the forward and aft section, two bulkheads, and a spacer. The avionics bay will be located entirely in the coupler between two bulkheads secured via threaded rod spacers. The bulkhead forward of the avionics capsule (mid bulkhead) is attached to the aft bulkhead on the opposite side of the coupler via threaded rods and nuts. Four 4-40 nylon shear pins secure the forward body tube to the coupler tube. The aft side of the coupler tube is attached to the aft body tube with two 4-40 nylon shear pins. The mid body tube "ring" is epoxied to the coupler. The mid section with the bulkheads and coupler combines to a length of 14.75 in. and a weight of 5.32 lb.

The aft section includes the aft body tube, drogue parachute and shock cords, motor tube and closures, motor retention, centering rings, fins and fin shells. The fins are fitted through slots machined into the aft tube and held in place by cutouts in the centering rings and epoxy set on either side of the interface between the fin and airframe. This combines to a length of 31.525 in., with a wet weight of 19.84 lb and a dry weight of 15.48 lb.

Below, in Tables 3-5, the final components of the launch vehicle are shown. Additionally, the mass of each component is included in the table. Masses in green have been physically measured while masses in black are estimated masses.

Table 3: Table of Forward Vehicle Components

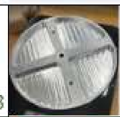
Component	Design Choice	Material	Dimensions	Weight (lb)	Image
Forward Section				*17.95*	
Nose Cone	5:1 Elliptical	G10 Fiberglass with aluminum tip	29 in long by 6.17 in wide at base	4.3	
Cameras	Universal AstroCam HD Rocket Cameras	PETG camera holders	2.32 in long by 0.67 in wide	0.062	
Forward Body Tube	6.17 in outer diameter, 6 in inner diameter	G12 Fiberglass	40 in long	4.53	
Payload	Board between two rotating tracks, electronics/camera deployment on top of board with battery on bottom	Plywood, PLA/PETG, alumininum	17 in long, 6 in diameter	5	
Forward Bulkhead	Disk with central hole eyebolt. Tapped holes on sides to be screwed into body tube	6061-T6 Aluminum	5.98 in diameter	0.53	
Main Forward Shock Cord	Tubular	Nylon	15ft 5/8"	0.38	
Main Aft Shock Cord	Tubular	Nylon	25ft 5/8"	0.46	
Main Parachute	Iris Ultra Standard Toroidal	Ripstop nylon	120" Diameter	2.25	
Recovery Components	Swivel joints, quick links, eybolts, nuts	Stainless steel/Carbon Steel	1 eye bolt, 2 swivel joints, 2 quicklinks	0.438	

Table 4: Table of Mid Vehicle Components

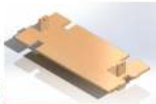
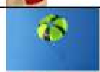
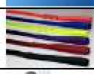
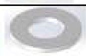
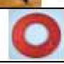
	Mid Section			*5.31*	
Mid Body Tube	6.17 in outer diameter, 6 in inner diameter	G12 Fiberglass	1 in long	0.31	
Tube Coupler	6 in outer diameter, 5.83 in inner diameter	G12 Fiberglass	14 in long	1.48	
Mid Bulkhead	Disk with slots and holes for avionics and recovery/separation systems	6061-T6 Aluminum	5.98 in diameter	0.65	
Avionics Bay and Spacers	Basswood board between mid and aft bulkheads, 15 in threaded spacers on each side of bay board	Basswood board, steel threaded rods, Avionics electronics	14 in long, 5.75 in wide	2.2	
Aft Bulkhead	Disk with slots and holes for avionics and recovery/separation systems	6061-T6 Aluminum	5.98 in diameter	0.61	
Faraday Cage	Rectangular tubing with pcb mounting holes	6061-T6 Aluminum	1.625 in long, 0.888 in wide, 0.808 in tall	0.06	

Table 5: Table of Aft Vehicle Components

Component	Design Choice	Material	Dimensions	Weight (lb)	Image
	Aft Section			*19.84*	
Aft Body Tube	6.17 in outer diameter, 6 in inner diameter	G12 Fiberglass	39 in long	4.81	
Drogue Parachute	Elliptical	Ripstop nylon	18" Diameter	0.11	
Drogue Shock Cords	Tubular	Nylon	15ft + 30ft 5/8"	0.46	
Motor Tube	3.08 in outer diameter, 2.88 in inner diameter	Cardboard	18.9 in long	0.58	
Motor Closures and Casing	75mm diameter, Green Propellant	Aluminium	Width: 3" (7.62 cm)	0.9	
Forward Centering Ring	6 in outer diameter, 3.08 in inner diameter	PLA Plastic	0.5 in long	0.15	
Aft Centering Rings	Slots for fin cores, 6 in outer diameter, 3.08 in inner diameter	PLA Plastic	0.5 in long	0.31	
Fin Cores	Clipped delta shape, epoxied to airframe	G10 Fiberglass	8 in long, 6.5 in wide, 0.25 in thick	1.85	
Fin Shells	NACA 0012 Airfoil Shell, glued to top of fin cores	PLA Plastic	5.7 in root cord, 2.5 in tip chord, 6.5 in width, 0.6 in thick	0.44	
Thrust Plate	6 in outer diameter, 2.95 in inner diameter	6061-T6 Aluminum	0.375 in thick	0.77	
Retaining Ring	3.65 in outer diameter, 3.26 in inner diameter	Aluminum	1.4 in long	0.31	
Wet Motor	AeroTech L1390G, 3946 Ns Impulse	Solid propellant	20.4 in long, 2.95 in diameter	8.55	N/A
Recovery Components	Swivel joints, quick links, eybolts, nuts, nomex blankets	Stainless steel/Iron	1 eye bolt, 2 swivel joints, 2 quicklinks	0.6	
	Combined Total			*43.1*	

Locations of Separation and Energetics

WURocketry created various designs for the energetics and separation of the rocket. The chosen design, as shown in Fig. 3, has separation points at the avionics bay. The team will use two longer body tubes that sit on either side of a 1 in body tube ”ring” epoxied to the exterior middle of the coupler.

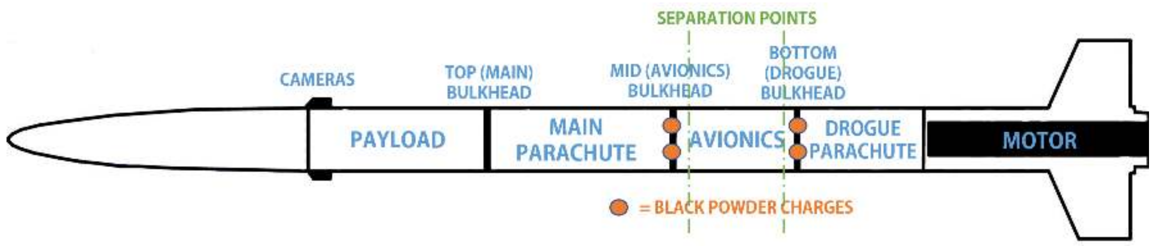


Figure 3: Vehicle In Flight Separation Point and Energetics

When determining which design will be the simplest, lightest, and easiest to assemble, the Structures sub-team chose the design in Fig. 3. Other design ideas located the separation events further away from the avionics coupler, which would protect the on-board electronics, but would require more time to assemble with extra body tubes and couplers. Fig. 3 positions two body tubes relative to a singular object (the avionics coupler), thus decreasing assembly time. It diminishes the need for an extra coupler and centering ring for the motor, which reduces overall rocket weight.

3.1.4 Launch Vehicle Material Summary

The launch vehicle is constructed mainly out of fiberglass, aluminum, basswood, plywood, and PLA. The airframe, nosecone, and couplers are made of G12 fiberglass. The fin cores are machined out of a G10 fiberglass sheet, and the fin shells are printed with PLA plastic due to its accesibility, affordability, and flexural strength. The bulkheads are milled out of 6061-T6 aluminum. The centering rings are printed from PLA plastic. The structure that supports the avionics component is laser cut from 1/4 in basswood. The payload bay board is laser cut from 1/4 in plywood. Phenolic tube is used for the motor mount as all thrust forces are directly transferred into the airframe from the motor retention system.

3.1.5 SolidWorks Model of Full-Scale Design

Figure 4 shows the exploded view of the entire Full-Scale rocket Assembly, marking the major components of the rocket design and their layout.

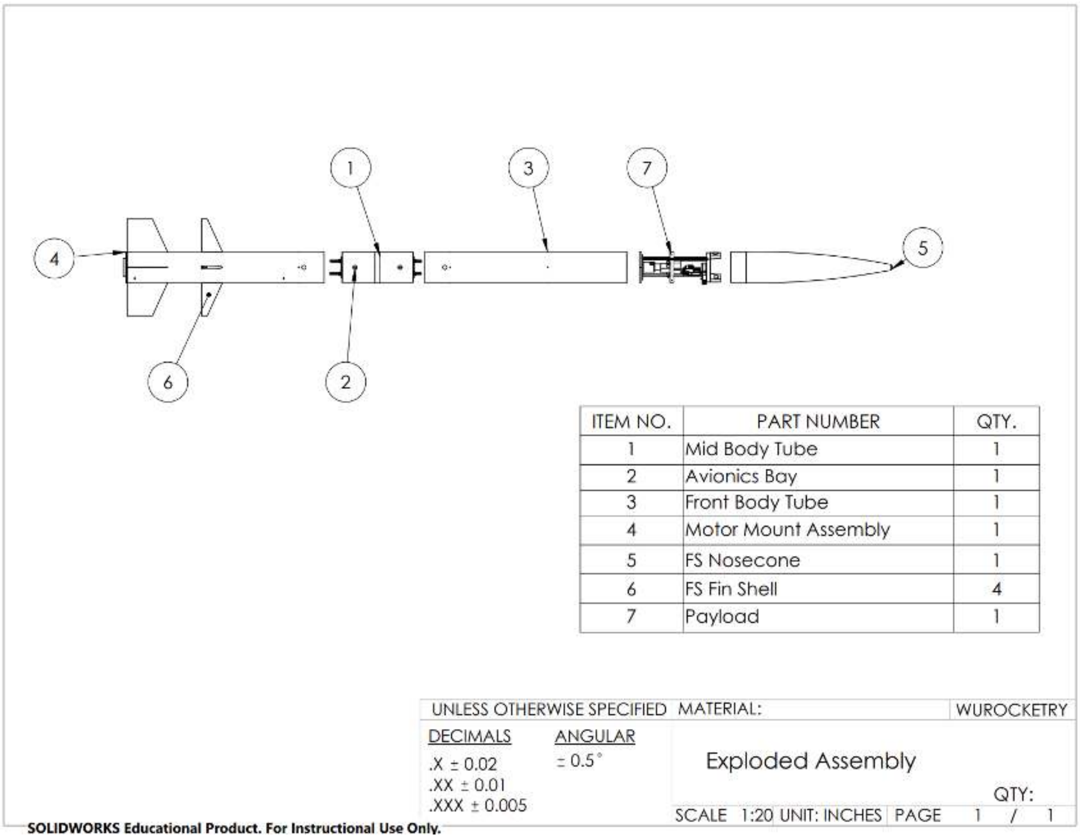


Figure 4: Full-Scale Assembly Exploded View

3.1.6 Nose Cone

The nose cone keeps the balance of the rocket in check, and with the right shape, it could greatly decrease the drag force effect on the rocket. The Structures sub-team considered using a tangent ogive, elliptical, parabolic, and Von-Karman shaped nose cone. The 5:1 elliptical nose cone was chosen for its aerodynamics and lower drag force.

The Structures team chose between fiberglass, plastic, and carbon fiber for the material of the rocket. The three materials were ranked based off of strength to weight ratio, availability, and RF transparency. Plastic nosecones are light but lack strength and are not widely available. On the other hand, carbon fiber has an advantageous strength-to-weight ratio, but it is expensive, difficult to find, and not RF transparent. G12 fiberglass was picked for its RF transparency, high strength-to-weight ratio, and ease of access. Fig. 5 displays a dimensional drawing of the 5:1 elliptical nose cone chosen for this year's launch vehicle with a 3.1 in shoulder attached.

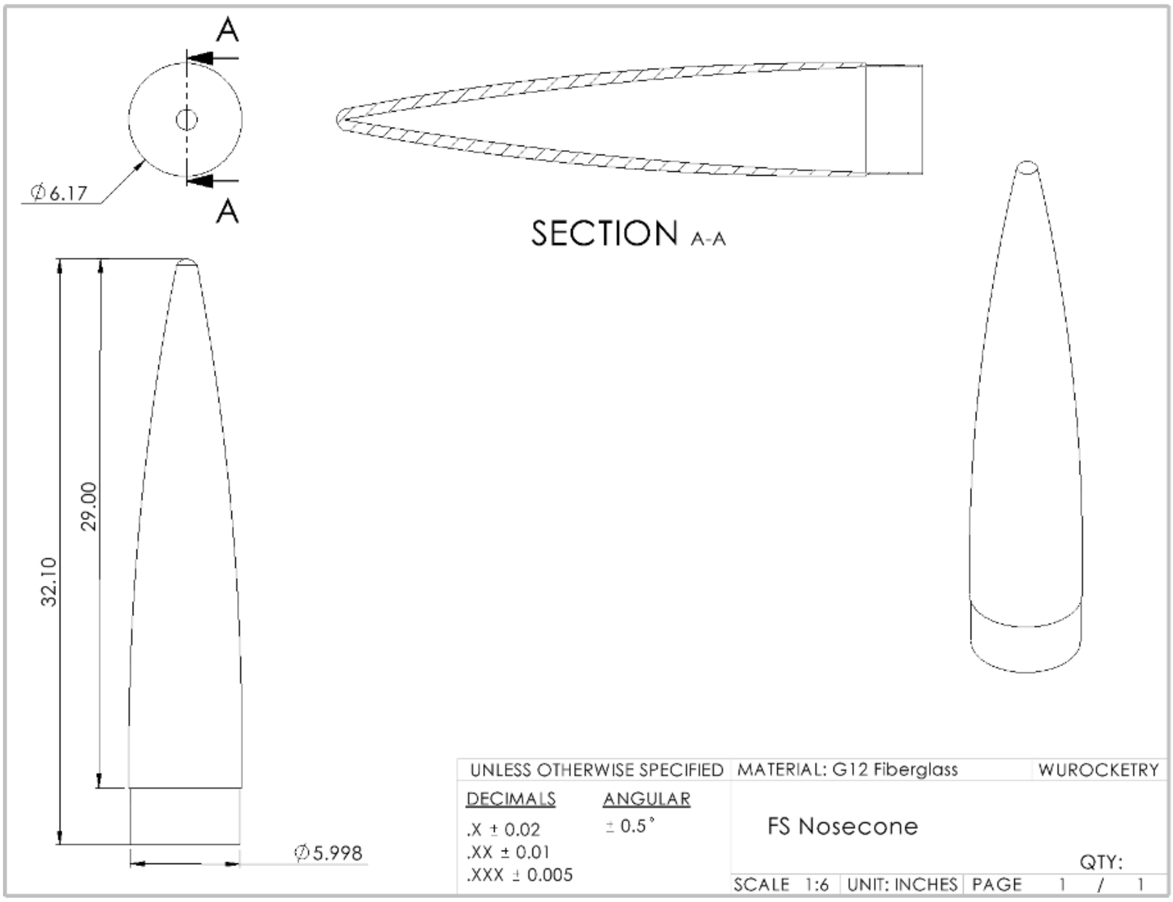


Figure 5: Nose Cone CAD Drawing

3.1.7 Cameras

WURocketry has decided to implement the addition of two Universal AstroCam HD Rocket Cameras on either side of the rocket immediately aft of the nosecone. These allow the team to clearly view the rocket and its flight for the duration of the ascent to apogee and also provide visual data for the deployment of the drogue and main parachutes. This data is vital in determining potential root causes of failures during testing and visual feedback of the impact of launch condition changes. Fig. 6 shows a dimensional drawing of the upwards facing camera mount.

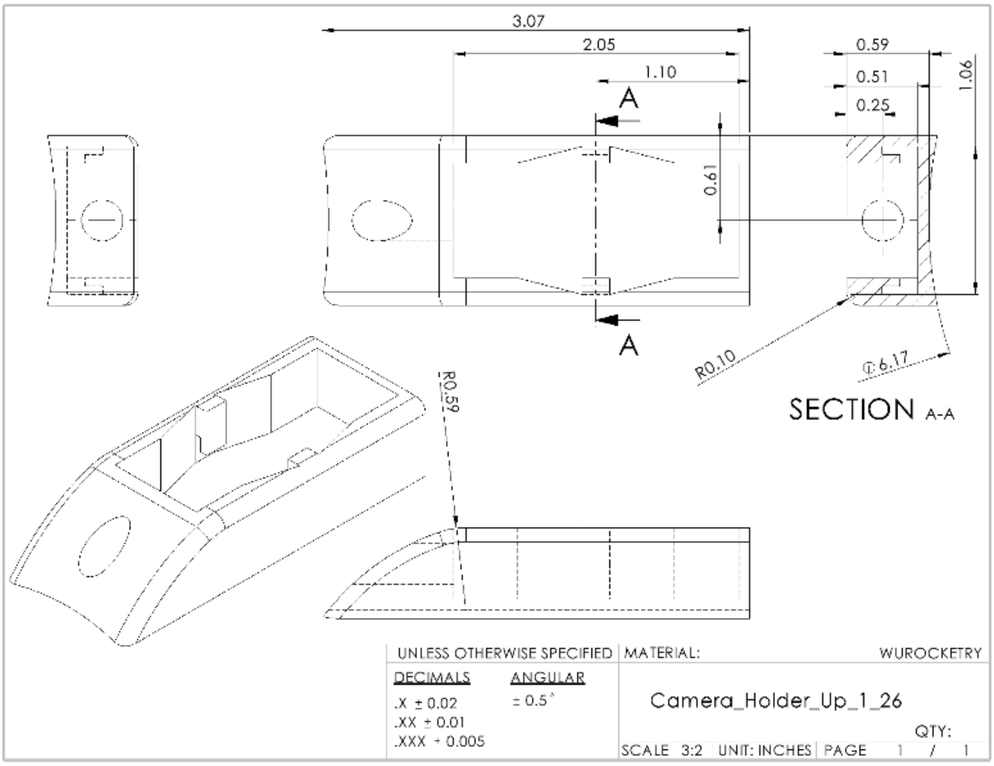


Figure 6: Dimensional Drawing of Upwards Facing Camera Holder

3.1.8 Airframe and Coupler

The team chose to use G12 fiberglass for the airframe and couplers of the rocket. This decision was based on the availability, cost, RF transparency, and compressive strength of the material. The launch vehicle has a diameter of 6.17 in and length of 111 in which made G12 fiberglass was the best option for the airframe. It is low cost and readily available, while still meeting the team's desired design requirements of RF transparency and large compressive strength. Because fiberglass is an insulator, a fiberglass airframe will be transparent to radio waves. G12 fiberglass has a compressive strength of around 22 ksi, making it suitable for use as the body tube of the rocket, as demonstrated by the calculation using a maximum thrust force of 300 lb in the Mission Performance Predictions.

A 6.17 in diameter body tube allows ample room for the avionics, payload, and recovery systems, while providing easy access to the interior of the rocket. The figures listed below detail cross-sectional assembly drawings of each individual section of the rocket, excluding the nose cone, cameras, and fasteners. Fig. 7 displays the forward body tube with the payload bay model, forward bulkhead, and main parachute simplified model.

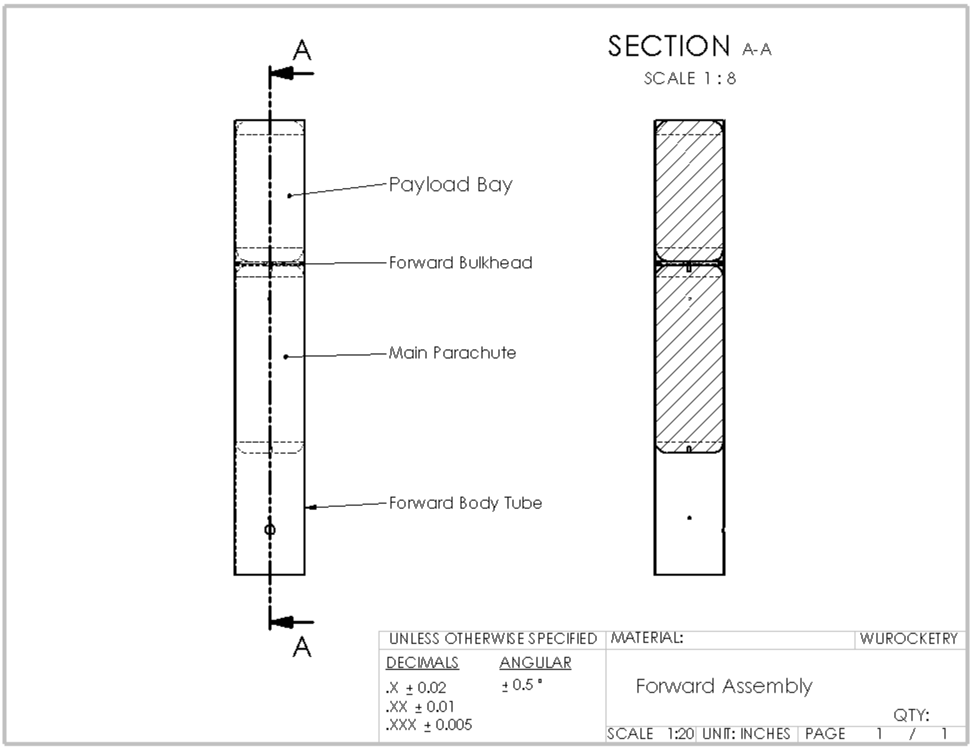


Figure 7: Forward Body Tube Sectional View

Fig. 8 displays the mid bulkhead, mid body tube, avionics coupler, avionics bay board, lead screws, flange nuts, and aft bulkhead.

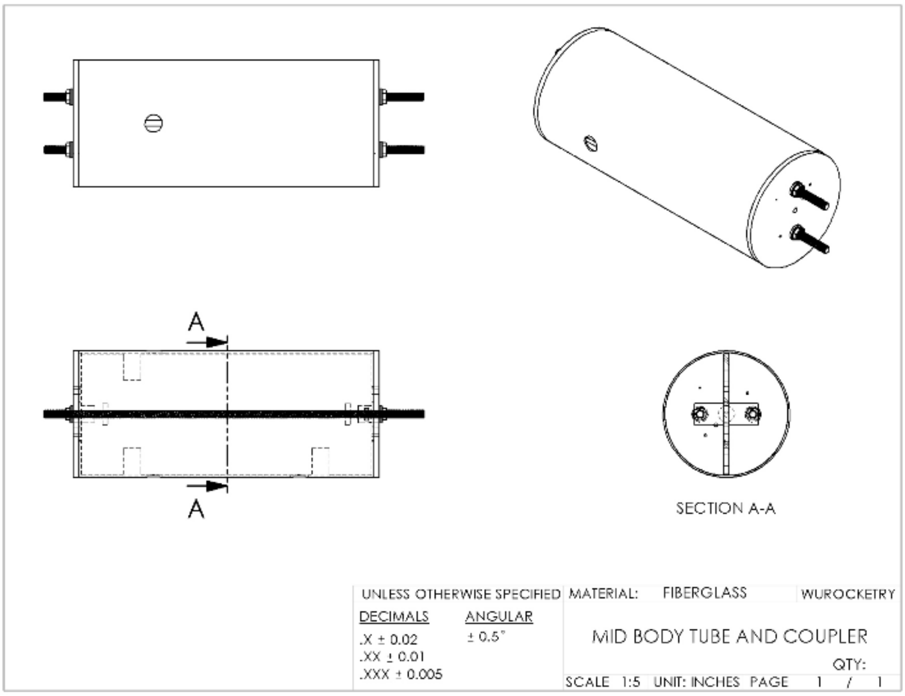


Figure 8: Mid Body Tube and Coupler Sectional View

Fig. 9 displays the drogue parachute model, aft body tube, motor tube, motor retention, centering rings, fin cores, and fin shells.

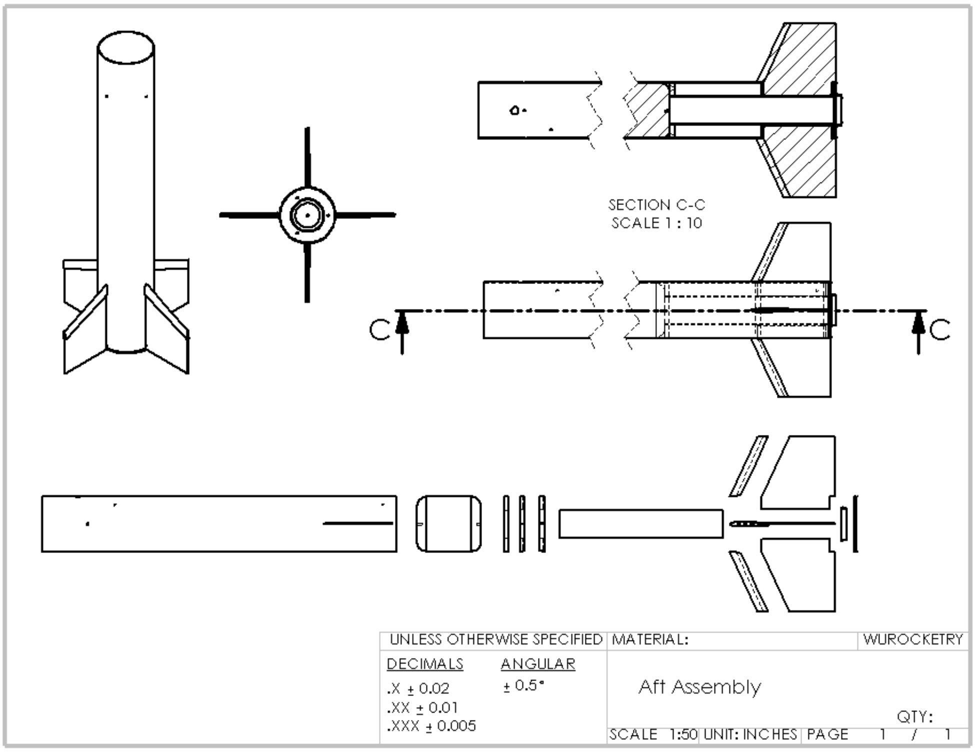


Figure 9: Aft Assembly Exploded View

3.1.9 Vent Hole Sizing

The reason for a vent hole is to allow the pressure inside the rocket to equalize to the external atmospheric pressure. This is important because atmospheric pressure decreases as altitude increases. If not accounted for, the difference in pressure inside and outside the rocket could be large enough to eject the nose cone of the rocket mid-flight. Two pressure sensors are housed inside the forward body tube used for redundant altitude measurement for the payload system. In order for these to produce accurate data, ventholes are necessary to stabilize the pressure inside the rocket throughout its accent to apogee, as well as the descent so that the pressure inside the rocket in the forward body tube is equal to the ambient pressure outside the rocket at any given time.

In order to determine the correct size of the vent hole so that it is not so large that it starts significantly affecting drag, and not so small that there is no pressure change occurring during flight, the following formula was used to calculate the diameter of the vent hole, which is derived upon the rule of thumb of $\frac{1}{4}$" vent hole for every 100 cubic inches of volume.

$$D_{venthole} = 0.004396 D_{bodytube} \sqrt{\frac{L}{N}}$$

$$D_{venthole} = \text{Diameter of vent hole}$$

$$D_{bodytube} = \text{Diameter of body tube}$$

$$L = \text{Length of body tube}$$

$$N = \text{Number of vent holes}$$

Using the above formula, the diameter of the vent holes was calculated as follows:

$$D_{bodytube} = 6\text{"}$$
$$L = 18\text{"}$$
$$N = 2$$
$$D_{venthole} = 0.004396 \times 6 \times \sqrt{\frac{18}{2}}$$
$$D_{venthole} = 0.079128\text{"} < \frac{3}{32}\text{"}$$

Two vent holes are also needed in the aft body tube. The reason for this is the mid body tube, which separates the forward and aft body tube, is air-tight so the aft section must have its own vent holes for flow exchange and pressure equalization with ambient conditions. The calculation for the diameter of the two vent holes in the aft body tube is as follows:

$$D_{bodytube} = 6\text{"}$$
$$L = 15\text{"}$$
$$N = 2$$
$$D_{venthole} = 0.004396 \times 6 \times \sqrt{\frac{15}{2}}$$
$$D_{venthole} = 0.072234\text{"} < \frac{3}{32}\text{"}$$

Using a factor of safety of 1.5 for the venthole diameters, the team drilled two $\frac{1}{8}$" ventholes in each the forward and aft body tubes that are 180 degrees from each other to maintain symmetry of the ventholes.

3.1.10 Bulkheads

The rocket will have three bulkheads. The mid and aft bulkhead form the forward and aft sides of the avionics bay. The forward bulkhead sits aft of the payload bay towards the nose cone of the rocket. Bulkheads support the loads that the rocket undergoes during flight and transfer the loads to the airframe. Each bulkhead needs a central 1/4 in hole to support an eye bolt, which connects the rocket section to the parachute. Additionally, the forward bulkhead requires four equally spaced 6-32 screw holes around the edge of the bulkhead to be fastened to the body tube. The mid and aft bulkheads have a 1/8 in lip that allows for them to rest on each end of the coupler tube and transfer perpendicular forces to the body tube. Additionally, the mid and aft bulkheads need two 3/8 in through holes for the avionics bay spacers that serve to hold the avionics coupler together. The mid and aft bulkheads will also have two #6-32 screw holes for the black powder charges as well as a 3/16 in hole for the wiring for the black powder igniters. There will be an additional 1/8 in hole in both the mid and aft bulkhead to facilitate measuring the air pressure in the parachute compartments with a pressure transducer.

In order to reduce mass, material was removed from all 3 bulkheads. The designs were verified using the Solidworks Simulation, ensuring that they will still not yield under the anticipated flight loads. Figure 10 shows the dimensional drawing for the forward bulkhead, showing the newly removed sections.

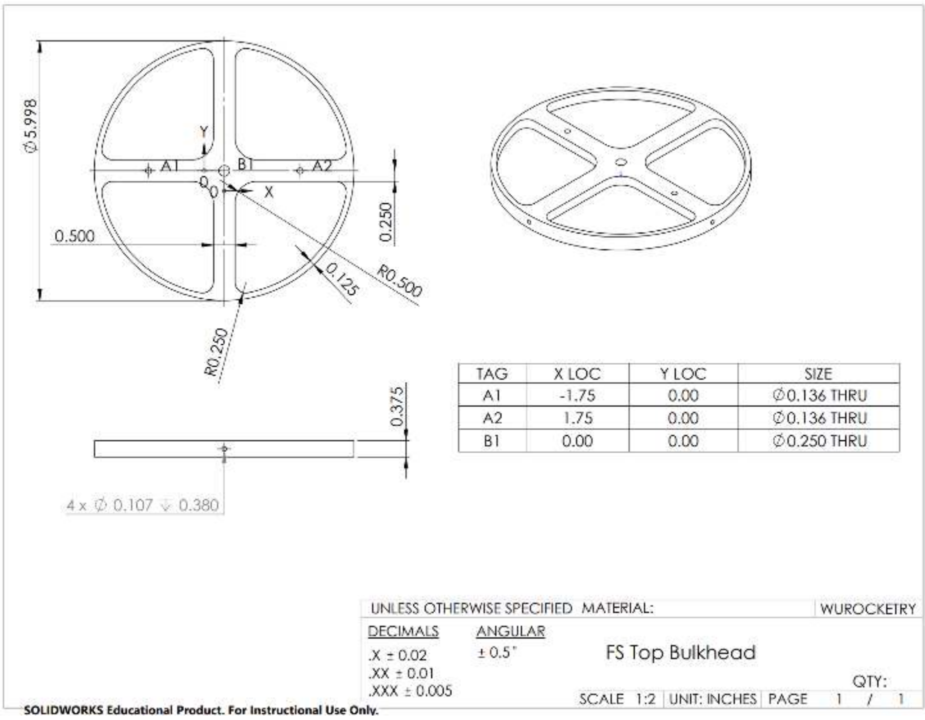


Figure 10: Dimensional Drawing of Forward bulkhead

Figure 11 is the dimensional drawing of the Mid bulkhead, showing the new mass optimized design.

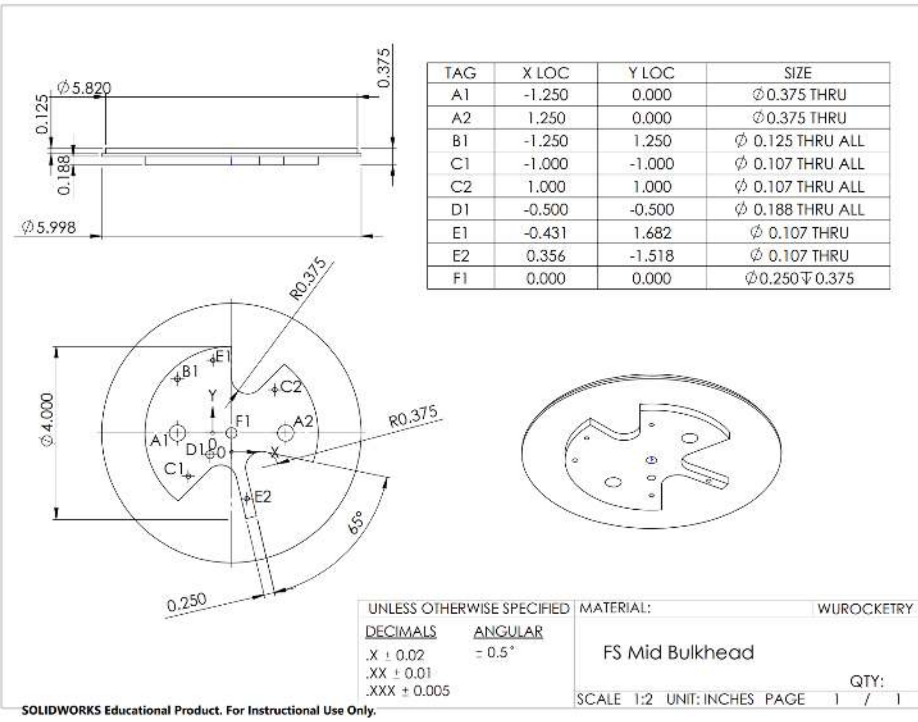


Figure 11: Dimensional Drawing of Mid bulkhead

Figure 12 is the dimensional drawing of the Aft bulkhead, showing the new mass optimized design.

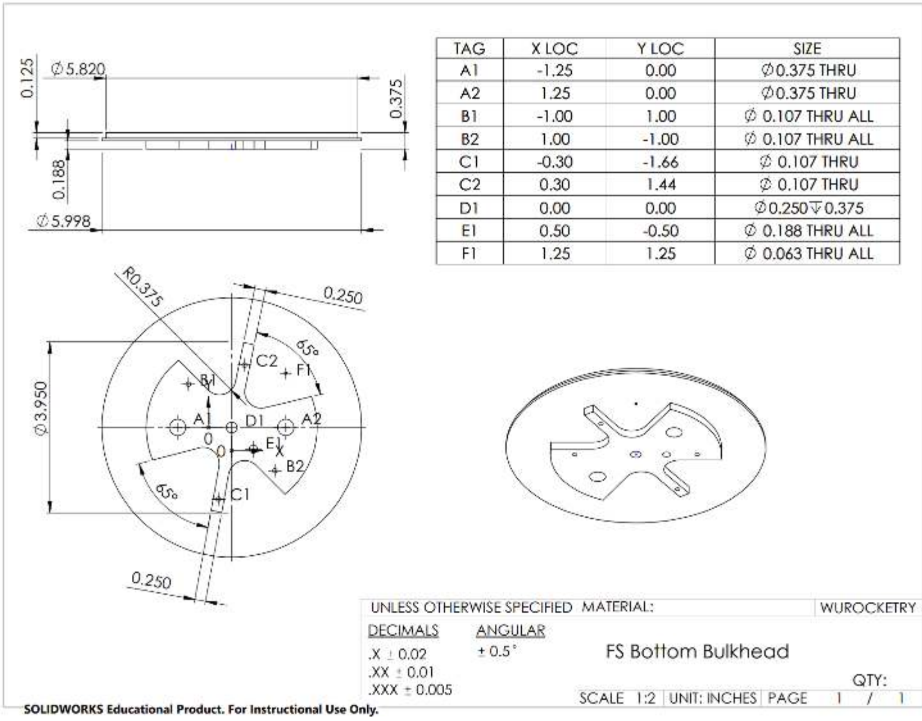


Figure 12: Dimensional Drawing of Mid bulkhead

3.1.11 Avionics Bay

WURocketry originally decided on using the same avionics bay for both the Full-Scale and Sub-Scale rocket. This allows the bay to be easily transferred between the Full-Scale and Sub-Scale rocket, reducing assembly time. Additionally, since the bay electronics are expensive, using the same bay would save money for the team. However, WURocketry has decided to use two separate avionics bay boards: one for the Sub-Scale and one for the Full-Scale rocket. WURocketry decided to use a basswood board because it is light, sturdy, and available in the size the team needs. The Avionics sub-team plans to include more sensors on the Full-Scale rocket, which requires more room on the board than the Sub-Scale board would have offered. Below is the dimensional drawing of the avionics bay and the mass of each material used for the bay, along with the total avionics bay mass, excluding the electronics.

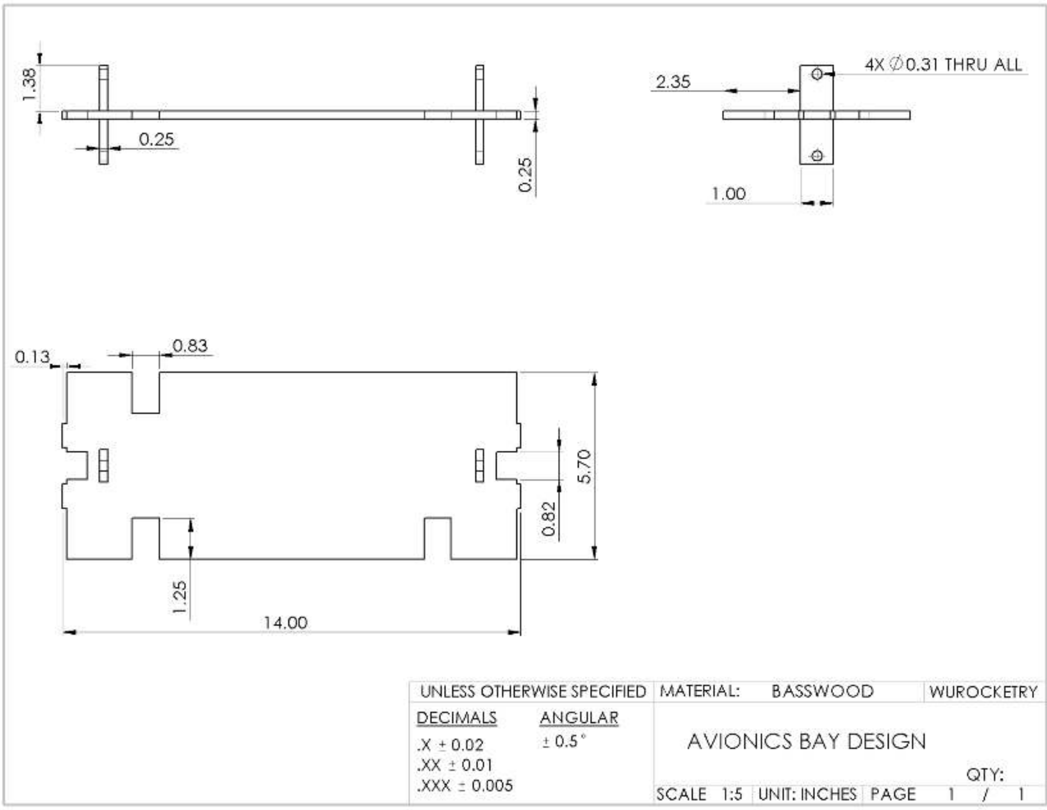


Figure 13: Dimensional Drawing of Avionics Bay

Table 6: Total Mass of Avionics Bay Without Electronics

Component	**Mass (lb)**
Basswood Bay Board	0.37
Switch Holders (x2)	0.02
Flange Nuts (x6)	0.0174
Lead Screws (x2)	0.12
Full-Scale Mid Bulkhead	0.52
Full-Scale Bottom Bulkhead	0.99
Combined Full-Scale Total	1.9074

When determining a design for the avionics bay, WURocketry took ease of manufacturing, cost, assembly time, reusability, and size of bay components into consideration. The team considered three designs for the avionics bay based on how the lead screws would be embedded in the bay and attached to the bulkheads. Ultimately, the team decided on a design incorporating ideas from earlier iterations. The design the team chose allows for usage of both sides of the bay, is easy to manufacture, and does not interfere with any holes or slots on the bulkhead. Elevating the lead screws off the board means they do not interfere with the bay components. The elevated height for the lead screws was determined using the largest height value that the bay components take on.

A 14 in coupler was chosen for the avionics bay to satisfy the NASA requirement of coupler lengths being at least two times greater than that of the diameter of the body tube. Additionally, 14 in couplers are readily available from manufacturers. Figure 14 displays the dimensional drawing of the avionics bay assembly with the mid and aft bulkheads, lead screws, flange nuts, and switch holders.

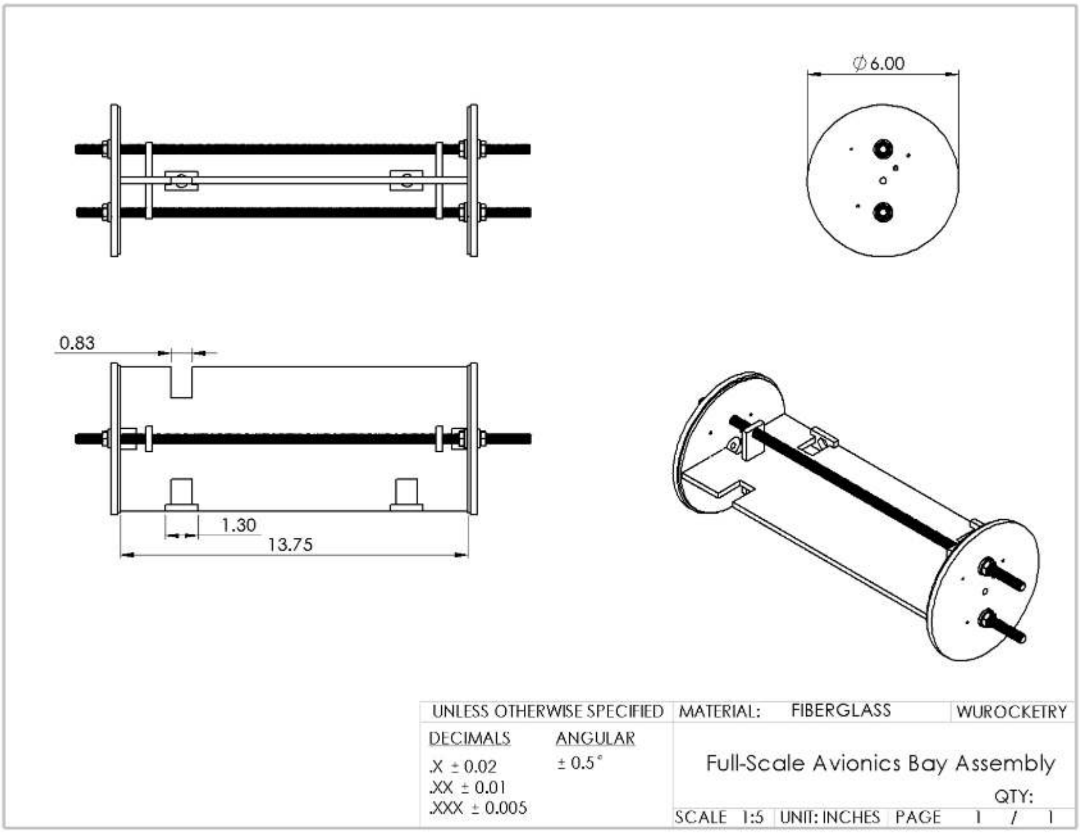


Figure 14: Full-Scale Avionics Bay Assembly

Faraday Cage

To further comply with NASA's RF interference requirements while also ensuring no external source of failure, two aluminum Faraday cages were designed to house the competition flight computers. These Faraday cages are constructed out of aluminum and are designed to be as continuous a piece of metal as possible in order to attenuate as much potential EMF as possible. These cages will be attached to the Avionics bay board pre-flight allowing the flight computers to be installed (with sufficient insulation from the aluminum) and protected from any potential interference. Figure 15 displays the dimensional drawing for Faraday cages that will be used in the Avionics bay of the rocket.

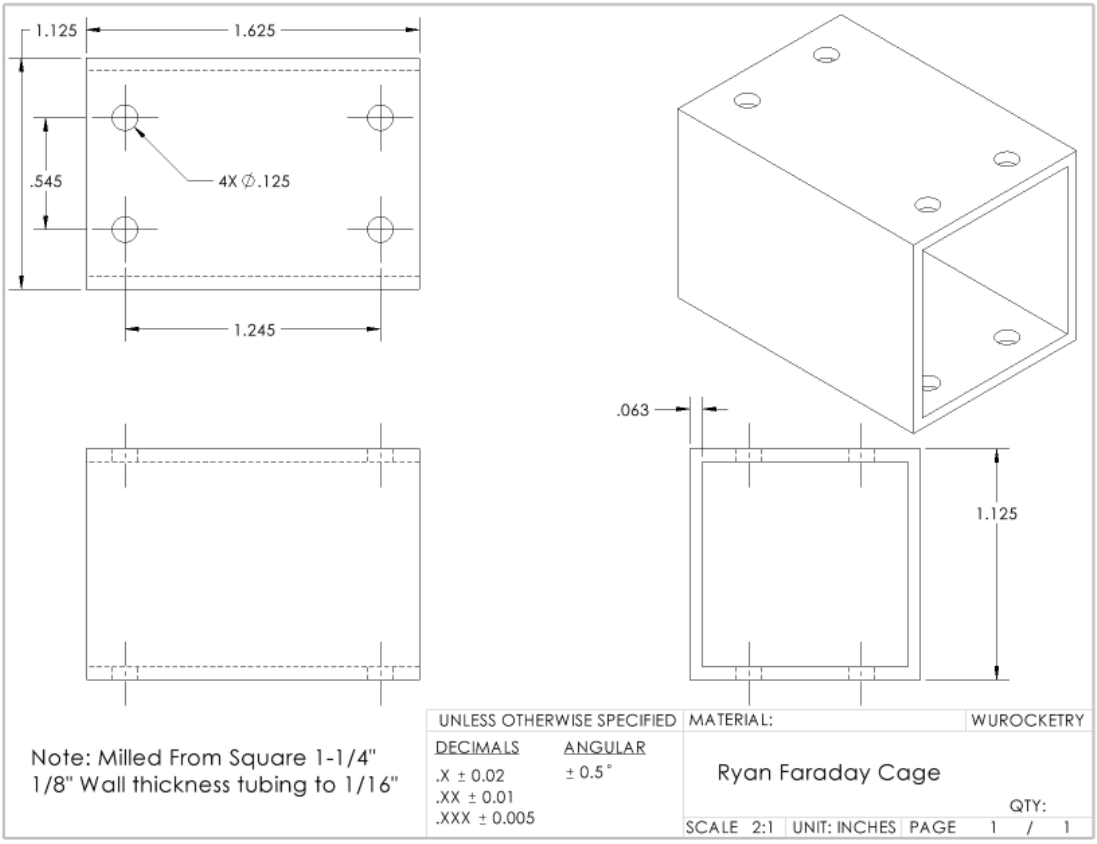


Figure 15: Dimensional Drawing of Faraday Cage

3.1.12 Centering Rings

WURocketry designed three centering rings to secure the motor in place in the aft tube of the launch vehicle. They will be spaced apart to ensure that the motor's axis is collinear with that of the rocket's aft tube. The aft-most, middle, and forward centering rings will be located 0.250 in, 7.75 in, and 17.000 in from the aft face of the aft body tube, respectively. 3D printers will be used to manufacture the centering rings because 3D printers are easily accessible, and the material cost for both PETG and PLA plastics are low. Additionally, PLA is lighter than PETG while both have relatively similar yield strengths.

A circular design for the PLA centering rings was selected because it maximizes contact with the motor tube's exterior as well as the interior of the rocket's aft tube. The weight of each of the centering rings is 0.15 lb. All three centering rings will be secured to the launch vehicle's aft tube with epoxy. The forward centering ring (nearer to the nose cone) is shown in Fig. 16. The aft two centering rings are differentiated from the forward centering ring by the presence of slots in which the G10 fin cores will be epoxied to the launch vehicle. These aft centering rings can be seen in Fig. 17. The aft-most centering ring will be secured to the motor's thrust plate with wood screws.

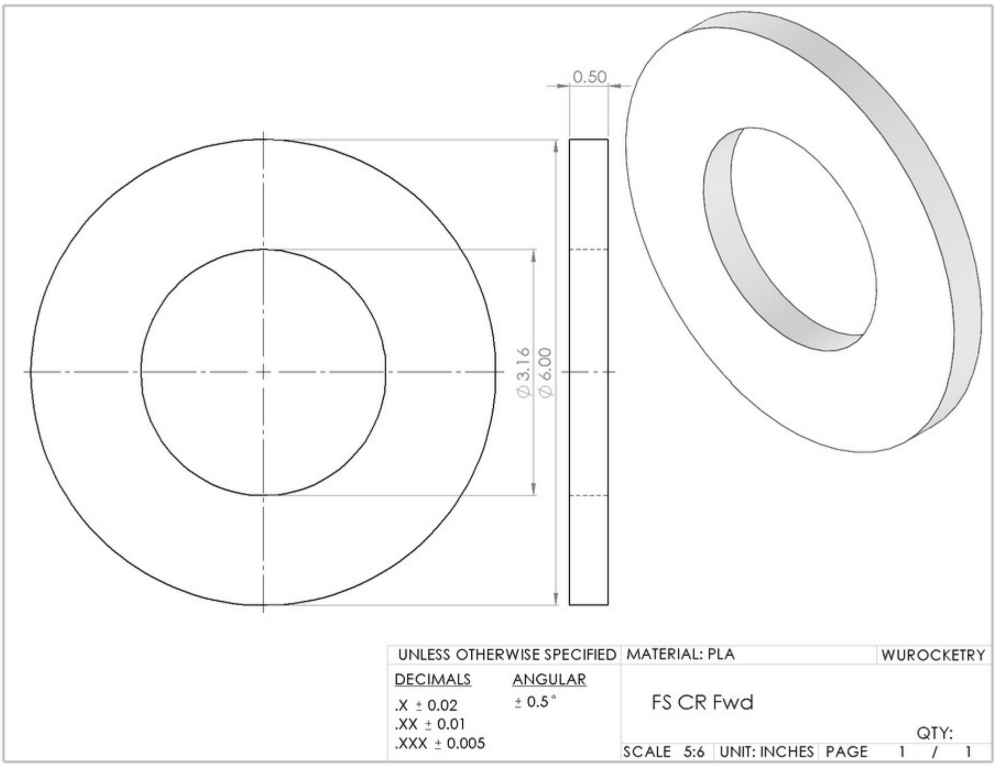


Figure 16: Forward Centering Ring

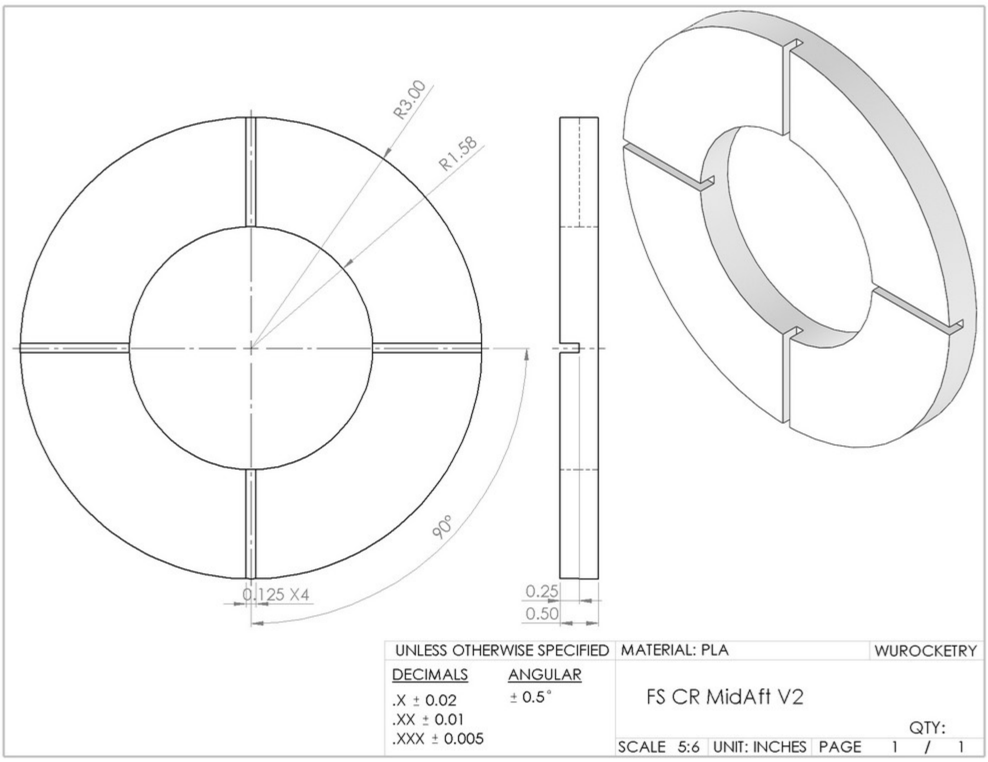


Figure 17: Aft Centering Rings

3.1.13 Fins

Fins are used to increase the rocket's stability by bringing the rocket's center of pressure lower to the base of the rocket. Although the introduction of fins adds drag to the launch vehicle, the team designed NACA 0012 airfoil fin shells to decrease some of the drag effects and improve the rocket's aerodynamics. The Structures sub-team selected materials and designs that would minimize these drag effects.

The number of fins greatly determines the stability of the rocket, but a higher number of fins could unnecessarily increase the weight and drag of the rocket. For the highest stability-to-weight ratio, the team decided to use 4 fins placed 90 degrees apart. This spacing made the fin slots easy to manufacture on a vertical mill.

The team analyzed the use of removable and non-removable fins. Removable fins allow the team to experiment with different shapes and materials. Since the Structures sub-team prioritizes structural integrity, it was decided that non-removable fins would be stronger, epoxying a solid G10 fiberglass clipped delta fin core to two centering rings inside the aft body tube. The team found that the square cross-section of the top of the fin was decreasing the rocket's aerodynamic efficiency due an increase of drag. The Structures sub-team thus developed airfoil-shaped fin shells that are superglued to the leading edge of the fin.

The fin shells were made from PLA, a material that is exceptionally stiff with a flexural strength of 103 MPa. Additionally, plastic is accessible and affordable to 3D print. In the event that a fin shell fracture does occur, the 3D-printed components can be easily replaced. The fin core, on the other hand, must be strong and light, as it cannot be replaced easily. Team chose to use G10 fiberglass as the material for the fin cores for its high strength-to-weight ratio.

Figure 18 below displays a dimensional drawing of the G10 fiberglass fin cores.

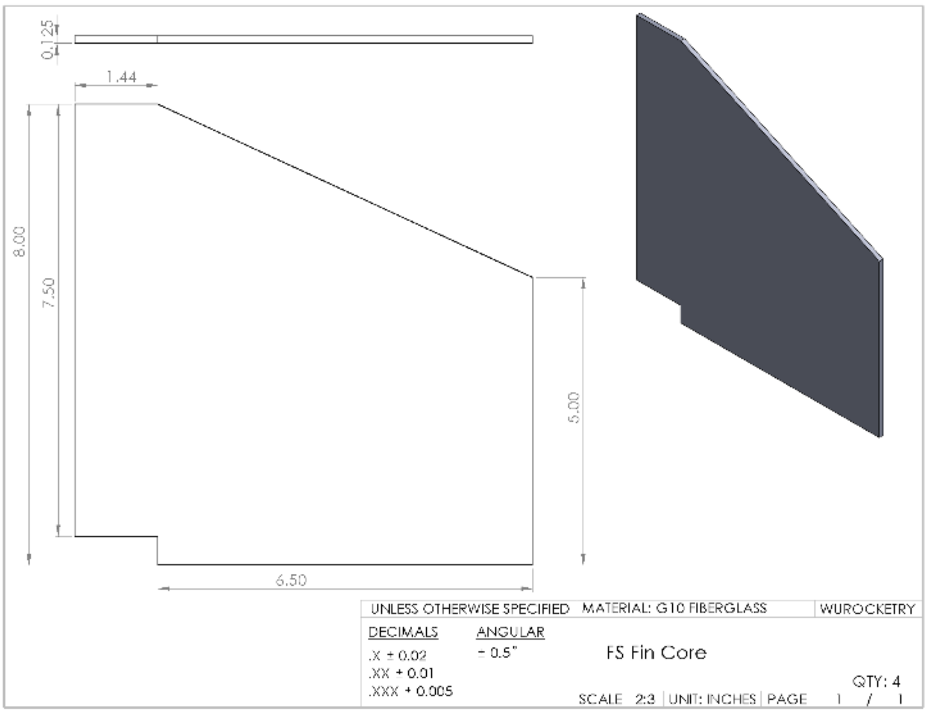


Figure 18: Fin Core Dimensional Drawing

Table 7 summarizes the clipped delta fin dimensions.

Table 7: Fin Core Dimension Summary

Number of Fins	4
Root Chord	8 in
Tip Chord	5 in
Height	6.5 in
Thickness	0.125 in
Sweep Length	3 in
Sweep Angle	24.78 degrees

Figure 19 below displays a dimensional drawing of the PLA airfoil fin shells.

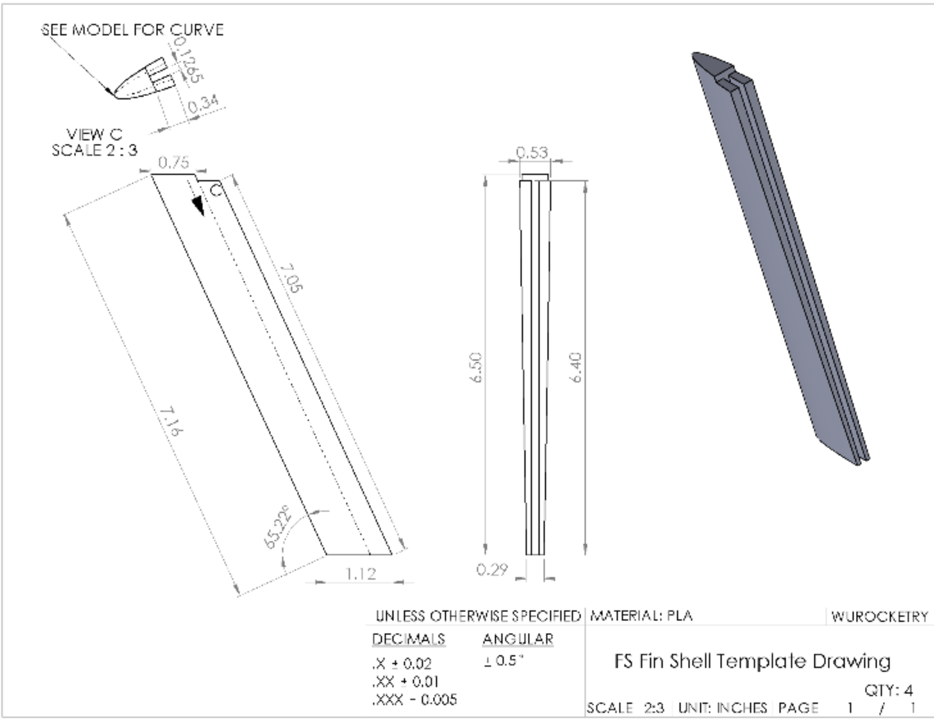


Figure 19: Fin Shell Dimensional Drawing

Fin Flutter Calculation

As the speed of the rocket increases, so does the chance for fin flutter. To ensure the safety of the fins and rocket, the structures team calculated the minimum velocity at which the fins begin to flutter. They then applied a factor of safety of 1.5 to guarantee the likelihood of the fins fluttering being null. Fin flutter can be calculated using Eq. 20 below:

$$V_f = 1.223\, C_s \sqrt{\frac{G}{P}} \sqrt{\left(\frac{T}{B}\right)^3 \left(\frac{2+B}{1+\lambda}\right)}$$

Figure 20: Fin Flutter Equation

Each variable represents a fin, an atmospheric, or a derived parameter. In the figure below, all these variables are defined in order to simplify calculations.

fin parameters

c_r = root chord, L
c_t = tip chord, L
b = fin height, L
t = fin thickness, L
G = fin material shear modulus, R

atmospheric parameters

$P(h)$ = pressure (function of altitude), R
$C_s(h)$ = sound speed (function of altitude), V

derived parameters

$S = \frac{h}{2}(c_r + c_t)$ fin area, L^2
$\lambda = \frac{c_t}{c_r}$ fin taper ratio
$B = \frac{b^2}{S}$ aspect ratio
$T = \frac{t}{c_r}$ normalized thickness

$$C_s(h) = C_{s0}\left(1 - 0.20\frac{h}{H}\right)^{1/2}$$

$$P(h) = P_0\left(1 - 0.190\frac{h}{H}\right)^{5.256}$$

Figure 21: Fin Flutter Variable Definition

Plugging in the dimensions for the team's fins and solving for the variables above, the final fin flutter is calculated in Fig. 22.

$$v_f = 1.223(1095.25)\sqrt{\frac{892857.14 \cdot 144}{2026.73}} \left(\sqrt{\left(\frac{0.01562}{1}\right)^3\left(\frac{2+1}{1+0.625}\right)}\right) = 894.89\ \frac{ft}{s}$$

Figure 22: Fin Flutter Calculation

The structures sub-team determined a factor of safety above 1.5 is sufficient in order to guarantee the low likelihood of fin flutter. Using the ratio of the fin flutter velocity (894.89 ft/s) and the current max velocity (580 ft/s), the number comes out to be 1.54, which is above the factor of safety.

3.1.14 Motor Selection

The motor selected for the final design was the AeroTech L1390G-P. The L1390G motor provides an average thrust of 1,390.0 N, and a simulated maximum thrust of 1,649.8 N, resulting in a thrust to weight ratio of approximately 8:1. At the PDR milestone, OpenRocket simulation use used to confirmed a sufficient thrust to achieve an apogee of 4,650 ft with the anticipated rocket wet mass of 42.8 lbs. However, since the rocket now weighs 43.1 lb, the team must determine ways to still reach 4650 ft with the extra mass from construction. Additionally, the team chose this motor due to the 530mm length and 75mm diameter dimensions to provide sufficient packing space for the drogue parachute and shock cords. Lastly, the L1390G meets the requirements of using Ammonium Perchlorate Composite Propellant (APCP), operating under NAR/CAR/TRA certifications, and the ability to reload for multiple launches.

Table 8: AeroTech L1390G-P Specifications

Apogee (ft)	4650
Max Velocity (ft/s)	600.0 (182.9 m/s)
Max Acc. (ft/s^2)	262.0 (79.9 m/s^2)
Average Thrust (N)	1390
Maximum Thrust (N)	1650
Total Impulse (Ns)	3949
Burn Time (s)	2.600

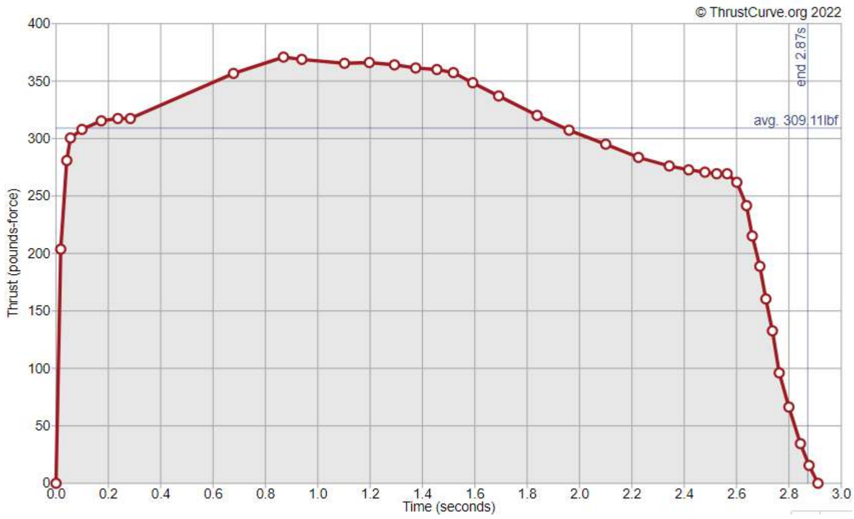


Figure 23: Thrust vs. Time for Aerotech L1390G-P

3.1.15 Motor Mounting and Retention

The L1390G-P motor is 75mm in diameter and 530mm in length. Due to these dimensions, the motor will be secured within the Aerotech RMS 75/3840 Rocket Motor Casing, with an Aerotech 75mm Forward Closure, Aft Closure, and Seal Disk. A 6 in - 75mm thrust plate from SC Precision will center the motor casing within the 6 in inner diameter aft tube. A 75mm Flanged Retainer Ring Set from Aero Pack will be used to secure the motor casing inside the rocket.

3.1.16 Flight Reliability Confidence

WURocketry has demonstrated that the design meets Mission Success Criteria (statements of work and team-derived requirements) in Section 8.1. Additionally, the team is confident that the designed and constructed rocket meets the competition requirements because the hand calculations and OpenRocket analysis in the Mission Performance Predictions section provide quantities that are realistic to past experimental data, and the Demonstration Flight proves that the vehicle can be launched, recovered, and reused successfully.

3.2 Construction of Vehicle

3.2.1 Schematics of As-Built Rocket

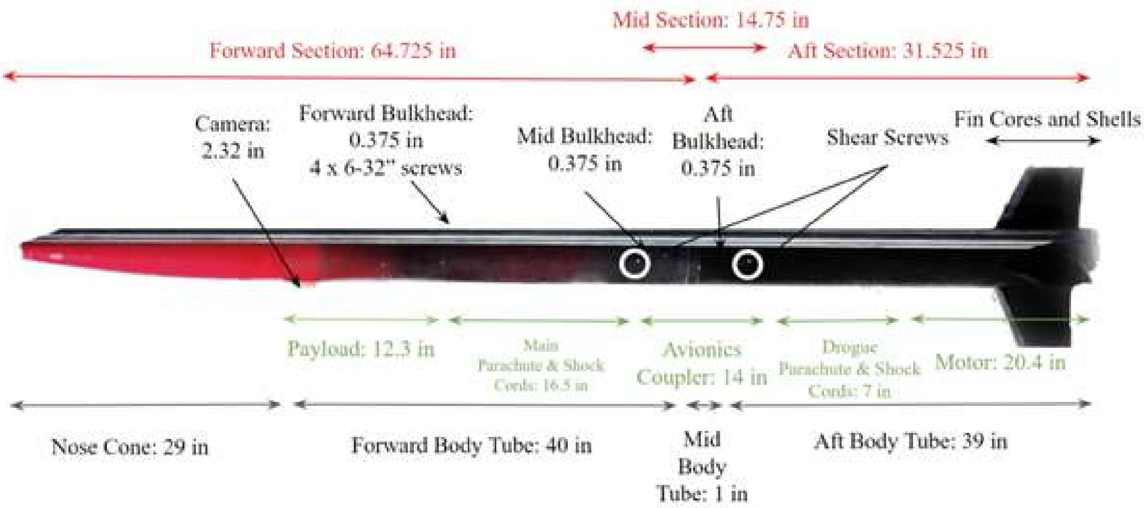


Figure 24: Schematics of Full Scale Rocket

3.2.2 Differences Between Designed and Constructed Rocket

The constructed rocket has two 1/8th in vent holes in the aft tube to release pressure from the black powder. Additionally, the designed rocket does not take the weight of the recovery hardware, fasteners, and epoxy into account. As a result, the launch vehicle is slightly heavier than originally designed. The rocket was designed with two cameras just aft of the nose cone, but during the Demonstration Flight the team placed only one camera and camera holder on the launch vehicle.

Additionally, the proposed design for the recovery subsystem differs slightly from the final design of the recovery subsystem. In the proposal, two 15 ft shock cords connected both the aft section and drogue parachute to the aft bulkhead. In addition, a 30 ft shock cord connected the main parachute, and a 25 ft parachute connected the forward section to the mid bulkhead. In contrast, the final design utilizes the 15 ft shock cord to connect the main parachute to the forward section, and the 30 ft shock cord to connect the main parachute to the mid bulkhead. Similarly, the second 15 ft shock cord connects the aft bulkhead to the drogue parachute and the 25 ft shock cord connects the drogue parachute to the eye-bolt on the motor. As a result, deployment of the recovery subsystem is guaranteed, and tangling of the shock cords or components is mitigated, providing a safe and reliable vehicle recovery.

The final design also utilized Nomex blankets and Nomex shock cord sleeves to fully block any heat from the ejection charges from coming into contact with the nylon cords, reducing the risk of fraying and extending the lifespan of the cords.

3.2.3 Nose Cone Construction

The Nose Cone construction consisted of joining the Nose Cone to a 5.998 in outer diameter shoulder, which could be joined to the forward body tube.

Materials:

- 5:1 Elliptical Nose cone (G12 Fiberglass)
- 6 in outer diameter Nose Cone Shoulder
- Aeropoxy Structural Adhesive - ES6209
- Fiberglass Powder

Procedure:

1. Mount shoulder section to along lathe z-axis.
2. Put on safety glasses and mask.
3. Use 120 grit surface for tight clearance fit with nose cone inner diameter.
4. Finish surface with finer 220 grit sand paper in preparation for epoxy application.
5. Apply isopropyl alcohol to clean fiberglass shoulder and Nose Cone inner diameter.
6. Prepare fume hood surface for epoxy mixing and application.
7. Apply nitrile gloves and mix equal weights of two part epoxy.
8. Apply epoxy to shoulder outer surface and insert into Nose Cone inner diameter until a length of 3.10 inches protrudes from Nose Cone bottom.
9. Dispose of excess mixed epoxy and tidy surface for next use.

3.2.4 Camera Attachment

The camera attachment construction consisted of converting the designed SolidWorks model into an .stl file and sending it to a 3D Printer.

Materials:

- Red PLA Filament

Procedure:

1. Export Solidworks model as an .stl file.
2. Position, orient, and slice .stl file using 3DPrinterOS.
3. Send .gcode to Prusa i3S Printer.
4. Load in Red PLA Filament.
5. Print both camera attachments with an extruder temperature of 210°C, a bed temperature of 60°C, layer height of 0.2 mm, and infill of 20%.
6. Remove printed part from print bed and take off support material on each part.

3.2.5 Machining Airframe Body Tubes

The aft, mid, and front body tubes were cut down from larger stock material. Working with the team mentor, the Structures sub-team cut down the stock material to the designed lengths for each body tube. Holes were then drilled around the body tubes for components such as the bulkhead screws, rail buttons and shear screws.

Materials:

- Fiberglass Aft Body Tube
- Fiberglass Mid Body Tube
- Fiberglass Forward Body Tube

Tools:

- Edge-finder
- Hexagonal Body Tube holder
- C-Clams
- 90 Degree Angle Blocks
- Parallels
- Hard Stop Magnet
- # 4 Drill Bit
- 1/8 in Drill Bit
- 1/8 in End Mill
- 53/64 in Drill Bit

Procedure:

1. Tie up hair, secure loose clothing pieces, wear long pants and close toed shoes, and take off any jewelry. Put on safety glass and put away phones.
2. Forward Body Tube
    (a) Remove vice and T-slot covers from mill and place 90 degree angle blocks on either side of mill bed using studs, clamps and step blocks. Ensure a even alignment by inserting parallels into open T-slots.
    (b) Insert body tube into hexagonal body tube holder and secure to 90 degree angle blocks using C-clamp. Attach a magnet to one 90 degree angle block to create a hard stop on the X-axis of the mill.
    (c) Turn on mill, set the speed to 1600 rpm, and edge-find to find zero on X-axis.
    (d) Insert #4 drill bit into the mill and set speed to 1500 rpm. Drill a hole 5 in from the zeroed end.
    (e) Rotate hexagonal body tube holder 90 degrees and repeat the previous step three times (four holes total).

(f) Using same drill bit, drill a hole 24.3125 in from the zeroed end.

(g) Rotate hexagonal body tube holder 90 degrees and repeat the previous step three time (four holes total).

3. Mid Body Tube

   (a) Remove vice and T-slot covers from mill and place 90 degree angle blocks on either side of mill bed using studs, clamps and step blocks. Ensure a even alignment by inserting parallels into open T-slots.

   (b) Mount insert body tube into hexagonal body tube holder and secure to 90 degree angle blocks using C-clamp. Attach a magnet to one 90 degree angle block to create a hard stop on the X-axis of the mill.

   (c) Turn on mill and set the speed to 1600 rpm and edge-find to find zero on X-axis.

   (d) Insert a 53/64 in drill bit and set the speed to 1500 rpm. Drill holes 2.13 in and 11.05 in from the zeroed end.

4. Aft Body Tube

   (a) Remove vice and T-slot covers from mill and place 90 degree angle blocks on either side of mill bed using studs, clamps and step blocks. Ensure a even alignment by inserting parallels into open T-slots.

   (b) Mount insert body tube into hexagonal body tube holder and secure to 90 degree angle blocks using C-clamp. Attach a magnet to one 90 degree angle block to create a hard stop on the X-axis of the mill.

   (c) Turn on mill and set the speed to 1600 rpm and edge-find to find zero on X-axis.

   (d) Insert a #4 Drill Bit into the mill and set speed to 1500. Drill a hole drill a hole 34 in from the zeroed edge.

   (e) Rotate the hexagonal body tube holder 90 degrees and repeat the previous step three times (four holes total).

   (f) Rotate the hexagonal body tube holder 45 degrees.

   (g) Drill a hole 1.37 in from the zeroed end and another in line with the first hole 30.87 in from the zeroed end.

   (h) Insert a 1/8 in drill bit into the mill and set speed to 1500 rpm. Drill two holes along the same line, one 0.5 in from the zeroed end and one 8 in from the zeroed end.

   (i) Insert a 1/8 in end mill into the mill and set speed 1500 rpm. Machine a slot from the 1st hole to the second making a 7.5 in slot.

   (j) Rotate the hexagonal body tube holder 90 degrees and repeat the previous steps three more times (four total slots).

   (k) Insert a 53/64 in drill bit and drill a hole 35.037 in from the zeroed end ensuring alignment with one fin slot.

3.2.6 Machining Bulkheads

The four bulkheads were machined from 6 in by 6 in stock material.
Materials:

- 3 pieces of 6 in by 6 in stock aluminum

Tools:

- Edge-finder
- Dial calipers
- 6-32 tap drill
- 10-32 tap drill
- 1/4 in two-flute end mill
- 5/16 in two-flute end mill
- 3/8 in five-flute variable carbide end mill
- 1/4 in 118 degree HSS drill bit
- 3/8 in 118 degree HSS drill bit
- 7/64 in 118 degree HSS drill bit
- 3/16 in 118 degree HSS drill bit
- 1/16 in 118 degree HSS drill bit
- 5/32 in 118 degree HSS drill bit
- Sharpie
- Lathe tool
- Blue cloth
- Parallels
- Trak K3 Vertical Mill
- Clausing Lathe
- Vertical Bandsaw

Procedure:

1. Tie up hair, secure loose clothing pieces, wear long pants and close toed shoes, and take off any jewelry. Put on safety glasses and put away phones.
2. All Bulkheads
   (a) Use dial calipers to check stock dimensions.

(b) Using the clean, machined stock edges as reference edges, place the stock in the vice on parallels. Use a hard stop on the vice against which to press the stock to ensure its consistent placement in the vice.
(c) Use the edge-finder to establish the center of the stock piece for the bulkhead.
(d) Use a 5/16 in two-flute end mill to remove 0.01 in from each non-machined edge. When rotating the stock, be sure to keep a machined edge against the back jaw of the vice and to press the stock against the hard stop located on the vice.
(e) Place a sharpie in a collet in the mill.
(f) Using the mill's CNC circular profile feature, draw a 6 in diameter circle on the face of the bulkhead.
(g) To mass optimize bulkheads, place rotary table on mill bed and mount bulkheads.
(h) Use Autodesk FeatureCAM to generate side and pocket operations down to 1/4 in depth.
(i) Use a 3/8 in five-flute variable endmill to remove material from CNC toolpaths generated above.

3. Forward Bulkhead

(a) Use a 1/4 in drill bit to drill a hole through the center of the bulkhead.
(b) Use a 5/32 in drill bit to drill a thru hole 1.75 in horizontally from the center of the bulkhead. Repeat on the opposite side of the center hole.
(c) Use a 10-32 tap drill to power tap the two 5/32 in holes. Be sure to use cutting fluid.
(d) Place the bulkhead on its side in the vice.
(e) Use the edge-finder to establish the center of the side of the bulkhead.
(f) Use a 7/64 in drill bit to drill a hole 0.380 in deep in to the center of the first chosen side of the bulkhead. Be sure to use cutting fluid.
(g) Use a 6-32 tap drill to power tap the 7/64 in hole previously drilled. Be sure to use cutting fluid.
(h) Repeat the previous four steps three more times, rotating the bulkhead 90 degrees such that all four sides have a tapped hole.
(i) Use a vertical bandsaw to remove each corner of the square bulkhead, bringing it closer to the sharpie-drawn circle.
(j) Use a Clausing Lathe (with a live center pushing the bulkhead into the headstock chuck with protective blue cloth between the bulkhead and the headstock chuck) to bring the diameter of the bulkhead to 5.998 in. The setup for this can be seen in Fig. 25.

4. Middle and Aft Bulkheads

(a) Use a 1/4 in drill bit to drill a hole through the center of the bulkhead.

(b) Use a 3/8 in drill bit to drill two holes 1.250 in from the center of the bulkhead in opposite directions along what will henceforth be declared the bulkhead's x-axis. See Fig. **??** for reference.

(c) Use a 1/4 in end mill and a CNC program to machine two slots along the bulkhead's y-axis (on opposite sides of the center hole). These slots, from their edges, are located 0.550 in from the center of the bulkhead, 0.750 in long, and 0.125 in deep.

(d) Use a 7/64 drill bit to drill two thru holes: a hole 1.0 in in the positive x direction of center and 1.0 in below the x-axis and a hole 1.0 in in the negative x direction of center and 1.0 in above the x-axis.

(e) Use a 3/16 in drill bit to drill a thru hole 0.50 in in the negative x direction and 0.5 in above the x-axis.

(f) Use a 1/16 drill bit to drill a thru hole 0.50 in in the positive x direction and 0.50 in below the x-axis.

(g) Use a bandsaw to remove each corner of the square bulkhead, bringing it closer to the sharpie-drawn circle

(h) Use a Clausing Lathe (with a live center pushing the bulkhead into the headstock chuck with protective blue cloth between the bulkhead and the headstock chuck) to bring the diameter of the bulkhead to 5.998 in. The setup for this can be seen in Fig. 25.

(i) Use a Clausing lathe (with a live center pushing the bulkhead into the chuck with protective blue cloth between the bulkhead and the chuck) to machine a lip into the bulkhead. This lip should have a diameter of 5.820 in and a depth of 0.125 in from the face of the bulkhead.

Figure 25: Setup for Using the Lathe for the Bulkhead

3.2.7 Machining Fin Cores

Materials

- G10 Fiberglass Stock

Tools

- Vertical Band Saw
- Scribe

- Vertical Mill
- Fine Core fixture
- 1/4 in endmill

Procedures

- Mark out dimensions of the fin onto fiberglass stock using scribe, putting at least one edge of the fin on the perimeter of the fiberglass stock.
- Use the vertical band saw to cut out the shape of the fins, leaving approximately $\frac{1}{4}$ in gap between the scribe mark and the cut.
- use Vertical mill to machine all four end cores at the same time, using fixture. Fixture ensures alignment between all four fin cores and aligns fin along their known good edge.

3.2.8 Motor Tube Assembly with Fin Cores

The motor tube construction consisted of the assembly of centering rings epoxied onto a paper motor tube, which was then inserted into the aft body tube.
Materials:

- Paper Motor Tube
- Fiberglass Powder
- Aeropoxy Structural Adhesive - ES6209
- Centering Rings
- Thrust Plate
- Retaining Ring
- 4 Fins

Procedure:

1. The plastic coating around the paper motor tube was removed, giving the tube a porous surface finish for epoxying later on.
2. Centering Rings:
   (a) The three centering rings were checked to see if they all fit into the aft body tube and over the motor tube. If the centering rings did not fit well over the motor tube or inside the aft body tube, the following was preformed.
   (b) With sand paper, the inside (for a better fit over the motor tube) or outside (for a better fit inside the aft body tube) of the centering ring was sanded. In between each sanding, the centering rings were checked to see if they had a better fit over the motor tube or inside the aft body tube.
   (c) This process was repeated for each of the three centering rings until all three were able to fit well around the motor tube and inside the aft body tube.

3. Location of Centering rings:

   Figure 26 represents one of the slotted centering rings flush against the end of the motor tube.

Figure 26: Slotted Centering Rings

   (a) One of the slotted centering rings was aligned so it sat flush against the end of the motor tube. Using a sharpie, mark the location of this centering ring.
   (b) Align the other slotted centering ring 7.5 in away from the bottom of the motor tube where the other slotted centering ring was. Mark of the location of this centering ring.
   (c) Align the last centering ring 3/4 in from the top of the motor tube. Mark the location of this centering ring.
   (d) Remove the centering rings to begin the epoxy process.

4. Cutting a small slot into the centering rings:

   (a) Since the rail buttons are already epoxied onto the aft body tube, the aft-most centering ring needs a small opening that allows the rail button to pass through when the motor tube is inserted into the aft body tube.
   (b) A small section of the aft-most centering ring, between two fin slots, was carved out using a hand saw, ensuring the rail button passes through.

5. Epoxying the centering rings onto the motor tube:

(a) Prepare fume hood surface for epoxy mixing and application.
(b) Apply nitrile gloves and mix equal parts of hardener, resin, and a spoon of fiber glass powder.
(c) Apply epoxy onto the motor tube where one of the centering rings will sit. Carefully twist the centering ring onto the motor tube until it reaches the sharpie location.
(d) For the slotted centering rings, use the fin cores as a guide to ensure the two slotted centering rings are aligned with the slots in the aft body tube while epoxying.
(e) Repeat the epoxy step for the remaining two centering rings.
(f) Once all three centering rings are epoxied on the motor tube, remove the fin cores that were used as an alignment guide, and wait 24 hours for the epoxy to cure.

6. Epoxying the motor tube and thrust plate onto the aft body tube:
   (a) With sand paper, rough up the area where the motor tube will go in the aft body tube.
   (b) Using isopropyl alcohol and paper towels, clean off the portions of the aft body tube that were just sanded.
   (c) Prepare the epoxy mixture using the steps used for epoxying the centering rings onto the motor tube.
   (d) Apply epoxy to the aft-most centering ring, creating fillets of epoxy around the edge of the ring. Make sure that the slots align with those of the fin slots.
   (e) Repeat the step above for the forward-most centering ring.
   (f) Apply epoxy to the thrust plate which will go on the aft-end of the aft body tube.
   (g) Apply additional epoxy to the edge of the thrust plate, ensuring there is a good bond between the aft body tube and thrust plate.
   (h) Wait 24 hours minimum for epoxy to cure.
7. Fin core attachment:
   (a) Using sand paper, rough up the area where the fin cores will attach to.
   (b) Using isopropyl alcohol and paper towels, clean off the sanded portions.
   (c) Prepare the epoxy mixture by turning on the fume hood, mixing equal parts of hardener and resin, and adding in a spoon of fiber glass powder.
   (d) Apply epoxy to the fin slot to ensure that epoxy gets onto the motor tube as well.
   (e) Apply epoxy to the edges of the fin core that will make contact with the motor tube and slotted centering rings.
   (f) Push the fin core into the fin slots.
   (g) Around the fin cores inserted, create epoxy fillets to ensure a secure bond between the fin cores and the aft body tube.
   (h) Wait 24 hours minimum for epoxy to cure.
   (i) Repeat this process for the next fin cores.

3.2.9 Laser Cutting Avionics Bay

The Avionics Bay board was constructed using laser cutting and a basswood board.
Materials:

- Basswood Board
- Painters tape

Tools:

- Universal Laser Systems v6.60
- Inkscape
- CorelDraw

Procedure:

1. Export Solidworks drawing of Avionics Bay board as a PDF file.
2. Open the Inkscape software and change the dimensions of the page to match those of the laser cut machine: 32 in * 18 in.
3. Import PDF drawing into Inkscape and change the line width and line color to red and hairline width, respectively.
4. Save new PDF drawing to be exported to the laser cut machine.
5. Turn on laser cut machine and compressed air.
6. Open the CorelDraw software and import the PDF drawing.
7. Ensure that the line width and line color have not changed. If so, fix them to red and hairline.
8. In the Materials database window, enter the material as basswood, thickness as 0.25 in, fixture type to none, and print direction up.
9. Check the positioning of the PDF drawing and align as necessary.
10. Check timing of the print.
11. Verify your settings and press the play button.
12. Wait 2-3 minutes for the fumes to decrease and pull out your part.

3.2.10 Fin Shell Attachment

After the fins were epoxied to the Motor Tube, the fin shells were joined to the fins.
Materials:

- 4 Fins attached to the Motor Tube
- Fin Shells made from PLA Plastic
- Super glue

Tools:

- Sand Paper
- Mallet

Procedure:

1. With the Sand Paper, rough up the outside of fin shell.
2. Apply a thin line of super glue along the surface of the fin that will make contact with the fin shell.
3. Push the fin shell onto the fin, making sure to line up the top edges.
4. Use the mallet to help get the fin shell securely onto the fin.
5. Repeat these steps for the remaining 3 fin shells.

3.2.11 Coupler and Mid Body Tube Attachment

The Coupler was epoxied to the Mid Body Tube. Below are the materials and tools used in this process.
Materials:

- Mid Body Tube
- Aeropoxy Structural Adhesive - ES6209
- Fiberglass Powder
- Tube Coupler

Tools:

- Paper Towels
- Plastic Cup
- Plastic Spoon
- Small Scale
- Sand Paper
- Craft Knife

- Xacto Knife
- Nitrile Gloves
- Safety Glasses
- Drying Stands

Procedure:

1. On the table where epoxy will be applied to the couplers and body tubes, cover the surface with paper towels.
2. Preparation for Epoxy:
   (a) Put on safety glasses and a set of nitrile gloves.
   (b) Mark center of coupler
   (c) Mark $\frac{1}{2}$ in from each side of center
   (d) Use painters tape to tape around edge of one of the $\frac{1}{2}$ in marks
   (e) Rough the surface in between the two $\frac{1}{2}$ in marks with sand paper and Xacto knife.
   (f) Rough inside surface of 1 in band ring with sandpaper and Xacto knife. This allows the epoxy to have a better hold on the coupler.
3. Epoxying the Coupler:
   (a) Add equal parts of hardener and resin in a plastic cup using the small scale. Mix both using a plastic spoon until the mixture becomes homogeneous.
   (b) Add in fiberglass powder until the mixture looks cloudy and becomes thicker. The mixture should appear similar to a soft caramel in color and consistency.
   (c) Spread epoxy evenly between the two $\frac{1}{2}$ in marks around the entire coupler. This is where the mid body tube will overlap it.
   (d) Slowly slide and rotate the 1 in band ring onto the coupler epoxy, setting it at the interior edge of the painters tape.
   (e) Wipe away excess epoxy using a paper towel.
   (f) Let the coupler sit for 5 minutes
   (g) Remove painter's tape carefully.
   (h) Set coupler on stands to cure for 24 hours.

3.2.12 Painting the Rocket

The fullscale rocket body was heavily spray painted for aesthetic opacity and "orange peel" texture. The body was then dry sanded with 400 grit, 1000 grit, and wet sanded with 2000 grit sandpapers to achieve a smooth finish. This process was conducted to reduce the drag experienced on the rocket and closer replicate ideal drag coefficients.

3.3 Recovery Subsystem

3.3.1 Materials Overview

Table 9 lists the parts used for in the recovery subsystem for the 2022-2023 competition year.

Table 9: Recovery & Propulsion Materials Summary

Item	Model	Manufacturer	Material/Dimensions
Main Parachute	Iris Ultra Standard	Fruity Chutes Inc.	120 in diameter Nylon
Drogue Parachute	Elliptical	Fruity Chutes Inc.	18 in diamter Nylon
Shock Cords	5/8 in Tubular	The Rocketman	15, 15, 25, 30 ft Nylon
Deployment Bag	CDB-55-10	Fruity Chutes Inc.	247 in^3 packing volume
Nomex Blanket	NB-13	Fruity Chutes Inc.	13 in diameter
Nomex Blanket	NB-21	Fruity Chutes Inc.	21 in diameter
Nomex Shock Cord Protector	TFR FSP-60	Sirius Rocketry	60 in length
Eyebolt	3014T256	McMaster-Carr.	Steel 500 lb capacity
Quicklink	QL-250	McMaster-Carr.	Steel 1200 lb capacity
Swivel	SWIV-3000	Fruity Chutes Inc.	Steel 3000 lb capacity

3.3.2 Flight Sequence

There are two stages to recovery system operations, characterized by four deployment events. Table 10 provides an overview of events and respective locations.

Table 10: Vehicle Section Details

Event	Description	Location	Redundancy
1	Middle and aft sections separate	Apogee	Apogee + 1 sec
2	Drogue parachute deployment	Apogee	Apogee + 1 sec
3	Forward and middle sections separate	600 ft	500 ft
4	Main parachute deployment	600 ft	500 ft

The first event occurs as the rocket reaches apogee. A black powder charge ignites, pressurizing the chamber, which separates the middle and aft body and deploys the drogue parachute. Next, one second after apogee is reached, a redundant black powder charge is ignited to ensure separation and release of the drogue parachute. The second stage takes place when the rocket reaches 600ft AGL. Another black powder charge is ignited between the forward and middle sections, separating them and deploying the main parachute. Once the rocket reaches 500ft AGL, a redundant black powder charge will fire to ensure proper separation and deployment of the main parachute.

3.3.3 System Layout

The recovery system is separated into two different sections within the rocket: the drogue parachute recovery section, and the main parachute recovery section. Figure

27 displays the drogue and main parachute sections after deployment to demonstrate the shock cord layouts and dimensions. The lengths of the shock cords were selected based on a few different design considerations. First, the difference in shock cord lengths that extend from each parachute will keep hanging sections of the rocket from colliding. Second, because the shock cords are nylon and more elastic, the bounce back of the section has to be considered after each separation and snatch motion. Closely related to the collision consideration is mitigating tangling while descending, so the shock cords must be long enough to ensure that any tangling does not have time to propagate up to the shroud lines during descent. With these considerations in mind, the team chose the shock cords lengths discussed and seen in Fig. 27.

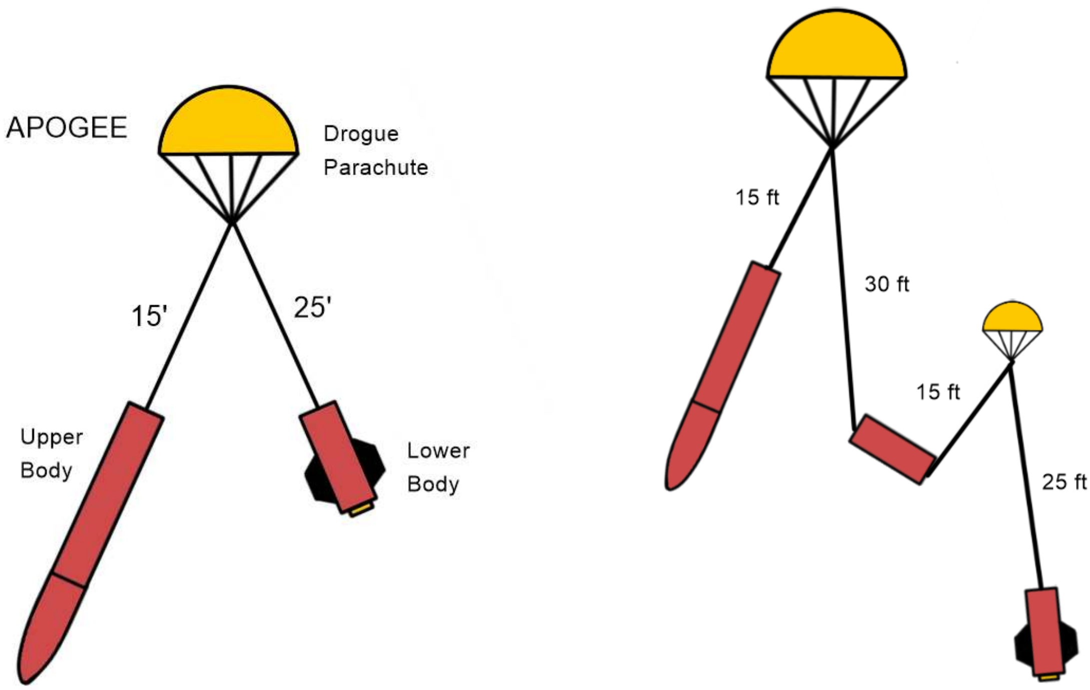


Figure 27: Drogue and Main Deployment

Discussed in Section 3.2.1, the avionics bay separating both ejection chambers is contained by the mid bulkhead and the aft bulkhead. Additionally, a forward bulkhead exists within the forward section, and the motor casing in the aft section contains an eyebolt forward closure attachment. Eyebolts at each of these locations are used to attach recovery hardware of quick links and swivel joints to secure the shock cord harness. Figure 28 below displays the order of assembly and means of component attachment of the recovery hardware.

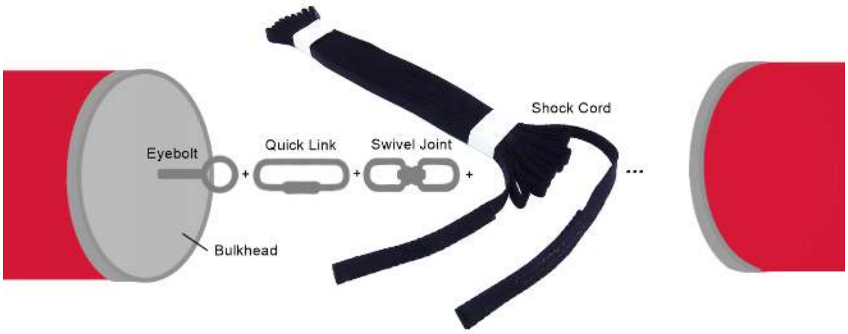


Figure 28: Hardware Diagram of Linkage Order

In the drogue section configuration, an eyebolt is attached to the aft bulkhead, along with a quick link. The drogue parachute is connected by a 15 ft shock cord to the aft bulkhead quicklink using an eye-to-eye swivel. In the same configuration, the 25 ft shock cord is attached to a eyebolt on the motor casing within the aft section. Swivel joints are located at each end of each shock cord. Therefore, an additional quick link is utilized to connect the 15 ft and 25 ft shock cords to the drogue parachute.
In the main section configuration, a 30 ft shock cord is connected to the mid bulkhead, and a 15 ft shock cord is connected to the forward bulkhead. Additionally, the Nomex deployment bag used for the main parachute is secured to the forward bulkhead with a seperate quicklink. Similar to the drogue configuration, an additional quick link is also utilized to connect the 30 ft and 15 ft shock cord swivel joints to the main parachute. Figures 29 and 30 display the recovery packing configurations.

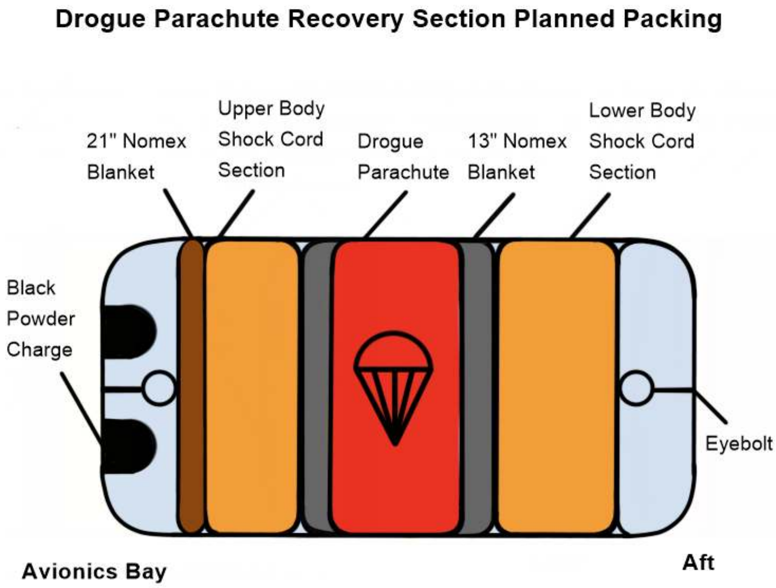


Figure 29: Drogue Parachute Packing Diagram

The drogue parachute is located in the middle of the chamber, wrapped in a 13 in diameter Nomex blanket. Surrounding the drogue parachute is the 15 ft shock cord, attached to the aft bulkhead, and the 25 ft shock cord, attached to the motor eyebolt.

Due to the two ejection canisters located on the aft bulkhead, the 15 ft shock cord is protected by a 60 in nomex sleeve. Due to extra space in the pressure chamber that will allow the high temperatures and flames to travel throughout the chamber, a nomex blanket is wrapped around the z-folded 15 ft shock cord bundle to prevent fraying from flames.

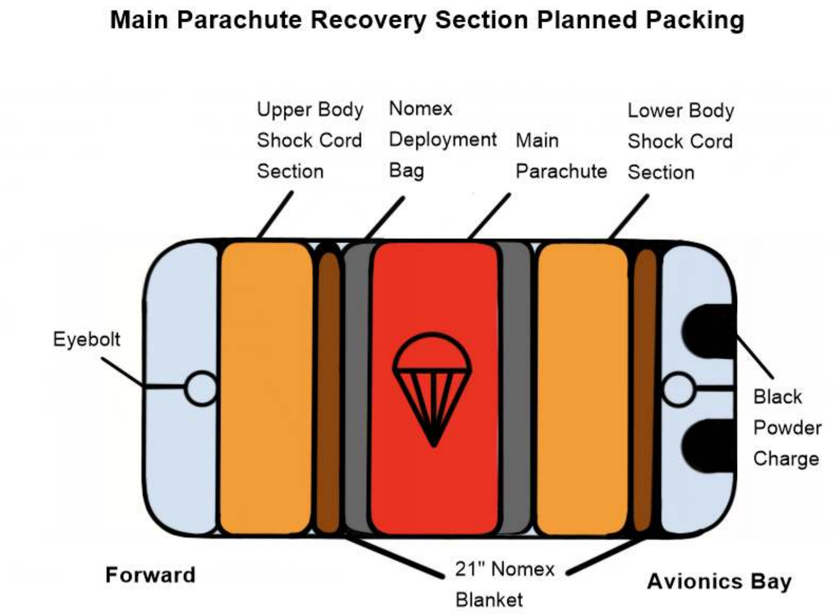


Figure 30: Main Parachute Packing Diagram

The main parachute is located in the middle of the chamber, packed in a 5.5 in diameter Nomex deployment bag. Surrounding the deployment bag is the 15 ft shock cord, attached to the forward bulkhead, and the 30ft shock cord, attached to the mid bulkhead. Mirroring the drogue chamber, two ejection canisters are located on the mid bulkhead. The 30 ft shock cord attached to the mid bulkhead eyebolt is also protected by a 60 in nomex sleeve. Due to the large amount of space in the pressure chamber, nomex blankets are wrapped around both 15 and 30 ft shock cord bundles to prevent heat damage. Figure 31 provides an example of the shock cord wrapping method.

Figure 31: Shock Cord Wrapping Method

3.3.4 Redundancy Features

Redundancy is exhibited by the shock cord protection methods and the parachute ejection method. The 6 in Nomex shock cord protectors encase the shock cords closer to the ejection canisters, where the maximum heat and largest flames will occur. For redundancy, 21 in diameter Nomex blankets are wrapped around exposed nylon shock cords within the body of the rocket to provide an additional barrier of heat resistance, as discussed in Section 3.3.3. This redundancy feature proves essential to the Full-Scale rocket, such that the nylon shock cords can withstand multiple launches without failure due to fatigue. Another element of redundancy within the recovery system is found in the use of a redundant ejection charge. The redundant ejection charges deployed one second after apogee, and again at 500 ft above ground level, have a factor of safety that is 25% greater than the primary charges. Specifically, the primary and redundant charge factor of safeties are 1.25 and 1.50 for both the main and drogue parachute sections. Ground testing ensures deployment occurs, however does not taken altitude pressures into account. The increased factor of safety ensures deployment will occur.

3.3.5 Recovery System Robustness

The recovery system's shock cords and hardware prove to be robust when under load. The snatch force experienced at main parachute deployment was calculated by the Structures sub-team by means of multiple calculation methods. The range of snatch forces determined can be averaged to approximately 7100 N (1600 lbf). Implementing a safety factor of 1.5 yields a force of 2400 lbf. The 5/8 in tubular nylon shock cords used in the recovery system are rated for 3200 lbf, which is well within the force constraints. Additionally, the quick links, swivel joints, and eyebolts used to secure the apparatus are rated for 1200 lbf, 3000 lbf, and 500 lbf maximum load respectively. Though the hardware are not rated to withstand 2400 lbf loads, it can be assumed that the manufacturer provides a smaller max load than found experimentally to provide a factor of safety. The Hardware Tensile Test in Section 6.2 determines a yield strength of 5107 N (1148 lbf), validating this statement. When taking the shock cords' strengths and elasticises into account, the calculated snatch force can be assumed much smaller than 2400 lbf. Therefore, none of the hardware are expected to reach their maximum loads and deform in flight. As all components of the system can withstand the high forces experienced on the rocket, the design is found to be robust.

3.3.6 Parachute Sizing Results

The results of parachute sizing calculations are seen in Table 11 below. Special considerations were made to parachute sizing based on three requirements; the impact kinetic energy of the rocket must be below 75 ft-lbf, the descent time from apogee must be less than 90 seconds, and the rocket must not drift more than 2500 ft from the launchpad.

Table 11: Parachute Sizing Calculation Results

Definition	Value	Units
Terminal Velocity at Main Deployment	16.37	ft/s
Minimum Diameter of Main Parachute	101.36	in
Impact Kinetic Energy	57.08	$ft-lbf$

The maximum allowed kinetic energy given by competition restraints was used to determine maximum terminal velocity. Using the terminal velocity and a selected drogue parachute size of 18 in diameter, the minimum area of the main parachute was calculated.

The minimum main parachute diameter was calculated to be 105 in. This value was scaled up to the next available size to purchase of 120 in. The resulting kinetic energy of the selected 18 in drogue parachute and the calculated 120 in main parachute was 57.08 ft-lbf. Additionally, the 18 in drogue parachute size aligns with manufacturer recommendation for the 120 in main parachute size.

Alternative Calculations To verify the efficacy of the parachute sizing calculations, a secondary calculation was performed. Rather than using Excel, calculations were done via a MATLAB program. Furthermore, a different approach to calculating the diameter was used. The original calculation treated the drogue parachute as not having a major effect on the terminal velocity, and thus did not factor in the impact its drag would have on the needed size of the main parachute. This allowed for the main parachute and drogue parachute to be calculated and selected independently, as otherwise there would be a sliding scale of possible values. The alternative calculation instead treated the drogue parachute diameter as a fixed value, as it has a smaller effect on the overall terminal velocity. This meant that the drogue parachute could be factored into the calculation, alloying the main parachute diameter to be slightly smaller. With this factor accounted for, a minimum main parachute diameter of 100.62 in was calculated. As this result is very close to the originally calculated value, it not only verifies the accuracy of the original method, but also shows that the previously stated assumption that the drogue parachute has little effect on the overall terminal velocity of the rocket is valid as well.

3.3.7 Black Powder Mass Results

Table 12 displays the masses of black powder packed into the ejection canisters for the main and drogue parachute separation events.

Table 12: Primary Method Black Powder Charge Quantities

Charge	**Mass (grams)**
Primary Drogue Ejection Charge	1.8
Redundant Drogue Ejection Charge	2.2
Primary Main Ejection Charge	4.1
Redundant Main Ejection Charge	4.9

The force required to shear the #4-40 shear screws was calculated to determine pressures required to separate the forward and aft ejection chambers. Both chambers have different quantities of shear screws do withstand different forces. The aft chamber is secured with two shear screws, and the forward chamber is secured with four to ensure the main parachute does not deploy during drogue parachute ejection. Using the pressures and volumes of the chambers, the quantities of black powder charges can be calculated using stoichiometry. A 25% FoS is applied to the primary black powder charges, and a 50% FoS is applied to the redundant charges.

Alternative Calculations The following equation was used to calculate the black powder masses, assuming a chamber pressure of 20 psi due to the dimensions of the chamber.

Black Powder Mass General Equation

$$BlackPowder(grams): N = \frac{Pressure * Volume}{266\frac{in*lbf}{lbm} * 3307R} * \frac{454grams}{1lbf} \tag{1}$$

Table 13: Alternative Method Black Powder Charge Quantities

Charge	Mass (grams)	% Difference
Primary Drogue Ejection Charge	2.3	24.39
Redundant Drogue Ejection Charge	2.9	27.45
Primary Main Ejection Charge	3.3	21.62
Redundant Main Ejection Charge	4.1	17.78

This method does not use a FoS for the primary charges, but uses a 25% FoS for the redundant charges. This is because a FoS of 50% would yield a black powder quantity of approximately 5.0g for the main redundant charge, which is against the R&P subteam derived requirements. A percent difference was found respective to the values calculated in the main method for comparison.

The final values used for the Full-Scale Demonstration flight are found in Table 13 below. These values were averaged between the primary calculation method and the alternative calculation method, then increased or decreased in ground testing to improve qualitative results, as well as remain under the 5g black powder team derived limit.

Table 14: Final Black Powder Charge Quantities

Charge	Mass (grams)
Primary Drogue Ejection Charge	2.5
Redundant Drogue Ejection Charge	3.0
Primary Main Ejection Charge	4.1
Redundant Main Ejection Charge	4.5

3.3.8 Recovery Avionics System Design

Overview The Recovery Avionics System was designed to be a simple, safe, and robust system capable of providing all the mission critical recovery functionality as well as other numeric data collection for testing and analysis. In short, the Avionics System consists of a fully redundant recovery event system utilizing simple but reliable Altus

Metrum EasyMini flight computers, a vehicle tracking system utilizing the Altus Metrum TeleGPS, and a flight data acquisition system utilizing a Raspberry Pi 4B+ and various sensors.

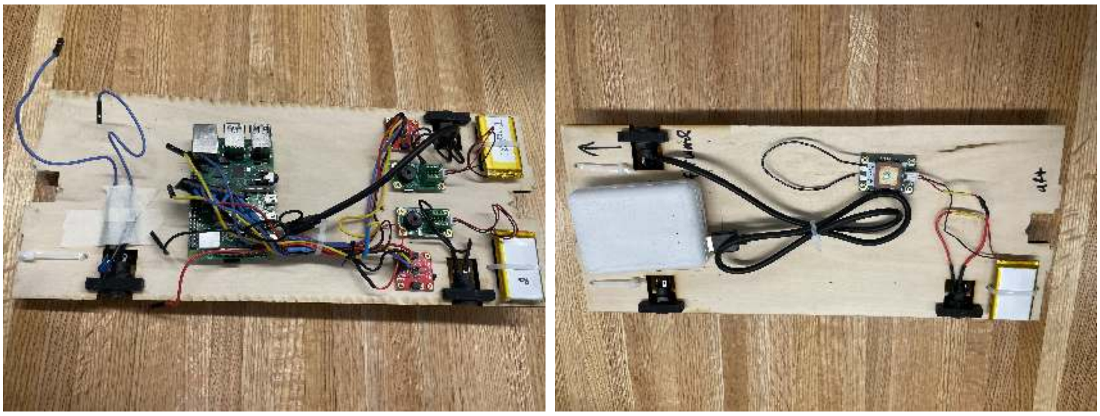


Figure 32: Avionics Bay Top View (left) and Bottom View (right).

Recovery Event System The primary instruments of the Recovery Event System are the two EasyMinis that will be used to fire the black powder ejection charges during the specified ejection windows in the recovery design of the rocket. As previusly mentioned, two separate EasyMini flight computers will be used along with their own 3.7v LiPo batteries and independent arming switch wiring. Both EasyMinis will fire one charge in each separation chamber (i.e. one charge during each separation event). These charges will be staged at Apogee and Apogee + 1s for the drogue parachute separation event and 600ft AGL and 500ft AGL for the main parachute separation event. One of these flight computers will be marked as the primary flight computer and will, for all scoring purposes, be recognized as the competition flight computer. A wiring diagram for the recovery system design is included below in Figure 33. The robustness of the recovery event system circuit is proven in by a continuity demonstration in section 6.3.3.

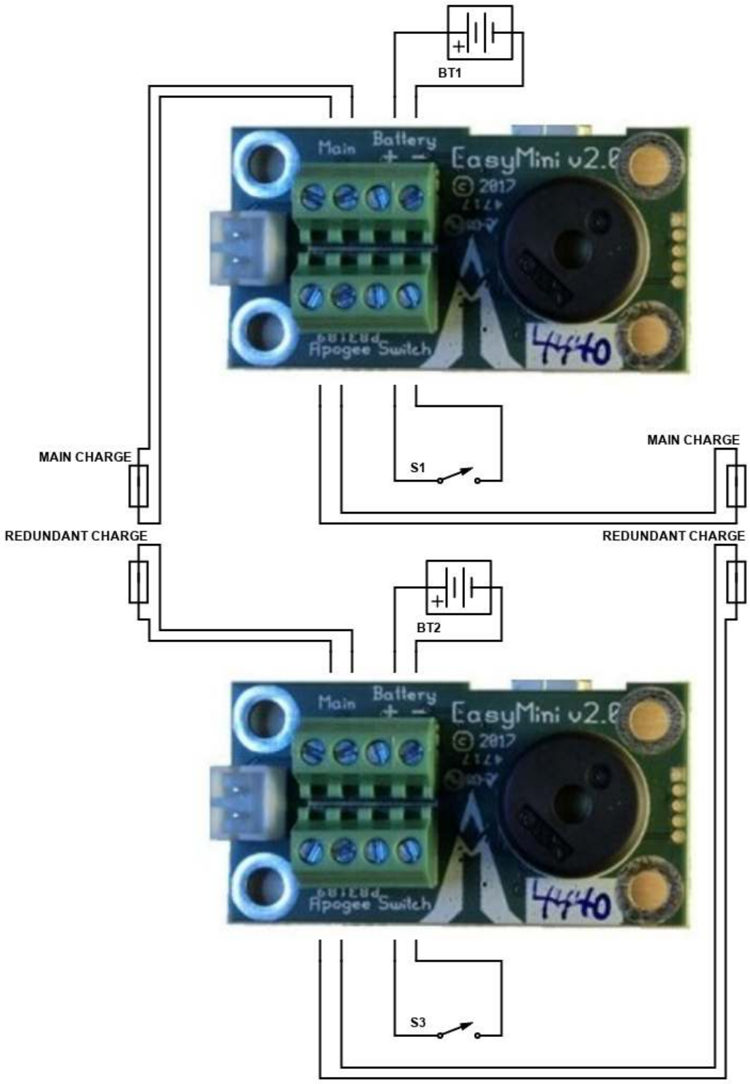


Figure 33: Recovery System Wiring Diagram

Vehicle Tracking System The purpose of the Vehicle Tracking System is to ensure the location of all independent sections of the rocket are known at all times. This will ensure an efficient recovery of the rocket post flight.

The design of the rocket this competition year is such that there is only one independent section during the recovery of the rocket as all sections of the rocket are tethered together via an elaborate system of shock cords. Considering this design, the Vehicle tracking system consists of only one on board flight computer, the Altus Metrum TeleGPS, communicating with the base station which consists of a 3-element yagi antenna and an Altus Metrum TeleBT. Both the TeleGPS and the TeleBT will be powered by 3.7v LiPo batteries. The data received by the TeleBT will be parsed via the AltosUI Application. The function and accuracy of the GPS tracking system has been demonstrated and tested in section 6.3.1.

Specifically regarding communication methods, the teleGPS will be communicating on the 70cm Ham Band with the 434.55 MHz frequency at a power of 10 mW. The TeleGPS maintains an approximate operational range of 20 miles line-of-sight, well beyond what is neccessary for the competition. The TeleGPS communicates with the base station by utilizing a handshake protocol to minimize interference.

Flight Data System The goal of the Flight Data System is to collect certain metrics of interest that are outside the capabilities of the flight computers themselves in order to enable further assessment and trouble shooting capabilities for test flights.

This system currently consists of a Raspberry Pi 4B+ operating an IMU and two Sparkfun Qwiic MicroPressure Sensors. The Purpose of the pressures sensors are to collect pressure data within the two separation chambers of the rocket during flight. This data will enable the team to trouble shoot any issues with the proper ejection of recovery equipment during flight. This data will also aid in the verification of black powder calculations, regarding the separations, ensuring the recovery system is operating as expected. The proper operation of the pi and pressure sensors has been demonstrated in section 6.3.5.

Recovery Electronics Redundancy The Recovery Electronics System is designed with redundancy and reliability at its core. The entire design is focused on eliminating any possible single point of failure within the system. This level of redundancy is achieved by providing entirely separate power sources, circuitry, and arming switches for the two separate flight computers in the Avionics Bay of the rocket. This Design makes certain that any single failure within the Recovery Electronics System does not prevent the proper function of the overall recovery system.

Device Sensitivity The EasyMini Flight computers are particularly vulnerable to current induced by EMF pulses emitted by the vehicle tracking transmitter within the rocket and other transmitters that will be present during the competition launch. To prevent any failures that could result from this EMF interference, the flight computers are placed such that they are as far from any in-rocket transmitters as possible and separated by a solid surface. Additionally, to defend against external and internal RF signals, the flight computers will be placed inside aluminum Faraday cages to attenuate as much RF energy as possible considering the limitations of designing a Faraday cage that needs access holes for wire connections and for securing to the bay board.

3.3.9 Design and Construction of the Avionics Bay

The procedure and materials necessary to fully describe the construction of the avionics bay as built is detailed below in the following procedure.

Necessary Equipment

- Soldering Iron
- Wire Strippers
- Flat file
- Wire Cutters
- Heat gun
- Scissors
- Cordless Drill
- Screw Drivers (sized set philips and flat)

Recovery Electronics Procedure
The Recovery Electronics Procedure breaks down the construction of the recovery related systems in the avionics bay, specifically the EasyMini flight computers and supporting equipment. all components of the recovery system can be seen on the avionics bay top view schematic Figure 34.

Materials:

- 8 #2 $\frac{3}{8}$ in brass screws
- 2 zip ties
- velcro
- 22 Gauge Wire
- 2 Lipo Batteries
- 2 Easy Mini Flight computers
- 2 Rotary switches
- 4 Terminal Blocks

Procedure:

1. The EasyMinis are attatched to the board with the screwdriver and four #2 $\frac{3}{8}$ inch screws.
2. Two LiPO batteries are fixed to the board with velcro and secured with zip ties threaded through small holes drilled on either side of the battery.
3. Two switches are held in place by 3d printed mounts that are glued to the board
4. Each easy mini is wired to one LiPO battery, one switch, and a main and drogue charge

Vehicle Tracking Procedure
The Vehicle tracking procedure details the mounting of the TeleGPS and supporting components on the avionics bay board. all components in this procedure can be seen on the avionics bay bottom view schematic in Figure 35.

Materials:

- 4 2 $\frac{3}{8}$ in brass screws
- zip tie
- velcro
- 22 Gauge Wire
- 3.7v LiPo Battery

- Altus Metrum TeleGPS v2.0
- 1 Rotary switch
- heat-shrink tubing

Procedure:

1. The GPS is secured to the board with four #2 x $\frac{3}{8}$ in brass screws.
2. The LiPO battery is secured to the board with velcro, two holes are drilled on either side of the LiPO and the zip ties are threaded through to secure the LiPO, the zip tie is trimmed with scissors.
3. The positive wire on coming from the lipo battery is cut and wired into a rotary switch. This joint is secured and insulated via heat-shrink tubing.

Data and Sensing Procedure
The Data and Sensing Procedure provides a detailed breakdown for the attachment of the Raspberry Pi 4B+ and sensing equipment to the avionics board. The Raspbery Pi and pressure sensors can be seen on the avionics bay top view schematic Figure 34 while the power supply can be seen on the avionics bay bottom view schematic Figure 35.

Materials:

- 2x SparkFun Qwiic MicroPressure Sensors
- 1x Raspberry Pi 4B+
- 12x 2 $\frac{3}{8}$ inch brass screws
- 8x female to female wires
- 1x soldering iron
- 1x 10000 mAh portable battery
- 1x 1ft USB A to USB C cable
- 1x cut perf board
- wire cutters
- zip ties
- $\frac{1}{16}$ inch ID silicone tubing for ported pressure sensors

1. The Raspberry Pi 4B+ is attached to the avionics board using the #2 $\frac{3}{8}$ inch brass screws.
2. Each SparkFun Qwiic MicroPressure sensor, one for the aft chamber and one for the forward chamber, is attached using the same #2 $\frac{3}{8}$ inch brsass screws with the port of the pressure sensor facing up.

3. Each pressure sensor was connected to the Raspberry Pi 4B+ using a 3.3 voltage and ground as well as each being connected to board pins 22 and 23 for the first pressure sensor and pins 8 and 9 for the second pressure sensor so that each sensor can interface with two different I2C busses.

4. The 10000mAh battery was also attached using velcro and zip ties to the other side of the board, along with a USB type A to USB type C cable to power the Raspberry Pi and the SparkFun Qwiic MicroPressure sensors.

5. During the avionics bay assembly, the $\frac{1}{16}$ inch ID silicone tubing were epoxied to holes in both the aft and forward avionics bay bulkheads and are each attached to the ports of the pressure sensors.

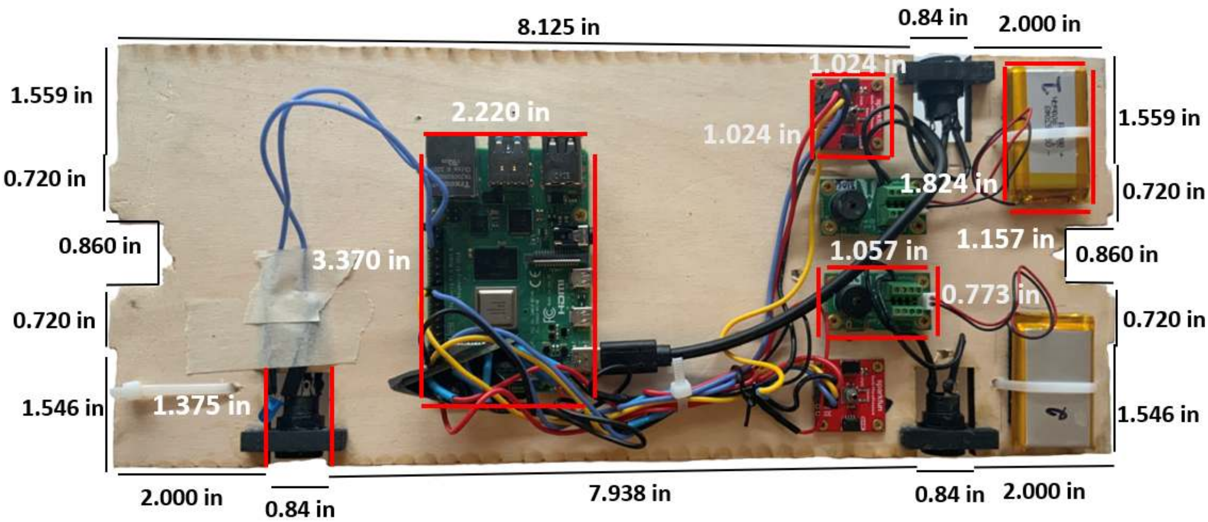


Figure 34: Avionics Top Bay Schematic

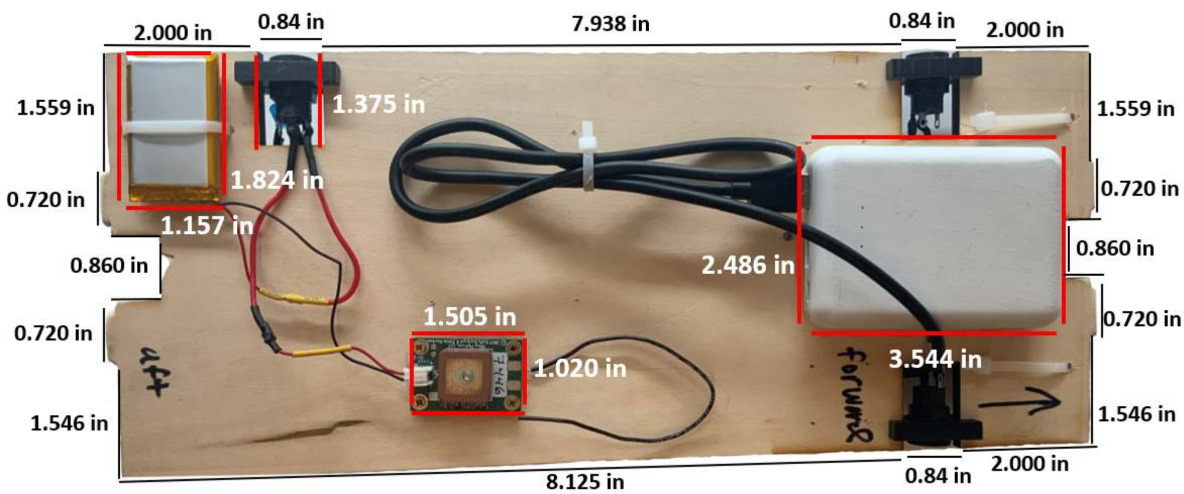


Figure 35: Avionics Top Bay Schematic

3.4 Mission Performance Predictions

3.4.1 Target Altitude

The target altitude for the 2022-2023 launch vehicle is 4,650 ft. This altitude was determined from simulating the layout and weights of components in OpenRocket. Section 3.4.2 displays the simulations used to determine this apogee.

3.4.2 Flight Profile

Open Rocket Predictions

Figure 36 below shows the average apogee, maximum velocity, maximum acceleration, and descent time of three separate simulations for each wind speed at 0, 5, 10, 15, and 20 mph at the expected conditions in Huntsville created by OpenRocket. The parameters used for OpenRocket simulations are 81°F, 34.7°N latitude, -86.6°E longitude, 600 ft altitude, 12 ft launch rail, and 5 degree launch angle.

	Average			
Wind Speed (mph)	**Apogee (ft)**	**Max Velocity (ft/s)**	**Max Acceleration (ft/s^2)**	**Descent Time (s)**
0	4680	578	251	75.6
5	4630	577	251	74.9
10	4562	576.7	251	75.1
15	4496	576	251	73.4
20	4415	574.3	251	73.5

Figure 36: Open Rocket Simulations at 0, 5, 10, 15, and 20 mph

Figure 37 shows the accompanying flight profile from OpenRocket for a Huntsville simulation at a 5 mph windspeed.

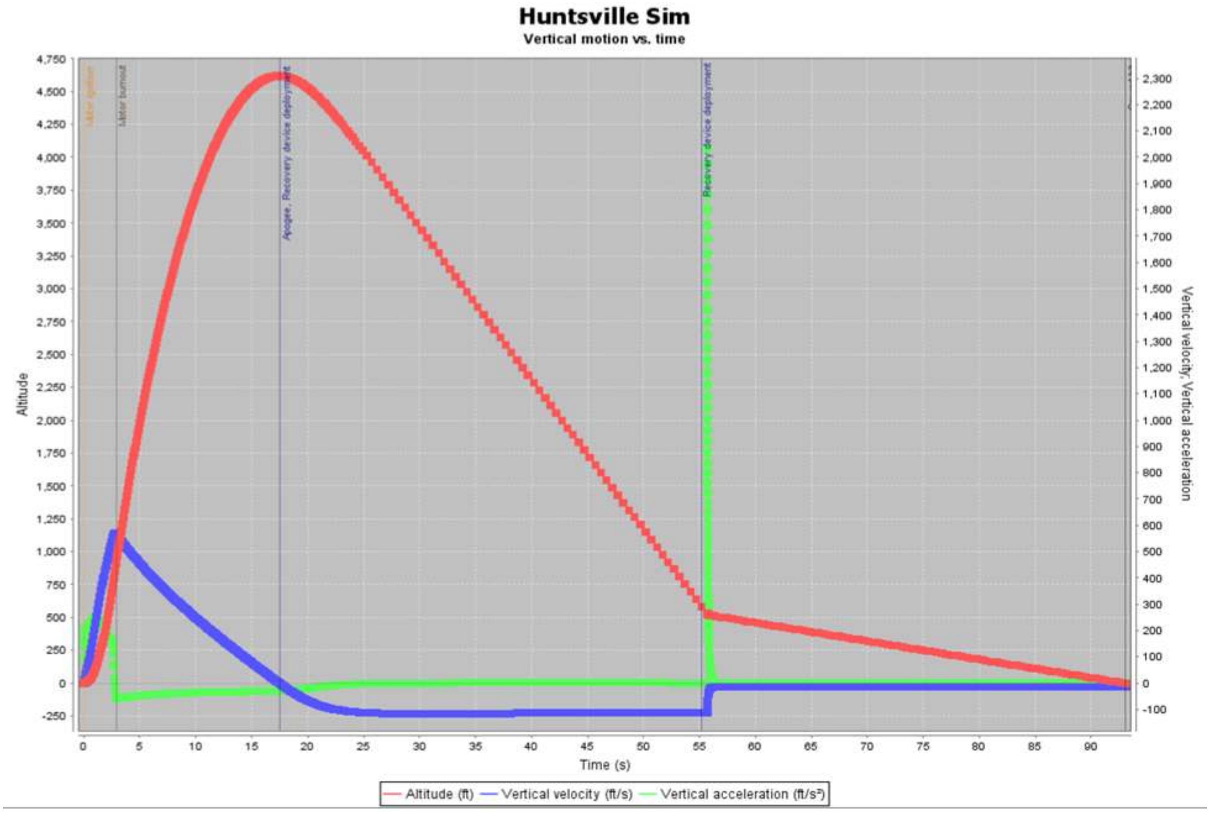


Figure 37: Huntsville Simualtion Altitude Profile

Simulated Apogee Precision

To verify the precision of the OpenRocket, multiple simulations were performed and a standard deviation was calculated from the data. Table 15 displays three trials for the apogee at various wind speeds from OpenRocket with an accompanying standard deviation. The Apogee variation at different wind speeds was determined to further understand OpenRocket's precision in varied atmospheric conditions for Sections 3.4.5 and 3.4.6.

Table 15: Simulated Apogee Precision

Wind Speed	**Simulation 1 Apogee (ft)**	**Simulation 2 Apogee (ft)**	**Simulation 3 Apogee (ft)**	**Standard Deviation (ft)**
0	4759	4759	4759	0
5	4747	4748	4748	0.471
10	4715	4718	4729	6.02
15	4680	4671	4653	11.2
20	4618	4629	4581	15.1

Alternative Calculations for Apogee

The table below summarizes the difference between the apogee determined from OpenRocket and the apogee determined through hand calculations.

Table 16: Calculated Apogee Comparison

OpenRocket Apogee (ft)	**Calculated Apogee (ft)**	**Percent Difference (%)**
4669	4945	5.9

The altitude was calculated based on known values defined in Appendix 9.1 as well as the L1390G thrust curve data retrieved from RockSim. A 10th degree polynomial best-fit line was applied to mathematically model the force applied to the rocket by the motor, F_t, as a function of time. With this equation, it is possible to approximate the graph of the altitude of the rocket over time. The force due to gravitaty on the rocket, F_g, was calculated using the constant $g = 9.81m/s$. The drag force was determined using values in Section 5.9 with the square of velocity, $\frac{d^2x}{dt^2}$, as a function of time.

There were a few assumptions made with this approximation. First, these calculations assume ideal conditions of 0 degree launch angle and 0 mph wind speeds. Additionally, it is assumed that the drag force on the rocket becomes positive (i.e. resists gravity) directly after reaching apogee.

In the RockSim data, the motor is recorded to burn for approximately 2.9 seconds. Therefore, the equation of force over time, $F(t)$, from t=0 to about t=2.91 becomes:

$$F(t) = F_t - F_g - F_d. \tag{2}$$

Rearranging to solve for acceleration over time, $a(t)$, where mass, $m(t)$, decreases with time as the motor fuel burns, the following expression is derived:

$$\frac{F(t)}{m(t)} = a(t) = \frac{F_t - F_g - F_d}{m(t)} \tag{3}$$

$$a(t) = -g + \frac{F_t - F_d}{m(t)}. \tag{4}$$

The variables a_t, v_t, and x_t denote acceleration, velocity, and position due to thrust over time, respectively. Additionally, simplifications of constants will be denoted with the following notation identified as C_i.

$$C_i = \frac{1}{2}\rho C_r A_r \tag{5}$$

$$a(t) = -g + a_t - (\frac{C_1}{m(t)}\frac{d^2x}{dt^2}) \tag{6}$$

Where ρ is the fluid density of air, C_r is the drag coefficient of the rocket, and A_r is the cross sectional area of the rocket.

Using the MATLAB function, Ode45, velocity can be defined as the derivative of position and acceleration as the derivative of velocity. This converts the second order differential equation into a set of two, first order equations. This is displayed in equations 7 and 8.

$$\frac{dx}{dt} = v \tag{7}$$

and

$$\frac{dv}{dt} = -g + a_t - (\frac{C_1}{m(t)}\frac{d^2x}{dt^2}) \tag{8}$$

This equation, however, is only valid until the motor runs out of fuel, so at 2.91+dt seconds (estimated to be about 2.91 s), at which point the only forces acting on the rocket are gravity and drag force. This reduces mass to a constant value (the difference of total mass of the rocket and the mass of the fuel). Therefore, equation 8 can be rewritten as:

$$\frac{dv}{dt} = -(g + \frac{C_1}{m}\frac{d^2x}{dt^2}) \tag{9}$$

Apogee was then determined by taking the maximum position value of the above two functions simulated to t=18 (a bit more than OpenRocket's predicted time of apogee). The time of apogee was found to be about 18.7 seconds with this model, and the vertical position of apogee was calculated to be 1507.2 m, or 4944.9 ft.

When comparing the hand-calculated value to OpenRocket, the time of ascent is approximately equal with an error within 3%, and location of apogee within 5.9%. Both calculations used the same RockSim thrust data, a 0 deg launch angle, 0 m/s wind speeds, and a drag coefficient of 0.6. The most likely source of error in these calculations can be found in the calculation of drag force. OpenRocket defines drag force as a sum of skin friction, body pressure, fin pressure, and parasitic drag. In contrast, these calculations only account for the axial drag using the cross-sectional area of the rocket. With an improved drag calculation, the hand-calculated apogee would be more accurate, better aligning with OpenRocket.

Body Tube Analysis

G12 fiberglass has a compressive strength of around 22 ksi, making it suitable for use as the body tube of the rocket, as demonstrated by the calculation using a maximum thrust force of 300 lb.

$$\sigma = \frac{F}{A} \tag{10}$$

$$\sigma = \frac{300lb}{\frac{\pi}{4} \times (6.17in - 6.0in)^2} \tag{11}$$

$$\sigma = 13.22ksi < 22ksi \tag{12}$$

Bulkhead Analysis

In order to mass optimize bulkheads, material was removed in four pockets leaving a cross pattern with an outer circumference equal to the stock thickness of the bulkhead, 3/8 in. In order to validate these design changes, Finite Element Analysis (FEA) studies were run to predict yielding based on the maximum snatch force estimate times the team factor of safety (FoS) of 1.5. This simulated snatch force is estimated to be 7500 N.

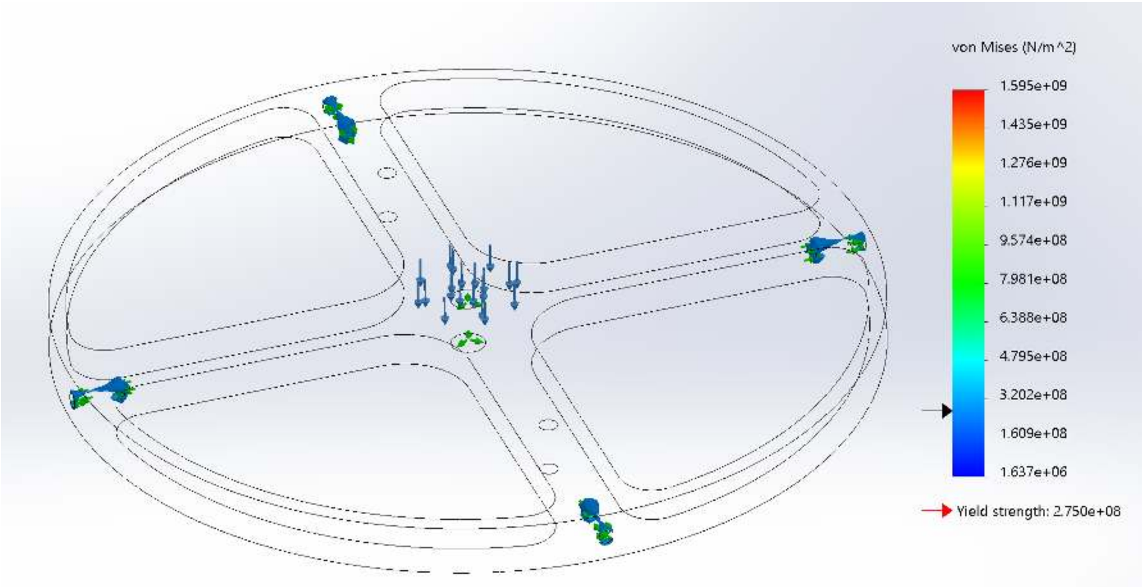


Figure 38: Forward Bulkhead FEA Study Results

The Forward Bulkhead is displayed in Fig. 38. The highest stress concentration was observed in the screw holes. Since SolidWorks cannot accurately simulate the load applied to threads, it believed the four threaded screws will be able to support the anticipated load without failing.

For the Mid Bulkhead, a similar process occurred. Material was primarily removed from the circumference of the part. This left a shape in the middle of full thickness where the most stress was predicted to be concentrated.

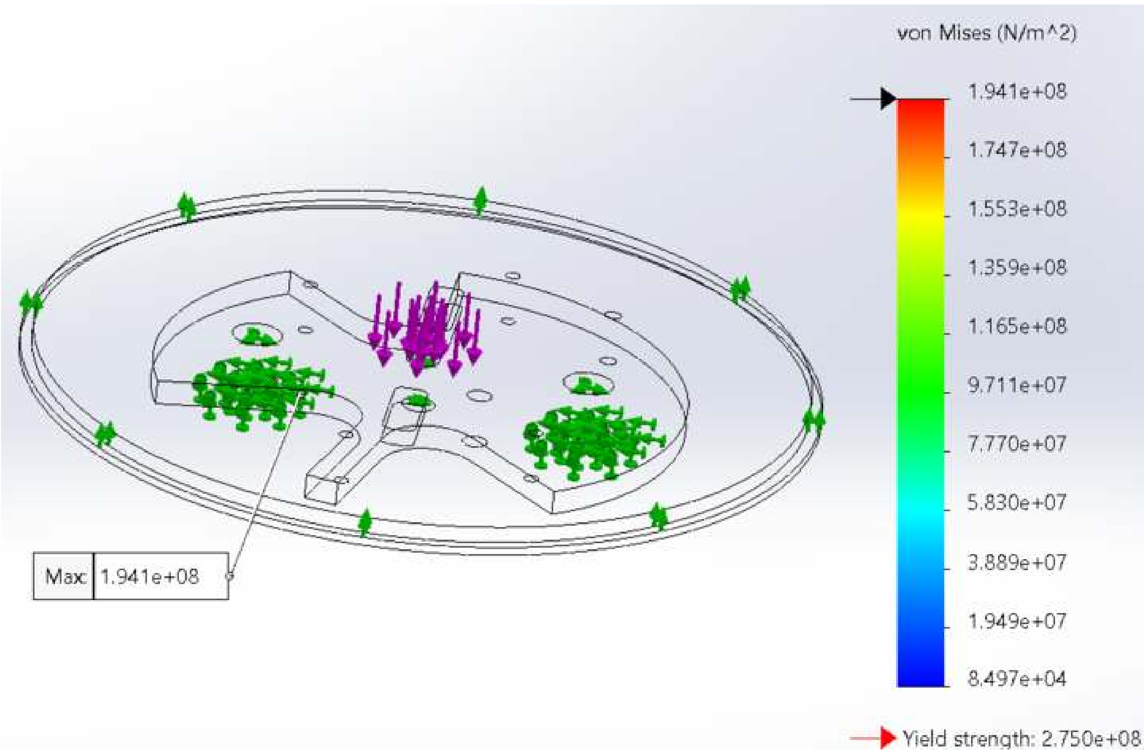


Figure 39: Mid Bulkhead FEA Study Results

As shown in Fig. 39, the maximum stress in the Mid Bulkhead reaches a value of

$1.941 \times 10^8 \frac{N}{m^2}$, which is lower than the yield strength of the aluminum 6061 used to machine the Mid Bulkhead. We can conclude that this part will not yield according to the FEA study conducted.

Similar to the two previous bulkheads, material deemed not essential to preventing yielding was removed to minimize total mass of the Bottom Bulkhead.

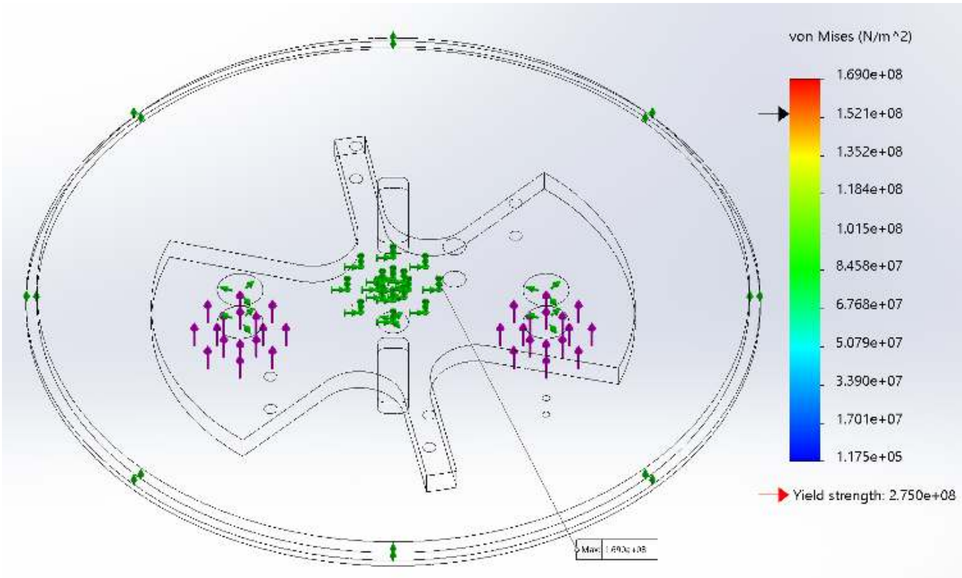


Figure 40: Aft Bulkhead FEA Study Results

Shown in Fig. 40, the maximum stress would not reach the aluminum's yield strength of $2.750 \times 10^8 \frac{N}{m^2}$. The Bottom Bulkhead shows no section which yields.

3.4.3 Rocket Stability

The stability of the rocket is integral to a safe, successful flight and one major contributing factor is the location of the center of gravity (CG) and center of pressure (CP). When the rocket has a CG that is closer to the nose cone than the CP, the rocket is more stable. Using Open Rocket, the team performed stability calculations to ensure that the CG would be safely above the CP.

Open Rocket Predictions

The Structures sub-team used the OpenRocket software to visualize the stability during the launch. Figure 41 below shows a stability vs time simulation of the rocket in Huntsville created by OpenRocket.

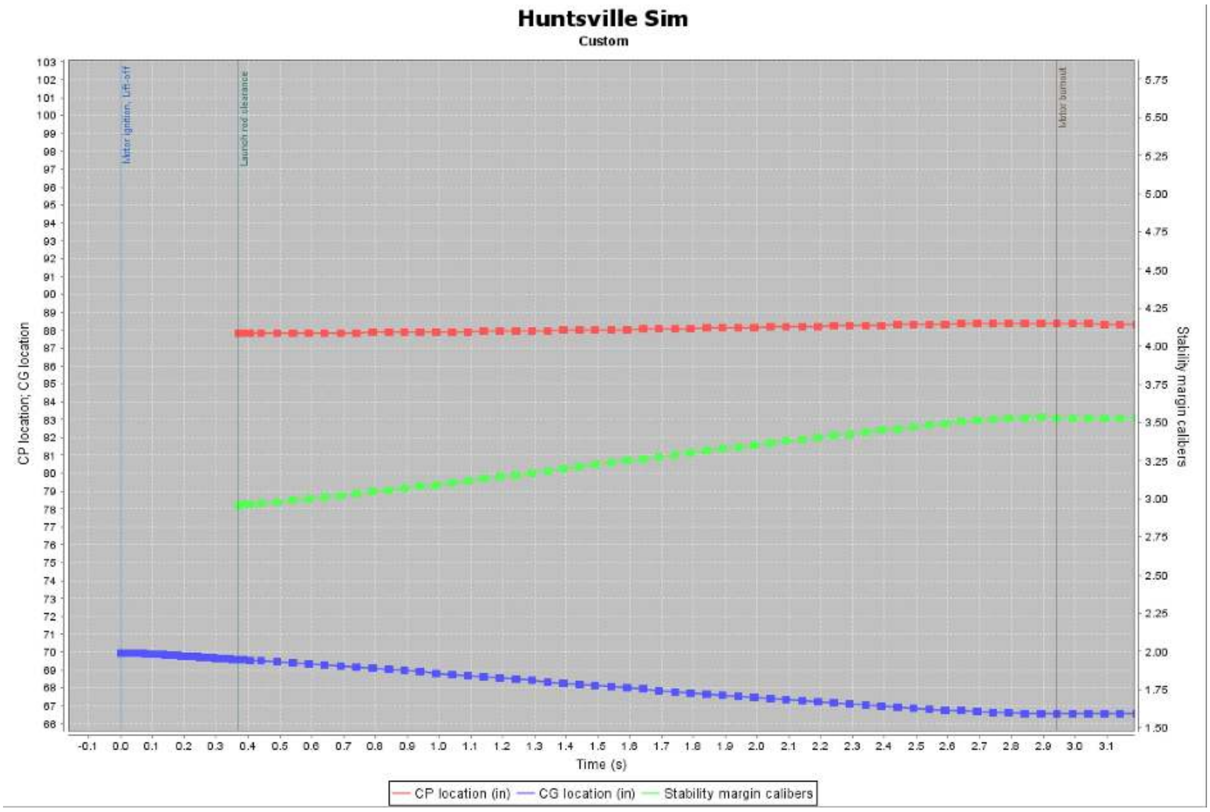


Figure 41: Open Rocket Vehicle Stability with Vertical Take off and 0 mph Wind

Location of CG and CP on Rocket

The calculations performed in Open Rocket ensure that the rocket is within the 2.00 cal stability margin. Figures 42-43 display the OpenRocket stability of the vehicle with and without a motor. Table 44 summarizes the OpenRocket CP, CG, and stability.

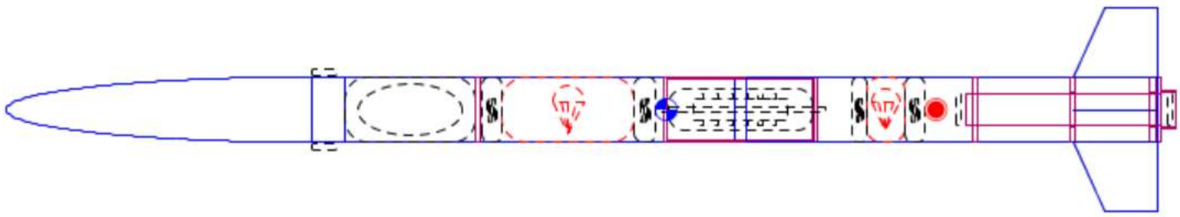


Figure 42: Open Rocket Vehicle without Motor

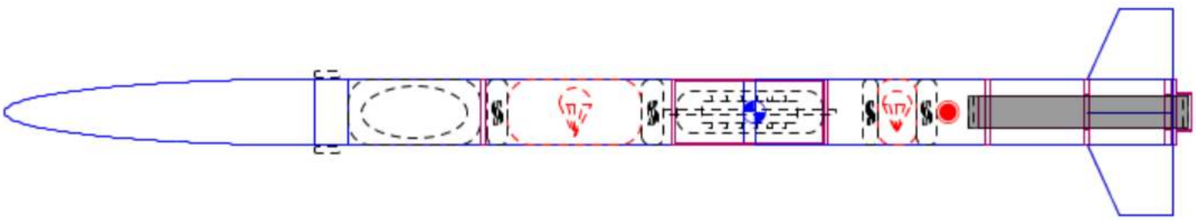


Figure 43: Open Rocket Vehicle with Motor

	Center of Pressure from Nose Cone (in)	Center of Gravity from Nose Cone (in)	Stability
With Motor	88.017	70.049	2.91
Without Motor	88.017	62.601	4.12

Figure 44: CG, CP, and Stability with or without Motor

Alternative Calculations

Using OpenRocket as the main software, the Structures sub-team was able to calculate the rocket's stability, which is determined by the center of pressure, the center of gravity, and the rocket diameter. Stability is a high priority as it keeps the rocket following a correct flight path, ensuring the safety of the rocket components and the accuracy of apogee calculations. Due to the importance of stability, this section will focus on double-checking the OpenRocket calculations by hand, seeing if the software gives a reasonable number for stability.

The Structures sub-team calculated the center of pressure using the Barrowman equations. An equation to find the center of gravity is provided but the final calculations for the center of gravity are calculated by OpenRocket due to the exact accuracy of the center of gravity and weights of all components. Figures 45-46 display the equations used along with variable definitions.

$$(C_N)_F = \left[1+\frac{R}{S+R}\right]\left[\frac{4N\left(\frac{S}{d}\right)^2}{1+\sqrt{1+\left(\frac{2L_F}{C_R+C_T}\right)^2}}\right] \longrightarrow X_F = X_B + \frac{X_R}{3}\frac{(C_R+2C_T)}{(C_R+C_T)} + \frac{1}{6}\left[(C_R+C_T)-\frac{(C_R C_T)}{(C_R+C_T)}\right]$$

$$CP\ Distance = \frac{\left((C_N)_N\right)(X_N) + \left((C_N)_F\right)(X_F)}{\left((C_N)_N\right) + \left((C_N)_F\right)}$$

$$CG\ Distance = \frac{D_F W_F + D_M W_M + D_A W_A}{W}$$

Figure 45: Stability Equations

L_N = length of nose

d = diameter at base of nose

C_R = fin root chord

C_T = fin tip chord

S = fin semispan

L_F = length of fin mid-chord line

R = radius of body at aft end

X_R = distance between fin root leading edge and fin tip leading edge parallel to body

X_B = distance from nose tip to fin root chord leading edge

N = number of fins

X_N = $0.446(L_N)$

$(C_N)_N$ = 2

D_M = distance to mid section centroid from the tip of the nose cone

D_A = distance to aft section centroid from the tip of the nose cone

D_F = distance to forward section centroid from the tip of the nose cone

W_A = weight of aft section

W_F = weight of forward section

W_M = weight of mid section

W = total weight

Figure 46: Stability Variable Definitions

With these equations and known parameters for the team's rocket, the CP was calculated and stability found in Fig. 47.

$$Stability = \frac{CP - CG}{d} = \frac{89.144 - 70.049}{6.17} = 3.09$$

Figure 47: Center of Pressure Calculation

The hand calculations resulted in a stability of 3.09 which is slightly above the 2.91 OpenRocket stability calculation. This is due to the higher value of the center of pressure the hand calculations computed, so the OpenRocket calculation is still reasonable. The structures sub-team determined the minimum stability that would be accepted would be 2.00 based on competition requirements and both values are well above this value.

3.4.4 Kinetic Energy Results

Table 17 displays the kinetic energy of each section. These kinetic energies were calculated using the terminal velocities after drogue and main deployments from Section 3.4.5.

Table 17: Kinetic Energies of Each Section

	Section 1 (ft-lbf)	**Section 2 (ft-lbf)**	**Section 3 (ft-lbf)**
Drogue Deployment	4616	3071	N/A
Main Deployment	60.18	17.82	51.97

After drogue parachute deployment, Section 1 is defined as the forward and mid body, Section 2 is the aft body. After main parachute deployment; Sections 1, 2, and 3 are the forward, mid, and aft bodies, respectively.

3.4.5 Descent Time Results

The results of descent time calculations are seen in Table 18 below. As mentioned in Section 3.4.5, parachute sizes were calculated with considerations of a 90s descent time constraint. Additionally, the team strived to achieve a descent time below 80 s. The following equation was used assuming an air density of 0.002376 lb/ft^3.

Descent time of the rocket:

$$t_{descent} = \frac{h_{apogee} - h_{main}}{v_{t,drogue}} + \frac{h_{main}}{v_{t,main}} \tag{13}$$

Table 18: Descent Time Calculation Results

Definition	**Value**	**Units**
Terminal Velocity with Drogue Deployed	113.0	ft/s
Terminal Velocity with Main Deployed	14.7	ft/s
Descent Time	76.5	s

Alternative Calculations An additional series of five simulations were performed in OpenRocket for each wind speed. These simulations were ran using expected conditions in Huntsville on launch day in order to confirm the validity of the calculated value shown in Table 18. These simulations, which are detailed in Table 19, were run at multiple different wind speeds as well to further ascertain how variance in launch day conditions would affect descent times. The results, while slightly higher than the original calculated value, are still quite close, with the largest percent difference being only 1.98%, meaning that the original value appears to be quite accurate regardless.

Table 19: Simulated Descent Time Precision

Wind Speed (mph)	**Average Descent Time (s)**	**Standard Deviation (s)**
0	75.8	0
5	74.5	0.339
10	75.7	0.688
15	73.1	0.760
20	73.9	1.26

3.4.6 Drift Results

Table 20 displays the predicted drifts ranging from 0-20 mph as calculated by-hand and in OpenRocket simulation. By competition requirements, the drift must be less than 2500 ft from launch point. At the maximum launch speeds of 20 mph, the maximum drift experienced is 2245.7 ft, 254.3 ft below the maximum.

Table 20: Drift Calculation Values

Wind Speed	**Hand Calculation Drift (ft)**	**Open Rocket Drift (ft)**	**% Difference**
0	0	0	0
5	561.4	561.0	0.07
10	1123	1122	0.09
15	1684	1683	0.06
20	2246	2244	0.09

The OpenRocket simulated values all come within 0.09% of the hand-calculated vlaues. This difference of values is found in the OpenRocket's average descent time being 76.0 s, whereas the hand calculated descent time was 76.5 s. This minor difference in descent time may be a result of aerodynamic effects such as drag on the rocket.

4 Payload Criteria

The construction process of VISiON has finalized various aspects of both the original mechanical and electrical design to meet as-built requirements and constraints. The specifics of these mechanical and electrical constructions are further discussed in the following sections.

4.1 Constructed Payload Differences from Earlier Models

Several high-level changes made to VISiON are the result of mass constraints and increased safety factors to ensure the success of mechanical deployment, primarily the separation and deployment of the vehicle nosecone and camera arm. Few changes were made to the design of the electrical system, aside from implementing new software libraries and hardware changes to optimize the performance of the imaging and electromotive systems.

4.1.1 Mechanical Differences

1. **Strengthened Motor Axle** During construction of the nosecone separation subsystem, the Payload team had concerns surrounding the potential risks of a weak separation motor axle. The design involved the use of an 0.31" thick steel rod driven by the DC motor via a D-shaft coupler. However, having the rod then thin out to accommodate the 1/8" pinion was evaluated as a risky point-of-failure. As a result, the steel rod was instead tapped on the inside and threaded to support a 3/16" bolt and nut that would allow the pinion gear to simply be screwed into the axle and finally sealed with Loctite.

2. **Static Separation Rods** In an effort to optimize mass and increase stability, the 3-D printed telescoping rods have been replaced with 8 mm aluminum rods. The aluminum rods are tapped on one end and are fastened to the aft rotating track. On the forward end, the aluminum rods fit through 10 mm holes on the rotating track. This modified design is multi-functional. It reduces weight, as the aluminum rods are lighter than the previous PLA telescoping rods. Additionally, the static rods prohibit rotation during flight, and thus eliminate the need for the third solenoid previously attached to the rotating track. The aluminum rods will keep the payload static until the body tube has been separated after landing.

3. **Shortened Scissor Lift** The originally designed scissor lift included at least 3 levels, which were pairs of struts that extended upwards. These were originally designed to each attain 2" of height, for a total of 6" with 3 levels. This was far above our requirement of 3.22 in, and the extra length of the camera made the payload unwieldy from two points: the scissor lift could not fit and the moment generated from the extension disturbed the uprighting mechanism. As a result, only a single level has been used to achieve 3.22 in of lift (as shown in the scissor lift test in section 6.4) and to keep the entire mechanism (lift with the camera components on top) within the bay.

4.1.2 Electrical Differences

1. **Servo Voltage Regulator** The primary change in the electrical system of the payload was the introduction of a 6v voltage regulator. The component was implemented into the electrical distribution subsystem where, originally, only 5v and 12v power was needed for two classes of components on the payload. The low voltage components, such as those on the electronics shield, are primarily sensors and communications devices that could be powered with 5v. The heftier electromotives, such as the solenoids and DC motor operated at 12v. However, it was realized that the servos that originally operated on 5v were under-performing in both precision and torque due to the less-than rated voltage of 6v. Thus, a 12v-to-6v regulator was implemented to supply the servo with a consistent 6v from the 12v output of the battery instead of directly from the 5v output.

4.2 Payload Design Overview

4.2.1 Mission Success Criteria

In order to consider the Payload mission as a success, the team derived several high-level criteria that a payload would have to generally achieve:

1. The payload must completely retain the nosecone of the vehicle throughout flight, failure to do so results in catastrophic failure of the mission and poses as a safety risk.

2. The payload sufficiently retains its internal components and self-rotating track. Slight disturbances are accounted for in correcting slightly off-skew angles in images taken by the payload, but retention must sufficiently protect components throughout turbulent flight.

3. The payload successfully separates and deploys its camera arm. This involves fully extending the nosecone to create a physical gap of 4” to have the camera arm extend 2” above the gap while remaining within 15 degress of upright. These values were determined through testing as the most reasonable conditions for capturing clear surrounding landing-site images.

4. No damage to any payload component throughout launch and recovery. Demonstrates that the payload design is suitable for its intended purpose without costly repairs or due to poor integrity.

4.2.2 Mission Execution Phases

Without deviation from the proposed mission execution of the payload from the CDR, the team has defined the following sequence of events that must be carried out to fulfill the Payload mission:

1. **Stage 1: Initialization**
   Payload hardware is loaded into vehicle and software is initialized to await launch. The payload periodically transmits status updates of its system to the base station.

2. **Stage 2: Flight**
   Payload detects launch sequence and awaits landing. Throughout flight the payload will frequently transmit telemetry to base station.

3. **Stage 3: Execution**
   Payload detects landing and, if stable, begins separating the nosecone from the body tube. When the vehicle is sufficiently separated, the payload deploys the camera arm and the imaging system enters a RAFCO execution loop that continuously listens and executes RAFCO transmitted over the APRS network.

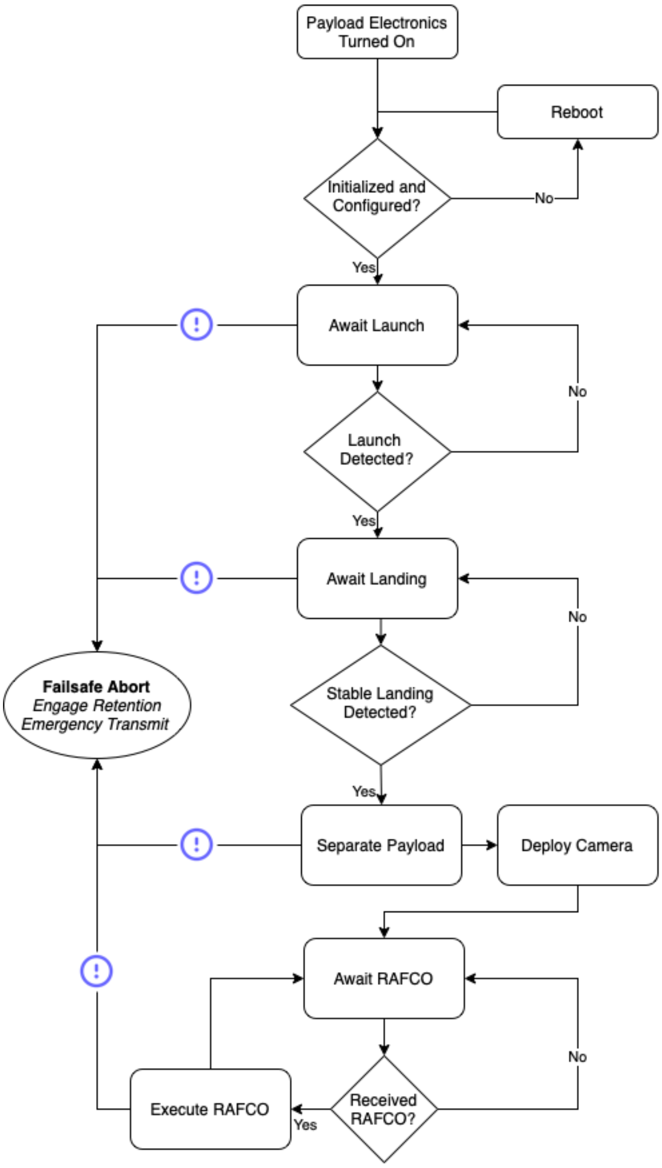


Figure 48: Payload Mission Phases Flowchart

4.2.3 Payload Component Total Masses

	Component	Qty.	Material	Weight (oz)
MECHANICAL	Separation Rack	2	Steel	13.2
	7880K18 Pinion Gear	2	Steel	0.2
	Separation Motor + Axle	1	Aluminum	15.8
	Motor Mount	1	PETG	2.82
	Compact Linear Solenoid	3	Steel	6.9
	Solenoid Housing	2	Steel	1.2
	Rotating Track	2	Steel	14.8
	Centering Rings	2	PLA	2.1
	Telescoping Rods	2	PLA	1.8
	Parallax Servo	2	Steel	3.32
			Subtotal	62.1
ELECTRICAL	Raspberry Pi	1	PCB	1.52
	Motor Hat	1	PCB	0.92
	Electronics Baes Board	1	Basswood	2.05
	TalentCell DC Battery	1	Lithium Ion	10.5
	Voltage Regulator	1	Aluminum	1.23
	Camera Scissor Lift	1	PETG	1.06
	Camera Housing and Camera		PETG	0.4
	APRS Antenna	1	Copper	1.8
	Telemetry Antenna	1	Copper	0.21
	Payload Avionic Shield	1	PCB	0.84
	Wiring	1	Cable	1.04
			Subtotal	21.6169
			Total	83.8

Figure 49: Payload Table of Measured Mass Values

Table 49 shows all of the measured masses of the components used in the payload section. The weights measured are the total weight for a component. So if there are 2 centering rings then the weight is the combined mass of both centering rings.

4.2.4 Payload Mechanical Structure

The mechanical structure of the payload design consists of three core mechanisms: a self-righting track, a nose-cone retention and payload-deployment system, and an electronics board to consolidate all necessary imaging and communication devices. Each aspect of the payload mechanical structure is discussed below. The final design of the payload mechanical structure is shown below in Fig. 50 and 51 below.

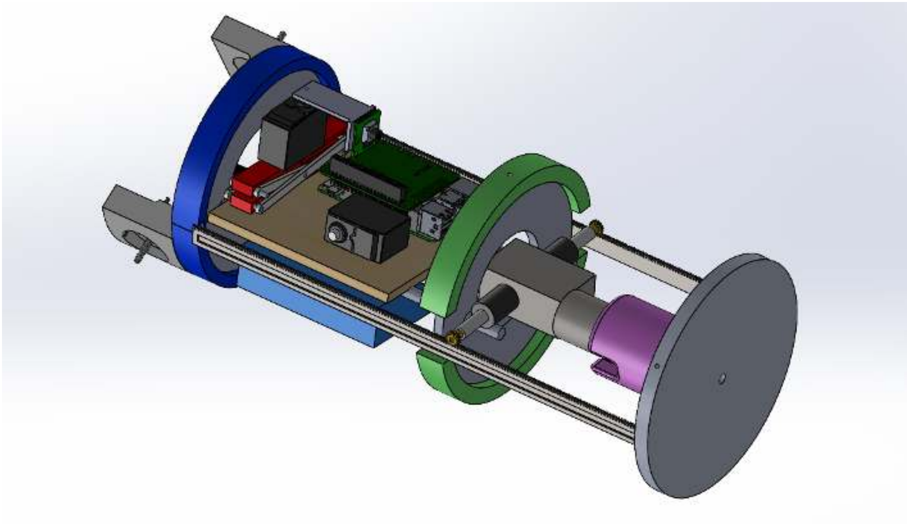


Figure 50: Payload Mechanical Structure: Iso View

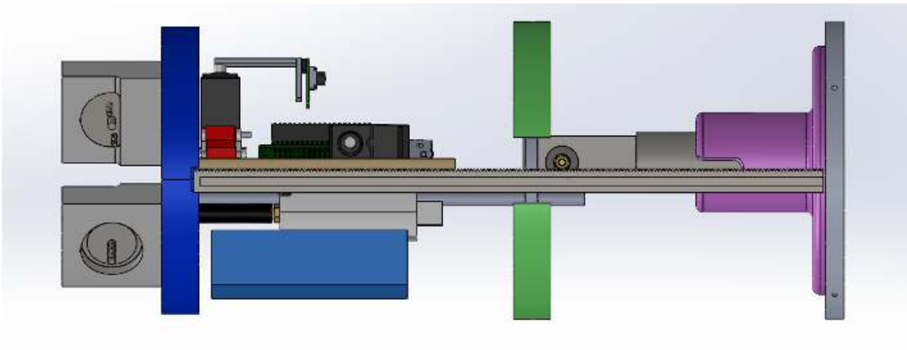


Figure 51: Payload Mechanical Structure: Right View

1. **Self-Righting Track** To properly orient the payload parallel to the ground after landing, a self-righting design was selected. The design utilizes a stainless-steel, rotating track that is fixed to the nose cone side of the payload interface. Screwed in to the rotating track are two tapped aluminum rods. The electronics board and imaging system are mounted to a plywood board, which is epoxied to the aluminum rods. On the opposite end, a static, 3-D Printed, PLA ring is fixed to the body tube side of the payload interface. When the payload is in the collapsed position, the aluminum rods are fixed in the static PLA ring, thus preventing rotation. After the payload lands, the separation process initiates. Once the payload has separated several inches, the aluminum rods loses contact with the PLA ring, and the rotating track is able to move freely. Because of the uneven weight distribution on the electronics board, the board automatically orients with the imaging system in the proper alignment.

2. **Payload Separation** The deploy the imaging system, the nose cone and body tube must separate after landing. To do so, a rack and pinion system was chosen for the design. Two stainless-steel racks feed through the static ring on the body tube side of the interface, and push against the rotating track on the nose cone side of the interface. This motion pushed the nose cone and body tube apart, and allows sufficient room for camera deployment. To help guide the separation (and

reduce mass), key slots were machined along the length of both racks. The pinions are epoxied to a Greartisan 12V 10RPM DC double shaft motor, and the motor itself is epoxied to a PLA mount which is screwed into the top bulkhead.

3. **Camera Deployment** To deploy the camera, a scissor lift mechanism was selected. All scissor lift components are 3-D printed, excluding the connecting pins which are aluminum. After the rocket has landed and the payload has separated, a servo motor will rotate and pull wire to raise the scissor lift. The scissor lift is mounted to the forward end of the electronics board, and is epoxied to the plywood.

4. **Retention Mechanisms** To ensure the payload does not separate during flight, a complex retention mechanism was implemented. Two linear solenoids, mounted to the static centering ring on the forward end of the payload interface, act as a main retention force. The solenoids are in the expanded position during flight, and feed through the nose cone and body tube. After flight, the linear solenoids retract, and allow for payload separation.

5. **Key-Slot Rack and Pinion** The rack and pinion system is responsible for separating the nose cone from the body tube upon landing. To ensure that the rack is secure during separation and will stay meshed with the pinion gear, a key slot was cut into the side of both racks. This slot is $\frac{3}{16}$" wide and runs the entire length of the rack. A screw will be screwed into the body tube and will act as the key that fits in this slot. The key-slot additionally reduces the mass of the rack by removing a significant amount of material for the slot.

6. **Electronics Board Layout** The electronics board was designed to efficiently space all components. The heavier components such as the Pi were placed on the bottom of the board so that the payload will be self-righting, meaning the camera will always be facing upward. The battery, the heaviest part of the payload, was also placed below the electronics board, but not directly touching the board. The intent of this design was that with a greater distance from the board, there is a larger moment, which will help with the self-righting. There was also not enough physical space on the board with all of the components, so this design allowed the battery to be attached to the board without being stuck to other electronics. The scissor lift with the camera was placed on top of the board with some of the lighter components.

4.2.5 Payload Electronics

1. **Vision and Imaging System** Regarding the camera system, all filters are implemented as global mode with the help of Python PiCamera module. For internal validation purposes, image transformations are also performed with Pillow, instead of the heavy weight OpenCV image library, accompanying the global changes in the camera mode in parallel. Camera system also modularized code to enhance readability and easier integration with testing for execution times. Optimized file management allowed for storing photos with timestamps in its name, adjusting to the local time zone.

2. **Payload Avionic Sensing System** The Payload avionics shield had transitioned from its initial wiring schematic design and PCB layout into a physically manufactured circuit board. Using 3rd-party manufacturing services from PCBWay, the

payload has successfully integrated the shield into connecting the avionics, telemetry, and servo components into the bay, minimizing the amount of manual wiring required of the team.

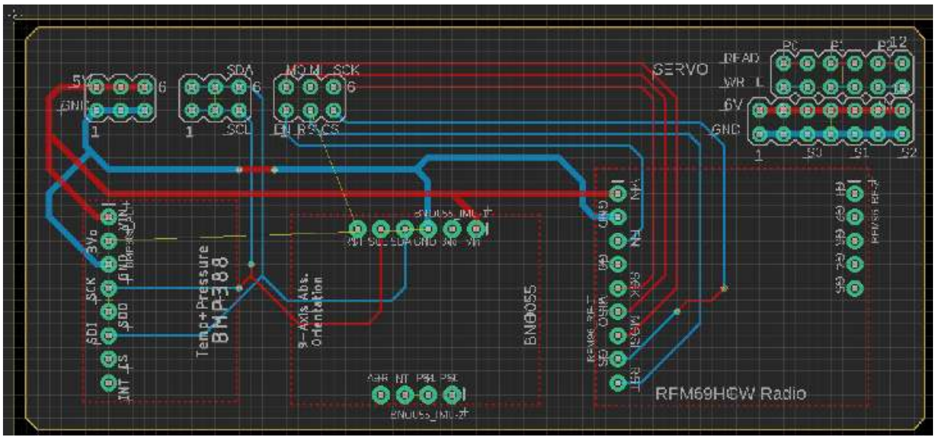


Figure 52: PCB Avionic Shield Layout Placement

The board layout was placed with several common PCB design practices in mind, especially since the team had to work with a 2-layer board that only supported independent traces on either side. Thus, power lines were made wider to reliably support current from the power pins and any crossing traces were made perpendicularly at 90 degrees to minimize electromagnetic noise. An illustration of the board manufactured layout is shown below.

The final CAD model of the board and physical model are shown below.

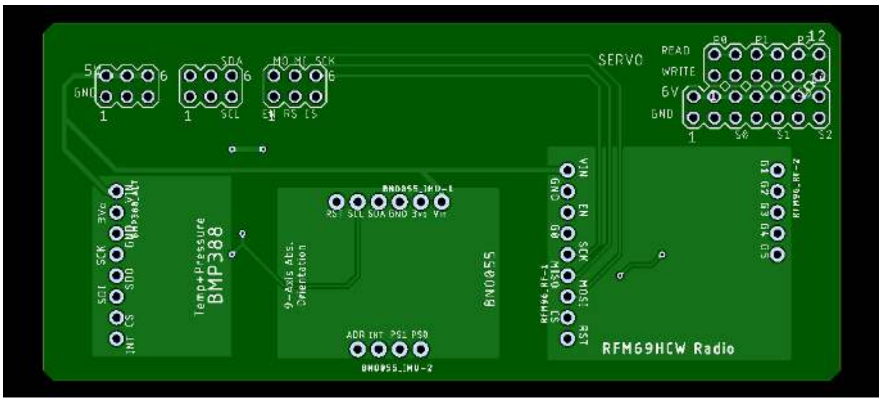


Figure 53: PCB Avionic Shield Manufacturer's CAD

The avionic shield also implemented a servo power and control distribution output (seen in top right corner) to ease in the connection of servos to the Raspberry Pi's logic and with the new 6V voltage regulator.

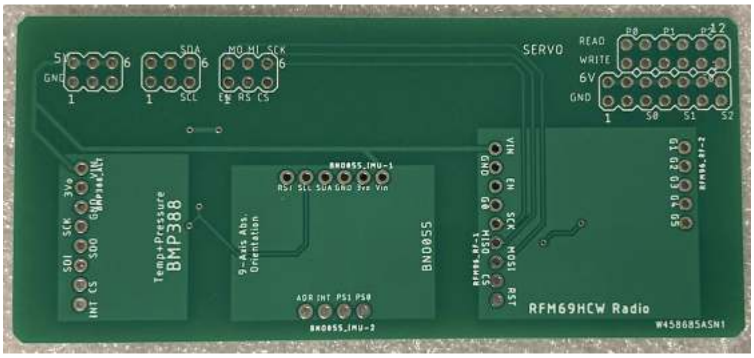


Figure 54: PCB Avionic Shield

The two main avionic components, the BNO055 IMU and the BMP388 altimeter, were interfaced in software with the Python language and the supporting Adafruit libraries.

(a) For the BMP388 Precision Barometric Pressure sensor, the team has been collecting data on the altitude, temperature, and pressure readings. For initial pressure, it was set equal to the sea level pressure from the python libraries, so that it can align and be more accurate with the readings from the ground at sea level. When the BMP388 was moved above and below its normal elevation, it had printed out the values for temperature, altitude, and pressure consecutively. The team noticed that the data acceptably matched the position of the sensor with varying degrees of accuracy after implementation of a rolling mean filter.

(b) The team has been also working on the BNO055 sensor as part of the data collection. A delta timing function where the BNO055 collects data readings including angular gyro meter acceleration, linear acceleration, and magnetic data. That data was only collected if the BNO055 was fully calibrated. If the sensor is not calibrated, it would instead print the calibration status each time. The team took into consideration that there would be some noises that may affect the calibration of the sensor. To prevent that, additional advanced noise filters (zero-velocity, Kalman) were implemented via various Python mathematics libraries in order to further improve the chances of the sensor readings. Thus the team was successfully able to use the BNO055 to determine motion along all 3-axes and to accurately determine the upright-orientation of the payload camera deployment system within 5 degrees of z-axis vertical.

3. **APRS Reciever System**

   The APRS Reciever System will use two Python modules: rtl-fm to control the RTL-SDR and multimon-ng to demodulate recieved APRS signals. The demodulated APRS packets will be loaded into an array within the overall Python control program. The RTL-SDR control code has been simplified to seemlessly integrate into an already running Python script to avoid having to also run bash scripts for RTL-SDR control.

4. **Telemetry & Base Station**

In order to receive information on how the payload mission is executing, the base station will receive raw ASCII formatted string data from the on-board telemetry system. Telemetry includes various system information, such as the sensor data from the on-board avionics (time, temperature, Payload bay pressure, payload orientation and acceleration, etc.) that serve essentially as "blackbox" data but is also transmitted after writing such data to memory on the Raspberry Pi. This data writing occurs after the end of each stage of mission execution as defined in the Payload mission execution flow from the CDR. The payload will also periodically inform the base station (at 1 minute intervals) with status updates throughout the entire mission, these will involve:

(a) Timestamp
(b) 'sys_flags'
(c) Mission Status

The timestamp provides a date and time indicator of the time the status update was transmitted to ensure real-time communication. The 'sys_flags' mask is a bitmask (series of 1s and 0s) each indicating an integer value for a defined series of system variables that describe the payload's status. From the leftmost position (0-th bit) onwards, the current flags are defined as:

(a) STAGE
(b) MOVEMENT_DECISION
(c) FLIGHT_STATUS
(d) IS_UPRIGHT
(e) IS_SEPARATED
(f) IS_DEPLOYED
(g) WARN_HEAT
(h) WARN_CAMERA
(i) WARN_AVIONIC
(j) WARN_MOTIVE

The descriptions of these stages are as followed:

(a) Mission stage is stored as the first flag, with the integers 1-3 indicating the stage the payload mission is in.
(b) The 'movement decision' variable indicates whether the payload detects movement resulting from acceleration exceeding a threshold along all 3 axes.
(c) 'flight status' observes drops in Payload bay pressure that has been detected due to atmospheric pressure being lower as the vehicle reaches higher altitudes. This will aide in determining whether the payload is ascending (integer value 1) or descending (integer value 0).
(d) 'is upright' uses the BNO055 IMU to derive orientation data, specifically if roll and pitch are within 5 degrees from absolute Earth x and y axes. This determines whether deployment of the camera arm can be proceeded with.

(e) 'is separated' indicates that the DC motor has extended the payload nosecone by a certain number of revolutions using a software timer per 10 RPM of the motor.

(f) 'is deployed' indicates whether the camera arm has fully extended or not by determining when the servo just begins to stall by counting the speed at which servo position changes. The rate at which the servo angle changes is relatively faster when the arm can still extend and then sharply decrease as it is stalled.

The last four variables are warning indicators of excessive heat, camera sensor failure, avionic sensor failure, or motive component failure respectively. Various combinations of these warnings will ultimately result in the triggering of the Payload fail-safe abort mechanism that discontinues the execution of the mission as described in the CDR.

4.3 Payload Construction

The following section outlines the construction of the main mechanisms and each of their components that form the payload. The specific dimensions, procedures, and equipment used during its construction process are also documented.

The primary constructed mechanisms of the payload are as listed below:

1. Nosecone Retention
2. Bay Separation
3. Rotating Track
4. Camera Lift
5. Payload Avionic Shield
6. Electronics Board

4.3.1 Dimensions

1. **Nosecone Retention**
   The nosecone retention system consists of two linear solenoids mounted to the nosecone with 3D printed mounts.

Component	Length (in)	Width (in)	Height (in)
Solenoid Mount	2	4.88	0.73
Solenoid	1.25	1.5	1.25

Table 21: Dimensions of the Nosecone Retention System

2. **Separation**
   The separation system is made of a rack and pinion that is powered by an electric motor. The rack has a 0.375" key slot cut into it for mass reduction and for more stability. The motor mount is also offset by 0.25" vertically and 0.35" to the right to make sure that the motor shaft is in the correct position to power the racks.

Component	Length (in)	Width (in)	Height (in)
Rack	12.65	0.23	0.48
Pinion	0.35	0.32	0.35
Motor	4.54	2.60	1.58
Motor Mount	2.00	2.60	2.00
Motor Axle	0.31	1.33	0.31
Shaft Coupler	0.67	0.98	0.67

Table 22: Dimensions of the Separation System

3. **Rotating Track**
   The inner bearings are mounted to the body tube and nosecone using 3D printed centering rings. There is a groove in each centering ring so the inner bearings can be held in place with.

Component	Inner Diameter (in)	Outer Diameter (in)	Width (in)
Inner Bearing	5.40	2.52	0.25
Nosecone Centering Ring	6.00	5.16	0.75
Body Tube Centering Ring	5.78	5.16	0.75

Table 23: Dimensions of the Rotating Track System

4. **Camera Deployment**
   Table 24 describes the dimensions of the scissor lift mechanism that the camera is resting on top of. It consists of several components, primarily the scissor lift and the servo-driven camera.

Component	Length (in)	Width (in)	Height (in)
Scissor Lift Extended	4.09	1.00	3.22
Scissor Lift Retracted	4.09	1.00	0.72
Parallax 360 Feedback Servo	1.69	0.83	1.46
Camera Mount	2.40	1.00	1.10
Pi Camera	0.98	0.94	0.50

Table 24: Dimensions of the Scissor Lift

5. **Payload Avionic Shield**
   The payload avionic shield is responsible for managing the wiring between the attitude and altitude sensors, as well as the telemetry RF module. It also routes 6V power from the battery to pins for use by the servos. It's height includes the header pins that have been soldered onto it and the components.

Component	Length (in)	Width (in)	Height (in)
PCB Shield	3.8	1.70	0.06
BMP388	1.00	0.70	0.26
BNO055	1.05	0.80	0.26
RFM96W	0.84	1.15	0.26
6v Regulator	6.26	3.11	0.39

6. **Electronics Board**
   The electronics board will hold all of the electrical components and the camera deployment system. The dimensions of the board are shown in Figure 25.

Component	Length (in)	Width (in)	Height (in)
Electronics Board	5.15	4.88	0.25

Table 25: Dimensions of the Electronics Board

4.3.2 Construction Procedure

Nose Cone Retention

The nose cone retention consisted primarily of the solenoid and 3D printed housing used to mount the solenoid onto the interior of the nosecone.

Equipment:

- Calipers/Tape Measure x1
- Sandpaper x1
- File x1
- Epoxy x1
- Body Tube Stands x2
- 12v DC Power Supply x1
- Multimeter x1
- Electrical Tape
- Jumper Cable

Procedure:

1. Take 3D printed housing units and sand/file down the inside so solenoids fit inside
2. Place solenoid into housing units with the front flush with the housing
3. Run solenoid wires through the groove in the housing
4. Take this partial solenoid and housing subassembly and epoxy the front face to the inside of the nosecone so that they press through a $\frac{3}{16}$ in drilled hole.
5. After epoxy has solidified, ensure solenoids are still functioning correctly by testing continuity of its two leads
6. Ensure solenoid is still capable of actuating by applying 12 V to its leads
7. File surface of the solenoid pins to assist in actuation (if needed)

Bay Separation

The entire separation mechanism consisted of two main components: the DC motor and rack & pinion. The two are described below.

Equipment:

- 3D Printed Motor Mount x1
- 8mm 6061 Aluminium Rods (Motor Axles) x2
- D-shaft axle to 8mm coupler x2
- Pinion Gears x2
- Sandpaper x1
- File x1
- Loctite
- Epoxy

Procedure (Motor):

1. Machine motor axle rods down to 1.05 in in length
2. Tap inner section of rods with $\frac{1}{8}$ in threads
3. Apply Loctite to screw threads and epoxy between pinion against motor axle to screw into place. Hold tight for several seconds
4. Obtain 3D printed motor mount housing
5. Remove supports and file edges of printed motor housing
6. Tap two 10-32 holes 1.75 in from the center to allow motor mount to be screwed into aft bulkhead
7. Insert 12 V DC motor into housing flush against edges applied with epoxy, while ensuring the motor wires are accessible through the side of the motor mount.
8. Attach D-shaft axle coupler to both ends of the DC motor shaft
9. Insert 8 mm machined motor axles into couplers, tighten with screw in coupler

Procedure (Rack and Pinion):

1. CNC mill a key slot in the side of the rack $\frac{3}{16}$ in wide and $\frac{5}{16}$ in deep
2. Use a metal-cutting band saw to shorten down the racks to 12.65 in long
3. With a drill press, drill two holes into the body tube for the keys to fit into the rack. The holes should be 5 in from the edge of the body tube and 180º apart from one another

4. Insert the racks into the payload so they fit into the key slot, nosecone centering ring, body tube centering ring, and mesh with the pinion gear

Rotating Track

The rotating track primarily involves the assembly of two variants of 3D printed centering rings (one fit to the body tube and another to the nosecone) to house the inner bearings and the separation racks. Despite minor differences in the design of the centering rings, they followed similar construction procedures.

Equipment:

- Sandpaper x1
- File x1
- Hand Drill x1
- Inner Bearing x2
- Nosecone Centering Ring x1
- Body Tube Centering Ring x1

Procedure:

1. Remove PLA support material from groove of the centering rings
2. File/sand down the groove after support material has been removed
3. Place the inner bearings inside the centering ring so they are secure
4. If necessary, the centering rings should be sanded on the outer edge for a smooth fit with the rocket
5. Use a hand drill with a #31 drill bit to remove support material from the screw holes for the body tube centering rings
6. Assemble the centering rings with their associated inner bearings and place in the nosecone and body tube
7. The body tube centering ring should be screwed in from the outside of the body tube 7.06 in away from the aft bulkhead
8. The nosecone centering ring is epoxied into the lip of the nosecone

Camera Deployment

Deployment of the camera arm involves the assembly of the 3D printed scissor lift and the mounting of two servos. One servo drives the lift while the other supports the camera to enable left and right rotation.

Equipment:

- Connecting Rod x5
- PLA Beam x4

- Bottom/Top PLA Platform x2
- Parallax 360 Feedback Servo x1
- Raspberry Pi Camera Model G
- Gorilla Glue
- Basswood
- Electrical Tape
- 50lb Braided Fishing Line

Procedure (Scissor Lift)

1. Place a connecting rod through the center of 4 beams. Where the 4 beams are split into two pairs each pair forming an X shape
2. Place a connecting rod into the hole of the bottom platform, then fit that rod into one corner of the X shape. The connecting rod should go through 2 of the PLA beams
3. Take another connecting rod and put it into the slot of the bottom platform. Then fit that connecting rod into an adjacent corner of the X shaped PLA beam.
4. The scissor lift should now be able to extend and retract without the top platform mounted
5. Repeat steps 2 and 3 with the top platform and make sure the holes of the top and bottom platforms are parallel with one another. The scissor lift should look like Figure 24.
6. Glue the scissor lift to the electronics board so it is 0.25 in from the short edge and there is a 0.55 in gap between one edge of the scissor lift and the edge of the board

Procedure (Lift Servo)

1. The servo was glued in the middle of 3 x 1.45 x 0.25 in piece of basswood
2. The basswood was placed 0.59 in from the long edge of the electronics board and 0.79 in from the short edge of the electronics board.
3. 0.125 in holes were drilled into the basswood and electronics board so the holes were 0.15 in from the glued-down servo
4. The basswood mounted servo was screwed into the electronics board using these holes.
5. A 0.5 in screw was screwed into the electronics board so that the excess screw sticks up in the air next to the scissor lift. This screw should be placed 0.25 in away from the corner of the scissor lift in the 0.55 in gap between the scissor lift and the edge of the board.
6. Wrap this screw in electrical tape to protect the fishing line from fraying.

7. Cut the fishing line so it is about 8 in. Then secure one end of the line to a connecting rod of the scissor lift; the other end should be connected to the shaft of the servo motor

Procedure (Camera Servo)

1. The camera was wrapped in electrical tape to protect the camera from glue.
2. The camera was glued to the 3D printed arm connector so that the bottom of the camera is horizontal with the ground.
   (a) **NOTE:** The glue was placed on the tape from the previous step to minimize the chance of damaging the camera.
3. The printed camera arm was then screwed into the servo using a screw with an $\frac{1}{8}$ in screw.

Payload Avionic Shield

Minimal assembly was required of the Payload avionic shield aside from soldering connections and assembly of electronic components.

Equipment:

- PCB Avionic Shield x1
- BMP388 Component x1
- BNO055 Component x1
- RFM96W Component x1
- 6 V Voltage Regulator x1
- 12 V Power Supply x1
- Multimeter x1
- Soldering Iron x1
- Solder
- Wire Heatshrink (22 AWG)
- Female Pin Headers
- Male Pin Headers

Procedure:

1. Secure PCB on soldering workspace with clips.
2. Measure number of male pin headers required per row of component pins on the PCB.
3. Solder male pin headers into the BMP388, BNO055, and RFM96W Shield holes.

4. After the solder has cooled, inspect by mounting each component onto the board's respective component shield. Remove components and set aside.
5. Measure number of female pin headers required per section of the DATA (I2C and SPI) and MOTIVE (servo) pin holes on the shield.
6. Solder female pin headers into the DATA and MOTIVE sections of the board
7. Again, inspect each pin by attaching jumper cables to them. Remove cables and set aside.
8. Obtain 6 V regulator and place the positive and negative terminals into the 6V pins of the shield, wrapping with heat shrink as necessary.
9. Solder the leads of the regulator on, slide the heatshrink onto any exposed contact, and heat.
10. Inspect by connecting 12 V supply to regulator and verify 6 V output on shield.

Electronics Board

The core of the payload electronics control was placed on the single board, mounted atop the rotating track mechanism. The electronics board's assembly was divided into its top and bottom sides, largely involving the integration of the formerly mentioned components onto the board.

Equipment:

- Servo x2
- Battery x1
- PCB x1
- Scissor lift x1
- Cut telescoping rod Housing x2
- 1/8 in Diameter Screws x6
- Wire 3 in
- Super Glue
- Antenna x1
- USB
- Female-Male Wires
- Camera-Servo Sub-assembly x1

Procedure (Top Board)

1. Outlined the final topside of the board in pen by placing components in their predetermined spots from the CAD model.

2. Next hand drilled holes with a 1/8 in drill bit for all of the components for the top of the board.
3. Before installing the scissor lift, a servo was glued into a stilt and was then bolted into the board.
4. Next the Pi and a small pole were then bolted into the board.
5. The bottom piece of the scissor lift was then placed into the board's outline and super glued to the board.
6. The camera-servo subassembly was taped to the top of the scissor lift platform. It was taped around the servo so that tape went under the top scissor lift platform and up around the top of the servo to ensure a snug fit.
7. Next a wire was wrapped around the pole and connected to the Lift servo on the board.
8. The scissor lift was installed, and then the PCB was screwed in at two of the 4 corners.
9. The voltage regulator was screwed into place next.
10. After the battery was connect to the electrical components on the top of the board.

Procedure (Bottom Board):

1. Outlined the final bottom side of the board in pen by placing components in their predetermined spots from the CAD model.
2. Next hand drilled holes with a 1/8 in drill bit for all of the components for the bottom of the board.
3. Took an old telescoping rod housing and cut it into 4 sections each 1 in long.
4. Drilled two holes into each of the above parts.
5. Screwed in remaining parts to their outlined spots using the holes drilled in step 2.
   (a) **NOTE:** This included an antenna and other various electronic components.
6. The battery was stuck to the bottom of the old telescoping rod housing pieces using Velcro.
7. After, the battery was connect to the electrical components on the top of the board.

4.3.3 Schematics of As-Built Payload

Figure 55 shows the full payload section retracted with the major dimensions labeled on the left and the fully extended payload section with the major dimensions labeled on the right.

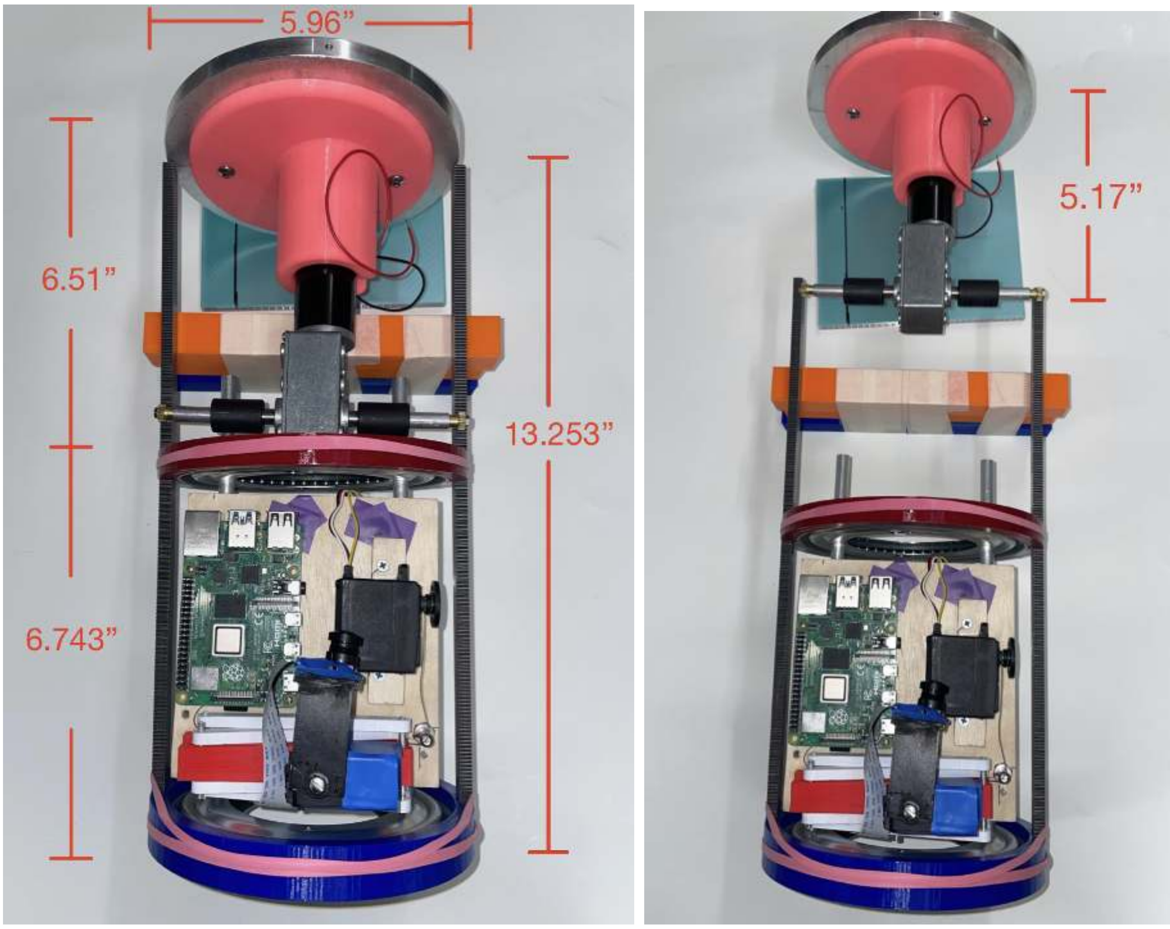


Figure 55: Schematics of the full as-built payload.

Figure 56 shows the fully extended scissor lift and electronics board section with the major dimensions labeled.

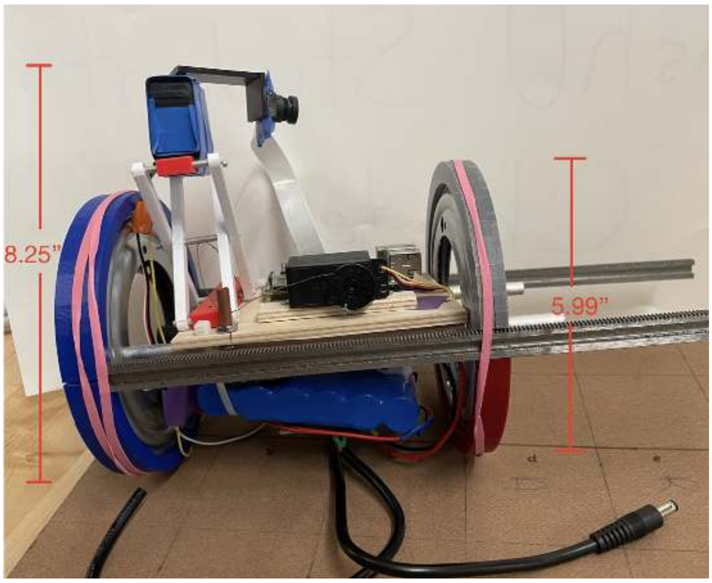


Figure 56: Schematics of the extended full payload

Figures 57 - 59 show the schematics of the as built subsystems of the full payload.

This includes the electronics board and the scissor lift mechanisms.

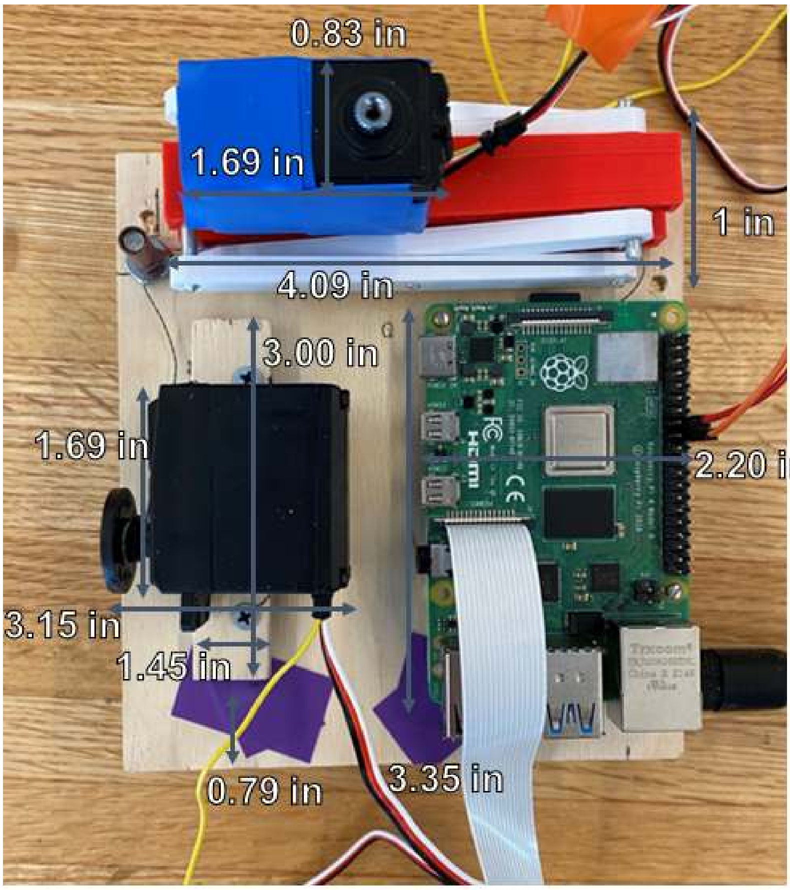


Figure 57: Schematics of the top of the Electronics Board

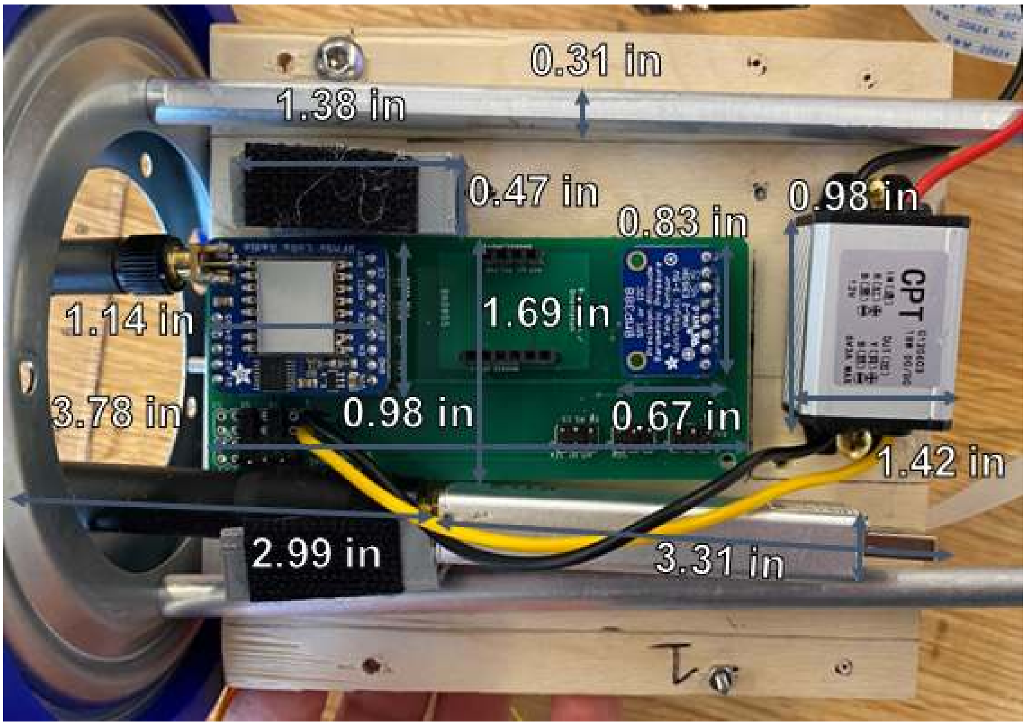


Figure 58: Schematics of the bottom of the Electronics Board

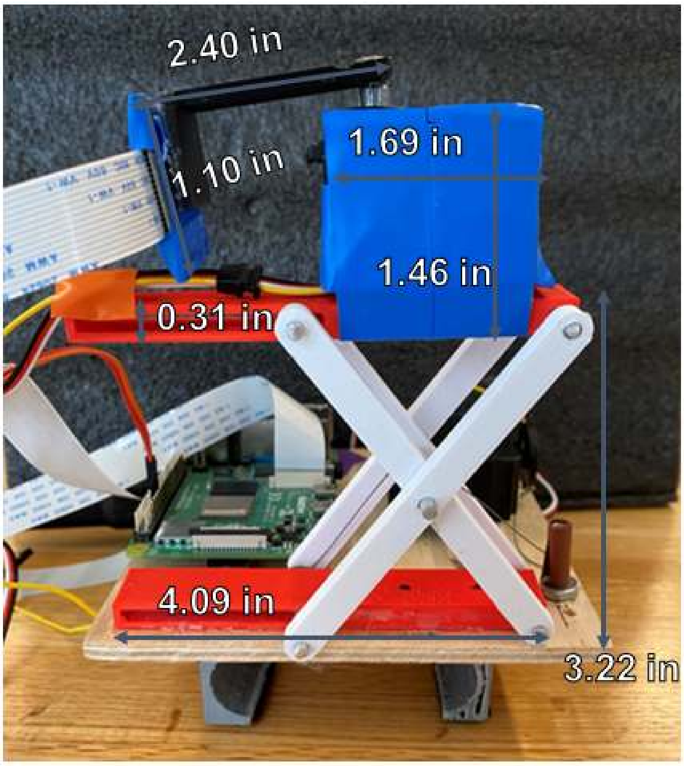


Figure 59: Schematics of the extended Scissor Lift

4.4 Payload Flight Reliability Confidence

4.4.1 Mechanical Confidence

Many tests of various mechanical components of the payload section have shown that our components will successfully remove the nosecone after landing, extend a camera beyond the body tube, and be able to rotate while taking pictures. The scissor lift ensures that the camera can be raised above the body tube. Having the scissor lift enables the camera to be raised 3.22 in above the body tube (see section 6.4 scissor lift test). Before the camera can be lifted the nosecone must be removed. First the solenoids used in nosecone retention are retracted. Once this is done a motor is used to push a rack utilizing a rack and pinion set up. VISION's specific motor was chosen for the high amount of torque (40 kg*cm or 34.718 lb*inch) that it can provide. It was able to push off the 4.05lb nosecone in the payload separation test (see section 6.4.2 payload separation test). The racks being utilized for pushing off the nosecone are made out of steel to ensure they do not deform or bend while pushing off the nosecone. A custom-made part that was 3D printed was used to connect the camera to a servo on the scissor lift. This allows the camera to be rotated and take pictures from many different perspectives.

As stated previously, steel solenoids are utilized in order to keep the nosecone on during flight. Due to the high strength material of the solenoids, and the results of the nosecone retention test, the solenoids can certainly prevent the nosecone from flying off prematurely during flight. To further confirm the abilities of the solenoids, an FEA analysis was conducted showing deformation under the yielding strength of the material in the solenoids even under forces much greater than predicted. This analysis is shown in Fig. 60.

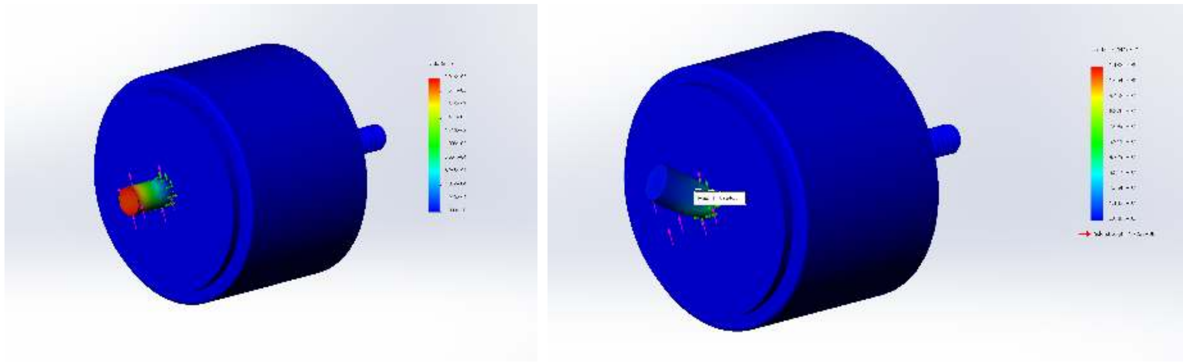


Figure 60: Displacement (left) and Von Mises Stress (right) FEA of nosecone retention solenoid

4.4.2 Electrical Confidence

The Payload electrical system has undergone various subsystem tests and code reviews to ensure reliability during flight. Physical tests have been conducted on every component within the electrical system to ensure continuity of wiring, the absence of short-circuits, forward voltages and current draws within ratings, and reasonable organization of electrical interconnects. In software, the code is well documented and presents a "blackbox" method of reporting data written to a log file on the Raspberry Pi computer to allow for analysis of data after system demonstrations, which have been verified to be as expected. The runtime of the software control system has been tested to meet the requirements of the mission's time constraints, as shown in the runtime test in section 6.4. Additionally, the software libraries used for the most processor complex tasks (e.g. taking image from camera hardware, running image transformations, etc.) were chosen for their lightweight code with minimal overhead in calling their routines. Mechanical integrity has been taken into account of the placement and layout of the payload structure, as well as the various previous tests to ensure the structural strength of the chassis in supporting the necessary elements of the system.

4.4.3 UAS/FAA Regulations

The finalized payload mission design and execution is within UAS regulations as dictated in the NASA USLI handbook. There are no use of any unmanned/detachable aerial/ground systems, all APRS RF frequencies will be respected by listening on the band outlined in the handbook, and any transmissions will be done within a uniquely assigned frequency and associated callsign with a valid HAM radio license.

4.5 Payload Demonstration Flight

The payload demonstration flight is currently scheduled for March 11, 2023, in Decatur, Illinois. In order for the payload demonstration flight to be a success, it must demonstrate the following capabilities:

- Successfully retain the nosecone without the solenoid pins causing damage to the holes of the fiberglass, as well as the pins not deforming or shearing at all.
- Payload self-uprights with its Z-axis within ±15 degrees from absolute ground Z-axis.

- The nosecone separates from the body tube by remotely releasing the solenoid retention pins.
- The motor racks push the nosecone ideally 5 in apart, at least 3 in.
- The scissor lift is capable of lifting the imaging system above the body tube, ideally at least 2.25 in.
- The APRS system is capable of receiving team generated HAM RAFCO and autonomously executing the RAFCO sequence.
- All telemetry data is recorded by the Pi and transmitted to a secondary base station Pi on-standby.
- The team maintains consistent RFM downlink with the vehicle at all times during the flight through periodic status pings.
- No payload hardware is damaged beyond use.
- The temperature within the Payload bay does not exceed 120 degrees Fahrenheit.

5 Demonstration Flights

5.1 Demonstration Flight Summary

Table 26 below summarizes the demonstration flight.

Table 26: Demonstration Flight Summary

Flight Conducted for: Full-Scale Flight Demonstration	**Date of Flight:** 02/12/23
Location of flight: Elsberry, MO Latitude: 39.2° Longitude: -90.8° Altitude: 449 ft	**Launch Conditions:** 44°F with an air pressure of 30.11 inHg, 4 mph wind NE
Motor Flown: Aerotech L1390G-P	**Ballast Flown:** No ballast flown
Final Payload Flown: No	**Air Brake System Status during flight:** N/A
Official target altitude: 4650 ft	**Kinetic energy at landing for each independent and tethered section of the launch vehicle:** Forward: 40.20 ft-lbf, Mid: 14.22 ft-lbf, Aft: 36.98 ft-lbf
Predicted altitude from simulations: 4330 ft	**Measured altitude:** 3854 ft

5.2 Altimeter Altitude Data

Figures 61 and 62 display the altimeter data from the primary and redundant flight computers, respectively.

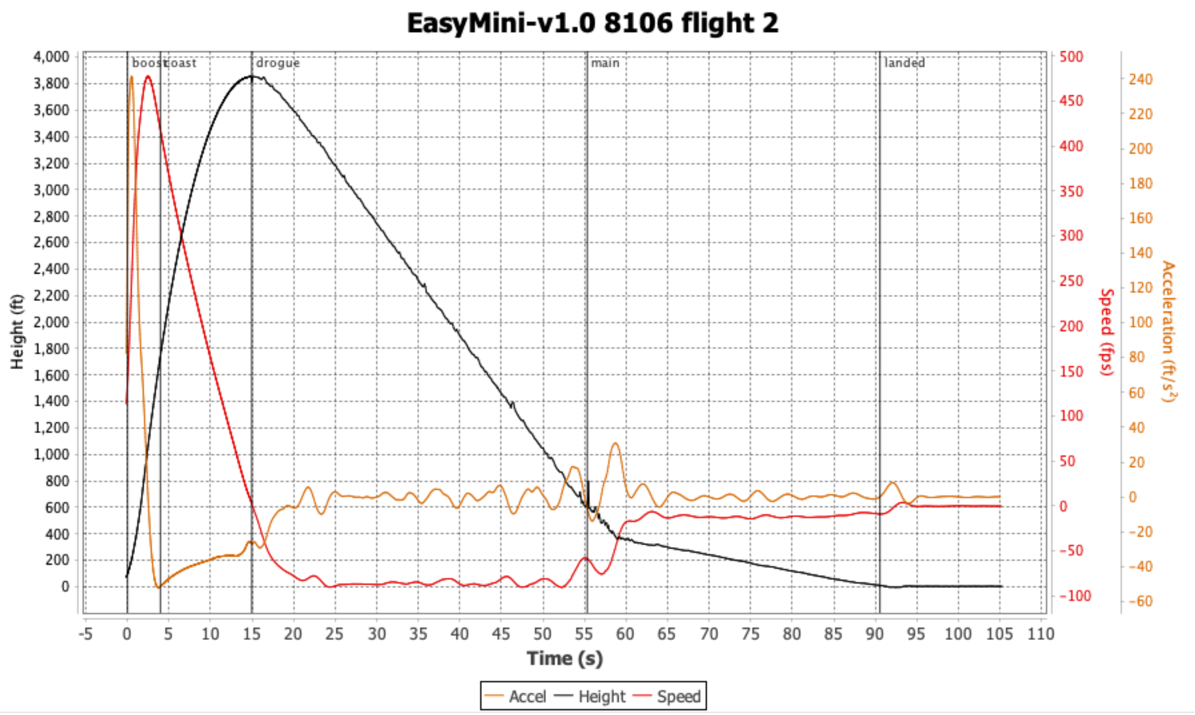


Figure 61: Primary Flight Computer Data

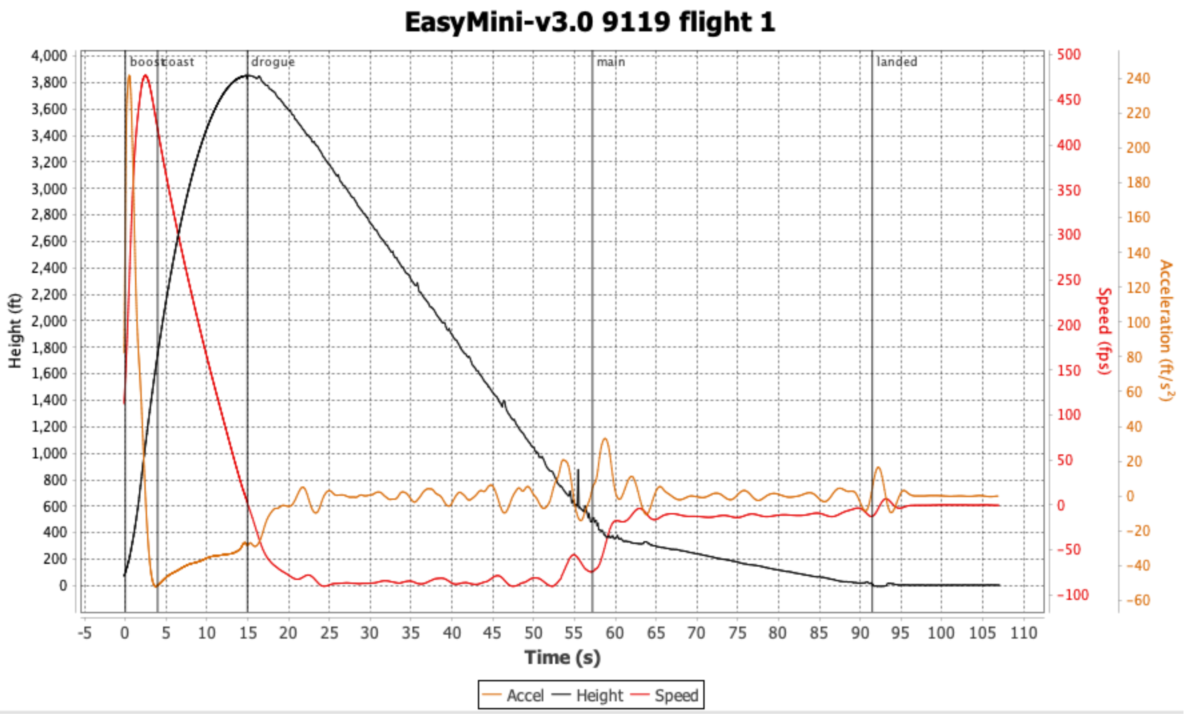


Figure 62: Redundant Flight Computer Data

The graphs in Figures 61 and 62 display clearly when the flight computers themselves sent the signals to fire both the drogue and main parachute charges. Further analysis of the data can prove these separations happened by referencing both the spike in acceleration surrounding the separation and the reduction in speed following the separation. Using flight data, the goal of main deployment at 600 ft above ground level can be verified. Additionally, this flight data verifies that descent time does not surpass the 90 s competition requirement. The heavy oscillations in the speed and acceleration graphs can be explained by rotation of the avionics bay during the recovery of the rocket. Finally, from the data in the graphs it can be determined that the rocket reached an approximate apogee of 3,800 ft AGL roughly 850 ft below the team apogee goal of 4,650 ft. This altitude discrepancy is explaine further in Section 5.8.2. Overall, the data provided by the flight computers above proves the success of the full scale design as a viable launch vehicle despite the issues with reaching the team apogee goal.

5.3 Separation Pressure Sensor Data

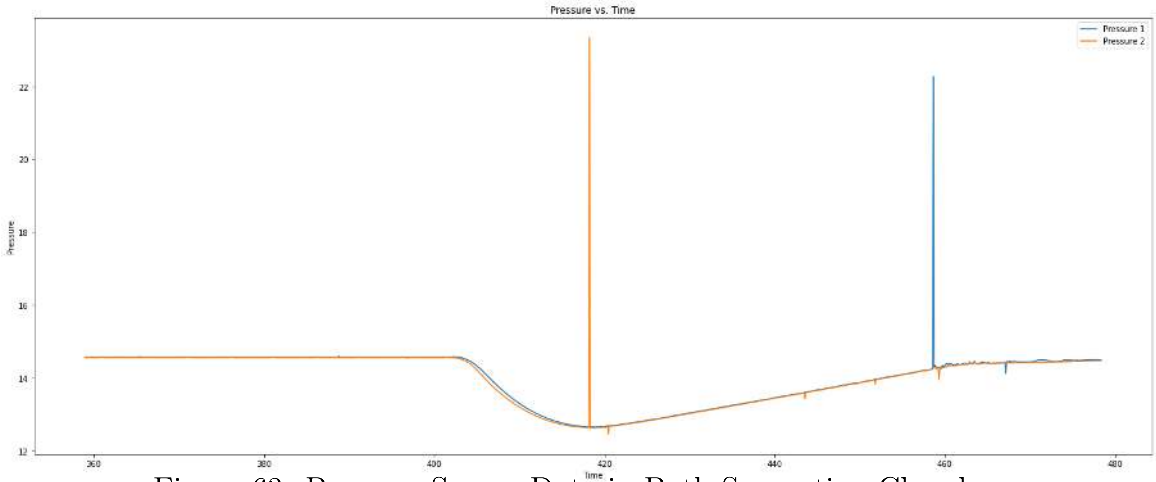


Figure 63: Pressure Sensor Data in Both Separation Chambers

Pictured above in Figure 63, the pressure data from each separation chamber of the rocket is plotted against time and measured in psi. The pressure data for the drogue separation chamber is marked in orange and spikes approximately when the pressure outside the rocket is at its lowest point (apogee). Further along in blue, the pressure spike for the main separation chamber can be seen. From this data, the team can conclude that the separation events during this test launch occurred as expected. Additionally, this data can be used to better calculate black powder separation charges as the calculated chamber pressure at ground level can be compared with the actual chamber pressure during the launch.

5.4 Pictures of As-Landed Rocket Configuration

Figures 64 to 67 provide and overview of the rocket component landing configurations. In Figure 64, the shock cords show no signs of tangling or twisting in flight or during landing. This was an improvement made from the Sub-Scale launch and is considered an ideal and successful recovery.

Figure 64: Forward and Mid Body Tube Landed

Figure 65: Aft Body and Drogue Parachute Landed

Figure 66: Main Parachute and Nose Cone Landed

Figure 67: Main Parachute to Mid Body and Mid Body to Drogue and Aft Tube

Figure 68 displays the three locations at which shock cords are at greatest risk of damage due to the black powder ignition.

Figure 68: Aft, Mid, and Non-Sleeved Black Powder Risk Locations Post-Launch

Shown in Figure 68, none of the four shock cords showed signs of damage in regards to singeing, fraying, or stiffening. Locations of high risk such as cords unprotected by nomex sleeves, or cords directly attached to the hardware ejection canisters (as seen above), provide no visible or physical damage. This indicates that the recovery protection methods were successful. Not depicted in Figure 66, the main parachute obtained a 1 in diameter hole due to the impalement of a corn stalk after landing. This hole does not have a great impact on the re-usability or performance of the main parachute, and has since been patched. Additionally, no evidence of damage to the body tubes or avionics components was found after launch.

5.5 Successfully Functioning Systems

Table 27 below summarizes the functionality status of all components of the rocket during the demonstration flight. Most of the systems functioned as intended. The systems that did not function as intended will be discussed in the following section.

Table 27: Summary of Component Functionalities

Component	Functioned as Intended?	If Not, What Went Wrong?
Nose Cone	Yes	N/A
Cameras	No	The camera was not turned on for the flight. The holder could have caused the rocket to tip.
Forward Body Tube	Yes	N/A
Payload Dummy Weight	Yes	N/A
Forward Bulkhead	Yes	N/A
Main Parachute Shock Cords	Yes	N/A
Main Parachute	Yes	N/A
Mid Body Tube	Yes	N/A
Avionics Coupler, Board, and Spacers	Yes	N/A
Avionics	Yes	N/A
Mid Bulkhead	Yes	N/A
Aft Bulkhead	Yes	N/A
Aft Body Tube	Yes	N/A
Drogue Parachute	Yes	N/A
Drogue Shock Cords	Yes	N/A
Motor Tube	Yes	N/A
Motor Closures and Casing	Yes	N/A
Forward Centering Ring	Yes	N/A
Aft Centering Rings	Yes	N/A
Fin Cores	Yes	N/A
Fin Shells	Yes	N/A
Motor	No	Thrust curve deviates greatly from expected.
Recovery Hardware	Yes	N/A

5.6 Unsuccessfully Functioning Systems

Cameras

One camera with a 3D-printed camera holder was placed on the launch vehicle forward body tube during flight. The camera has a single button and does not have a digital or LED readout showing whether it is turned on. When placing the camera on the rocket, the team believed the camera was recording, but it was not. Additionally, only one camera holder was placed on the side of the rocket instead of two.

Motor

The team believes that the motor used for launch could have been a dud. This is because the flight data provided a thrust curve that did not match the expected curve. Due to this, the motor is believed to be the major factor in why the rocket was unable to reach its predicted apogee. This may be a result of a number of causes; many of which are credited to the method by which the motor was stored, as well as its age. The conditions under which the motor is stored can impact the performance of the motor. Too much heat can warp the motor and its casing, while conditions that are too cold can cause the motor to become brittle. Humidity can also affect the condition of the rocket, as the humidity can compromise the propellants chemical composition, especially with solid propellant being as volatile as it is. The motor used for the flight was kept in a garage with neither climate control nor any specific form of temperature control. This meant the motor, while shielded from the brunt of the climate by the garage, was still exposed to much of the changes in temperature as the seasons changed, as well as any humidity caused by the summer heat. The motor was approximated to have been stored in the garage for at least a year, and so having been exposed to the extremes of each season at least once over the course of a year, we concluded it was the most likely explanation for the under-performance of our rocket. Further analysis of the motor and its measured thrust is found in Section 5.7.2 (Full-Scale Flight Analysis).

5.7 Payload Simulation During Flight

During the demonstration flight, the final payload was not flown. As a result, the payload was simulated by using two 2 lb weights enclosed in two 3D printed cylindrical holders, each weighing 0.5 lbs. The length of these 3D printed holders was determined using the estimated length of the payload in the team's simulations. These cylindrical holders have cutouts in the middle for the hand weights to go into. When the holders are put into the rocket, the hand weights are secured to the holders using tape, allowing for one holder to sit on top of the other with little movement of the weights. This design was chosen as the mass of the actual payload is estimated to be around 5 lb as used in the team's simulations. In addition, since the hand weights are not a fixed shape, they need to be kept in this cylindrical holder so that they do not move around in the rocket when it is launched. Since this is only a simulation of the payload, the results of this compared to the actual payload may be different if the payload weight changes. In addition, how the final payload is enclosed could affect the results. CAD models of the simulated payload versus the actual payload is shown in Fig. **??**.

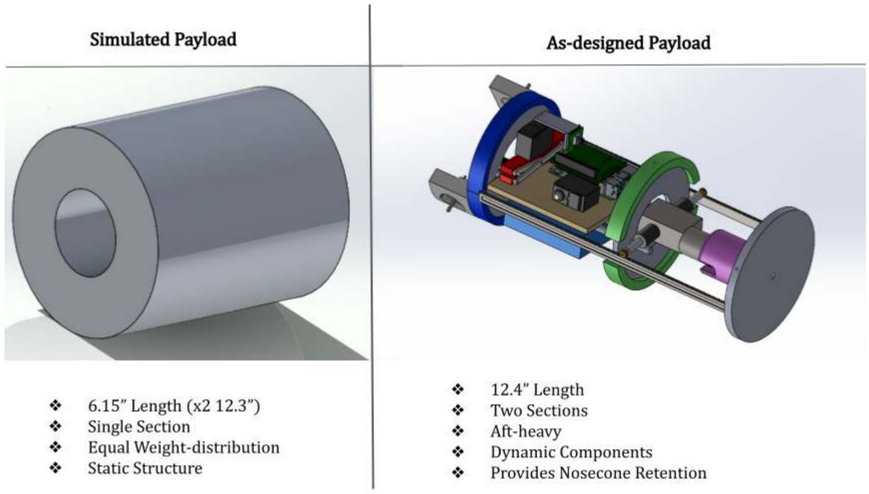


Figure 69: Payload Simulation Comparison

5.8 Simulated Flight vs. Actual Flight

5.8.1 Simulated Flight Model with Launch Day Conditions

OpenRocket simulations were used to predict how the launch vehicle would fly in Elsberry, MO for the Vehicle Demonstration Flight. Table 28 below summarizes the predicted flight information. Figure 70 displays the predicted flight profile from OpenRocket.

Table 28: Simulated Flight with Launch Day Conditions

Parameter	**Value**
Predicted Apogee	4330 ft
Static Stability Margin	3.01 cal
Drogue Parachute Deployment Altitude	Apogee
Main Parachute Deployment Altitude	600 ft
Descent Time	71.8 sec
Velocity Off Rail	69.7 ft/sec
Maximum Velocity	548 ft/sec
Maximum Acceleration	239 ft/sec^2

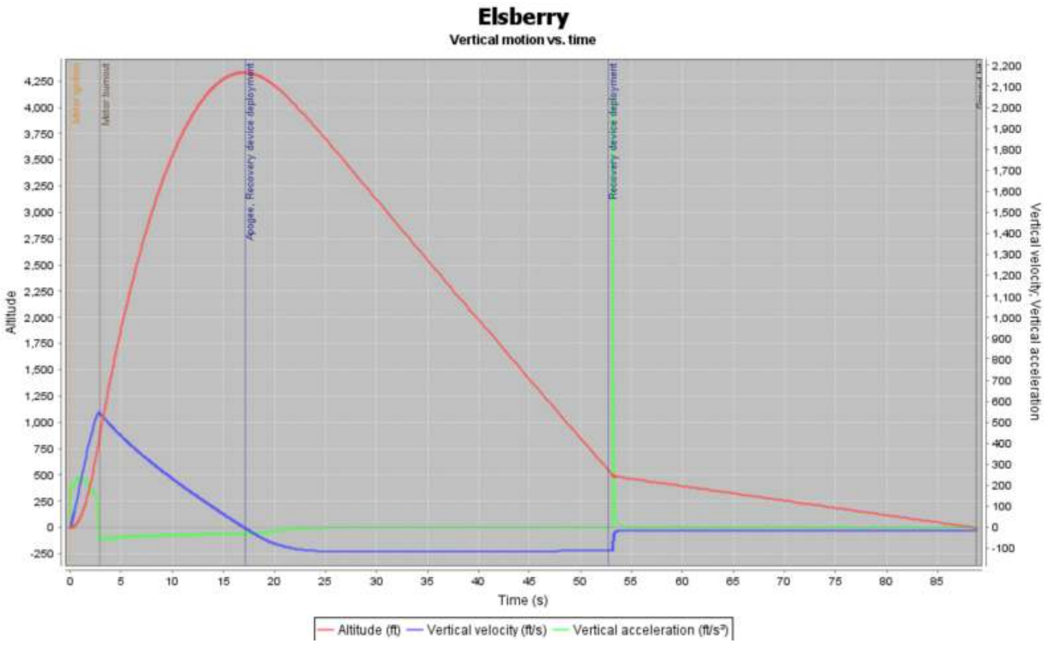


Figure 70: Simulated Flight Graph with Launch Day Conditions

Tables 29 and 30 compare the actual flight data to the simulated flight data for the primary and redundant flight computers, respectively.

Table 29: Full-Scale Primary Altimeter Data Summary

Vehicle Property	Simulated Value	Recorded Value	Percent Difference
Maximum Velocity	548 ft/s	477 ft/s	12.9%
Maximum Acceleration	239 ft/s^2	241 ft/s^2	0.84%
Time of Maximum Velocity	2.75 s	2.47 s	10.2%
Apogee	4330 ft	3854 ft	11.0%
Ascent Time	17.0 s	15.0 s	11.8%
Descent Time	71.8 s	75.6 s	5.29%
Impact Energy	60.18 ft-lbf	13.36 ft-lbf	77.80%

Table 30: Full-Scale Redundant Altimeter Data Summary

Vehicle Property	Simulated Value	Recorded Value	Percent Difference
Maximum Velocity	548 ft/s	477 ft/s	12.9%
Maximum Acceleration	239 ft/s^2	242 ft/s^2	1.3%
Time of Maximum Velocity	2.75 s	2.47 s	10.2%
Apogee	4330 ft	3854 ft	11.0%
Ascent Time	17.0 s	15.0 s	11.8%
Descent Time	71.8 s	76.5 s	6.54%
Impact Energy	60.18 ft-lbf	40.20 ft-lbf	33.20%

Looking at the data in Tables 29 and 30, the first differences that stand out are the lower apogee, ascent time, max velocity, and impact energies. The launch vehicle undershot its predicted apogee by about 500 ft. This can be attributed to the Aerotech

L1390G motor not performing as predicted, as seen with the lower ascent time and max velocity reached. This is further discussed in Section 5.8.2. Since the motor's maximum acceleration was achieved, the team believes the motor burnt out earlier than expected, rather than there being an issue with the power of the motor. Due to the rocket dropping in thrust quickly, the maximum velocity was not reached before burnout, leading to a major loss in energy which decreased the apogee. This is also evidenced by the shorter time to reach maximum velocity. For the impact energies, it was assumed that the vehicle descends at a constant rate after main deployment. After looking at the flight data, it was found that the vehicle's descent rate was much slower right before ground hit than simulated. This overestimate of the ground hit velocity led to the large discrepancy between the simulated value and actual impact energy. Appendix 9.4 shows the full flight data from both flight computers and it can be seen that the descent rate decreases over time. Due to this, the velocity right before ground hit was chosen as the speed for the kinetic energy calculation. For the primary, that was $\approx$8 ft/s, and redundant was $\approx$12 ft/s.

5.8.2 Full-Scale Flight Analysis

There were a few issues encountered on launch day that caused the Full-Scale flight performance to differ from the flights simulated in OpenRocket.

Mass Discrepancy

The mass of the rocket was higher on the pad than expected. The team originally predicted the rocket would weigh 42.8 lb, but these predictions did not take fasteners and hardware such as quick links, swivel joints, and eye bolts into account. The rocket weighed 45 lb on the pad. The final weight of 45 lb was taken into account for the OpenRocket simulations for the flight analysis conducted in this section.

Motor

In order to analyze motor performance and compare it to the expected performance, a thrust curve was extracted from the flight computer data. Using the measured acceleration values and known mass of the rocket, the sum of the forces experienced by the rocket can be observed. This sum is equivalent to the thrust of the motor minus the drag force experienced by the rocket. Therefore, we can approximate the thrust of the rocket by the sum of the observed force and the drag force of the rocket. Figure 71 shows the measured thrust curve compared to the theoretical thrust curve for the L1390G motor.

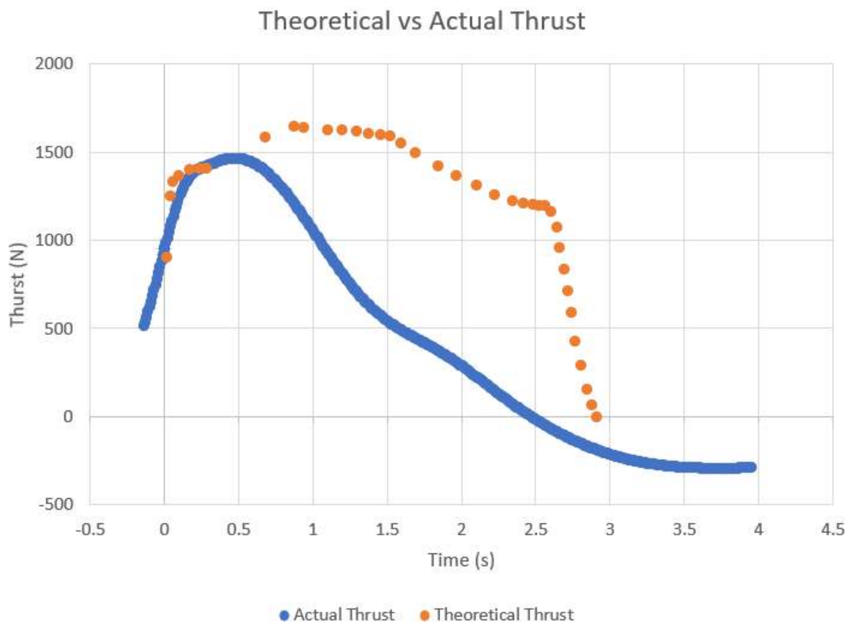


Figure 71: Simulated Flight Graph with Launch Day Conditions

5.9 Drag Coefficient Estimation

5.9.1 Sub-Scale Drag Coefficient from Test Flight Data

Calculation Method	Drag Coefficient
OpenRocket	0.52
Sub-Scale Test Flight	0.549

Table 31: Sub-Scale Drag Coefficient

The drag coefficient is the numerical value which characterizes a geometry's drag force as it moves through a fluid. The drag coefficient, as well as its relationship with the drag force, is given by the equation:

$$C_d = \frac{2F_d}{u^2 A} \tag{14}$$

where F_d is the drag force, is the fluid density of the stream, u is the free stream velocity or flow speed, and A is the reference area, or the cross-sectional area of the interest geometry as seen by an upstream observer at infinite distance.

The drag coefficient for the rocket was estimated using two methods: a purely computational estimation using the OpenRocket simulation software, and an estimation that incorporates the available flight data for the Sub-Scale test launch. The OpenRocket software gives a drag coefficient estimation of the rocket once the rocket is fully modelled. The OpenRocket drag coefficient estimation for the Sub-Scale rocket is $C_d = 0.6$.

The drag coefficient can also be calculated from the flight data of the Sub-Scale flight. The drag coefficient is in this case calculated using the work done by the drag force, found by conservation of energy principles. In an ideal environment, the total mechanical energy difference between any two physical states of the rocket is equal to the net work done by the motor between those two physical states. However, the air makes it impossible to accurately model the physics according to this ideal. To account for non-ideal behavior, a work due to losses term is added to the model, giving the following relationship:

$$K_1 + U_1 + W_{in} = K_2 + U_2 + W_{out}. \tag{15}$$

K is the kinetic energy at a given state, given by $K = \frac{1}{2}mv^2$, U is the potential energy at the state, given by $U = mgh$. It is assumed that all work into the system is done by the rocket motor, where the work done by the rocket motor is given by the integral:

$$W_{in} = \int_{y1}^{y2} F_{motor}\, dy \tag{16}$$

where the limits of integration are the distances between which the motor is firing. It is also assumed that all losses in the system are due to drag:

$$W_{out} = \int_{y1}^{y2} F_d\, dy \tag{17}$$

where the limits of integration are the reference states 1 and 2. For the analysis of the Sub-Scale flight, it is easiest to choose reference state 1 at the instant where the rocket has just begun to fire, and reference state 2 at the instant where the motor shuts down. Additionally, equation 16 can be simplified by assuming a constant motor force, giving the simplified $W_{in} = F_{motor,avg}\Delta y$ where $F_{motor,avg}$ is the average motor force and Δy is the distance between the two reference states where the motor is firing.

The work output given by equation 17 can be simplified by treating it as the work done by a constant force, where the force represents the time-wise average drag force in the time between the two reference states. This simplifies the equation to $W_{out} = F_{d,avg} * \Delta y$.

The choice of reference states 1 and 2 determines that $U_1 = K_1 = 0$ because the rocket at the instant of ignition is stationary at zero altitude. K_2 is given by the mass and speed at the instant of motor burnout. The mass at this moment is the dry mass of the rocket. U_2 is given by the dry mass and the height of the rocket at motor burnout. The gravitational acceleration is treated as constant at $g = 9.81m/s^2$. With these simplifications, the energy balance (equation 15) becomes:

$$F_{motor,avg}y_2 = \frac{1}{2}m_{dry}v_2^2 + 9.81m_{dry}y_2 + W_{out} \tag{18}$$

The velocity and height at state 2 were taken from an average of the 5 data points centering on the point of motor burnout in order to reduce the impact of sensor noise on the calculation. Solving for W_{out} in equation 18, the aerodynamic losses between the states is $232,300J$. Equation 14 is used to find the drag coefficient from the average drag force. Because the drag force given by the force balance is a time-wise average force, the velocity used in the drag coefficient calculation should be the time-wise average velocity between the two reference states. This calculation gives a drag force of $C_d = 0.5490$. The percent error compared with the OpenRocket value (0.6) is 9.1%. It should be noted the OpenRocket value is the average during the entirety of the ascent, while the experimental value is only derived from the motor burn.

Possible sources of error in the drag calculation by OpenRocket includes improper simulation and modelling of aspects such as skin friction, surface roughness, and differences in the real environmental conditions and the ideal simulation conditions. Sources of error in the Sub-Scale flight test energy balance method include differing qualities of the Sub-Scale and full scale vehicle, such as skin friction and surface roughness, different fluid conditions due to differing Reynolds numbers, and other sources of energy loss from the system including deformation energy and heat energy.

5.9.2 Full-Scale Drag Coefficient from Test Flight Data

Calculation Method	Drag Coefficient
OpenRocket	0.39
Full-Scale Test Flight	0.402

Table 32: Full-Scale Drag Coefficient

The drag coefficient for the full scale rocket used in the competition was found using the same methods as for the Sub-Scale model. Data was gathered from the avionics recording of a full scale rocket test launch, and the data were put into the framework of the conservation of energy relation (equation 18). In order for this expanded relation to remain valid, the reference states must refer to the same stages of flight as the Sub-Scale analysis. Therefore, reference state one refers to the rocket at the moment of motor ignition, and reference state two refers to the rocket at the moment of motor burnout.

This arrangement of the reference states allows the total work done by the motor to be treated as the time-wise average of the motor's thrust times the difference in altitude, rather than having to compute a complex integral of the thrust curve.

Similarly, the integral describing the work done by the system by drag (equation 17), can be simplified using time-wise averages. The aerodynamic force on the rocket can be treated as a constant force for the purpose of calculating work, where the constant force used will correspond to the time-wise average force over the reference frame. By solving the force balance and for the resulting aerodynamic work, this average drag force can be found using the test flight data.

Then, to find the drag coefficient from the full scale test flight data, the average drag force was put into equation 14. Because the drag force is represented by the time-wise average drag force, the free stream velocity used in the calculation must also be the time-wise average over the frame of reference. Using this method, the full scale calculated drag coefficient is 0.402.

5.10 Full-Scale vs. Sub-Scale Flight

In the Sub-Scale flight demonstration, the rocket had two cameras attached to the exterior of the rocket. However, in the Full-Scale demonstration, only one camera was attached to the rocket. As a result, the stability of the rocket when it left the rail could have been impacted, causing the rocket to veer sideways. Additionally, the launch rod was tilted by 4 degrees for the Full-Scale flight. The Sub-Scale flight had no launch angle. When the rocket left the rail, it shot straight up. This could be from the stability not being affected since both cameras were attached to the forward body tube and, more importantly, the Sub-Scale launch rail was not angled. With the Full-Scale rocket, there was a 2.2 lb difference between the simulated weight of the rocket and the actual weight of the rocket. While with the Sub-Scale, there was only a 1 lb difference. With the launch day ground conditions, the Full-Scale ground was very muddy, while the Sub-Scale ground was not. This could have affected the Full-Scale launch as more energy was absorbed into the ground during initial ignition. The shock cord lengths were increased for the Full-Scale flight in comparison to the Sub-Scale shock cord lengths. In the Sub-Scale flight, the shock cords became tangled with the avionics coupler, and the drogue parachute wrapped around the main parachute shock cord, which risked a partial inflation of the main parachute. The Full-Scale shock cord layout was adjusted to prevent these issues, as shown in the Full-Scale demonstration flight, of which the landing configuration indicated no tangling or wrapping of shock cords in flight or landing.

5.11 Hardware Damage

No visual deformation or damage was experienced by the hardware attached to the launch vehicle after recovery. An example of this can be seen in Figure 72 below. No replacements for any swivel joints, quick links, or eye bolts are required.

Figure 72: Post-Launch Hardware Analysis

5.12 Lessons Learned

Since the launch vehicle was heavier than expected, the team decided to mass-optimize the three aluminum bulkheads. 1 lb will be removed from the total weight of the three bulkheads (originally 3 lb) to ensure that the rocket would be light enough to reach its target apogee of 4650 ft for the next flight. The team also realized that it would be much easier to add weight later on as opposed to subtracting even more weight. Additionally, the team will ensure that the cameras are turned on by capturing a short video before placing it onto the rocket to ensure that the camera is off up until the rocket is placed on the launch rod. The team will plan to use one camera holder with a camera on each side of the rocket (for a total of two) instead of one because the singular camera and holder could have affected the stability of the flight leaving the rail, causing it to veer sideways very quickly after leaving the launch pad. Finally, the team will only purchase motors within three months of an anticipated launch date to prevent environmental effects from storage conditions and limitations.

5.13 Off-Nominal Events

On launch day, the launch site ground was very muddy, which could have impacted the launch rod angle. The original angle that the launch rod was set to was 3°. However, with the muddy ground of where the launch pad was located, the angle could have changed, causing the results of the launch to be unexpected. Additionally, during the launch there were abrupt gusts of wind which could have caused the rocket to turn, and not reach the target altitude it was supposed to.

5.14 Future Demonstration Flight

The payload demonstration flight is currently scheduled for March 11, 2023. This date is reserved for a launch with the intention of proving the design of the Full-Scale rocket with the inclusion of the payload. This launch will include a fully operational payload, and will also be an attempt to properly execute the payload mission once the rocket has landed. The team has a backup launch scheduled for March 25, 2023, in the event that the launch on March 11 is not successful, or cannot happen due to weather. The next launch after these two possible flight windows is the competition launch in Huntsville, AL, on April 15, 2023. The intention of this launch is to prove to NASA judges that the design of the rocket is robust and accurate to the documentation that has been submitted. The Huntsville competition launch is also intended to prove the design and execution of the designed payload mission.

6 Testing and Demonstrations

6.1 Structural Tests and Demonstrations

6.1.1 Snatch Force Test

The possibility of the snatch force from the parachute deployment deforming the rocket bulkhead necessitates this test. Whether or not the Delrin plate yields at the calculated forces below will determine the viability of using the lower-weight Delrin material on a full-scale rocket and verifies the use of a stronger material like 6061-T6 Aluminum.

Objective	**Criteria for Success**	**Test Variables**
Determine whether Delrin or Aluminum bulkhead can withstand the calculated snatch force without visual deformation.	The bulkheads must show little signs of deformation and numerically deform less than 10mm when 15kN of force is applied to it	Delrin and Aluminum bulkheads are tested.

Delrin and Aluminum bulkheads were tested to determine whether the structural limits of Delrin and Aluminumwould withstand the calculated and experimental snatch force data. The bulkheads must have a yield strength that meet or exceed the snatch force from parachute deployment. The three methods used to calculate snatch forces are displayed in Table 33.

Using the OSCALC snatch force calculator, a maximum force of 4,096.215 N was obtained. Calculating the max drag force on the parachute using its drag coefficient, and substituting the values in for air density, the velocity at the moment before the parachute opens, and the area of the main parachute into the equation provided by NASA results in a predicted force of 11,488 N. In addition, the team utilized a set of coupled differential equations to estimate the peak tension force in the shock cord, taking into account the spring coefficient of the shock cord. The differential equations approximate the rocket system on descent as the main parachute and a high mass object, with a tension force applied between them. The appropriate drag and mass terms are applied to both object considered. This system of coupled differential equations was solved with Wolfram Mathematica, yielding a predicted max tension force of 5750 N.

Below are the calculated force values derived from each method.

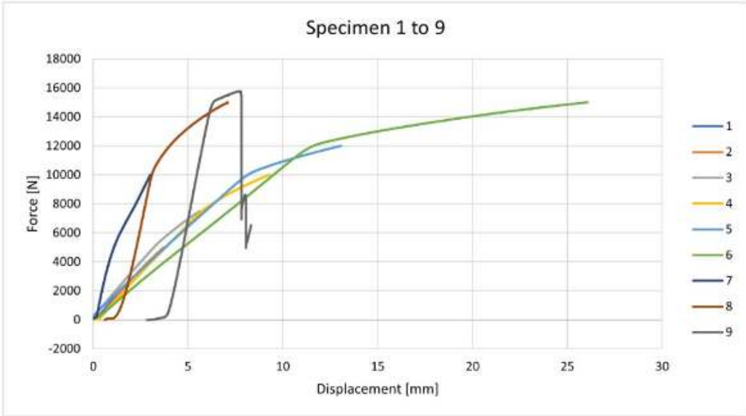
Table 33: Snatch Force Success Criteria

Method	**Equation**	**Force (N)**	**Safety Factor**	**Calculated Force with Safety Factor (N)**
NASA	$\frac{1}{2}C_p\rho A_p V_{open}^2$	11,488	1.5	17,232
OSCALC	N/A	4,096.22	1.5	6,144.32
Diff. Eq.	N/A	5750	1.5	8625

Testing Procedure

1. Attach both bulkheads between the coupler with 3/8-16 lead screws and 1/4-28 flange nuts.
2. Mount eye-bolts to bulkheads with flange nuts.
3. Secure eye-bolts to Instron Load Frame with wedge action tensile grips.
4. Calibrate load frame until there there is no tension applied to the testing sample.
5. Perform tensile test using 68TM-30 Load Frame, increasing force applied by 2.5kN increments to observe any deformations.
6. Compare yielding results to calculated snatch force data to determine whether Delrin or Aluminum bulkhead reaches required yield strength.

Image 73 contains the results for this test.



	Specimen Name	Rate [mm/min]	Maximum Load [N]	Extension at Maximum Load [mm]	Visible Yielding?
1	Delrin 2.5kN	2.00	2500.02	1.79	No
2	Delrin 5.0kN	2.00	5000.02	3.71	No
3	Delrin 7.5kN	2.00	7500.02	5.61	No
4	Delrin 10kN	2.00	10000.00	9.29	No
5	Delrin 12.5kN	2.00	12001.73	13.07	No
6	Delrin 15kN	2.00	15000.01	26.06	Yes
7	Aluminum 10kN	2.00	10000.00	3.01	No
8	Aluminum 15kN	2.00	15000.03	7.09	No
9	Aluminum 15.78kN	2.00	15780.68	7.73	Yes

Figure 73: Bulkhead Yielding Results

Figure 74: Aluminum Bulkhead Setup

For the tensile test, an Instron 68TM-30 Load Frame stretched the bulkheads apart with a tensile force, as seen in Figure 74. The tensile force within the test simulated the snatch force of the parachute. The Delrin bulkheads yielded 26.06 mm after 15kN of force was applied, and visible, permanent deformation could be seen after release from the load frame. Thus, the results demonstrate that the Delrin bulkhead could not withstand up to 15kN without yielding 10mm, and the test was unsuccessful. After 15kN of force, the Aluminum bulkheads yielded 7.73 mm. The test results in Table 73 demonstrate that the Aluminum bulkheads could withstand up to 15kN without yielding more than 10 mm; the Aluminum bulkhead test was successful. Based on the data gained, Aluminum seems to be an appropriate choice for a full scale application as it was able to withstand more force than what was calculated for expected maximum snatch force based off the OSCALC and Diff. Eq methods. Aluminum suffered less visible deformation than Delrin at the same force of 15kN, and the 7.73 mm of extension at maximum load falls within the success criteria of 10 mm.

These results did not match with the predicted results. WURocketry anticipated both Delrin and Aluminum to withstand a maximum force of 15kN without deformation of more than 10 mm. However, Delrin yielded approximately 15mm more than what was predicted to meet the success criteria. Aluminum proved to be the only test that yielded less than 10 mm at 15kN. The team learned that Aluminum was able to tolerate more force than Delrin, proving to be a stronger material for the bulkheads.

6.1.2 Fin Shell Material Test

Introduction

The team performed two tests in order to drive the design for the 3D-printed fin shells: a subjective smoothness test and an empirical compression test. The following table contains the objectives, success criteria, and variables for these tests.

Test	**Objective**	**Criteria for Success**	**Test Variables**
Smoothness	Determine which print material will have the most aerodynamic finish in order to aid in reaching the expected apogee.	Print material is ranked based on the roughness of the surface. Ideal smoothness has few to no ridges and should feel completely even to the touch.	PLA and PETG prints are tested both as printed and after sanding. Resin is tested as printed and Polysmooth is tested after smoothing using alcohol according to the manufacturer's instructions.
Compression	Determine which print material can withstand the most force in order to ensure that structural stability is not compromised for surface finish.	Small samples of each print material are placed into a compression machine. The print material with the highest yielding force is determined to be the strongest. A successful test will determine each sample's yielding and ultimate forces for later comparison.	PLA, PETG, Resin, and Polysmooth are tested.

PLA, PETG, and resin print materials were tested for smoothness and compressive strength. During the October 29th, 2022, sub-scale launch, the vehicle undershot its calculated apogee. The team theorized that the ridges (caused by the manufacturing method of extrusion printing) in the sub-scale's PLA fin shells increased drag. WURocketry intended to test an additional polysmooth filament in December, 2022, but a shipping delay necessitated that the polysmooth material results be omitted from the initial test. The team performed these tests in February of 2023.

The purpose of these test was to determine which 3D print material would decrease aerodynamic drag while not forgoing strength. The subjective smoothness test provided the team with a uniform subject to compare each material's relative smoothness in order determined which of the tested materials would produce the least aerodynamic drag. The compression test determined which print material could withstand the largest force. The subjective smoothness test provided the team with a uniform subject to compare each material's relative smoothness.

The testing subteam predicted that the Polysmooth (Dip) sample would be the smoothest due to its submersion in the smoothing solution. Resin was predicted to be the next smoothest with the control sample for PETG being the least smooth. For the compression test, the testing subteam expected that the resin sample would be the strongest and that the Polysmooth sample will perform similarly to the PLA sample and that PETG would be the least strong.

Testing Procedure

1. Print PLA, PETG, Resin, and Polysmooth testing cylinders.
2. Smooth each material (see below for techniques for each material).
3. Perform subjective smoothness test.
4. Perform compression test using 68TM-30 Load Frame to the point of material failure.
5. Analyze the maximum force each print can sustain to determine which material can sustain the highest force.

The PLA and PETG were sanded until smooth to touch to reduce ridges along the outside of the print caused by extrusion printing. Polysmooth is a specific type of extrusion print material that smooths when in contact with Isopropyl Alcohol. Two methods for distributing the alcohol across the part will be tested: spraying and dipping. The Resin print was not smoothed because resin prints are comparably smooth by nature. After smoothing, Polysmooth (dipped) was the smoothest, followed by resin, Polysmooth (sprayed), sanded PLA, sanded PETG, Polysmooth (un-smoothed) un-sanded PLA, and un-sanded PETG. Thee results match the subteam's predictions.

For the compression test, an Instron 68TM-30 Load Frame applied a force via compression plates, as seen in Figure 75. The PLA, PETG, and all Polysmooth samples were compressed to the point of clear plastic deformation, but the resin sample reached the maximum load of the testing apparatus before yielding. As such, the compression test for the resin sample was deemed inconclusive and a failed test.

Table 34 contains the results for this test along with each sample's weight and manufacturing cost.

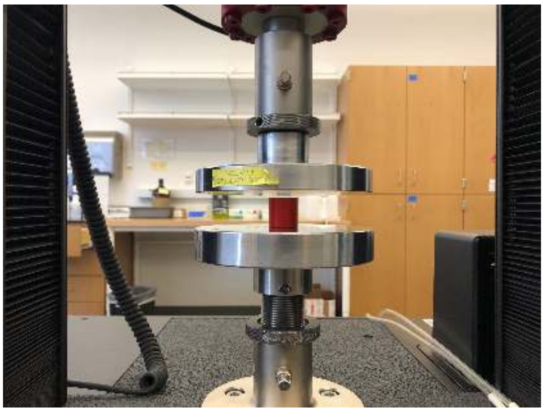


Figure 75: Compression Test Setup

Table 34: Fin Shell Test Results

	PLA	**PETG**	**Resin**	**Polysmooth (Control)**	**Polysmooth (Spray)**	**Polysmooth (Dip)**
Weight (g)	5	5	15	5	5	5
Yielding Force (kN)	4.92	3.75	Inconclusive (failed test)	9.45	8.71	8.59
Ultimate Force (kN)	4.92	3.75	Inconclusive (failed test)	9.45	8.71	8.59
Smoothness Rank (1(best) - 6(worst))	5	6	1	4	3	2
Cost (USD)	0.255	0.265	3.2125	N/A	N/A	N/A

As shown in Table 34, the resin sample exceeded the force range of the Load Frame which caused a failed test. While this confirmed the team's prediction that resin would be the strongest, given the weight and high cost of the material, the Structures subteam elected not to use it on the rocket, so no further testing was required. The Polysmooth (Control) experienced a yielding and ultimate force of 9.45kN which was the highest compared to the other materials successfully tested. Since the strength-to-weight ratio between the Polysmooth (Control) and the Polysmooth (Dip) was comparable and that Polysmooth (Dip) sample was determined to be the smoothest, the Structures subteam recommends that Polysmooth (Dip) be used for the full-scale fin shells.

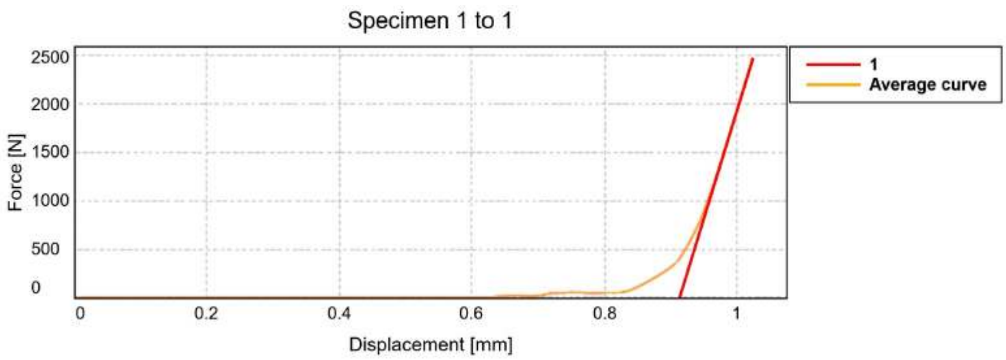
Compared to our predictions, the Polysmooth samples exceeded expectations as it outperformed PLA by a significant margin. Additionally, we predicted that the Polysmooth (Dip) would be smoother than the resin which was incorrect. However, due to the resin being a failed test, the team's prediction that Polysmooth (Dip) would be the smoothest was accurate. The team learned that the chemical smoothing of Polysmooth is more effective than sanding techniques, which is information the team can use for manufacturing fin shells for future launch vehicles to increase the aerodynamics of the sub-component). Additionally, from the compression test, the testing the subteam learned the relative yielding and ultimate strengths of tested materials. The team can apply this information to the selection process for relevant 3D-printed components of future launch vehicles.

6.1.3 Body Tube Compression Test

The objective of this test is to understand how the body tube deforms in compression to simulate launch forces from the motor. The thrust forces from the motor are transferred to the thrust plate, which transfers the forces to the body tubes. The test will be successful if the body tube survives the max thrust force times the factor of safety without damage. This test will demonstrate the reusability of the body tubes between launches. If the test fails, an alternate body tube material will need to be chosen because the motor cannot be changed. The team used an Instron Compression Testing in the Shared Instrument Lab at Washington University to apply compressive force to a sample of the sub-scale body tube because the maximum-diameter compression plates could not safely support a sample of the full-scale body tube. Figure 76 shows the data from this test.

Testing Procedure

1. Acquire a sample of a G12 Fiberglass body tube from scrap.
2. Ensure that both sides of the body tube are level and flat.
3. Place the sample in the center of the 68TM-30 Instron Load Frame.
4. Perform compression test using the load frame. Compress the sample until the maximum force value is 1.5 (safety factor) times the thrust force from the motor.
5. Inspect the sample when it is removed from the load frame to ensure that there are no cracks.



	Specimen number (included)	Specimen label	Rate 1 [mm/min]
1	1	Text Entered Here will Distinguish Between Individual Specimens	1.00

	Diameter [mm]	Height [mm]	Maximum Force [kN]
1	136.00	286.50	2.48

	Force at Yield (Zero slope) [kN]	Modulus (Young's Compressive stress 0.8 mm - 1 mm) [MPa]
1	0.05	440.16

Figure 76: Compression Test Raw Data

These actual results did not differ from predicted results. No deformation was expected or observed. WURocketry learned that the G12 Fiberglass body tube chosen was sufficient to tolerate the thrust force. As demonstrated here, the body tube withstood the rocket's calculated thrust force of 2.48 kN without yielding. Therefore, this test can be considered a success.

6.1.4 Plumbline Center of Pressure Test

Introduction The center of pressure (CP) test set out to compare a more empirically determined CP to OpenRocket's calculated CP. The WURocketry team decided on the plumbline test as its means to do so, using a method of cutting the frame of the rocket out using some material and balancing it using a small fulcrum (although the goal is to balance, so fulcrum is a bit of a misnomer here) to find its CP. This test will provide insight into the accuracy and reliability of this method, to ascertain its use in WURocketry's future ventures.

Objective	Criteria for Success	Test Variables
Compare the plumbline test's CP values to OpenRocket's	5% precision relative to OpenRocket's value for CP	Found CP

Testing Procedure

1. Trace the rocket's outline on a piece of cardboard, or depending on the size of the rocket, a more sturdy material.

2. Cut out the outline of the rocket.

3. Use some thin material stood upright as a balance point, and place it on a surface where there is plenty of space in either direction, at least $\frac{3}{4}$ of the rocket's total height.

4. Place the rocket's cutout on the fulcrum so as to balance it somewhere along the rocket's height.

5. Record the point from the fins the rocket is balanced at. This is its center of pressure (CP)

Figure 77 provides a visual of the CP locations listed in Table 35. The green circle is the plumbline test CP, the blue circle is the OpenRocket simulated CG, and the red circle is the OpenRocket simulated CP.

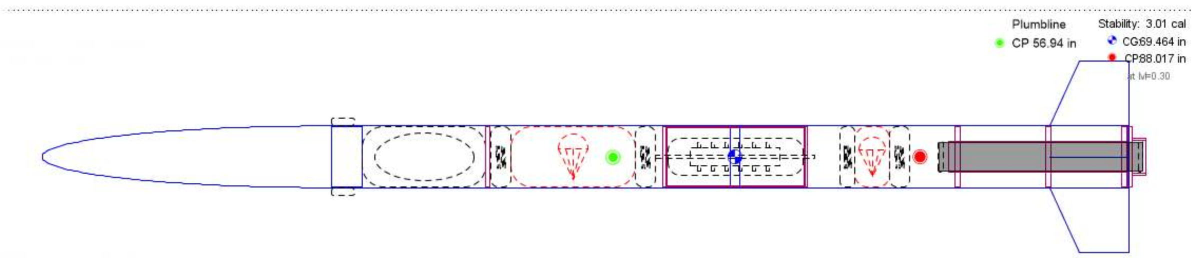


Figure 77: Locations of Simulated and Experimental CP

Table 35: Simulated Versus Found CP

OpenRocket Value	Plumbline Value	% Error
88.02 in	56.94 in	35.31 %

Results
The plumbline test did not result in a CP within any reasonable error from OpenRocket's values. The location of CP is assumed to be the center of gravity (CG) for the cardboard cutout of the rocket, as the found value is a 18.02% error from the OpenRocket simulated CG of 69.46 in. As the percent error was not within 5% of the simulated CG, the test was not a success and the plumbline test will not be used in the future for determining CP. Moving forward, WURocketry will pursue using the Barrowman equations and RockSim simulations for higher accuracy.

6.2 Recovery Tests and Demonstrations

6.2.1 Deployment Bag Demonstration

Introduction The Deployment Bag Demonstration ensures that the main parachute is not packed too tightly in its associated deployment bag. A successful demonstration is when the parachute can be pulled out of the bag with little applied force. If the test fails, the folding procedure or method will be reconsidered and re-tested.

Objective	Criteria for Success	Test Variables
Demonstrate successful deployment of the parachutes	Parachutes deploy with minimal applied force	Applied Force

Testing Procedure

1. Fully assemble the rocket to reflect launch readiness; neglecting shear screws
2. Pull the Aft and Forward sections apart in parallel opposite directions while supporting the avionics bay.

Results
Both the main parachute, and drogue parachute, packing configurations were easily removed from the rocket as body tubes were pulled apart due to the large amount of space in the pressure chambers. Due to this observation, the Full-scale Deployment Bag Demonstration is considered a successful demonstration. Therefore, no changes have been made to the parachute folding as a result of their performance.

6.2.2 Black Powder Separation Test

Introduction The objective of this test is to ensure the forward and aft chamber pressurization from black powder ignition is neither too low nor too high, as the first would prevent the parachute from deploying and the latter could cause damage to the components of the rocket. If testing fails, increasing or decreasing the mass of black powder by 25%-35% may be an effective solution. The percentage of increase or decrease will be chosen with the advice of the team mentor, Mike Walsh.

Objective	Criteria for Success	Test Variables
Demonstrate the resulting separation of the rocket due to calculated black powder quantities	Full rocket separation with no resulting damage to the rocket	The mass of black powder for primary drogue and main section charges

Procedure

1. The Safety Officer, Drew DeRubertis, and the Recovery Propulsion Team will travel to Team Mentor Mike Walsh's house for the separation test.

2. Mike Walsh, Drew DeRubertis, and the Recovery and Propulsion team will put on appropriate protective equipment, including safety glasses and gloves. The rocket will be assembled following launch procedures.

3. Mike Walsh will place the following quantity of black powder into the primary charge ejection canister to test the first section separation for the drogue parachute deployment.

   Full-Scale Charge: 1.8 g

   Sub-Scale Charge: 0.9 g

4. Mike Walsh will insert an e-match into the main ejection canister.

5. The recovery and propulsion team lead, Mikayla Jenkins, will close the rocket with two 4 shear pins.

6. Team members will distance themselves at least fifteen feet from the side of the rocket. Caution is taken not to stand in line with either ends of the rocket.

7. Mike Walsh will wire the e-match to a nine volt (9V) battery. The team will observe the separation of the rocket sections.

8. If the rocket does not separate successfully, the mass of black powder will be increased by 25-35 percent of the previous test value.

9. Steps 3-8 will be repeated with new black powder quantity until successful separation occurs.

10. The same steps will also be repeated with the following quantity of black powder, and four 4 shear pins, for the second section separation for the deployment of the main parachute.

    Full-Scale Charge: 4.1 g

    Sub-Scale Charge: 1.8 g

11. Once both sections' separation tests are successful, black powder masses will be recorded and the tests will be complete.

    Note: The redundant charge is not tested in any separation test.

Figure 78 provides a visual of the ejection ground test for both drogue and main primary charges.

(a) Drogue Ejection

(b) Main Ejection

Figure 78: Black Power Ground Test

Results

Table 36 contains the calculated black powder quantities for the full-scale rocket. These are the predicted values that were tested first.

Table 36: Predicted Full-scale Black Powder Charge Quantities

Charge	**Mass (grams)**
Primary Drogue Ejection Charge	1.8
Redundant Drogue Ejection Charge	2.1
Primary Main Ejection Charge	4.1
Redundant Main Ejection Charge	4.9

Table 37 contains the results for this test.

Table 37: Final Full-scale Black Powder Charge Quantities

Charge	**Mass (grams)**
Primary Drogue Ejection Charge	2.5
Redundant Drogue Ejection Charge	3.0
Primary Main Ejection Charge	4.1
Redundant Main Ejection Charge	4.5

The main and drogue parachute deployments were both successful, however the main deployment black powder quantities were both increased by approximately 40% for improved performance. Additionally, the redundant drogue deployment mass was decreased slightly to avoid the 5g maximum team derived limitation.

Conclusion The Full-scale and Sub-scale Black Power Separation Tests have both been completed successfully with an approximate 25% increase in full-scale main deployment charge quantity, and 35% increase in sub-scale drogue deployment charge quantity when compared to the predicted values.

6.2.3 Parachute Durability Test

Introduction The objective of the parachute durability test is to determine various parachute models' ability to withstand harsh environmental conditions or obstacles, such as corn stalks upon landing. This is to be done by plotting the resulting stress-strain curves of the parachutes from their output yield strength values. The following procedure is conducted with a universal tensile testing machine.

Objective	**Criteria for Success**	**Test Variables**
Determine the durability and viscoelastic effects of various parachute models	Quantitative Measurements of elasticity and strength	Material Ultimate Strength, Elasticity

Testing Procedure

1. Spread a section of the Ultra Compact parachute over the threaded opening of a PVC pipe, making sure to pull all sides tight to avoid wrinkles
2. Screw another section of PVC pipe on top of the parachute to secure the parachute in place
3. Attach a 500N load cell to the machine or high accuracy readings
4. Attach the puncture attachment to the load cell
5. Set the machine to a slow compression rate (1mm/min)
6. Once the probe breaks through the parachute, the max values of force and energy applied will be shown on the digital readout
7. Raise the probe back to its starting position and remove the top section of PVC pipe holding down the parachute
8. Remove the parachute from the machine

9. Repeat steps for a fast rate of 10 mm/min
10. Repeat steps for the Iris Ultra Standard parachute model

Figure 79 displays the apparatus of the parachute testing.

Figure 79: Parachute Durability Apparatus

Results

Both slow and fast tests were completed for the compact parachute. Since the two force values approximately equivalent, there was no evidence of viscoelasticity. For this reason, only a fast test was performed on the ultra standard parachute to compare ultimate strengths of both models. Table 38 provides a summary of the forces required to puncture.

Table 38: Parachute Ultimate Strength Results

Model	Trial 1 (1mm/min)	Trial 2 (10mm/min)
Ultra Compact	54.41 N	50.15 N
Ultra Standard	N/A	41.65 N

Conclusion The Ultra Standard parachute model was found to have an ultimate strength of 26.6% greater than the Compact model. As both models are 0.025 in thick ripstock Nylon, the difference in material strengths is likely related to the parachute's weave. The test is successful as both parachutes were compared and found to have differing strengths. Understanding the higher durability of Ultra Standard parachutes allows improved design decisions for future rocket generations.

6.2.4 Hardware Tensile Test

Introduction The hardware tensile test sets out to prove that the hardware apparatus connecting the shock cords to the body of the rocket can withstand a minimum load of 500 Ibf, which was the smallest quoted force for a component of the apparatus. The test will run with constant increasing load until maximum yield strength is determined. The Recovery and Propulsion (R&P) Subteam will perform this test through the use of a Universal Testing Machine. This test will determine if the components of the hardware apparatus reflect the expected tensile strengths quoted by their manufacturers, and therefore can withstand the separation force of the rocket. If the test fails, new hardware will be purchased with greater maximum strength.

Objective	**Criteria for Success**	**Test Variables**
Validate the maximum load of our hardware	No visible deformation or breakage before 500 lbf is applied	Maximum strength of hardware apparatus

Testing Procedure

1. Assemble the hardware in the following order: eyebolt, quicklink, swivel joint, quicklink, eyebolt.
2. Screw the eyebolts into aluminum blocks
3. Clamp the aluminum blocks, ensuring that the hardware is vertically aligned between the tensile clamps.
4. The machine will separate the tensile clamps at a rate of 1 mm/min until deformation is detected.
5. Once deformation occurs, the maximum yield strength will be recorded from the digital readout. The machine will continue to separate at a constant rate until the fracture strength is recorded.

Figure 80 displays the apparatus of the parachute testing.

Figure 80: Hardware Strength Apparatus

Results

Table 39 displays the maximum yield strength of the hardware apparatus, followed by the ultimate strength at the fracture point.

Table 39: Hardware Strength Results

	Strength
Yield Strength	5107 N (1148 lbf)
Fracture Strength	12234 N (2750 lbf)

The hardware apparatus was found to yield at 5107 N of applied force, (1148 lbf). The percent difference from the expected 500 lbf is 78.64%. As the hardware withstood a force much greater than the minimum quoted strength, the test was successful and alternative hardware will not have to be purchased. Additionally, it is important to note that although the hardware began to deform around 1148 lbf, the fracture strength had a much greater value of 2750 lbf. Therefore, in actuality, the hardware can withstand a much greater force before total failure. This means our hardware is more robust and less likely to be a point of failure during separation events.

6.2.5 Masking Tape Strength Test

Introduction The objective of the masking tape strength test is to determine the amount of force needed to break the loops of masking tape wrapped around the shock cords. This force will indicate if break banding is a useful practice in reducing snatch force experienced on the rocket. If the test is successful, break banding will be used on the drogue shock cords to further prevent premature separation of the main parachute at deployment. If the test is unsuccessful, break banding will no longer be utilized in launch procedures. The following procedure is conducted with a Universal Tensile Testing Machine.

Objective	Criteria for Success	Test Variables
Determine the maximum strength of various masking tape thicknesses	The amount of force required to break the masking tape is greater than 25% of the snatch force experienced by the drogue parachute	Masking tape loop thickness and maximum strength

The descent velocity after drogue deployment is 116.2ft/s, with a coefficient of drag of 1.5 and drogue parachute area of 1.696 ft^2. Using NASA's method in Section 6.1.1 Snatch Force Testing, a snatch force of 180.7 N (40.6 lbf) was calculated. If a masking tape band can withstand up to 10.15 lbf, this quantity would be considered substantial enough to utilize in launch configurations.

Testing Procedure

1. Prepare three 2 in loops of masking tape between two triangular carabiners, varying from two layers of tape to four layers of masking tape
2. Screw the eyebolts into aluminum blocks
3. Clamp the aluminum blocks, ensuring that the hardware is vertically aligned between the tensile clamps.

4. Secure triangular carabiners to the eyebolts within the machine jaws
5. Set the machine to a tensile rate of 1mm/min until the material fractures
6. Once the loop of tape breaks, the max force will be recorded and graphs of the data will be shown
7. Remove the tape from the carabiner
8. Repeat steps 2-8 until two trials for each loop thickness is completed. The average of the two trials will be taken.

Figure 81 displays the apparatus of the parachute testing.

Figure 81: Break Banding Apparatus

Results
Table 40 displays the ultimate strength of multiple loop variations for break bands.

Table 40: Break Band Strength Results

	2 loops	**3 loops**	**4 loops**
Maximum Force	115.782 N	349.379 N	424.771 N

A substantial force absorbed was found to be 10.15 lbf from snatch force testing. The least number of loops broke at 115.78 N (26.03 lbf), which is approximately 3x greater than the minimum value. Due to this, the test was successfully and can aid in the understanding of energy dissipation for future recovery hardness designs. No changes will be made for the 2022-2023 full-scale rocket.

6.2.6 Shock Cord Tensile Test

Introduction The shock cord tensile test sets out to compare the maximum elongation of nylon shock cords and its alternative, Kevlar shock cords, when elongated at constant rate. The Recovery and Propulsion (R&P) Subteam will perform this test through the use of a Universal Testing Machine. This test will provide more accurate elasticity's of the two shock cord materials for calculations due to their variation in braid and thicknesses.

Objective	**Criteria for Success**	**Test Variables**
Compare nylon's elasticity to Kevlar's's under a constant rate of elongation	Quantitative values for elasticity and ultimate strength	Elasticity and ultimate strength

Testing Procedure

1. Cut the nylon shock cord into 3 separate 5 in strips.
2. Adjust the lower and upper clamps to fit the length of the shock cord.
3. Place the shock cord between the tensile clamps, gripping at least $\frac{3}{4}$ of the material's surface area into the vise.
4. Ensure that the material is vertically aligned between the clamps.
5. The machine will separate the tensile clamps at a rate of 1 mm/min
6. Remove the deformed shock cord from the clamps.
7. Repeat this process for a total of two trials, the second being performed at an elongation rate of 100 mm/min, and take the average extension value.
8. Repeat steps 1-9 for the Kevlar shock cord.
9. Calculate and compare the percent differences in extension of the two materials.

Figure 82 displays the apparatus of the shock cord tensile testing.

Figure 82: Nylon (left) and Kevlar (right)

Results

The shock cords were gripped such that 2.132 in of the shock cords were exposed between the two grips of the testing machine. During testing it was observed that the shock cords tended to slip from the clamps at greater extensions. This was mediated by marking where the shock cords met the grips with a white line. The grips also marred the surface of the shock cords, leading to possible error. Table 41 displays the elasticities recorded for 5/8 in tubular nylon and kevlar shock cords.

Table 41: Elasticity Results

Material	**Slow Rate (1mm/min)**	**Fast Rate (100mm/min)**
5/8 in Nylon	3.115 N	2.983 N
5/8 in Kevlar	3.136 N	3.207 N

At an elongation rate of 1 mm/min, the percent difference between the Nylon and Kevlar shock cords was 4.33% (Nylon being the greater of the two). At an elongation rate of 100 mm/min, the percent difference was 2.24% (Kevlar being the greater of the two). As the kevlar has approximately the same elasticity at both rates, it can be approximated that kevlar will not become more elastic at high speeds. However, the nylon material has a 4.33% difference between the slow and fast rates, indicating that nylon may not exhibit highly elastic properties at high rates. This information can be used to influence shock cord choices for future designs. Overall, quantitative values for both elasticity and strength were recorded for both materials, therefore this test was successful.

6.3 Avionics Tests and Demonstrations

6.3.1 GPS Demonstration

Introduction The purpose of this demonstration is to verify that the TeleGPS V2 and base station computer/device are properly communicating with each other via the TeleBT and a bluetooth connection. This is done by checking the "age" datapoint on the base station software and confirming that the GPS coordinates from the software are accurate.

Objective	**Criteria for Success**	**Demonstration Variables**
Prove the proper function of the GPS Vehicle Tracking system	Verify proper GPS start up, communication, and data transmission	Transmitted GPS coordinates and signal age

Materials

- TeleGPS V2
- TeleBT
- Bluetooth Capable Base Station Computer/Device and Receiver
- 3-Element Yagi Antenna
- Cellular Device

Procedure

1. Assemble 3-element yagi antenna and connect antenna to TeleBT via SMA connection.
2. Connect TeleBT to the base station computer/device via a bluetooth connection.
3. Verify that the "age" datapoint on the base station software is 0 or 1 that indicates that data is being received from the TeleGPS V2.
4. Verify that the GPS coordinates are accurate by checking GPS coordinates online with a cellular device.

Conclusion The TeleGPS V2 successfully turned on, and the data stream of GPS coordinates was validated and compared using Google Maps and Google Earth. The difference between the GPS coordinates and the coordinates given by Google Maps and Google Earth is suitable for our purposes. Furthermore, the TeleGPS V2 efficiently connected to more than ten satellites offering a stable and precise connection. Overall, the demonstration was successful and proved that the TeleGPS V2 is functional for our needs, and no further design changes were required.

6.3.2 GPS Accuracy Test

Introduction The purpose of this test is to measure the accuracy of the TeleGPS V2's distance tracking. This is conducted by moving the TeleGPS V2 by a set of predetermined distances and comparing and contrasting the predetermined distances with the distances given by the base station software.

Objective	**Criteria for Success**	**Test Variables**
Determine the accuracy of the reported GPS coordinates provided by the TeleGPS and ensure that the distance percent error is below 3 %	Reported GPS coordinate's standard deviation is minimal	Distance from the base station

Materials

- TeleGPS V2
- TeleBT
- Bluetooth Capable Base Station Computer/Device and Receiver
- 3-Element Yagi Antenna
- 2 Individuals to Perform the Test
- Measuring Tape

Procedure

1. Assemble a 3-element yagi antenna and connect the antenna to TeleBT via SMA connection.
2. Connect TeleBT to the base station computer/device via a Bluetooth connection.
3. Person 1 holds the TelegGPS V2 and walks away from the base station, while person 2 monitors the data appearing at the base station.
4. The place where person 1 stopped is marked using a piece of tape, and the distance between the piece of tape and the base station is measured using a measuring tape. All measurements and GPS recordings are recorded.
5. Steps 1 and 2 are repeated for 5 trials. In each trial a different distance is covered by person 1: 5 m, 10 m, 15 m, 20 m, and 25 m.
6. The data from the base station is compared with the data physically measured with the measuring tape, and several key statistics such as percent error and standard deviation are calculated.

Table 42: GPS Testing Data

Distances (m)	**Trial 1 (m)**	**Trial 2 (m)**	**Trial 3 (m)**	**Trial 4 (m)**	**Average (m)**	**Standard Deviation (m)**
20	30	18	22	25	23	4.69
50	52	48	49	50	49.8	1.48
100	97	96	102	99	98.8	2.39

Conclusion The TeleGPS V2 successfully sent its location to the TeleBT accurately. The average of all the trials was within five meters of the desired distance, and on average, the distance was off by less than three meters, approximately 2.85 meters, based on the standard deviation of the trials. It is important to also note that the TeleGPS V2 was more accurate as the distance increased and less accurate at very close distances from the base station. This can be seen by the standard deviation for a distance of twenty meters is much higher than that of the fifty-meter distance and one hundred-meter distance. Overall, the TeleGPS V2 and the TeleBT can be successfully used to pinpoint the location of the rocket with less than 1% error across an average of all the differences. This is less than the 3 percent error threshold we set for the efficacy of the TeleGPS. This accuracy will give us accurate measurements for the rocket's location at all times, increasing the efficiency of recovery, safety, and a redundant measurement for the apogee. It was learned that no further design capital was needed for further developing the GPS system.

6.3.3 Recovery Circuit Continuity Demonstration

Introduction This demonstration sets out to prove the complete continuity of the flight computer circuit by using a multimeter to authenticate that each section of the circuit is flowing as expected. The tested variable is whether or not a connection has continuity.

If continuity is true for all connections, then the criteria for success is reached. The continuity of this circuit is vital to ensuring that no components are set off prematurely or act in an unpredictable manner.

Objective	**Criteria for Success**	**Demonstration Variables**
Prove the continuity of the recovery avionics circuit	The multi meter shows continuity across each solder joint and temporary connection in the circuit	Electrical continuity

Materials

1. Multimeter
2. Circuit
   (a) Two EasyMini v2.0 flight computers
   (b) Two Lithium Polymer 3.7V 900mA batteries
   (c) 2 Rotary Switches
   (d) Terminal Blocks
   (e) Wires

Procedure

1. Test for continuity at the appropriate locations. Turn on multimeter, turn dial to continuity setting.
2. Touch the test leads to each point indicated on the figure below. Each pair of triangles of the same color indicate a pair where continuity should be tested (i.e. one test lead should be at one location indicated by a triangle in figure —, the other should be at the other location with the triangle of the same color).
3. If the multimeter beeps, continuity is true.

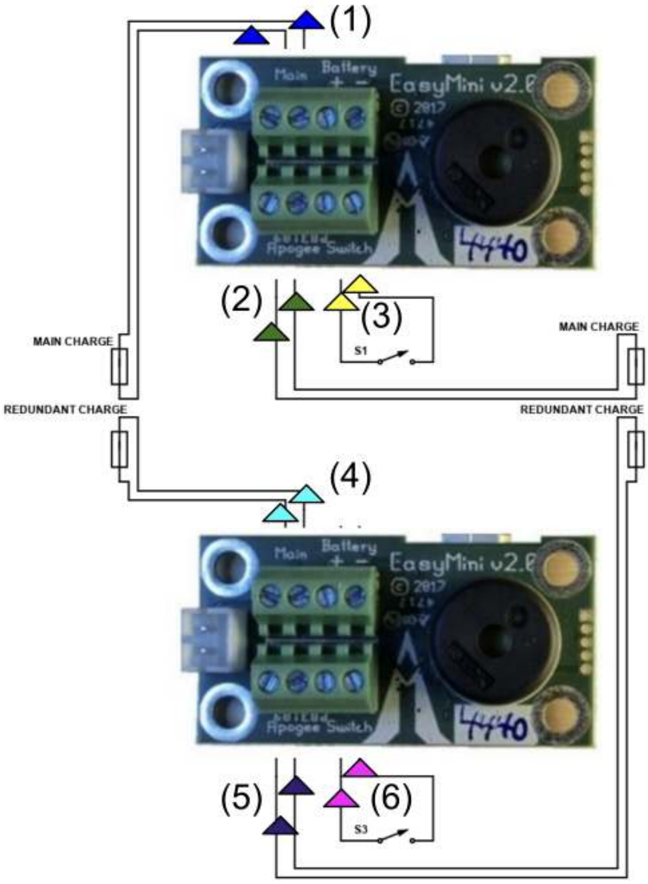


Figure 83: Places to test for continuity. Each set of colored triangles represents the location of the multimeter prongs for each individual test. (Note: locations 1,2,4, and 5 are being tested at the respective terminal blocks for those charges)

Connection Number	**Continuous**
1	True
2	True
3	True
4	True
5	True
6	True

all connections were predicted to be true, and after testing the continuity of all connections, all were found to be true, matching our predictions. Assuming each individual component is continuous (a reasonable assumption, as the components were bought and presumed to be quality-tested), this confirms the continuity of the entire circuit when all the connections are properly made. Therefore, this test can be considered a success. From this demonstration the team learned that the recovery circuit should work in the event of a launch, thus no launch error should be derived from the circuitry aspect of this system.

6.3.4 Flight Computer Deviation Test

Introduction This test aims to determine the average differences in data between the main and redundant flight computer using flight information from a previous subscale launch. The flight computers should experience the same data as input and should therefore have no significant difference in data. This specifies that the value of 0 difference in the data must be within the standard deviation in order for the test to be considered successful. Thus, if the redundant data is within one standard deviation of the main, then the criteria for success is reached. This information can then be utilized to distinguish outliers in recorded flight data as well as provide an understanding of the range of error of the data.

Objective	**Criteria for Success**	**Test Variables**
Determine the average difference between data read by the two on board flight computers	The data between the two flight computers is precise with a low standard deviation	Acceleration, height, and speed

Materials

1. AltosUI
2. Flight Data
3. Flight computers
4. Micro USB Cable

Procedure

1. Pull flight data from each flight computer.
2. Open AltosUI on computer, connect USB cable to computer and flight computer of interest(main or redundant).
3. Download data in spreadsheet form.
4. Transfer data into spreadsheet(Google sheets and excel work well)
5. Convert data points into imperial.
6. Calculate difference between the redundant and main data points for each tick.
7. Find the average difference and standard deviation for each data column(acceleration, height, speed, etc.).

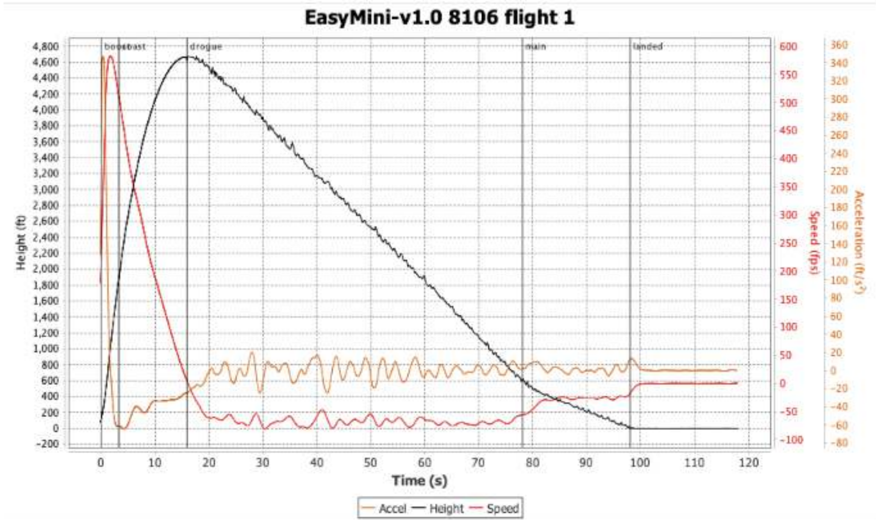


Figure 84: Primary flight computer acceleration, height, speed plotted

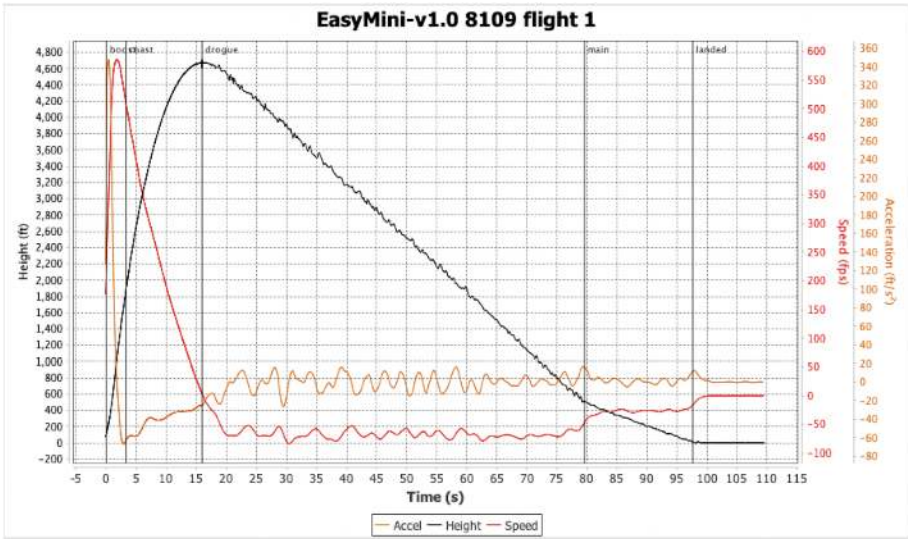


Figure 85: Redundant flight computer acceleration, height, speed plotted

	Acceleration Difference	Height Difference	Speed Difference
Avg	0.0946 ft/s^2	0.5333 ft	0.0661 ft/s
SD	3.3849 ft/s^2	5.8856 ft	2.3627 ft/s

Conclusion Observing this data, it concluded that the main and redundant altimeters should have an average difference of 0.0946 ft/s^2 in their acceleration, an average difference of 0.5333 ft in recorded height, and an average difference of 0.0661 ft/s in recorded speed. These values can be used, along with the calculated standard deviation, to determine whether or not data from a given flight is anomalous in some way. All averages are within one standard deviation of zero, showing that the two flight computers had roughly the same readings and they didn't deviate. Seeing as the average differences for all variables are within one standard deviation of zero, as seen in Table 31, our test's success criterion was reached. through test is it was learned that the main and redundant flight computers have a slight difference in their recorded data, but not a significant discrepancy.

6.3.5 Pressure Sensor Demonstration

Introduction The purpose of this demonstration is to verify that the Sparkfun Qwiic MicroPressure Sensors are accurately reading the atmospheric pressure, writing to the data to a file, and correctly interfacing with the Raspberry Pi 4B+. To do this, both pressure sensors read data at 20 Hz for a duration of 10 seconds. This was then compared to the actual pressure obtained from the weather app in inHg.

Objective	**Criteria for Success**	**Demonstration Variables**
Verify proper function of the Raspberry Pi 4B+ and the pressure sensors	Verify that proper pressure data is read from the pressure sensors by the Raspberry Pi	Pressure data

Materials

- 2x Sparkfun Qwiic MicroPressure Sensors
- RaspberryPi 4B+ 4GB Model
- Jumper Cables
- LED light
- Base Station Computer
- USB-C Cable
- Weather App to Read Actual Pressure

Procedure

1. The Pi was connected to via an ssh connection with an Ethernet cable to the base station computer.
2. A Python script using the adafruit mprls library was written locally on the RaspberryPi in order to read the data from each of the sensors configured on I2C Bus 3 and I2C Bus 4 at a frequency of 5 Hz that would run on boot.
3. An LED was added to the RaspberryPi and output high each time the read function returned a value that was not type None to ensure the function was actually returning a value.
4. The script was ran outside and the data.txt file was produced with the measurements from each pressure sensor and the time the value was returned from the read function.
5. The values were plotted as a function of time for the ten seconds the script was running to compare the values to each other and to the actual atmospheric pressure (14.87 psi).

Collected Data The actual atmospheric pressure was measured at 14.87 psi.

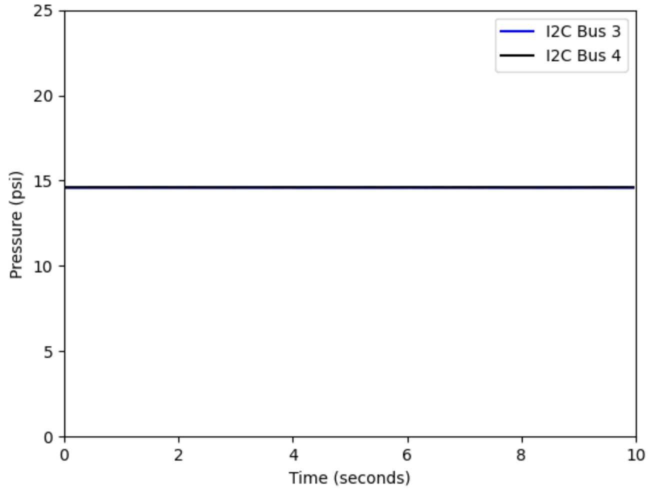


Figure 86: Both Sparkfun Pressure Sensors Plotted over 10 second duration while outside

Conclusion The values from both pressure sensors overlap just below where the actual atmospheric pressure would be. These pressure sensors are intended to troubleshoot possible separation failures by tracking the change in both the forward and aft chambers at a frequency of 20 Hz. Based on the accuracy for both pressure sensors, seeing that the values were writing to a text file, and the LED continuously blinking, the pressure sensors will be able to troubleshoot these issues post-flight, **thus** the demonstration was a success.

6.3.6 Pressure Sensor Accuracy Test

Introduction Attached to our Raspberry Pi 4B, there are two identical pressure sensors that will be used to collect pressure data throughout our rocket's flight to troubleshoot possible separation failures. In order to determine the accuracy of our pressure sensor, a test must be conducted to find the uncertainty range that its outputted data lies within. This will be achieved by running pressure tests and finding the uncertainty of one of our sensors.

Objective	**Criteria for Success**	**Test Variables**
Determine the accuracy of the pressure data read by the Raspberry Pi 4B+ from the pressure sensors	Pressure data is accurate to actual environmental readings by comparing the readings to the atmospheric pressure.	Pressure data

Materials

- 2x Sparkfun Qwiic MicroPressure Sensors
- RaspberryPi 4B+ 4GB Model

- Jumper Cables
- LED light
- Base Station Computer
- USB-C Cable

Procedure

1. The Pi was connected to via an ssh connection with an Ethernet cable to the base station computer.
2. The data collected from the first and second pressure sensor respectively.
3. Ten short trial periods with 6 pieces of pressure data each were collected for each pressure sensor using a Python script and the Raspberry Pi.
4. The average for each trial period was taken by adding the 6 values together and dividing them by 6.
5. The standard deviation was also taken so that both values could be compared to measure the accuracy and similarities of the values being read from each of the sensors.

Collected Data The following tables below show the collected data for both pressure sensors:

Table 43: Data for Pressure Sensor Test 1

Trial #	Pressures Value 1	Pressures Value 2	Pressures Value 3	Pressures Value 4	Pressures Value 5	Pressures Value 6	Average (psi)
1	14.2967	14.2983	14.2972	14.2961	14.2959	14.2985	14.2971
2	14.2849	14.2816	14.2854	14.2827	14.2839	14.2840	14.2837
3	14.2868	14.2856	14.2850	14.2819	14.2833	14.2853	14.2847
4	14.2816	14.2813	14.2838	14.2842	14.2819	14.2843	14.2829
5	14.2859	14.2842	14.2828	14.2833	14.2828	14.2834	14.2838
6	14.2823	14.2832	14.2825	14.2859	14.2831	14.2841	14.2835
7	14.2833	14.2832	14.2830	14.2838	14.2830	14.2834	14.2833
8	14.2854	14.2798	14.2838	14.2849	14.2843	14.2840	14.2837
9	14.2827	14.2837	14.2841	14.2822	14.2816	14.2825	14.2828
10	14.2837	14.2859	14.2826	14.2856	14.2825	14.2849	14.2842

Table 44: Data for Pressure Sensor Test 2

Trial #	Pressures Value 1	Pressures Value 2	Pressures Value 3	Pressures Value 4	Pressures Value 5	Pressures Value 6	Average (psi)
1	14.2967	14.2983	14.2972	14.2961	14.2959	14.2985	14.2971
2	14.2969	14.2956	14.2965	14.2979	14.2949	14.2965	14.2964
3	14.2997	14.2956	14.2955	14.2965	14.2952	14.2947	14.2962
4	14.2960	14.2958	14.2982	14.2957	14.2959	14.2980	14.2966
5	14.2920	14.2949	14.2977	14.2962	14.2966	14.2964	14.2956
6	14.2979	14.2949	14.2962	14.2963	14.2969	14.2955	14.2963
7	14.2969	14.2966	14.2990	14.2970	14.2971	14.2948	14.2969
8	14.2975	14.2965	14.2979	14.2937	14.2940	14.2966	14.2960
9	14.2977	14.2966	14.2958	14.2950	14.2965	14.2972	14.2964
10	14.2978	14.2952	14.2977	14.2963	14.2966	14.2946	14.2964

Conclusion The individual uncertainties of each pressure sensor is mostly negligible, as their measurements are very consistent under equivalent conditions. However, there seems to be a small discrepancy between the two sensors themselves of about 0.013 psi. Based off of these readings, the test was a success, seeing that the pressure values were very close to what was expected. The main lesson learned would be that the test showed that the pressure sensors both work well and that the small discrepancy between each of the sensors is negligible for troubleshooting possible separation failures.

6.4 Payload Tests

6.4.1 Scissor Lift Test

Introduction

The objective of this test is to ensure that the scissor lift will be able to raise the camera and rotating camera components into the air so unobstructed pictures can be taken. The scissor lift will need to be powered by an electric motor, and must be able to extend the camera components by a minimum of 2.25 in. The camera components will include a servo motor, a 3D printed servo housing, and a wide angle Raspberry Pi camera.

Objective	Criteria for Success	Test Variables
Measure the extensional length of the scissor lift device to ensure it will work in operational environment.	The scissor lift can be powered by an electric motor and extended to at least 2.25 in with the camera components mounted on top of the lift	The weight of the camera components mounted on top of the lift, and extentsional length of device

Testing Procedure

1. The scissor lift will need to be 3D printed with PETG and the pins will need to be cut from a 1/8” aluminum rod into 1” and 1.5” lengths
   (a) The scissor lift will be composed of two mounting boards, 8 arms, and 8 middle pins

2. The bottom mounting board will be fixed and the lift will be stationary in the collapsed position
3. The motor will be temporarily mounted so the shaft of the motor is parallel with the z-axis that the scissor lift extends
4. A spool of 50lb braided fishing line will be attached to the shaft of the motor, and one end of the fishing line will be attached to the bottom right pin of the scissor lift
5. Use the rotation of the motor to extend the scissor lift vertically by compressing the scissor lift horizontally
6. The masses of each of the weights used will be recorded. Then, each weight will be secured to the top mounting board of the scissor lift
7. The weight of the camera components are approximately 60g, so weights above and below this will be tested
   (a) Electrical tape will be used to secure test weights to the top mounting board
8. To test if the motor can power the scissor lift, electrical power will then be provided to the motor to determine if the motor provides enough force to extend the scissor lift.

Test Parameters & Measurements

Table 45: Parameters of Scissor Lift

Parameter Type	**Value**
Retracted Height	0.72in
Extended Height	3.22in
Δ Height	$3.22 - 0.72 = 2.49$in
Total Height	$3 + 2.49 = 5.49$in
Operating Voltage	6V

Results

The results show that the scissor lift was extended at least 3.22 in fully extended while being able to lift a weight of 49g (almost 3x heavier than the expected camera components) without drawing more than 0.5A of current. Since the camera sits at about 0.2 in from the top of the inner body tube, the scissor lift only brought the camera about 2.05 in above the body tube, about 0.05 in (2.47% difference) above our predicted target height. Both of these results are consistent with the success criteria parameters and thus the test was considered successful.

Table 46: Test Results

Weight Type Peak Current Draw (A)	Weight (g) Lift Height (in)
Box of Screws 0.04	96 2.49
Servo Motor 0.03	41 2.49
Servo Motor and Camera 0.03	50 2.49
Servo Motor, Camera, and Screws 0.05	146 2.49

Lessons Learned

Throughout the process of this testing procedure, several aspects of the camera deployment were noted. Primarily the efficacy of driving the scissor lift: in order to ensure that the lift deploys, both the fishing wire must be in-tension to ensure that the pulley system immediately deploys the arm when the servo is driven. This will be easily resolved by inspection during the assembly of the payload into the bay. Secondly, the scissor lift requires a much more frictionless base to ensure that the legs of the scissor lift are collapsed without stalling the servo. This was resolved by further sanding of the 3D printed base slot of the scissor lift to reduce friction.

6.4.2 Payload Separation Test

Introduction The aim of the separation test was to inspect and analyze the efficacy of

the rack and pinion mechanism in separating the nosecone from the payload bay. The factors involved were primarily the load weight of the nosecone and the current and voltage of the DC motor as it operated.

Objective	Criteria for Success	Test Variables
The separation rack is capable of extending in forwards and reverse directions, ultimately pushing the nosecone off.	Separating least 5” to create a 3” gap between the Payload bay and nosecone.	Separation distance and current draw at the operating voltage of 12v.

Testing Procedure

1. Insert motor mount and bulkhead assembly into aft section of the Payload bay
2. Retain motor assembly via screws through the body tube
3. Wire both leads of the DC motor with alligator clips that extend out of the body tube
4. Insert body tube rotating track into the Payload bay, 5” from the aft bulkhead
5. Tighten key screws into side of the drilled body tube holes

6. Insert rack into the body tube centering ring slots and align racks with the key screws
7. Connect alligator clips to 12v DC power supply
8. Confirm racks can translate in forwards and backwards direction (reversing polarity manually or via motor controller hat)
9. Reset racks, attach nosecone to body tube and confirm racks are capable of pushing nosecone off

Results

The results of the separation test were inconclusive, as the rack and pinion mechanism was capable of translating in both forwards and backwards directions but did not separate the nosecone due to technical and partial design issues as discussed in the section below. As a result, the observations made from this test was not substantial enough to fail nor prove that our design works.

Nosecone Separated?	No
Forward Direction	Yes
Reverse Direction	Yes
No-Load Power Consumption	0.07 A @ 12V
Load Power Consumption	0.09 A @ 12V

Table 47: Test Results

Lessons Learned

Several observations were made during this testing procedure. The primary reason why the nosecone did not successfully separate was due to poor meshing between the pinion gear and the rack. This is due to the use of a former version of 3D printed centering rings that had too wide of slots that were too loose for the racks, thus making consistent meshing difficult when the racks encountered the nosecone. However, during the test new 3D print jobs were queued for a fixed design. Another reason was due to the lack of guidance for the racks, where it was proposed that additional keys be screwed into the body tube to keep the rack guided along its entire path during separation for better directing of the force along the nosecone. Lastly, the nosecone centering ring required deeper "inset" pockets for the separation racks in order to provide additional guidance to the racks and better distribute the forces to the nosecone, assisting in its separation.

6.4.3 Payload Retention Test

Introduction The purpose of this test is to determine whether or not the nosecone retention keeps the nosecone attached to the payload. The nosecone must also be able to separate from the payload when the solenoids are retracted to push the camera out and raise it up. Another parameter will also be investigated to ensure a flawless set up on launch day. The time to set up the nose cone retention system will be examined and practiced to smooth out the launch day procedures.

Objective	Criteria for Success	Test Variables
Testing mechanisms to keep the nosecone on, activating and retracting the solenoids, and pulling nosecone off	The nosecone stays on when solenoids are inactive, the solenoids retract when activated, and the nosecone comes off when solenoids retract	Nose cone retention and release, time to set up the nose cone retention system

Testing Procedure

1. Start the timer to test the setup time.
2. Connect the wires on the solenoids to the battery.
3. Push the solenoid pins in so they clear the body tube.
4. Push nosecone onto payload. Slide and twist until the solenoids pop into place in their respective holes in the forward body tube.
5. Turn the battery on and observe whether the solenoids retracted or not.
6. Pull nosecone off. If the solenoids retracted properly, this will be possible. If they did not, the nosecone will not come off.

Results

All of the tests passed the criteria except for test number 4. In this test, the body tube was shaken before the battery was connected to simulate the snatch force. Unfortunately with this additional force, one of the solenoids did not retract as there was too much friction between the pin and the body tube. A solution for this problem is to file down the threads on the pin so there is less friction. This solution was implemented and the fifth trial passed the tests. It can also be noted that the setup time was within reason for each trial, so no further design changes will happen to mitigate launch day set up challenges. Comparing these results from the predicted outcomes of the test, we observe that the retention performs similarly to as the team expected with the traditional retention system through the use of two stainless steel screws. This reinforces our confidence in the retention system of the nosecone.

Test #	Setup Time	Nosecone retention when inactive?	Did solenoids retract?	Did nosecone come off?	Pass/Fail
1	55 seconds	Yes	Yes	Yes	Pass
2	27 seconds	Yes	Yes	Yes	Pass
3	26 seconds	Yes	Yes	Yes	Pass
4	17 seconds	Yes	No	No	Fail
5	26 seconds	Yes	Yes	Yes	Pass

Lessons Learned

Due to the failure in the retention system to retract when the nosecone experiences an outward force (separating force of nosecone from body tube) that causes the solenoid pin to dig into the sides of the vehicle's fiberglass hole, several changes will be made to the system to ensure utmost confidence in a successful operation during mission execution.

These changes will not be drastic and are relatively simple to implement. The first solution can be implemented by having a cable attach from the nosecone centering ring to the motor, such that prior to separation the motor performs a slight reverse rotation that pulls to realign the nosecone back into a position that allows the retention system to detract with ease. Lastly, it was observed that "pulsing" the solenoids increased the likelihood of the induced magnetic field from pulling the pins back, thus this behavior will be implemented in software control as well.

6.4.4 RTL-SDR Performance Test

Introduction

The RTL-SDR tests set out to prove that the RTL-SDR was a viable method for receiving APRS packets at large distances without any packet loss. The test also measured the temperature of the RTL-SDR to make sure overheating was not a risk. The Payload subteam will perform this test using the APRS-droid app (to generate test transmissions) and the Baofeng UV-S9 Plus (to broadcast the transmissions). This test will provide distance-based data on the ability of the RTL-SDR to receive transmissions.

Objective	Criteria for Success	Test Variables
Confirm that the RTL-SDR can receive transmissions over long distances and not overheat	Zero packet loss on transmissions from 0 to 656 feet and no temperature warnings	The packet loss measured by the number of bits received and the temperature of the RTL-SDR

Testing Procedure

1. Set the Baofeng UV-S9 Plus to VOX ON
2. Connect the Baofeng via cable to android phone running APRS-DROID
3. Turn on the Raspberry-Pi and tune the RTL-SDR APRS Frequency
4. Click the message icon and broadcast a message within APRS-DROID
5. Validate that the Pi recieved the message as sent

Results

The RTL-SDR test successfully showed that temperatures stayed well within their operating spec even after two hours of running. The test also showed that the RTL-SDR received all sent packets at all tested distances. Comparing these results to our proposed criteria, we observe that the operating temperature of the RTL-SDR does not exceed the electronics safety threshold of 120 degrees Fahrenheit, allowing us to assume that the RTL-SDR will contribute to any excessive heat (which will still be likely during the launch environment climate and enclosed Payload bay).

Table 48: Temperatures of the RTL-SDR

Time	**Temperature (ºF)**
15m	64
30m	66
45m	69
1h	74
1h 15m	76
1h 30m	78
1h 45m	78
2h	77

Table 49: Tested Distances of the RTL-SDR

Distance (ft)	**Success (Yes/No)**
165	Yes
328	Yes
496	Yes
656	Yes
790	Yes
900	Yes
1500	Yes

Lessons Learned

The observation of the RTL-SDR's temperature will influence the design and layout of the component within the payload. To ensure that it is properly ventilated, it has been laid out on the bottom side of the Payload electronics board in a vertical orientation to ensure a greater surface area of the RTL-SDR's sides will be exposed to air for improved ventilation and isolating any heat-sensitive components from the RTL (which mainly reside on the top side of the board).

6.4.5 Software Runtime Test

Introduction

This runtime test is designed to determine if the camera functions are working properly and is running according to NASA's guidelines. Once a sequence is called, it will run each of the camera functions that are aligned with the sequence. As a test, we ran all of the functions one at a time, with each collecting the elapsed time for ten trials.

Objective	Criteria for Success	Test Variables
Take photos within 30 seconds maximum	Elapsed timing of the photos under 30 sec, calling the take picture function	Elapsed delta timing for photos taken over 5 trials
Camera can rotate image 180 degrees (upside down) within 30 seconds maximum	Picture showing upside down from previous picture	Calling the rotate function and timing it over 5 trials
Camera can go to greyscale within 30 seconds maximum	Picture showing a black and white image	Calling the greyscale function and timing it over 5 trials
Camera can change color filters (from RBG to BGR) within 30 seconds maximum	Picture showing a BGR-quality picture	Calling the RBG2BGR function and timing it over 5 trials
Camera can change from greyscale to color mode within 30 seconds maximum	Picture showing a color picture from the black and white picture	Calling the color mode function and timing it over 5 trials
Camera can remove all filters within 30 seconds maximum	Picture showing a regular, color picture with no filters	Calling the remove filter function and timing it over 5 trials

Testing Procedure

1. The team ran all of the image functions over ten trials, calling them one at a time over 5 trials each and timing the function using system time functions.
2. After the program ran the test, the data was compiled from the output and put into a sheets file, with each of our elapsed time over the image functions.
3. To make the data cleaner, five trials were conducted over each function with the time collection.
4. Several parameters were then calculated, including the average, minimum, and maximum time for each imaging functions.

Results

It was found that each image output corresponded to the image functions in the order that was declared accordingly. All of the image functions that were executed work according to each of the function's declarations. For the elapsed time data, the average time it took for the camera to take picture was approximately 5.5 seconds, significantly lower than the NASA's maximum requirement of 30 seconds with 24.5 seconds to spare. Thus it was concluded that the test was successful. For the other functions, the average time for them were below one second, within the millisecond range, thus were consumed a negligible amount of time per execution and thus successfully met the criteria.

	imaging.take_picture	imaging.rotate	imaging.to_greyscale	imaging.rgb2bgr	imaging.to_color_mode	imaging.remove_filter
	5.56	0.08565115929	0.000302314758	0.1303036213	0.000304937362	0.001989364624
	5.49	0.094176054	0.000224113464	0.05945396423	0.000183820724	0.001485347748
	5.5	0.06347322464	0.000221729278	0.05690670013	0.000214815139	0.001389503479
	5.49	0.06058382988	0.000224590301	0.05744123459	0.000216484069	0.001362323761
	5.54	0.06148219109	0.000211477279	0.05632138252	0.000223875045	0.001465320587
Min:	5.49	0.06058382988	0.000211477279	0.05632138252	0.000183820724	0.001362323761
Max:	5.56	0.094176054	0.000302314758	0.1303036213	0.000304937362	0.001989364624
Mean:	5.516	0.07307329178	0.000236845016	0.07208538055	0.000228786468	0.00153837204
	NOTE: ALL TIME IN SEDONDS					

Figure 87: Camera Imaging Time Testing Results

Lessons Learned

Although this test was successful, it was observed that the current design of the FSM does not demonstrate true parallelism but rather concurrency. Concurrent in the sense that each command within the FSM runs along with all the other software control routines (e.g. avionic sensing, telemetry transmitting, etc.) through a delta-time loop that polls each routine, but during the execution of a RAFCO, the overall process blocks until completion.

For the sake of this mission, this does not pose an issue as the mission dictates a maximum of 30 seconds *between* each RAFCO execution. Thus it is very unlikely that a single command will exceed a time limit of 30 seconds, but the team proposed the idea that if an entire *sequence* of RAFCO had to be completed within 30 seconds, a true parallel design could be implemented to execute each command by spawning a child process to execute the command while the parent process manages the scheduling of such commands.

7 Safety

7.1 Safety Officer Responsibilities

The Safety Officer's responsibilities include the following:

1. Oversee the general safety of the team and its members during all aspects of club engagement.
2. Ensure that all broader WURocketry, WashU, and USLI competition safety requirements are being followed throughout the year.
3. Administer safety briefings throughout the school year including pre-testing, pre-machining, and pre-launch safety briefings.
4. Attend all testing, manufacturing, and launch operations to oversee safety guidelines. If the Safety Officer is unable to attend, the team president or chief engineer assumes this responsibility.
5. Monitor the completion of all safety forms that team members are required to sign before machining, testing, and launching.
6. Research any new materials that are used by the team that could be potentially harmful or hazardous in any way.

The procedures for various stages of rocket launch are outlined in the following pages. These procedures are printed and included in the safety binder along with the Material Safety Data Sheet (MSDS) for use on launch day.

Recovery and Propulsion Procedure

Supplies

- ☐ Aft body tube
- ☐ Avionics coupler
- ☐ Forward body tube + Nose Cone
- ☐ Toolkit
- ☐ Hardware kit
    - ☐ Shear screws (No. 2 [6] and/or No. 4 [])
    - ☐ Philips head screwdriver
    - ☐ Putty
    - ☐ Superglue
- ☐ Baby powder

Warnings

⚠**The rocket is live. Do not aim the end of the rocket at any person.**

⚠**Move the rocket slowly and carefully.**

⚠**Be careful with fiberglass edges**

Procedure

To be completed by R&P Team Lead and Chief Engineer

Component - Drogue Parachute

- ☐ Secure the drogue parachute in the Nomex blanket
- ☐ Attach the 15ft drogue shock cord to the drogue parachute
- ☐ Z-Fold the 15ft drogue shock cord
- ☐ Use painter's tape to "break band" the 15ft drogue shock cord
- ☐ Attach the other end of the 15ft drogue shock cord to the avionics bottom bulkhead of the avionics coupler
- ☐ Attach the 25ft shock cord to the aft coupler eye bolt
- ☐ Attach the remaining side of the 25ft shock cord to the bottom bulkhead of the avionics coupler
- ☐ Z-Fold the 15ft drogue shock cord
- ☐ Use painter's tape to "break band" the 25ft drogue shock cord
- ☐ Pack the folded 25ft cord, 15ft cord, and drogue parachute into the aft coupler

Component - Main Parachute

- ☐ Pack the main parachute into the deployment bag
- ☐ Attach the 15ft forward main shock cord to the main parachute
- ☐ Attach the 30ft forward main shock cord to the main parachute

- ☐ Z-fold the 15ft forward main shock cord
- ☐ Use painter’s tape to “break band” the 15ft forward main shock cord
- ☐ Z-fold the 30ft aft main shock cord
- ☐ Use painter’s tape to “break band” the 30ft aft main shock cord
- ☐ Attach the 15ft forward main shock cord to the nose cone eyebolt
- ☐ Confirm BP charges are correct with team mentor and Chief Engineer

⚠At this point, only the Structure Team Lead, R&P Team Lead, and Chief Engineer should be handling the rocket

- ☐ Attach the 30ft aft main shock cord to the forward bulkhead of the avionics coupler

Team Lead:__________ Safety Officer:__________

Payload Subsystem Preparation Procedure

Supplies

- ☐ Philips Head Screwdriver
- ☐ Allen wrench
- ☐ Toolki
- ☐ Payload Bay - board
- ☐ Avionics Electronics (Telemetry)
    - ☐ RPi (1)
    - ☐ Altimeter (1)
    - ☐ IMU (1)
- ☐ Payload Mission Electronics
    - ☐ Micro servos (2)
    - ☐ Micro actuators (2)
    - ☐ RF Transceiver (1)
    - ☐ DC Motor

Warnings

⚠**The rocket is live. Do not aim the end of the rocket at any person.**

⚠**Move the rocket slowly and carefully.**

⚠**12V Power Supply for the motor - Lithium Ion Battery**

⚠**Wiring - loose wires**

Procedure

To be completed by Payload Team Lead and Chief Engineer

- ☐ Insert and mount the payload bay

⚠**12V Power Supply for the motor - Lithium Ion Battery**

- ☐ Switch on the electronics (avionics)
    - ☐ Altimeter
    - ☐ IMU
    - ☐ RF Transceiver

⚠**Wiring - loose wires**

- ☐ Check wiring

Team Lead:__________ Safety Officer:__________

Avionics Procedure

Supplies

- ☐ Aft body tube
- ☐ Avionics coupler
- ☐ Forward body tube + Nose Cone
- ☐ Toolkit
- ☐ Laptop computer with OpenRocket installed
- ☐ Hardware kit
    - ☐ Shear screws (No. 2 [6] and/or No. 4 [])
    - ☐ Philips head screwdriver
    - ☐ Putty
    - ☐ Superglue
- ☐ Avionics board
- ☐ Avionics hardware (attached to avionics board)

Warnings

⚠**The rocket is live. Do not aim the end of the rocket at any person.**

⚠**Move the rocket slowly and carefully.**

⚠**Be sure to be able to see the switches in the avionics coupler**

⚠**Be careful with fiberglass edges**

Procedure

To be completed by Structures Team Lead, R&P Team Lead, and Chief Engineer

- ☐ Setup avionics board
- ☐ Give avionics bay to team mentor to load black powder charges
- ☐ Attach the other end of the 15ft drogue shock cord to the avionics bottom bulkhead of the avionics coupler
- ☐ Attach the remaining side of the 25ft shock cord to the bottom bulkhead of the avionics coupler
- ☐ Insert avionics coupler into the aft tube and ensure holes are lined up
- ☐ Avionics team lead check the holes to ensure power switch is accessible
- ☐ Confirm BP charges are correct with team mentor and Chief Engineer

⚠At this point, only the Structure Team Lead, R&P Team Lead, and Chief Engineer should be handling the rocket

- ☐ Attach the 30ft aft main shock cord to the forward bulkhead of the avionics coupler
- ☐ Pull forward tube over the avionics coupler, ensuring holes are lined up
- ☐ Have avionics team lead check the holes to ensure power switch is accessible
- ☐ Immediately before taking rocket to launch rail, avionics team lead turn on the GPS arming switch and confirm GPS lock and communications with base station

- ☐ When rocket is on launch rail, avionics team lead flip the arming switches for the flight computers and the Raspberry Pi

Team Lead:__________ Safety Officer:__________

Full Scale Preparation Procedure

Supplies

- ☐ Aft body tube
- ☐ Avionics coupler
- ☐ Forward body tube + Nose Cone
- ☐ 15 minute epoxy
- ☐ Red Solo Cups
- ☐ Toolkit
- ☐ Scissors
- ☐ 3D printed rocket stands
- ☐ Laptop computer with OpenRocket installed
- ☐ Hardware kit
    - ☐ Shear screws (No. 2 [6] and/or No. 4 [])
    - ☐ Philips head screwdriver
    - ☐ Putty
    - ☐ Superglue
- ☐ Baby powder

Warnings

⚠**The rocket is live. Do not aim the end of the rocket at any person.**

⚠**Move the rocket slowly and carefully.**

⚠**Line up shear screw holes**

⚠**Be sure to be able to see the switches in the avionics coupler**

⚠**Be careful with fiberglass edges**

Procedure

To be completed by Structures Team Lead, R&P Team Lead, and Chief Engineer

- ☐ Setup avionics board - see avionics preparation procedure
- ☐ Give avionics bay to team mentor to load black powder charges
- ☐ Secure the drogue parachute in the Nomex blanket
- ☐ Attach the 15ft drogue shock cord to the drogue parachute
- ☐ Z-Fold the 15ft drogue shock cord
- ☐ Use painter's tape to "break band" the 15ft drogue shock cord
- ☐ Attach the other end of the 15ft drogue shock cord to the avionics bottom bulkhead of the avionics coupler
- ☐ Attach the 25ft shock cord to the aft coupler eye bolt
- ☐ Attach the remaining side of the 25ft shock cord to the bottom bulkhead of the avionics coupler
- ☐ Z-Fold the 15ft drogue shock cord
- ☐ Use painter's tape to "break band" the 25ft drogue shock cord

- ☐ Pack the folded 25ft cord, 15ft cord, and drogue parachute into the aft coupler
- ☐ Insert avionics coupler into the aft tube and ensure holes are lined up
- ☐ Have avionics team lead check the holes to ensure power switch is accessible
- ☐ Insert shear screws
    - ☐ 2 No. 2's for subscale - elaborate on exactly how many
- ☐ Pack the main parachute into the deployment bag
- ☐ Attach the 15ft forward main shock cord to the main parachute
- ☐ Attach the 30ft forward main shock cord to the main parachute
- ☐ Z-fold the 15ft forward main shock cord
- ☐ Use painter's tape to "break band" the 15ft forward main shock cord
- ☐ Z-fold the 30ft aft main shock cord
- ☐ Use painter's tape to "break band" the 30ft aft main shock cord
- ☐ Attach the 15ft forward main shock cord to the nose cone eyebolt
- ☐ Confirm BP charges are correct with team mentor and Chief Engineer

⚠At this point, only the Structure Team Lead, R&P Team Lead, and Chief Engineer should be handling the rocket

- ☐ Attach the 30ft aft main shock cord to the forward bulkhead of the avionics coupler
- ☐ Pull forward tube over the avionics coupler, ensuring holes are lined up
- ☐ Have avionics team lead check the holes to ensure power switch is accessible
- ☐ Insert shear screws in forward connection
- ☐ Immediately before taking rocket to launch rail, avionics team lead turn on the GPS arming switch and confirm GPS lock and communications with base station
- ☐ When rocket is on launch rail, avionics team lead flip the arming switches for the flight computers and the Raspberry Pi

Team Lead:__________ Safety Officer:__________

Motor Procedure

Supplies

- ☐ Motor
- ☐ Motor Casing

Procedure

To be completed by team mentor

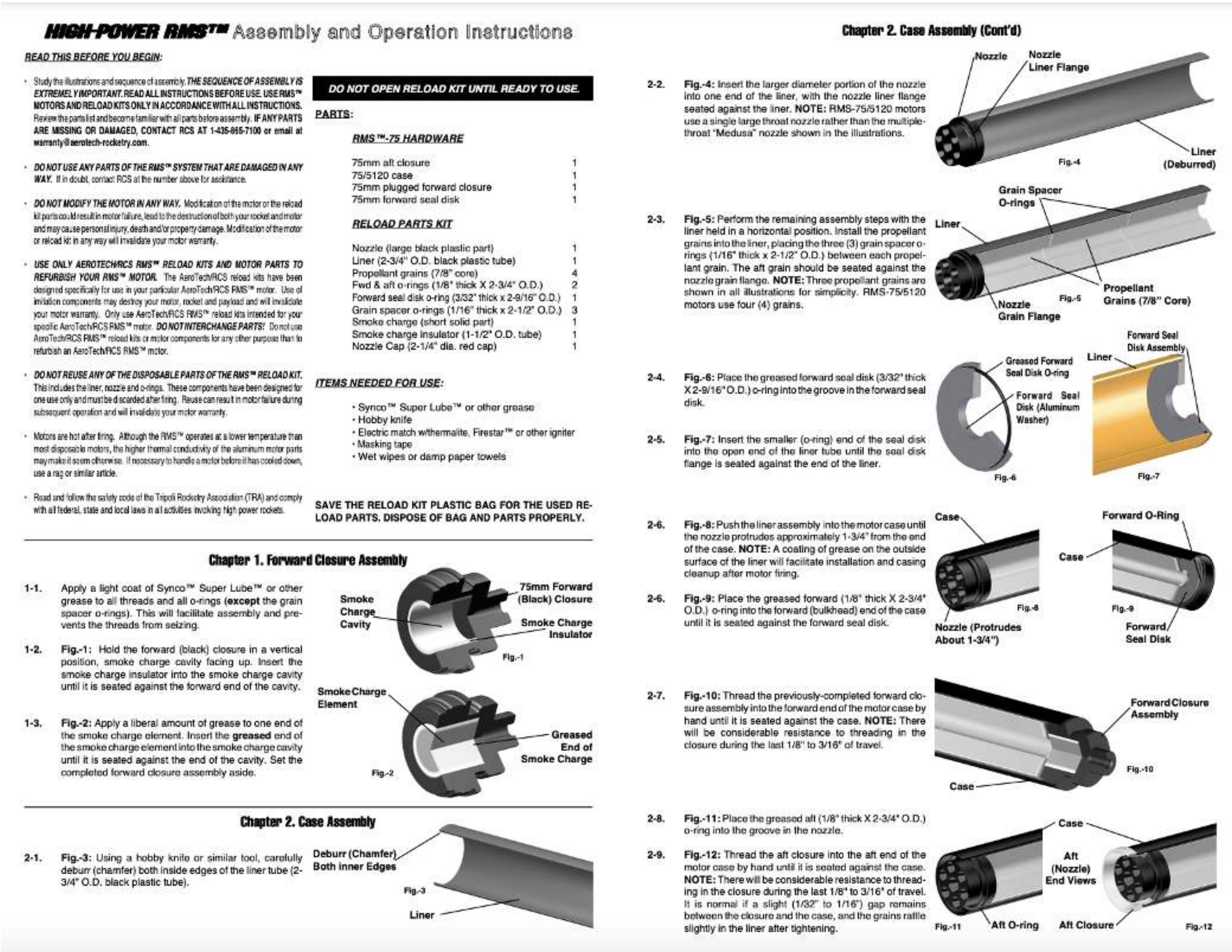
⚠**The motor is loaded. Do not aim the end of the rocket at any person.**

⚠**Lift the rocket slowly and carefully.**

- ☐ Follow standard High-Power RMS rocket motor preparation procedure below

Team Lead:__________ Safety Officer:__________

MOTOR PREPARATION PROCEDURE



HIGH-POWER RMS™ Assembly and Operation Instructions

READ THIS BEFORE YOU BEGIN:

- Study the illustrations and sequence of assembly. ***THE SEQUENCE OF ASSEMBLY IS EXTREMELY IMPORTANT. READ ALL INSTRUCTIONS BEFORE USE. USE RMS™ MOTORS AND RELOAD KITS ONLY IN ACCORDANCE WITH ALL INSTRUCTIONS.*** Review the parts list and become familiar with all parts before assembly. **IF ANY PARTS ARE MISSING OR DAMAGED, CONTACT RCS AT 1-435-865-7100 or email at warranty@aerotech-rocketry.com.**
- ***DO NOT USE ANY PARTS OF THE RMS™ SYSTEM THAT ARE DAMAGED IN ANY WAY.*** If in doubt, contact RCS at the number above for assistance.
- ***DO NOT MODIFY THE MOTOR IN ANY WAY.*** Modification of the motor or the reload kit parts could result in motor failure, lead to the destruction of both your rocket and motor and may cause personal injury, death and/or property damage. Modification of the motor or reload kit in any way will invalidate your motor warranty.
- ***USE ONLY AEROTECH/RCS RMS™ RELOAD KITS AND MOTOR PARTS TO REFURBISH YOUR RMS™ MOTOR.*** The AeroTech/RCS reload kits have been designed specifically for use in your particular AeroTech/RCS RMS™ motor. Use of imitation components may destroy your motor, rocket and payload and will invalidate your motor warranty. Only use AeroTech/RCS RMS™ reload kits intended for your specific AeroTech/RCS RMS™ motor. ***DO NOT INTERCHANGE PARTS!*** Do not use AeroTech/RCS RMS™ reload kits or motor components for any other purpose than to refurbish an AeroTech/RCS RMS™ motor.
- ***DO NOT REUSE ANY OF THE DISPOSABLE PARTS OF THE RMS™ RELOAD KIT.*** This includes the liner, nozzle and o-rings. These components have been designed for one use only and must be discarded after firing. Reuse can result in motor failure during subsequent operation and will invalidate your motor warranty.
- Motors are hot after firing. Although the RMS™ operates at a lower temperature than most disposable motors, the higher thermal conductivity of the aluminum motor parts may make it seem otherwise. If necessary to handle a motor before it has cooled down, use a rag or similar article.
- Read and follow the safety code of the Tripoli Rocketry Association (TRA) and comply with all federal, state and local laws in all activities involving high power rockets.

DO NOT OPEN RELOAD KIT UNTIL READY TO USE.

PARTS:

RMS™-75 HARDWARE

75mm aft closure	1
75/5120 case	1
75mm plugged forward closure	1
75mm forward seal disk	1

RELOAD PARTS KIT

Nozzle (large black plastic part)	1
Liner (2-3/4" O.D. black plastic tube)	1
Propellant grains (7/8" core)	4
Fwd & aft o-rings (1/8" thick X 2-3/4" O.D.)	2
Forward seal disk o-ring (3/32" thick x 2-9/16" O.D.)	1
Grain spacer o-rings (1/16" thick x 2-1/2" O.D.)	3
Smoke charge (short solid part)	1
Smoke charge insulator (1-1/2" O.D. tube)	1
Nozzle Cap (2-1/4" dia. red cap)	1

ITEMS NEEDED FOR USE:

- Synco™ Super Lube™ or other grease
- Hobby knife
- Electric match withermalite, Firestar™ or other igniter
- Masking tape
- Wet wipes or damp paper towels

SAVE THE RELOAD KIT PLASTIC BAG FOR THE USED RE-LOAD PARTS. DISPOSE OF BAG AND PARTS PROPERLY.

Chapter 1. Forward Closure Assembly

1-1. Apply a light coat of Synco™ Super Lube™ or other grease to all threads and all o-rings (**except** the grain spacer o-rings). This will facilitate assembly and prevents the threads from seizing.

1-2. **Fig.-1:** Hold the forward (black) closure in a vertical position, smoke charge cavity facing up. Insert the smoke charge insulator into the smoke charge cavity until it is seated against the forward end of the cavity.

1-3. **Fig.-2:** Apply a liberal amount of grease to one end of the smoke charge element. Insert the **greased** end of the smoke charge element into the smoke charge cavity until it is seated against the end of the cavity. Set the completed forward closure assembly aside.

Chapter 2. Case Assembly

2-1. **Fig.-3:** Using a hobby knife or similar tool, carefully deburr (chamfer) both inside edges of the liner tube (2-3/4" O.D. black plastic tube).

Chapter 2. Case Assembly (Cont'd)

2-2. **Fig.-4:** Insert the larger diameter portion of the nozzle into one end of the liner, with the nozzle liner flange seated against the liner. **NOTE:** RMS-75/5120 motors use a single large throat nozzle rather than the multiple-throat "Medusa" nozzle shown in the illustrations.

2-3. **Fig.-5:** Perform the remaining assembly steps with the liner held in a horizontal position. Install the propellant grains into the liner, placing the three (3) grain spacer o-rings (1/16" thick x 2-1/2" O.D.) between each propellant grain. The aft grain should be seated against the nozzle grain flange. **NOTE:** Three propellant grains are shown in all illustrations for simplicity. RMS-75/5120 motors use four (4) grains.

2-4. **Fig.-6:** Place the greased forward seal disk (3/32" thick X 2-9/16" O.D.) o-ring into the groove in the forward seal disk.

2-5. **Fig.-7:** Insert the smaller (o-ring) end of the seal disk into the open end of the liner tube until the seal disk flange is seated against the end of the liner.

2-6. **Fig.-8:** Push the liner assembly into the motor case until the nozzle protrudes approximately 1-3/4" from the end of the case. **NOTE:** A coating of grease on the outside surface of the liner will facilitate installation and casing cleanup after motor firing.

2-6. **Fig.-9:** Place the greased forward (1/8" thick X 2-3/4" O.D.) o-ring into the forward (bulkhead) end of the case until it is seated against the forward seal disk.

2-7. **Fig.-10:** Thread the previously-completed forward closure assembly into the forward end of the motor case by hand until it is seated against the case. **NOTE:** There will be considerable resistance to threading in the closure during the last 1/8" to 3/16" of travel.

2-8. **Fig.-11:** Place the greased aft (1/8" thick X 2-3/4" O.D.) o-ring into the groove in the nozzle.

2-9. **Fig.-12:** Thread the aft closure into the aft end of the motor case by hand until it is seated against the case. **NOTE:** There will be considerable resistance to threading in the closure during the last 1/8" to 3/16" of travel. It is normal if a slight (1/32" to 1/16") gap remains between the closure and the case, and the grains rattle slightly in the liner after tightening.

MOTOR PREPARATION PROCEDURE

Chapter 3. Preparation For Flight

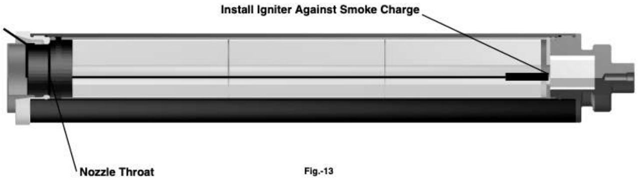


Fig.-13

3-1. **Fig.-13:** Insert the coated end of a Firestar™ or other igniter through the nozzle throat until it stops against the smoke charge element.

3-2. Secure the igniter to the nozzle with a piece of masking tape or the 2-1/4" dia. red nozzle cap supplied with the reload kit. NOTE: Cut a 1/8"-1/4" wide slot in the corner of the cap to allow for igniter venting.

3-3. Install the motor into the rocket's motor mount tube. Ensure that the motor is securely retained in the rocket by using positive mechanical means to prevent it from being ejected during recovery system deployment.

3-4. Prepare the rocket's recovery system and then launch the rocket in accordance with the Tripoli Rocketry Association (TRA) Safety Code and National Fire Protection Association (NFPA) Code 1127.

Chapter 4. Post-Recovery Cleanup

NOTE: Perform motor clean-up as soon as possible after motor firing. Propellant and smoke charge residues become difficult to remove after 24 hours and can lead to corrosion of the metal parts. Place the spent motor components in the reload kit plastic bags and boxes and dispose of properly.

4-1. After the motor has cooled down, unthread and remove the forward and aft closures.

4-2. Remove the smoke charge insulator from the forward closure and discard. Using wet wipes or damp paper towels, remove all smoke charge and propellant residues from the closures.

4-3. Remove and discard the forward and aft o-rings from the motor case. Remove the liner, forward seal disk and nozzle from the casing by pushing on the nozzle end. Remove the forward seal disk from the liner, and remove and discard the forward seal disk o-ring. ***DO NOT DISCARD THE FORWARD SEAL DISK!*** Discard the nozzle and liner. Using wet wipes or damp paper towels, wipe the inside of the casing and the forward seal disk to remove all propellant residue.

4-4. Apply a light coat of grease to all threads and the inside of the motor case. Reassemble metal parts and store motor in a dry place.

Chapter 5. First Aid

WARNING: For a minor burn, apply a burn ointment. For a severe burn, immerse the burned area in ice water at once and see a physician as quickly as possible. In the unlikely event of oral ingestion of the propellant, induce vomiting and see a physician as quickly as possible. The AeroTech/RCS composite propellant consists primarily of Ammonium Perchlorate and a rubber-like plastic elastomer.

Chapter 6. Disposal

Damaged or defective reload kits should be returned to RCS.

Chapter 7. Fire Safety

Tests show that the pyrotechnic components of RMS™ reload kits will not explode in fires and normally will not ignite unless subjected to direct flame and then will burn slowly. Use water to fight any fires in which AeroTech/RCS RMS™ reload kit pyrotechnic components may become involved: Direct the water at the AeroTech/RCS RMS™ reload kit pyrotechnic components to keep them below their 550 deg. F autoignition temperature. Foam and carbon dioxide fire extinguishers will NOT extinguish burning propellants of the type used in RMS™ reload kit pyrotechnic components. Keep reload kit pyrotechnic components away from flames, sources of heat and flammable materials.

Disclaimer and Warranty

NOTICE: As we cannot control the storage and use of our products, once sold we cannot assume any responsibility for product storage, transportation or usage. RCS shall not be held responsible for any personal injury or property damage resulting from the handling, storage or use of our product. The buyer assumes all risks and liabilities therefrom and accepts and uses AeroTech/RCS products on these conditions. No warranty either expressed or implied is made regarding AeroTech/RCS products, except for replacement or repair, at RCS's option, of those products which are proven to be defective in manufacture within one year from the date of original purchase. For repair or replacement under this warranty, please contact RCS. Proof of purchase will be required. Note: Your state may provide additional rights not covered by this warranty.

AeroTech Division
RCS Rocket Motor Components, Inc.
Cedar City, UT 84720
www.aerotech-rocketry.com

P/N 20087 Rev. 12/30/09
Made in U.S.A.

AEROTECH® CONSUMER AEROSPACE Division of RCS Rocket Motor Components, Inc.

HIGH-POWER RMS™
Reloadable Motor System™
RMS™ 75/5120 BLACK MAX™

This Package Contains One Reload Kit:

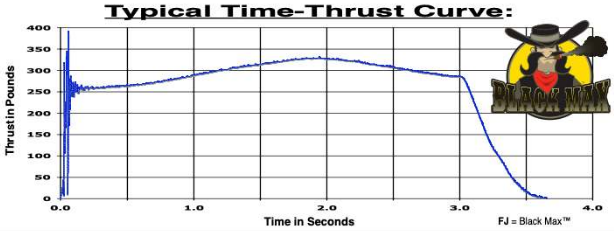
☐ ***L1170FJ-P*** (75/5120)

NOTE: This reload kit MUST be used with separately packaged L1170FJ propellant grains (P/N 03616-4) and motor liner tube (03035-4). RMS™-75 reload kits do not include an ejection charge. RMS™-75 motors must be used in conjunction with a timer, altimeter or radio-actuated recovery system.

NOTE: This reload kit is *ONLY* for use in AeroTech/RCS, Dr. Rocket™ or Rouse-Tech™ RMS™ 75/5120 high-power motors. Certified by the Tripoli Rocketry Association (TRA).

DO NOT OPEN RELOAD KIT UNTIL READY TO USE

Typical Time-Thrust Curve:



RMS™ 75MM BLACK MAX RELOAD KIT DATA

Hardware Designation	Performance Designation	Total Impulse (Typical)	Propellant Weight	Loaded Motor Weight
RMS™-75/5120	*L1170FJ-P*	4,218 N-sec	2,800 g (6.17 lb)	5,021 g (11.06 lb)

NOTE: Total impulse shown is typical.

RMS™ 75MM HARDWARE DATA

Hardware Designation	Motor Diameter	Motor Length	Hardware Weight	Reload(s) Used
RMS™-75/5120	2.965" (75mm)	26.20"	1,408 g (3.10 lb)	L1170FJ-P

NOTE: Motor lengths are measured from end of aft closure to end of forward closure.

NOTE: SALE TO PERSONS UNDER 18 YEARS OF AGE PROHIBITED BY FEDERAL LAW. WARNING-FLAMMABLE: Read Instructions Before Use. KEEP OUT OF REACH OF CHILDREN. FOR USE ONLY BY CERTIFIED HIGH-POWER USERS 18 YEARS OF AGE OR OLDER. DO NOT SMOKE when loading these motors or use in the vicinity of open flames.

Setup on Launch Pad Procedure

Supplies

- ☐ 1515 Launch Rails
- ☐ Fully Assembled Rocket
- ☐ Flat Head Screwdriver

Procedure

To be completed by mentor and two L2 certified members

⚠**The rocket is live. Do not aim the end of the rocket at any person.**

⚠**Lift the rocket slowly and carefully.**

- ☐ A minimum of 2 team members, who are High Power Rocket certified, will carry the rocket to the launch rail
- ☐ Inspect the rail to ensure it is in proper condition and ready for launch

⚠**Move the rail slowly to not disturb connections.**

- ☐ With the assistance and oversight of a High Power Rocket certified member or the team mentor, tilt the launch rail to an angle such that the rocket can be easily slid onto the rail, insert the two rail buttons, and return the now connected rail and rocket to the upright position.

⚠**Beware of pinch points when turning on switches.**

- ☐ With a flat head screwdriver, turn the arming switch for one flight computer to the on position and monitor the flash of the LED in conjunction with the audible tone produced by the flight computer to ensure proper startup and power connection to the flight computer. Now, beeping/LED flashes should come 3 beeps at a time, indicating that main and drogue ejection charges have been detected. Repeat these steps with the redundant flight computer.

Team Lead:__________ Safety Officer:__________

Ignitor Installation Procedure

Supplies

- ☐ Ignitor
- ☐ Wire Stripper
- ☐ 12VDC Firing Module

Procedure

To be completed by mentor

⚠**The motor is live. Do not aim the motor at any person.**

⚠**Beware of shock hazards while handling live electronics.**

- ☐ Ensure the 12VDC firing module is turned to off

⚠**Beware of sharp points of lead wires.**

- ☐ Separate the leads on the bottom of the ignitor

⚠**Beware of sharp edges of wire stripper.**

- ☐ Strip each lead to expose approximately 1 inch of wire

⚠**Beware of sharp points of lead wires.**

- ☐ Attach one lead to the positively charged (red wire) alligator clip and wrap the wire around the clip to ensure good connection
- ☐ Attach the other lead to the negatively charged (black wire) alligator clip and wrap the wire around the clip to ensure good connection
- ☐ Bend the ignitor into a Z-shape and place it into the motor opening on the bottom of the aft section of the rocket. The motor should sit as high as possible in this opening.

Team Lead:__________ Safety Officer:__________

Launch Procedure

Supplies

- ☐ Ignitor

Procedure

To be completed by RSO, Mentor, and two L2 Certified Members

⚠**The rocket is live. Do not aim the end of the rocket at any person.**

- ☐ Walk at least 300’ from the rocket and clear a diameter of at least 100’
- ☐ Communicate to the RSO that the rocket is ready to launch

⚠**Ensure all members are quiet and attentive during countdown.**

- ☐ RSO begins countdown from 5 to launch
- ☐ If the rocket does not launch, RSO waits 10 seconds and initiates new countdown
- ☐ If the rocket still does not launch, certified members wait 60 seconds before approaching to inspect the ignitor and attempt to diagnose the issue

Team Lead:__________ Safety Officer:__________

Troubleshooting Procedure

Supplies

- ☐ 9V Battery
- ☐ Wire Stripper
- ☐ Soldering Iron
- ☐ WD-40
- ☐ Quick Links
- ☐ Payload Filler Material (paper, cardboard, foil)
- ☐ Scissors
- ☐ Toolkit
- ☐ 15 minute epoxy

Procedures for Avionics Troubleshooting

Problem to troubleshoot: GPS to Base Station connection failed

Re-check connection upon completion of each step

⚠**Beware of shock hazards from live electronics.**

⚠**Beware of pinch points when connecting wires**

- ☐ Disconnect and reconnect power to the GPS
- ☐ Check all connections to ensure they are secure and not shorted
  - ☐ LiPo to GPS
  - ☐ TeleGPS to Antenna
  - ☐ TeleGPS to Base Station Computer
- ☐ Connect the GPS directly to the Base Station
  - ☐ Open user interface and connect or configure TeleGPS manually
  - ☐ Verify battery charge using Altos to monitor TeleGPS

Team Lead:__________ Safety Officer:__________

Problem to troubleshoot: GPS lock failed

Re-check GPS lock upon completion of each step

⚠**Beware of shock hazards from live electronics.**

⚠**Beware of pinch points when turning on switches.**

- ☐ Verify the charge of the GPS LiPo with user interface
- ☐ Disconnect and reconnect power to the TeleGPS
- ☐ Verify the GPS is out of range of any significant sources of interference (telephones, radios, transmitters, metal barns, etc.)

- ☐ Verify the TeleGPS is not obstructed by any large structures that may inhibit signal transfer (metal barns, etc.)

Team Lead:__________ Safety Officer:__________

Problem to troubleshoot: Wire connections are cut or otherwise disconnected

⚠**Beware of shock hazards from live electronics.**
⚠**Beware of sharp edges of wire stripper.**
- ☐ Strip both sides of disconnected wires. If extra wire length is needed, strip both ends of an additional wire for soldering connection

⚠**Beware of sharp edges on stripped wires.**
- ☐ Twist the wires together where connections are needed to initiate soldering points
- ☐ Obtain damp paper towel that will be used for cleaning the soldering iron

⚠**Beware hot surfaces on solder and soldering iron. Wear eye protection.**
- ☐ After powering on and heating up the solder, use the solder on all solder connections using the damp towel to clean it when necessary
- ☐ Insulate all new solder joints to prevent accidental shorts using electrical tape

Team Lead:__________ Safety Officer:__________

Procedures for Recovery and Propulsion Troubleshooting

Problem to troubleshoot: Parachutes or shock cords become tangled

⚠**Beware pinch points during detachment**
- ☐ Detach recovery system from the rocket and detangle any knots that developed

⚠**Beware pinch points during attachment**
- ☐ Re-attach recovery system to rocket, refold shock cords, and re-pack parachutes

Team Lead:__________ Safety Officer:__________

Problem to troubleshoot: Threading on recovery connection quick link is damaged

⚠**Beware pinch points when using quick links**
- ☐ Use WD-40 to loosen the opening and closing of the quick link
- ☐ Replace quick link from surplus

Team Lead:__________ Safety Officer:__________

Procedures for Payload Troubleshooting

Problem to troubleshoot: Body tube diameter interfering with payload install

⚠ **Beware of shock hazards from live electronics.**
⚠ **Avoids sharp edges of body tube**

- ☐ To fill space that is not reached by the payload bay encasing, use paper or cardboard to fill this space. These materials are chosen because they will not damage electrical components and are not good conductors.
- ☐ To shorten the payload encasing if it is too long, use a mallet to hammer in the payload and ensure holes are lined up

Team Lead:__________ Safety Officer:__________

Problem to troubleshoot: Screws to secure payload fails to tighten

⚠ **Beware of shock hazards from live electronics.**
⚠ **Avoids sharp edges of body tube**

- ☐ Ensure the payload bay holes are aligned with the proper body tube holes before sliding the payload bay into the body tube.

⚠ **Be careful to not over-torque screws and cause damage or injury**

Team Lead:__________ Safety Officer:__________

Post-flight Inspection Procedure

Supplies

- ☐ Camera
- ☐ Philips Head Screwdriver
- ☐ Avionics Base Station Computer

Procedure

To be completed by Structures, Recovery, Avionics, and Payload

⚠**Avoid sharp edges of body tube**

- ☐ Upon approaching the rocket, focus should be on the avionics bay and determining that the black powder charges have all detonated. If Avionics team has any preliminary flight data, they should try to point out drogue detonations
- ☐ Approach rocket cautiously and take photos of landing site
- ☐ Inspect forward, mid, and aft body tubes for any damage
- ☐ Inspect fins and nose cone for damage

⚠**If black powder residue is not present, treat charge cups as live black powder and do not aim at any person**

- ☐ Now, closely inspect black powder charges for proper ignition
  - ☐ If charge has not detonated, ensure there are no loose or frayed wires near the ejections canisters
- ☐ Inspect parachute shock chords for any fraying or singeing
- ☐ Inspect drogue and main parachute for rips, tears, and holes

⚠**Treat aft end of rocket as live and do not aim at any person**

- ☐ Inspect motor tube to ensure proper burn out

⚠**Avoids sharp edges of body tube**

- ☐ After complete outer inspection, remove avionics bay

⚠**Beware of shock hazards from live electronics.**

- ☐ Connect avionics bay to base station computer to obtain flight data
- ☐ Remove payload bay and inspect for proper camera deployment

Team Lead:__________ Safety Officer:__________

Table 50: Risk Assessment Categories

Category	**Represented Percentage Range**
Rare	0% - 25%
Unlikely	25% - 50%
Possible	50% - 75%
Likely	75% - 100%

The primary goal of the likelihood categorization is to quantify the likelihood of some hazard leading to an event that causes harm either to the rocket or to a person. The extent of an injury or rocket damage is independent of these percentages, and high likelihood percentages do not necessarily mean the injury or damage will be extensive and likewise with lower percentages. The primary goal of the severity categorization is to quantify the extent of harm or damage that could occur due to different failures. The safety team analyzed risks for all the materials and facilities that are used during the construction and launch process.

Table 51: Risk Severity Categories

Category	**Severity To Human**	**Severity To Rocket**
Minor	Injury requiring no treatment.	Superficial damage to rocket requiring no repair.
Moderate	Injury requiring some medical care/treatment (bandage, ice, etc.).	Damage to the rocket requiring some repairs (retighten hardware, re-align component, etc.)
Major	Injury requiring professional medical care/treatment (sutures, concussion protocol, etc.)	Damage requiring significant repair (Patching parachute, correcting bent components, etc.)
Severe	Injury requiring hospitalization or other prolonged treatment	Damage requiring purchase of entirely new component

Table 52: Personnel Hazard Analysis

Risk	Likelihood	Cause	Effect	Severity	Mitigation	Verification
Burns to skin from hot tools, machines, or parts	Rare	Incorrect or lacking PPE while performing tasks, insufficient training on machine or tool usage techniques	Damage to skin or body, scarring	Moderate	Members are trained to use each tool and machine properly and wear PPE when necessary	Safety Officer maintains up to date information on trainings and certifications for each team member. Safety Officer or Chief Engineer oversees machining tasks verifying proper PPE and techniques
Contact with rotating or fast moving parts in machines	Rare	Incorrect use of machines due to improper training or careless workflow procedures	Bodily injury in the form of lacerations, bruises, burns, or broken bones	Major	All team members complete training and certification for usage of machines in the shop and makerspace, safety briefings conducted before rocket construction begins and immediately after any known breach of safety rules or event in which member is harmed	Safety Officer maintains up to date information on trainings for team members. Safety Officer or Chief Engineer oversees machining tasks verifying correct usage of machines.

Harmful contact with fiberglass parts	Possible	Incorrect or insufficient PPE, careless or rushed movements in machining or transporting fiberglass components	Bodily injury in form of cuts, lacerations, splinters	Minor	Members must wear PPE when working with fiberglass including safety glasses, gloves, long pants, and closed shoes	Safety Officer informs team members of proper PPE required for different tasks, including tasks with fiberglass. Safety Officer or Chief Engineer overses construction activities including working with fiberglass.
Inhalation of toxic or inflammatory fumes from epoxy and other toxic chemicals	Possible	Incorrect or insufficient PPE when working with epoxy and other chemicals	Respiratory harm, difficulty breathing, headaches	Major	Materials Safety Data Sheet is up to date and available to all team members. Safety Officer reviews the location of this file with team members periodically so team always knows where to find it. Members conducting activities with toxic chemicals are briefed by Safety Officer before the activity.	Safety officer keeps up to date list of team members training and certifications, including list with names of members who attended briefings on toxic chemical usage. Safety Officer or Chief Engineer oversee all construction processes including epoxying.

Skin contact with epoxy or other inflammatory materials	Possible	Incorrect or insufficient PPE, careless transport of components or materials	Burns, rashes, inflammation	Minor	Materials Safety Data Sheet is up to date and available to all team members. Safety Officer reviews the location of this file with team members periodically so team always knows where to find it. Members conducting activities with toxic chemicals are briefed by Safety Officer before the activity.	Safety officer keeps up to date list of team members training and certifications, including list with names of members who attended briefings on toxic chemical usage. Safety Officer or Chief Engineer oversee all construction processes.
Spread of illness from close contact in meetings	Possible	Viral infections going around, time of year, close contact	Illness	Minor	If illness seems to be spreading at WashU or amongst the team, the Exec team will move meetings to Zoom whenever possible, sick team members will not attend in-person meetings	Safety Officer and President keep track of attendance with reasons why members might miss, allowing for tracking of illness-related absences to monitor health of team
Severe illness from weather conditions	Rare	Unprepared members during launches	Heat stroke or frost bite	Major	Safety Officer informs team of the weather conditions prior to launch; Exec team coordinates presence of food and water at launches	Safety Officer confirms launch plan with President and informs team of conditions

Inhalation of toxic fumes from battery fire	Unlikely	Improper storage or charging of batteries, specifically Lipo batteries, can lead to battery burnouts.	Depending on the nature of the burnout, carbon monoxide or hydrogen flouride could be released as a product of the burn, both of which are toxic to humans. Carbon monoxide decreases oxygen uptake and hydrogen flouride can turn to hydroflouric acid in the nose and throat causing extensive irritation and tissue damage.	Severe	Safety Officer ensures that all teams members that use and store batteries are aware of the proper storage and charging protocols. In the event of a fire, all team members have been made aware by the Safety Officer to avoid fumes and only approach a burn with proper masking and PPE once safe to do so.	Safety Officer inspects the storage of batteries in team storage facilities and ensures all team members using batteries know the proper charging protocol.

Inhalation of machining dust with fiberglass fragments	Possible	Insufficient PPE for machining fiberglass and improper machining training.	Inflammation of nasal passages and throat, difficulty breathing.	Moderate	Safety Officer ensures that all teams members involved in drilling or cutting fiberglass body tubes are properly trained on the hazards of fiberglass fragments and understand the necessary PPE required - masks and safety glasses.	Safety Officer and Chief Engineer oversee all machining activity and ensure proper PPE is being used.
Contact injuries from hand tools (files, drills, hammers, mallets, screwdrivers, etc.)	Possible	Insufficient background training and experience with hand tools.	Scrapes, cuts, bruises to body from hand tool.	Moderate	While no specific training certification is required to use hand tools, the hand tools are used in the Machine Shop and Makerspace, and these facilities require training to use. The Safety Officer will converse with each team that is working in these facilities and make sure that members understand how to use hand tools properly and safely.	Safety Officer and Chief Engineer oversee all machining activity and ensure proper PPE is being used.

Injuries from transportation-related accidents to WURocketry events.	Unlikely	Unsafe transportation methods or illegal practices being used (too many team members in a vehicle above the legal amount of passengers)	Minor injuries to life-threatening injuries based on extent of accident.	Severe	WURocketry will practice safe transportation methods and abide by United State and Missouri state law when transporting members to team-related events. Safety Officer will monitor designated drivers, and team will abide by maximum continuous driving times allowed by the university's club rules.	Safety Officer stays up to date on University's driving time requirements for student clubs and checks in with members that designated drivers are driving safely and legally.
Allergic reaction to food or drinks present at rocketry activities.	Unlikely	Lack of consideration of allergies by team members	Allergic reaction causing difficulty breathing, rashes, or other medical emergencies	Severe	While food is not explicitly outlawed, team members will only have food where it is allowed by University facilities. Safety officer will keep a list of team members' food and drink allergies make periodic reminder announcements to avoid these food types at club events if necessary.	Safety Officer maintains allergy list for team members and monitors cooperation with university facility food rules.

Rocket lands on person after descent	Unlikely	Members and observers not paying attention to rocket descent or standing too close to launch pad.	Extensive bodily harm from blunt force trauma.	Severe	Safety Officer will inform the team that when rockets are launched and descending, member are required to always watch the rocket descent and point at the rocket if it starts descending towards any humans on the ground. Minimum distance from launch pad will be maintained according to the rules of the organization hosting the launch and NASA rules and requirements.	Safety Officer will attend launches and ensure that all members are always paying attention when rockets are being launched and that members are pointing at rockets that descend toward the group.

7.2 Failure Modes and Effects Analysis (FMEA)

7.2.1 Payload FMEA

Table 53: Failure Modes and Effects Analysis

Failure	Likelihood	Cause	Effect	Severity	Mitigation	Verification

Structural Retention System Failure	Possible	Forces from launch, parachute deployment, and landing exceed load capacity	Components come loose, can not properly execute mission	Severe	Design and select material to withstand launch, deployment, and landing forces	Drop tests and FEA load simulations for retention structures and materials
Nosecone Retention Failure	Unlikely	Latching mechanism within the body tube break from shear stress	Fractures the payload camera deployment rails	Severe	Ensure latching mechanism material is durable enough and firmly locked into place prior to flight	Drop tests, and FEA load simulations
Battery short	Rare	Poor battery quality; battery overheated	Electronic components die, unable to receive commands, motors unable to drive camera deployment	Severe	Choose battery with reliable and appropriate power output	Payload team leads checks battery requirements and new batteries used for launch
Wire detaching	Possible	Battery wiring incorrect	Damage to electronics	Major	Follow proper procedures on battery wiring	Payload team leads review battery wiring
Transmitter interferes with avionics electronics	Possible	Improper frequencies chosen or transmitted due to software mistakes	Loss of connection with avionics electronics including flight computer and loss of ability to initiate timed BP detonations	Severe	Position transmitter as far as possible from avionics bay, use frequency far from avionics frequency range	Test transmitting signals from both avionics and payload prior to launches

Camera failure	Unlikely	Lens damage during flight	Unable to provide mission critical imaging upon payload deployment	Major	Camera casing system designed to be durable and withstand launch forces	Drop tests and FEA load simulations
Loss of RF Communication	Possible	Vehicle travels out of range, signal interference	Unable to complete mission	Severe	RF module is selected for the simulated vehicle flight range, and electronic components are properly shielded to prevent interference	Payload team inspects the RF component before launch and tests data reception
Failure of pressure sensors to accurately reflect flight regime	Possible	Ventholes not large enough to allow sufficient flow exchange and ambient pressure equalization	Ineffective redundant altitude tracking mechanism	Moderate	Venthole sizes calculated based on theoretical pressure force equations and volume of pressurized chamber. Aerodynamics team runs CFD simulations to analyze flow exchange through vent hole at different points in flight.	Chief Engineer and Safety Officer review vent hole sizing calculations and nose cone/payload retention system is rated for larger force than resulting pressure force if the ventholes were to perform suboptimally.
Servo fails to properly lift the scissor lift	Unlikely	Poor connection of servo to scissor lift, connection disrupted during launch	Failure of payload system to push camera high enough body tubes to take necessary photographs after landing.	Major	Servo to scissor lift connection will be designed to withstand strong forces during launch	Chief Engineer and Payload Lead will ensure proper servo to scissor lift connection during assembly of payload systems.

Payload bearings underperform in righting operation and images are not proper orientation	Possible	Excessive friction between bearing and housing	Failure of payload to take properly oriented photos	Major	Bearings will be bathed in alcohol and then coated in a bearing lubricant cream tp minimize friction.	Payload team will try multiple lubricants and qualitatively see which lubricant works best and ensure that a sufficient amount is applied to each bearing during assembly of the payload.
Nose cone fails to get fully pushed off upon landing	Possible	Motor not strong enough to overcome extra friction added from corn husks in front of the nose cone after landing.	Nose cone does not push off fully and payload system camera can not extend to take required photos.	Severe	Payload design includes strongest motor possible within size and mass constraints, designing and taking into account extra friction force due to corn husks.	Chief Engineer and Payload Lead will review team's motor choice and ensure design accounts for possible extra friction from corn husks.
S Payload system fails to operate after landing due to dead batteries	Unlikely	Batteries die	Entire payload system can not function properly with loss of important part due to dead battery.	Severe	New and fully charged batteries will be used for launches with payload system, payload team will design for long-lasting batteries. Electronics will not be turned on until just before payload system is inserted into rocket.	Chief Engineer and Payload Lead will ensure that batteries expected life is acceptable and that batteries used for launches are new and fully charged.

Parts of payload system fail due to launch forces and payload can not properly orient camera for photos	Unlikely	Centering rings or centering rods are not strong enough to withstand launch forces.	Failure of payload system to function properly.	Severe	Centering ring and centering rod materials designed for high strength and strength tested.	Chief Engineer and Payload Lead ensure that design of centering ring and rods accounts for strong launch forces.

7.2.2 Avionics FMEA

Table 54: Failure Modes and Effects Analysis

Failure	Likelihood	Cause	Effect	Severity	Mitigation	Verification
Battery short	Unlikely	Improper or weak wire connections, possibly caused by movement during setup or flight	Fire that damages electronics and vehicle structures, rendering the vehicle incapable of performing satisfactorily and potentially dangerous to team members	Severe	Use proper soldering techniques and test connections to make sure they are sufficient with multimeter, ensure avionics components are attached securely to the board	Avionics team lead teaches proper soldering techniques, oversees new members demonstrate their soldering abilities before soldering on final components

Power loss	Rare	Faulty or disconnected batteries	Disabling of avionics components and other vehicle communication subsystems, resulting in failure to properly initiate altitude-triggered events like separation and parachute deployment	Major	Maintain and follow a procedure for charging each type of battery and test each battery before rocket assembly, ensure stable connections when batteries are placed into rocket by testing power before and after insertion	Practice battery assembly for rocket prior to launch daya, Safety Officer reviews charging procedures for each type of battery, Chief Engineer oversees battery insertion and placement into subsystems
Loss of communication signal	Unlikely	Poor positioning of directional antenna at base station	Interruption of real-time flight data transmission making recovery difficult without GPS data on landing location, poor quality and continuity of test launch data for test launch review	Minor	Use procedure for proper antenna setup and positioning, with pre-launch checks to confirm that the handshake between rocket and base station is complete and signal is received	Avionics lead tests the signal after assembly, Chief Engineer certifies connection and results before launch

Improper GPS calibration	Rare	Failure to establish or loss of satellite connection due to interference	Poor quality GPS data for test launch analysis and difficulty locating the rocket via GPS data	Moderate	Test connectivity with GPS satellites prior to launch	Avionics lead ensures that reliable GPS connection is established before launch, Chief Engineer approves final connection before rocket is assembled with avionics bay inside
Raspberry Pi Bug	Rare	Software issues not discovered prior to launch	Reliable data not retrieved from computer, issues with GPS data and locating rocket	Moderate	Test all code before launch	Avionics team conducts peer review of code included in all avionics subsystem components, peer-review process overseen by Chief Engineer and other skilled coders on the team
Ejection Timing Failure	Unlikely	Improper pressure reading due to blocked pressure port on flight computer	Failure to initiate ejection events at correct times or altitudes, parachute failures and damage to rocket	Severe	Design avionics bay with extra room for flight computer to ensure unblocked pressure ports	Test flight computer pressure readings before launch
Lipo Fire	Rare	Improper lipo battery connection, or overcharged battery	Fire and damage to components on avionics board and other rocket subsystems	Severe	Design lipo battery casing to withstand launch forces to prevent battery disconnection, obtain documentation on proper lipo charging times and capacity	Test lipo connection prior to launch, charge lipos ahead of launch only to proper charge capacity, Safety Officer obtains and maintains proper battery charging procedures

7.2.3 Recovery and Propulsion FMEA

Table 55: Failure Modes and Effects Analysis

Failure	Likelihood	Cause	Effect	Severity	Mitigation	Verification
Shear pins do not shear	Unlikely	Incorrect (low) black powder charges, charges fail to detonate	Parachute does not eject, catastrophic damage to the rocket due to free fall, danger to humans in landing area	Major	Use more black powder than calculated based on Factor of Safety, Include redundant black powder charge which is 1.25x the amount of the preliminary charge	Test the black powder charge with mentor present, Present results to be confirmed by Chief Engineer
Fire damage to parachutes	Possible	Insufficient protection from flames from black powder detonation, parachute material becomes exposed during flight	Parachute fails to deploy, catastrophic rocket damage from free-fall, Endangerment of humans in landing area with decreased reaction time	Severe	Utilized a deployment bag for main parachute, protective nomex blanket for drogue parachute, include parachutes using final folding and assembly during black powder testing and look for any singes parachute material during these tests, Add dog barf when necessary	Recovery and Propulsion team lead packs parachutes using careful documentation written in conjunction with Safety Officer, Confirm test results with Chief Engineer, Confirm final installation with Chief Engineer

Tangled shroud lines	Likely	Improper parachute packing, movement during flight	Incomplete parachute opening, Catastrophic rocket damage from free-fall or partial free-fall, Unpredictable drift	Moderate	Research and document appropriate packing methods in parachute packing procedures, Test packing methods with drop tests when possible	Demonstrate packing Chief Engineer, Practice parachute packing prior to any launches, Confirm final installation with Chief Engineer
Hardware (quicklink, swivel joint, eyebolt) failure	Rare	Underestimated snatch forces, Insufficient hardware strength, Eye bolt not screwed in fully	Catastrophic rocket damage from free-fall	Severe	Research proper calculation methods for snatch forces, Calculate worst cases snatch force for eye bolt connection design	Validate tensile strengths with experimental testing, Confirm values with Chief Engineer during design reviews, Confirm that eye bolts are properly secured and tightened in final assembly with Chief Engineer
Fire Damage to Shock Cords	Possible	Insufficient protection against black powder charges	Shock cords fray and rip during flight, resulting in freefall of a body section of the rocket	Moderate	Protect shock cords at risk of burn from black powder with nomex blankets and kevlar sleeves	Clarify protection method of nomex blankets around the shock cords with Chief Engineer during assembly prior to flight.

Shock Cords Twisting or Tangling	Possible	Insufficient shock cord lengths used for parachutes, lack of swivel joint hardware in recovery system.	Poor parachute performance, excessive descent speed, impact speed, and impact kinetic energy.	Major	Design for long shock cords to mitigate fast tangling, include swivel joints in the recovery hardware attachments.	Chief Engineer and Recovery team lead will ensure that shock cord lengths in design phase are appropriately long and that recovery hardware includes swivels.
Drogue Parachute wrapping around the Main Parachute	Rare	Improper length differences between drogue and main parachute shock cords.	Main parachute fails to fully inflate.	Severe	Design shock cord lengths with potential overlap between parachutes in mind.	Chief Engineer and Recovery team lead ensure that shock cord lengths are appropriate to mitigate tangling.
Black Powder Charges do not go off	Rare	Ejection canisters incorrectly fixed, team mentor incorrectly connects e-matches	Rocket does not separate and free falls out of sky	Severe	Use team mentor that has rocketry experience and experience with hooking up e-matches.	Chief Engineer ensure that Structures team properly connects ejection canisters to the rods extending from bulkheads.

7.2.4 Structures FMEA

Table 56: Failure Modes and Effects Analysis

Failure	Likelihood	Cause	Effect	Severity	Mitigation	Verification

Plywood board fracture	Possible	Snatch force from parachute deployment	Structural fracture/failure and damage to rocket, New weaknesses in airframe due to structural damage	Major	Research plywood force ratings and calculated allowable forces with factor of safety, design with worst case flight forces considered	Use CAD models to simulate forces and ensure plywood can withstand these forces
Fin fracture	Unlikely	Flutter in fins from high flight turbulence, or impact damage, increased drag on fins due to failure of new fin covers	Fin damage leading to unstable flight path, critical damage to rocket	Severe	Research flutter calculations and consult Chief Engineer to choose best calculation method, multiple structures members calculate these flutter values to cross-check and verify results	Use CAD models when possible to check the allowable forces, Chief Engineer confirms calculated vibrations are allowable given fin design
Bulkhead fracture	Rare	Large shear force at connection points	Catastrophic damage to rocket due to free-fall, danger to humans in landing area	Severe	Research calculation methods for shear of bulkheads and verify these methods with Chief Engineer, test bulkhead shear strength in school labs when available	Use CAD models to check the allowable forces, Chief Engineer confirms the forces calculated are below requirements with factor of safety considerations, Require larger safety factor to reduce likelihood of failure

Airframe buckling	Rare	Compression force from rocket during launch or upon landing impact	Catastrophic damage to rocket due to free-fall, Danger to human in landing area, Unstable flight conditions and unstable flight path	Severe	Test airframe material in school labs when possible, calculate compressive forces from both maximum motor forces and maximum ground impact forces	Use CAD models when possible to check the allowable forces with large safety factor, Chief Engineer confirms that the forces involved are below requirements
Fin shells break off and fall free fall	Possible	Fin shells not attached properly	Free falling object present danger to observers and team members below, unstable rocket ascent with asymmetric fin attachments.	Moderate	All structures members are trained to epoxy before epoxying and the fin shells are inspected after epoxying to ensure sufficient connection.	Inspect fin shells for proper attachment, Chief Engineer oversees epoxying activities.
Mass of rocket comes in overweight leading up to launch	Rare	Improper accounting of masses across subsystems. Insufficient machining of bulkheads, payload components	Failure to reach target apogee and changes in center of mass affecting stability of rocket	Major	Subsystem parts will be weighed often throughout the machining and construction process of the rocket during the year. Mass accounting will stay up to date with any changes made to the design reflected in the mass accounting tables.	Before launches, a final practice assembly and preparation will be performed and the fully assembled rocket will be weighed to verify it is within weight margins.

Friction between body tubes presents difficulty assembling rocket or issues with separation	Unlikely	Incorrect tolerancing for body tube fittings, foreign material stuck to body tubes from external sources due to careless construction of other subsystems	Failure to assemble rocket, failure to separate and release parachutes	Major	Sliding fit tolerancing will be used for body tube fittings, baby powder will be brought to launches and spread along the body tube to body tube connection points, foreign materials like glue, epoxy, etc. will be sanded and removed from body tubes.	Chief engineer will inspect body tubes for foreign material contamination, team will ensure body tubes fit together during assembly practice prior to launch.

7.3 Environmental Concerns for Launch Site

Table 57 includes both concerns for the environment that a rocket launch poses, as well as concerns that the environment and weather pose to the team during an attempted launch.

Table 57: Environmental Concerns for Launch Site

Concern	Likelihood	Cause	Effect	Severity	Mitigation	Verification
Fire near launch rail	Possible	Motor ignition failure, improper connection of ignitors, burning of dry grass in the exhaust plume of the rocket upon launch	Damage to environment at launch site, risk of injury to team members if fire spreads or team members are not safe distance away, harm to wildlife if fire spreads	Severe	Verify e-match connections with team mentor, purchase motor from reputable dealer, use safe storage techniques for motor, check launch site conditions	Confirm final installation of ignitor with Chief Engineer, Safety Officer, and team mentor, follow prescribed launch preparations procedures and operations

Rocket parts break off upon impact with ground and leave polluting materials behind	Unlikely	Crashed rocket, Loose hardware, careless rocket preparation and cleanup procedures	Pollution of launch site habitat, harm to local wildlife	Moderate	Test components connections, test hardware for sufficient fastening; follow construction procedure without rushing, clean up after launch	Chief engineer confirms finals attachments and fastenings, exec team supervises cleanup procedure after launch
Team leaves materials behind at the launch site including forgotten items and garbage	Unlikely	Careless rocket preparation and cleanup procedures, rushing to leave	Pollution of launch site habitat, harm to local wildlife and agriculture	Minor	Have concentrated clean up period after each launch with each subteam being responsible for accounting for all of the items they brought the launch in their specific subteam box.	Exec team (President, Chief Engineer, Safety Officer, and Program Manager) oversee the cleanup after launches and are the last to leave, ensuring that all items, garbage and otherwise, have been removed from the launch site.
Chemical pollution	Rare	Crashed rocket, improper application of epoxy, unfavorable weather conditions for paint	Pollution of launch site habitat from motor exhaust, battery leaks, chipped paint, epoxy fragments, epoxy fumes, soil contamination	Major	Practice safe battery storage and usage, purchase motors from reputable dealers to ensure acceptable emissions, minimize last minute epoxy or painting activities on the launch field	Chief engineer and structures team lead inspect paint and epoxy for chips or deterioration, clean up as much as possible if paint chips or epoxy fragments are released onto ground

Noise pollution	Likely	Motor ignition; black powder ignition	Potential damage to nearby structures and harm to local wildlife	Minor	Follow NAR regulations which require launch to occur a safe distance from buildings and roads, check with RSO for noise issues with wildlife at launch site	Safety Officer confirms launch site is in compliance with NAR codes, Safety Officer confirms with RSO that noise will not have impact on wildlife
Wind	Unikely	Uneven heating of the Earth's surface leading to pressure imbalances	Altered rocket trajectory, endangering launch spectators and wildlife	Major	Check wind speeds prior to launch; if they exceed the maximum 20 mph limit proposed by NAR, do not launch; if they fall below this number (yet continue to pose a safety risk), proceed with additional caution and vigilance, increasing launch radius when necessary	Safety Officer confirms launch site is in compliance with NAR codes
Moisture in air/humid conditions	Unlikely	Evaporation and precipitation	Poor motor performance, malfunction of avionics systems	Major	Verify rocket components at risk of impairment due to moisture are indeed dry, taking requisite measures to dry said components when necessary	Safety officer checks with respective team leads to confirm rocket components are ready for launch, and team only proceeds with launch in conditions meet minimal acceptable launch conditions as defined by executives and team mentor

Extreme Temperatures	Rare	High or low ambient heat, exposure to sun	Overheating of the motor, compromised structural integrity (i.e. expansion/-contraction of constructive material), impaired fuel usage, danger to team members—hypothermi heat exhaustion, sun burn	Moderate	Keep rocket out of direct sunlight when possible to avoid overheating, dress appropriately according to temperature, store rocket at a mild temperature	Safety officer verifies with RSO the temperature does not pose a risk to launch

Lipo Battery Fire	Unlikely	Improper storage, overcharging of battery, excessive external heat	Fire spreads on the launch field polluting the air with fumes from the battery including hydrogen flouride and carbon monoxide - depending on the nature and extent of the battery burnout, or fire ignites explosion on the launch field causing release of fumes and debris	Major	Avionics team who is responsible for Lipo batteries is trained and understand the necesarry precautions when storing and chargin the Lipo batteries.	Safety officer ensures that each Avionics team member is aware of proper storage and charging protocol for Lipo batteries at the beginning of the school year.
Mud near launchpad	Possible	Rain or snow in days prior to launch that leaves the ground wet	Trouble with igniter lighting motor, decreased motor performance due to slipping and kickback of the launch rail in the mud	Major	Exec team and mentor will discuss acceptable launch conditions and if these conditions are not met, the launch will be scrubbed.	Upon arrival to the launch site, the team mentor and executives or leads with L1 certification will approach launch pad and inspect the area to verify that it is acceptably dry to launch.

Trampling of crops in farm fields near launch site	Likely	Paths to launch site are through farm fields where crops are planted or will be planted	Crops ruined, fields to be used for future farming are trampled and soil ruined	Moderate	Team President and team mentor will discuss launch dates with farmers (landowners) and work to establish dates that will minimally affect the farmers' harvest periods. Routes will be taken to get the launch pad that are minimally invasive and preferred by farmer.	Before launch, team president will verify with farmer what routes should be taken to walk around and which areas should be avoided. This message will be relayed to team members attending the launch.
Uneven ground causes injuries walking	Possible	Paths to launch site through farm fields are uneven and there are crops covering visibility of holes in the ground.	Twisted ankles and ankle or foot bone injuries.	Minor	Team will exercise caution when walking through farm fields and only use designated paths through the fields to get around.	Safety officer will make team members aware of the possibility of uneven ground and warn them to exercise caution when walking around.
Skin damage from weather conditions	Possible	Excessive wind or excessive sun without cloud cover	Sunburn, windburn	Moderate	Sunscreen will be kept in the safety materials box and brought to every launch in case a members forgets and wants to use suncreen. If weather conditions are extreme, Safety Officer will brief members on necessary protective equipment to bring to launches.	Safety Officer will be present at launches to observe that all members are staying safe from weather conditions and remind them to take precautions against wind and sun exposure.

8 Project Plan

8.1 Requirements Compliance

8.1.1 Statement of Work Requirements

Table 58: General Requirements

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference

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Table 58 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW1.1	Students on the team will do 100% of the project, including design, written reports and presentations. Teams will submit new work. Excessive use of past work will merit penalties	Inspection	The leadership structure of the team is implemented in a way that ensures the full completion of work by team members on all project milestones, construction, and design. The executive board of the team oversees the design, construction, and documentation process to ensure that the work is done fully by team members. The Program Manager schedules and outlines the details regarding the work that needs to be done, and communicates this information to the team. Documentation will undergo a careful review from the executive board as well as a plagiarism checker program to ensure that team members have not copied documentation from past work.	In progress, subteam leaders and the executive board have ensured that no one outside of the team has contributed to any aspect of the overall project. Plagiarizing of documentation has been periodically assessed throughout the writing process. The Safety Officer has indicated that handling of dangerous material has been left to only the people with proper certification.	N/A

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Table 58 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW1.2	The team will provide and maintain a project plan to include, but not limited to the following items: project milestones, budget and community support, checklists, personnel assignments, STEM engagement events, and risks and mitigations.	Inspection	The President and the Program Manager have created a project plan outline that details a schedule of deadlines to be completed for each of the project milestones for each of the subteams. Each subteam lead will then delegate these tasks to team members to ensure that they are completed properly. The project plan includes details related to budgeting, community support, checklists, personnel assignments, STEM Engagement events, and risks and mitigation. The risks and mitigation section of the project plan will be assisted by the Safety Officer to ensure accuracy and attention to detail in the process.	In progress, the aforementioned project plan is checked daily by the executive team to ensure deadlines are being met. The plan is updated as changes are made, with the Safety Officer signing off to ensure changes are safe.	Section 6

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Table 58 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW1.3	The team shall identify all team members who plan to attend Launch Week activities by the Critical Design Review (CDR). Team members will include: 1.4.1. Students actively engaged in the project throughout the entire year. 1.4.2. No more than two adult educators.	Inspection	The President has collected contact information of team members attending Launch Week using a Google Form. The compiled results will be submitted as part of the WURocketry CDR package.	Complete, emailed to Allison Chouinard in Excel Format.	N/A
SOW1.4	Teams shall engage a minimum of 250 participants in Educational Direct Engagement STEM activities in order to be eligible for STEM Engagement scoring and awards. These activities can be conducted inperson or virtually. To satisfy this requirement, all events shall occur between project acceptance and the FRR due date. A template of the STEM Engagement Activity Report can be found on pages 77-80.	Inspection	These events will be documented by the STEM Engagement Chair in the STEM Engagement Activity Report that has been provided by the USLI team, and will be submitted completely at the FRR deadline. The STEM Engagement Chair and President are currently planning events to engage over 250 kids. It is required that all team members attend two STEM engagement events to ensure participation and success for the kids at these events	Completed. WURocketry has completed multiple STEM Engagement events and engaged with 415 students in direct STEM activities. The completed events have been documented and will be submitted with the FRR.	Section 1

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Table 58 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW1.5	The team will establish and maintain a social media presence to inform the public about team activities.	Inspection	The social media accounts on Instagram, LinkedIn, Facebook, Twitter, and TikTok are consistently used to document construction and design processes for all of the followers. The social media pages the team uses have dramatically increased visibility for the team as well as NASA and provides insights into the team that strum up interest from students not currently involved. All team events are posted on social media so that the public can keep up with team progress.	In progress. The Social Media chair ensures that posts go up on a regular basis and are documenting all important events in which the team might participate. The Social Media Chair is kept accountable by the executive board.	N/A

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Table 58 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW1.6	Teams will email all deliverables to the NASA project management team by the deadline specified in the handbook for each milestone. In the event that a deliverable is too large to attach to an email, inclusion of a link to download the file will be sufficient. Late submissions of PDR, CDR, FRR milestone documents shall be accepted up to 72 hours after the submission deadline. Late submissions shall incur an overall penalty. No PDR, CDR, FRR milestone documents shall be accepted beyond the 72-hour window. Teams that fail to submit the PDR, CDR, FRR milestone documents shall be eliminated from the project.	Inspection	Milestone documentation is checked on a periodic basis in the two weeks leading up to the submission deadline. The executive board independently reviews the necessary materials for submission and creates each milestone package together to ensure nothing is missing and all information is complete.	In progress. The executive board continuously reviews the deadlines and requirements to ensure that submissions happen properly	N/A

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Table 58 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW1.7	Teams who do not satisfactorily complete each milestone review (PDR, CDR, FRR) shall be provided action items needed to be completed following their review and shall be required to address action items in a delta review session. After the delta session the NASA management panel shall meet to determine the teams' status in the program and the team shall be notified shortly thereafter.	Inspection	The executive board will work as quickly and accurately to assess the necessary changes that need to be made following the possibility of an unsatisfactory submission. The delta review session will be scheduled efficiently through effective communication between the team and the USLI board.	In Progress. The team has so far not had to deal with this issue, but should it arise, the executive team will call a meeting to sort out the issues so that whatever documentation needs to be altered can be done as efficiently as possible.	N/A
SOW1.8	All deliverables shall be in PDF format.	Inspection	The executive board is responsible for ensuring all documentation is in PDF format	In Progress. All milestones have been submitted in PDF format. All upcoming milestones will be submitted in this format as well.	N/A

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW1.9	In every report, teams will provide a table of contents including major sections and their respective sub-sections.	Inspection	The executive board will ensure upon review of documentation that all sections and sub-sections are accounted for in the table of contents	In Progress. Milestone reports so far submitted have all included a table of contents that has been checked for accuracy. This will be the standard moving forward with future milestone documents.	N/A
SOW1.10	In every report, the team will include the page number at the bottom of the page.	Inspection	The executive board will ensure that page numbers are included at the bottom of each page of the deliverable reports	In Progress. All submitted reports have thus far included page numbers. Future reports will include page numbers at the bottom of the page.	N/A
SOW1.11	The team will provide any computer equipment necessary to perform a video teleconference with the review panel. This includes, but is not limited to, a computer system, video camera, speaker telephone, and a sufficient Internet connection. Cellular phones should be used for speakerphone capability only as a last resort.	Demonstration	WURocketry has meetings scheduled in Washington University conference rooms with reliable network connection and video/audio capabilities for teleconferences with the USLI board. These systems are checked to ensure reliability by the Washington University IT staff prior to the conferences	In progress. A reliable conference room has been reserved with the audio and video capabilities necessary for a successful conference	N/A

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Item	**Requirement**	**Verification Method**	**Verification Plan**	**Verification Status**	**Reference**
SOW1.12	Teams will track and report the number of hours spent working on each milestone.	Inspection	Each subteam leader is required to ensure that subteam members record all time worked on each milestone to provide an accurate value for the hours worked on each report.	Complete. Hours have been tracked for all report milestones and have been reported in the summary section of each report.	Section 1

Table 59: Vehicle Requirements

Item	**Requirement**	**Verification Method**	**Verification Plan**	**Verification Status**	**Reference**
SOW2.1	The vehicle will deliver the payload to an apogee altitude between 4,000 and 6,000 feet above ground level (AGL).	Analysis	OpenRocket will be utilized to design a rocket that can deliver a payload to an apogee between 4,000 and 6,000 feet AGL.	Complete. The OpenRocket simulation of the full-scale vehicle showed that expected apogee altitude is 4,630 ft.	Section 3.4
SOW2.2	Teams shall declare their target altitude goal at the PDR milestone.	Analysis	The team will declare the target altitude based on OpenRocket simulations and cumulative experience from previous flights.	Complete. A target altitude of 4,650 feet AGL was declared in the PDR.	Section 3.4
SOW2.3	The launch vehicle will be designed to be recoverable and reusable. Reusable is defined as being able to launch again on the same day without repairs or modifications.	Inspection	The rocket will be designed to be robust and sturdy enough to be recoverable and reusable on the same day. Motors will be chosen that can be replaced on the same day.	Complete. The rocket was constructed using sturdy, high strength materials and designed to be recoverable and reusable on the same day. An Aerotech L1390G motor was chosen for its reloading capabilities.	Section 3

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Table 59 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.4	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.	Inspection	The team will design a launch vehicle to ensure that there are a maximum of four independent sections which are tethered to each other. The launch vehicle will not jettison a section.	Complete. The vehicle is designed to have three separation points. The payload pushes the nose cone off of the forward body tube on the ground. The forward body tube separates from the mid body tube and coupler for the main parachute deployment. The aft body tube separates from the mid body tube and coupler for the drogue parachute deployment.	Section 3.1
SOW2.4.1	Coupler/airframe shoulders which are located at in-flight separation points will be at least 2 airframe diameters in length. (One body diameter of surface contact with each airframe section)	Inspection	The team will inspect each part of the launch vehicle to ensure that the coupler will have one body diameter of surface contact with the airframe.	Complete. The launch vehicle will have three independent sections. All coupler shoulders are double the length of the body diameter of the launch vehicle, which is 6.17 in. The avionics coupler is 14 in.	Section 3.1.3

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Item	**Requirement**	**Verification Method**	**Verification Plan**	**Verification Status**	**Reference**
SOW2.4.2	Nosecone shoulders which are located at in-flight separation points will be at least $\frac{1}{2}$ body diameter in length.	Inspection	The team will inspect each part of the launch vehicle to ensure that the nose cone shoulder will have one half of a body diameter of surface contact with the airframe.	Complete. The Structures subteam designed the nose cone shoulder to be 3.1 in long, which is over half the diameter of 6.17 in.	Section 3.1.8
SOW2.5	The launch vehicle will be capable of being prepared for flight at the launch site within 2 hours of the time the Federal Aviation Administration flight waiver opens	Test	Calculations will be run to determine the minimum total battery power necessary for each component to properly function for at least 2 hours in the launch-ready configuration. The power supplies for each component well be selected accordingly.	Complete. The on-board batteries have been selected such that they will satisfy operational capacity for a comfortable margin beyond 2 hours.	Flysheet

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.6	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.	Test	Power consumption of each electrical component at their rated voltage and current draw will be calculated to determine if the selected battery provides enough capacity to remain launch-ready for at least 2 hours.	Complete. The on-board batteries have been selected such that they will satisfy operational capacity for a comfortable margin beyond 2 hours.	Flysheet
SOW2.7	The launch vehicle will be capable of being launched by a standard 12-volt direct current firing system. The firing system will be provided by the NASA-designated launch services provider.	Inspection	Motors will be chosen such that they can be fired by a standard 12-volt direct current firing system.	Complete. The Aerotech L1390G motor is capable of being launched by a standard 12-volt direct current firing system.	Section 3.1.14

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.8	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).	Inspection	The design of the vehicle will include the incorporation of all electrical components within its structure. It will be designed to launch without the need for external circuitry or special equipment on the ground.	Complete. The vehicle design incorporates all electrical components within its structure. It can launch without the need for external circuitry or special equipment on the ground.	Section 3.1.14
SOW2.9	Each team shall use commercially available ematches or igniters. Hand-dipped igniters shall not be permitted.	Inspection	The igniters used for the ignition of the black powder charges will not be made by the students nor the mentor nor purchase from anywhere other than a commercial vendor.	Complete.	N/A

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.10	The launch vehicle will use a commercially available solid motor propulsion system using ammonium perchlorate composite propellant (APCP) which is approved and certified by the National Association of Rocketry (NAR), Tripoli Rocketry Association (TRA), and/or the Canadian Association of Rocketry (CAR).	Inspection	NAR S&T's Combined Motor List will be used to verify the certification of the chosen motor	Complete. The L1390G-PS is certified by TRA	Section 3.1.14
SOW2.10.1	Final motor choices will be declared by the Critical Design Review (CDR) milestone.	Inspection	The final motor selection will be presented in the CDR	Complete. The final motor selection has been declared in the CDR.	3.1.14

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Item	**Requirement**	**Verification Method**	**Verification Plan**	**Verification Status**	**Reference**
SOW2.10.2	Any motor change after CDR shall be approved by the NASA Range Safety Officer (RSO). Changes for the sole purpose of altitude adjustment will not be approved. 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.	Analysis	Any motor change due to motor restrictions or other non-altitude related reasons will be checked and approved with the NASA Range Safety Officer.	Complete. The team is using a TRA approved Aerotech L1390G motor which will not be changed for altitude or non-altitude reasons.	Section 3.1.14
SOW2.11	The launch vehicle will be limited to a single motor propulsion system.	Inspection	The team will ensure that any motor system on the launch vehicle adheres to the requirements.	Complete. The current proposed launch vehicle is limited to a single motor system.	Section 3.1.14
SOW2.12	The total impulse provided by a College or University launch vehicle will not exceed 5,120 Newton-seconds (L-class).	Inspection	The team will ensure that any motor system on the launch vehicle does not exceed L-class.	Complete. The Aerotech L1390G-P has a total impulse of 3949 N-s.	Section 3.1.14

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Item	**Requirement**	**Verification Method**	**Verification Plan**	**Verification Status**	**Reference**
SOW2.13	2.13. Pressure vessels on the vehicle will be approved by the RSO and will meet the following criteria: 2.13.1. 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. 2.13.2. 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. 2.13.3. 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.	Inspection	The team will ensure that any pressure vessels on the launch vehicle adhere to the requirements.	Complete. The current proposed launch vehicle does not have any pressure vessels.	Section 3.1.3

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Table 59 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.14	The launch vehicle will have a minimum static stability margin of 2.0 at the point of rail exit. Rail exit is defined at the point where the forward rail button loses contact with the rail.	Analysis	The team will use OpenRocket to verify that the launch vehicle design meets the static stability requirement at rail exit.	Complete. Using the proposed vehicle design, OpenRocket has confirmed that the static stability margin at rail exit is 3.0 cal.	Section 3.4.3
SOW2.15	The launch vehicle will have a minimum thrust to weight ratio of 5.0 : 1.0.	Analysis	Thrust to weight ratio will be verified by dividing the maximum acceleration predicted for the launch vehicle from OpenRocket by Earth's gravitational constant.	Complete. The thrust to weight ratio of the rocket is significantly above this 5:1 ratio. The full-scale maximum acceleration was determined to be 252 $\frac{ft}{s^2}$ using OpenRocket. Dividing this acceleration by 32.2 $\frac{ft}{s^2}$ yields a thrust to weight ratio of 7.86:1.	Section 3.1

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.16	Any structural protuberance on the rocket will be located aft of the burnout center of gravity. Camera housings will be exempted, provided the team can show that the housing(s) causes minimal aerodynamic effect on the rocket's stability.	Inspection	The rail buttons and fins on the rocket will be located below the burnout CG. The camera housings will be placed forward of the burnout CG.	Complete. The fins and rail buttons on the rocket will be placed aft of the burnout center of gravity. The cameras are located forward of the burnout center of gravity but weigh a total of 1 oz, which will not significantly affect the center of gravity location, according to OpenRocket. Additionally, fluid dynamics simulations have shown that the cameras do not significantly affect the aerodynamics of the rocket.	Section 3.4.3
SOW2.17	The launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	Analysis	The team will use OpenRocket to verify that the launch vehicle will accelerate to a minimum velocity of 52 fps at rail exit.	Complete. Using the proposed vehicle design, OpenRocket has confirmed that the rail exit velocity is 71.2 fps.	Section 3.4.2

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.18	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	Inspection	Lithium Polymer Batteries will be securely attached to the avionics board and marked as a fire hazard. This will prevent any danger of damage upon landing.	Complete. The Lithium Polymer batteries in the avionics bay of the rocket are securely attached to the board via Velcro and zip ties.	N/A
SOW2.19.1	The launch vehicle will not utilize forward firing motors.	Inspection	The team will ensure that launch vehicle will not utilize forward firing motors	Complete. The current proposed launch vehicle does not include forward firing motors.	Section 3.1.14
SOW2.19.2	The launch vehicle will not utilize motors that expel titanium sponges (Sparky, Skidmark, MetalStorm, etc.)	Inspection	The team will ensure that the launch vehicle will not utilize motors that expel titanium sponges	Complete. The current declared motor does not expel titanium sponges.	Section 3.1.14
SOW2.19.3	The launch vehicle will not utilize hybrid motors.	Inspection	The team will ensure that the launch vehicle will not utilize hybrid motors.	Complete. The current proposed launch vehicle does not include a hybrid motor.	Section 3.1.14
SOW2.19.4	The launch vehicle will not utilize a cluster of motors.	Inspection	The team will ensure that the launch vehicle will not utilize a cluster of motors.	Complete. The current proposed launch vehicle does not include a cluster of motors.	Section 3.1.14

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.19.5	The launch vehicle will not utilize friction fitting for motors.	Inspection	The team will not use friction fitting to secure the motor to the launch vehicle.	Complete. Retainers are used to secure the motor to the launch vehicle.	Section 3.1.15
SOW2.19.6	The launch vehicle will not exceed Mach 1 at any point during flight.	Analysis	The team will use OpenRocket simulations to verify that the launch vehicle design does not exceed Mach 1.	Complete. Using the proposed vehicle design, OpenRocket has confirmed that the maximum velocity is at Mach 0.52.	Section 3.4.2
SOW2.19.7	Vehicle ballast will not exceed 10% of the total unballasted weight of the rocket as it would sit on the pad (i.e., a rocket with an unballasted weight of 40 lbs. on the pad may contain a maximum of 4 lbs. of ballast).	Inspection	The team will ensure that any ballast designed for the rocket meets the requirements.	Complete. The vehicle design does not have a ballast.	Section 3.1.3
SOW2.19.8	Transmissions from onboard transmitters, which are active at any point prior to landing, will not exceed 250 mW of power (per transmitter).	Inspection	All transmitters will be selected and programmed to successfully communicate without exceeding the maximum power of 250mW.	Complete. All selected transmitters are capable of functioning for the team's purposes without exceeding the power cap.	Flysheet

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW2.19.9	Transmitters will not create excessive interference. Teams will utilize unique frequencies, handshake/-passcode systems, or other means to mitigate interference caused to or received from other teams.	Inspection	All transmitter systems will not utilize excessive means to communicate or mitigate interference that may cause greater interference for other teams.	Complete. The selected transmitters make use of handshake systems to mitigate interference	N/A
SOW2.19.10	Excessive and/or dense metal will not be utilized in the construction of the vehicle. Use of lightweight metal will be permitted but limited to the amount necessary to ensure structural integrity of the airframe under the expected operating stresses	Inspection	All vehicle prohibitions of excessive or dense metal will be adhered to throughout the conception, design, manufacturing, and testing process.	Complete. The vehicle has been designed with the only metal being 6061 aluminum for the bulkheads as it is a material deemed necessary to maintain structural integrity of the body tubes.	Section 3.1.4

Table 60: Recovery System Requirements

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference

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Table 60 – *Continued from previous page*

Item	**Requirement**	**Verification Method**	**Verification Plan**	**Verification Status**	**Reference**
SOW3.1	The full scale launch vehicle will stage the deployment of its recovery devices, where a drogue parachute is deployed at apogee, and a main parachute is deployed at a lower altitude. Tumble or streamer 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.	Inspection	Flight computers will use altitude and velocity data to detonate black powder charges inside the recovery sections of the rocket, pressurizing the vessel and severing the shear pins for the separation events. When flight velocity reaches zero, the flight computers will ignite the primary drogue separation charge, releasing the drogue parachute at apogee. A larger, redundant black powder charge will ignite one second following the primary charge to ensure the deployment of the drogue parachute within 2 seconds of reaching apogee. The main parachute will be deployed in a similar process when the rocket has reached 600 ft above ground level, and redundant charges will ignite at 500 ft.	Complete.	Section 3.3.2

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW3.1.1	The main parachute shall be deployed no lower than 500 feet.	Inspection	The EasyMini flight computers will be set to main parachute ejection altitudes of 600ft and 500ft respectively, ensuring the separation and safe ejection of the main parachute before 500ft	Complete.	Section 3.3.2
SOW3.1.2	The apogee event may contain a delay of no more than 2 seconds.	Inspection	The apogee separation, releasing the drogue parachute, will be set to occur at apogee for the primary flight computer and 1 second after apogee for the redundant, ensuring proper drogue separation before 2 seconds after apogee.	Complete.	Section 3.3.2
SOW3.1.3	Motor ejection is not a permissible form of primary or secondary deployment.	Inspection	The team will not use motor ejection as a form of primary or secondary deployment.	Complete.	Section 3.3.2

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Table 60 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW3.2	Each team will perform a successful ground ejection test for all electronically initiated recovery events prior to the initial flights of the subscale and full scale vehicles.	Test	A ground ejection test will be conducted for the primary black powder charges of both the drogue and main parachute separation events. Testing will be completed at any change of black powder quantity and two weeks prior to each launch of sub-scale and full-scale rockets.	Complete.	Section 6.2
SOW3.3	Each independent section of the launch vehicle will have a maximum kinetic energy of 75 ft-lbf at landing.	Analysis	OpenRocket simulations will be conducted to verify an impact kinetic energy below competition requirements	Complete. The forward, mid, and aft sections have kinetic energy values of 57.08, 17.72, and 47.19 ft-lbf, respectfully.	Section 3.4.5
SOW3.4	The recovery system will contain redundant, commercially available barometric altimeters that are specifically designed for initiation of rocketry recovery events. The term “altimeters” includes both simple altimeters and more sophisticated flight computers.	Inspection	The recovery electronics will consist of two Altus Metrum EasyMini flight computers.	Complete.	Section 3.3.8

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Table 60 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW3.5	Each altimeter will have a dedicated power supply, and all recovery electronics will be powered by commercially available batteries.	Inspection	Both EasyMini flight computers will have their own 3.7v Lithium Polymer battery.	Complete.	Section 3.3.8
SOW3.6	Each altimeter will be armed by a dedicated mechanical arming switch that is accessible from the exterior of the rocket airframe when the rocket is in the launch configuration on the launch pad.	Inspection	Each flight computer will be armed by a separate rotary arming switch that will be accessible via a cutout in the airframe at all stages of assembly.	Complete.	Section 3.3.8
SOW3.7	Each arming switch will be capable of being locked in the ON position for launch (i.e. cannot be disarmed due to flight forces).	Inspection	The rotary switches used for arming the flight computers lock upon changing state and are designed such that flight forces cannot disarm the flight computers.	Complete.	Section 3.3.8

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Table 60 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW3.8	The recovery system, GPS and altimeters, electrical circuits will be completely independent of any payload electrical circuits.	Inspection	The recovery system electronics, although positioned within the avionics bay with the rest of the avionics system, will be entirely independent of the rest of the avionics system or payload system for power, function, and arming.	Complete.	Section 3.3.8
SOW3.9	Removable shear pins will be used for both the main parachute compartment and the drogue parachute compartment.	Inspection	The Structures team will hand drill shear screw holes onto the airframe and coupler connections to be fitted for the necessary shear pins.	Complete.	Section 3.1.3
SOW3.10	The recovery area will be limited to a 2500 ft. radius from the launch pads.	Analysis	The rocket's drift was calculated to be 2255 ft at maximum windspeeds of 20 mph, 245 ft below the maximum	Complete	Section 3.4.6
SOW3.11	Descent time of the launch vehicle will be limited to 90 seconds (apogee to touch down).	Analysis	The rocket's descent time was calculated to be 76.88 seconds, 13.12 s below the maximum and 3.12 seconds below the bonus goal	Complete	Section 3.4.5

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Table 60 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW3.12	An electronic GPS tracking device will be installed in the launch vehicle and will transmit the position of the tethered vehicle or any independent section to a ground receiver.	Inspection	The Altus Metrum TeleGPS will be fitted to the avionics bay and will track the rocket (consisting of only one independent section) transmitting down to the TeleBT ground receiver.	Complete.	Section 3.3.8
SOW3.12.1	Any rocket section or payload component, which lands untethered to the launch vehicle, will contain an active electronic GPS tracking device.	Analysis	Any section that fits the requirements previously stated will be fitted with its own GPS tracking device. Presently, there is no such section aside from the main rocket section.	Complete	N/A
SOW3.13	The recovery system electronics will not be adversely affected by any other on-board electronic devices during flight (from launch until landing).	Inspection	The EasyMini flight computers will be shielded from any RF interference by use of an aluminum Faraday cage. All continuities will be verified preflight and no bare wires will be present within the avionics bay.	Complete.	N/A

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Table 60 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW3.13.1	The recovery system altimeters will be physically located in a separate compartment within the vehicle from any other radio frequency transmitting device and/or magnetic wave producing device.	Inspection	The EasyMini flight computers will be located in the avionics bay and separated from the TeleGPS system by the avionics bay board by as much distance as possible	Complete.	N/A
SOW3.13.2	The recovery system electronics will be shielded from all onboard transmitting devices to avoid inadvertent excitation of the recovery system electronics.	Inspection	The EasyMini flight computers will be shielded from any RF interference by use of an aluminum Faraday cage. All continuities will be verified preflight and no bare wires will be present within the avionics bay.	Complete.	N/A
SOW3.13.3	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.	Inspection	The EasyMini flight computers will be shielded from any RF interference by use of an aluminum Faraday cage. All continuities will be verified preflight and no bare wires will be present within the avionics bay.	Complete.	N/A

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Table 60 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW3.13.4	The recovery system electronics will be shielded from any other onboard devices which may adversely affect the proper operation of the recovery system electronics.	Inspection	The EasyMini flight computers will be shielded from any RF interference by use of an aluminum Faraday cage. All continuities will be verified preflight and no bare wires will be present within the avionics bay.	Complete.	N/A

Table 61: Payload Requirements

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW4.2.1	Launch Vehicle shall contain an automated camera system capable of swiveling 360^{o} to take images of the entire surrounding area of the launch vehicle.	Demonstration	The team will transmit RAFCO commands for the camera to take images at various positions. These positions can include clockwise and counterclockwise rotations that sum to 360 degrees of rotation. The team can visually verify that the camera system is capable of swiveling 360 degrees.	Complete. The APRS receiver has been demonstrated to work with messages sent by the team's license HAM radio operator and shown that the servo can rotate both left and right at intervals of 60 degrees.	Section 4.5

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Table 61 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW4.2.1.1	The camera shall have the capability of rotating about the z axis. The z axis is perpendicular to the ground plane with the sky oriented up and the planetary surface oriented down.	Demonstration	This will be confirmed by performing multiple tests of the rotating track (on both the prototype and final design) with mock weights to simulate pulling the camera upright about the z-axis. Demonstrations will also be made to prove that a selected servo can rotate the Raspberry Pi camera.	In Progress. The Payload subteam has built the physical assembly of the rotating track mechanism, but is still working on reducing the amount of friction generated between the rotating tracks. An alternative design to the rotating tracks is currently in discussion, specifically a single rod rotation mechanism that exactly follows the original prototype uprighting concept.	Section 4.5. Future work involves transitioning the prototype to the final parts.
SOW4.2.1.2	The camera shall have a FOV of at least 100º and a maximum FOV of 180º	Test	Will take various images of a flat plane with a viewing angle perpendicular to the plane. The plane will be marked with measured lengths so that calculations can be performed to ensure that the selected camera produced images of FoV between 100º and 180º.	Complete. The camera test resulted in a calculated PoV of around 160º.	Section 6.1.2

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW4.2.1.3	The camera shall time stamp each photo taken. The time stamp shall be visible on all photos submitted to NASA in the PLAR.	Inspection	After the imaging program modifies the image file captured by the camera, the team will visually inspect the file on a computer display for the timestamp.	Complete. The team has successfully take images and added a timestamp with a CST timezone to the resulting image.	Section 4.6
SOW4.2.1.4	The camera system shall execute the string of transmitted commands quickly, with a maximum of 30 seconds between photos taken.	Demonstration	The routine used to execute the camera system functions will have code to time the runtime of each RAFCO execution.	Complete. The runtime of each RAFCO execution routine has been timed using system software timers to ensure that each command took less than 30 seconds to complete.	Section 4.8

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Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW4.2.2	NASA Student Launch Management Team shall transmit a RF sequence that shall contain a radio call sign followed by a sequence of tasks to be completed. The list of potential commands to be given on launch day along with their radio transcriptions which shall be sent in a RF message using APRS transmission in no particular order are: A1—Turn camera 60° to the right. B2—Turn camera 60° to the left. C3—Take picture. D4—Change camera mode from color to grayscale. E5—Change camera mode back from grayscale to color. F6—Rotate image 180° (upside down). G7—Special effects filter (Apply any filter or image distortion you want and state what filter or distortion was used). H8—Remove all filters.	Inspection and Demonstration	Each command will be sent to the camera imaging system to observe its motion and the output of its image transformations.	Complete. Each RAFCO execution routine has been developed in software and illustrated to perform the necessary physical camera rotations and digital image transformations.	Section 4.5.

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Table 61 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW4.2.3	The NASA Student Launch Management Panel shall transmit the RAFCO using APRS.	Demonstration	The payload will be capable of receiving data packets from the APRS network.	Complete. The payload RTL-SDR has been demonstrated capable of receiving packets sent from the team's licensed HAM radio operator.	Section 4.5
SOW4.2.3.1	NASA will use dedicated frequencies to transmit the message. NASA will operate on the 2-Meter amateur radio band between the frequencies of 144.90 MHz and 145.10 MHz. No team shall be permitted to transmit on any frequency in this range. The specific frequency used will be shared with teams during Launch Week. NASA reserves the right to modify the transmission frequency as deemed necessary.	Inspection	Inspection of software will ensure that all radio transmitters are configured at the frequency assigned by NASA.	Complete	Section 4.5

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Table 61 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW4.3.1	The NASA Management Team shall transmit the RAFCO every 2 minutes.	Demonstration	The Payload subteam will simulate transmission of a RAFCO sequence every 2 minutes to verify that the RAFCO is received as expected.	Complete. The Payload team has generated it's own simulated RAFCO packets and ensured the payload has received them at 2 minute intervals.	Section 4
SOW4.2.3.3	The payload system shall not initiate and begin accepting RAFCO until AFTER the launch vehicle has landed on the planetary surface.	Demonstration	The Payload software that controls initialization of RAFCO execution will only begin once the on-board avionics subsystem has detected a stable landing.	Complete. The Payload team has been able to sample the on-board IMU and altimeter for data and process it to determine whether the payload is moving or not below a certain altitude.	Section 4
SOW4.2.4	The payload shall not be jettisoned.	Demonstration	The Payload subteam will not eject any portion of the payload from the vehicle.	Complete	Section 4
SOW4.2.5	The sequence of time-stamped photos taken need not be transmitted back to ground station and shall be presented in the correct order in your PLAR.	Demonstration	The Payload subteam will not tranmist any images to the ground station, but will save the images on-disk in order that they were taken so that the PLAR can be easily organized.	Complete. The subteam has been able to save the images captured with the filename incorporating a timestamp such that they are sorted on the filesystem.	Section 4

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Table 61 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW4.3.1	Black Powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Energetics shall not be permitted for any surface operations.	Demonstration	The Payload subteam will not interact with any energetic for the payload.	Complete	Section 4
SOW4.3.2	Teams shall abide by all FAA and NAR rules and regulations.	Demonstration	WURocketry will thoroughly read and review the rules with members prior to launch to ensure no regulations are violated.	Complete	Section 4
SOW4.3.3	Any secondary payload experiment element that is jettisoned during the recovery phase will receive real-time RSO permission prior to initiating the jettison event, unless exempted from the requirement the CDR milestone by NASA.	Demonstration	WURocketry will not fly a secondary payload experiment.	Complete	Section 4

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Table 61 – *Continued from previous page*

Item	**Requirement**	**Verification Method**	**Verification Plan**	**Verification Status**	**Reference**
SOW4.3.4	Unmanned aircraft system (UAS) payloads, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAS.	Demonstration	WURocketry will not fly a UAS as part of the payload mission.	Complete	Section 4
SOW4.3.5	Teams flying UASs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft (Public Law 112-95 Section 336; see https://www.faa.gov/uas/faqs).	Demonstration	WURocketry will not fly a UAS as part of the payload mission.	Complete	Section 4
SOW4.3.6	Any UAS weighing more than .55 lbs. shall be registered with the FAA and the registration number marked on the vehicle.	Demonstration	WURocketry will not fly a UAS as part of the payload mission.	Complete	Section 4

Table 62: Aerodynamics System Requirements

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW5.1	The rocket will have vent holes in the forward body tube and aft body tube that satisfy required vent hole sizing calculations based on theoretical equations for a pressurized chamber.	Inspection and Measurement	Upon drilling the vent holes into the rocket, placement and size will be measured according to the vent hole sizing calculations.	Complete.	N/A
SOW5.2	The rocket will have symmetric camera mounts along the nose cone.	Inspection and Measurement	Upon placing the camera mounts on both sides of the rocket, measurements will be made to ensure that the chosen placement is indeed symmetric.	Complete.	N/A
SOW5.3	The epoxy applied on the fin shell shall be smooth in order to reduce drag.	Inspection	After applying the epoxy along the fin shells, members shall ensure that there are no bumps and check that the surface is not rigid.	Complete	N/A
SOW5.4	The paint on the exterior of the rocket shall be smooth in order to reduce drag.	Inspection	After applying paint to the exterior of the rocket, members shall examine the rigidness of the paint and check that it is indeed smooth.	Complete	N/A

Table 63: Safety Requirements

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW5.1	Each team will use a launch and safety checklist. The final safety checklists will be included in the FRR report and used during the Launch Readiness Review and any Launch Day Operations.	Inspection	Safety checklists will be written by the Safety Officer using the launch regulations and the safety plans in Section 5 of this document.	Complete. Checklists and procedures with safety warning are written	Section 5.1
SOW5.2	Each team shall identify a student safety officer who will be responsible for all items in section 5.3.	Inspection	WURocketry Safety Officer is Andrew DeRubertis and he is responsible for the items in section 5.3.	Complete. Andrew DeRubertis is aware of his responsibility for all items in section 5.3 of this document.	N/A

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Table 63 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW5.3.1	Monitor team activities with an emphasis on safety during: 5.3.1.1. Design of vehicle and payload. 5.3.1.2. Construction of vehicle and payload components. 5.3.1.3. Assembly of vehicle and payload. 5.3.1.4. Ground testing of vehicle and payload. 5.3.1.5. Subscale launch test(s). 5.3.1.6. Full-scale launch test(s). 5.3.1.7. Competition launch. 5.3.1.8. Recovery activities. 5.3.1.9. STEM Engagement Activities.	Inspection	The Safety Officer is responsible for reading and understanding all safety requirements and regulations regarding the USLI competition and WashU club affairs. The Safety Officer will use this knowledge to monitor all WURocketry activities.	In Progress. Andrew DeRubertis has read and understands all safety requirements and regulations from the NASA Student Launch Handbook and from WashU.	N/A
SOW5.3.2	Implement procedures developed by the team for construction, assembly, launch, and recovery activities.	Inspection	The Safety Officer will review all construction and assembly procedures for subteams, as well as enforcing school required training for specific machine use.	In Progress. The Safety Officer will review construction, assembly, launch and recovery plans with the team and brief them any time a change or addition is made to these procedures.	N/A

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Table 63 – *Continued from previous page*

Item	**Requirement**	**Verification Method**	**Verification Plan**	**Verification Status**	**Reference**
SOW5.3.3	Manage and maintain current revisions of the team's hazard analyses, failure modes analyses, procedures, and MSDS/chemical inventory data.	Inspection	The Safety Officer is responsible for updating all safety documents including but not limited to the documents mentioned here.	In Progress. The Safety Officer attends all WURocketry activities to ensure that all safety documentation is up to date and encompasses all related procedures and team activity.	N/A
SOW5.3.4	Assist in the writing and development of the team's hazard analyses, failure modes analyses, and procedures.	Inspection	The Safety Officer is responsible for writing team safety documents.	Complete. The Safety Officer and auxiliary safety officer(s) write all safety documents	N/A

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Table 63 – *Continued from previous page*

Item	Requirement	Verification Method	Verification Plan	Verification Status	Reference
SOW5.4	During test flights, teams will abide by the rules and guidance of the local rocketry club's RSO. The allowance of certain vehicle configurations and/or payloads at the NASA Student Launch does not give explicit or implicit authority for teams to fly those vehicle configurations and/or payloads at other club launches. Teams should communicate their intentions to the local club's President or Prefect and RSO before attending any NAR or TRA launch.	Inspection	The Safety Officer is responsible for contacting the RSO and the team-mentor prior to test flights to go over the local rocketry associations rules and launch location rules. The Safety Officer is responsible for explaining the payload mission and confirming with the RSO and local regulations that the payload is permissible for test flight at the local launch.	In Progress. The Safety Officer and any members conducting the launch discuss the payload and any pertinent rules or regulations with the RSO and team mentor prior to a test launch with the payload.	N/A
SOW5.5	Teams will abide by all rules set forth by the FAA.	Inspection	In pre-flight safety briefings, the Safety Officer will discuss the rules of the local rocketry association, the configuration of the launch vehicle, and the recommendations of the RSO.	In Progress. The Safety Officer and any members conducting the launch discuss rules and regulations with the RSO and team mentor prior to launch.	N/A

8.1.2 Team-Derived Vehicle Requirements

Table 64: Team-Derived Vehicle Requirements

Item	Requirement	Justification	Verification Method	Verification Plan
TDVR 1	The Status LED for the Raspberry Pi 4B needs to be visible from the outside of the rocket	Since no audible status notification is provided by the Raspberry Pi 4B it is neccessary to include a status LED indicating proper function of the microcontroller.	Demonstration and Inspection	A status LED will be attached to the Raspberry Pi 4B and programmed to provide a useful indication of the pi's status. A hole will be cut into the airframe to allow visual access to the status LED.
TDVR 2	The launch vehicle must be able to fit in the back of a car trunk.	The budget limits the team transportation options to students' cars, so the launch vehicle must fit within the back of a car to be easily transported.	Inspection	The team will determine if the launch vehicle fits in the back of a car by placing each section and its components in the back of a team member's car.
TDVR 3	Zippered body tubes and couplers must be avoided.	The team observed a zippered coupler in a previous launch due to the placement of the shock cords and couplers within the body tubes.	Inspection	All couplers must have an anti-zipper design. The attachment points of the shock cords are placed at the end of the couplers in the design using eye bolts.

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Table 64 – *Continued from previous page*

Item	Requirement	Justification	Verification Method	Verification Plan
TDVR 4	There must be a fully self-contained telemetry down-link.	In order to provide a simplified method for tracking the rocket that does not risk communication errors brought on by running GPS data through a separate micro controller before transmission to the base station, a fully self contained telemetry down link is necessary.	Demonstration	The Altus Metrum TeleGPS will be used to transmit telemetry data to the base station. This design has been demonstrated in Section **??**.
TDVR 5	The e-matches should be able to connect to the avionics bay after it has been fully constructed.	The ability to fully construct the avionics bay prior to launch day will dramatically reduce the time necessary to assemble the rocket. In order to fully enable prior assembly of the avionics bay, it is necessary to attach terminal blocks to the bulkheads of the avionics bay that will be used to attach E-matches to the flight computers on launch day.	Inspection	Two sets of terminal blocks will be attached to the bulkheads for each separation chamber enabling the attachment of E-matches for both the primary and redundant charges contained within each separation section.

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Table 64 – *Continued from previous page*

Item	**Requirement**	**Justification**	**Verification Method**	**Verification Plan**
TDVR 6	The fins do not break during launch.	The team wants to ensure that the rocket is stable throughout its entire flight from rail exit to landing. If the rocket lands in free fall, the fins must be designed to withstand the force of hitting the ground at a high velocity.	Inspection	Many different materials were studied for the fin design. WURocketry chose to create four G10 fiberglass non-removable fin cores. Additionally, the team will 3D print PETG fin protective shells with an airfoil as a removable option to decrease the likelihood of fin fracture during launch (the vehicle hits the ground in free fall).
TDVR 7	The bulkheads do not degrade below required strength.	The bulkheads will be reused multiple times for each launch and the bulkheads must remain capable of supporting the applied loads repeatedly.	Demonstration	As part of the testing campaign the strength of the sample bulkheads over cycles will be examined and recorded. The second-to-last cycle before the cycle at which the loads can no longer maintain structural integrity will be used as the cycle limit of the bulkhead part.

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Table 64 – *Continued from previous page*

Item	Requirement	Justification	Verification Method	Verification Plan
TDVR 8	The fastener holes on both the airframe and coupler do not degrade and widen after multiple assemblies and dis-assemblies	If holes wear out, they will need to be drilled in new locations. It is difficult to move hole locations once holes are drilled in the airframe because the avionics bay must sit in a particular orientation and cannot be rotated with new holes.	Inspection	At each hole in the airframe and couplers where the fasteners sit, a small amount of super glue on the outside edge of the hole will be applied after one or two uses of the rocket.
TDVR 9	The bulkheads should be as light as possible.	Bulkheads should help allow for other design freedom for the rocket by being as light as possible while still being able to support the required load.	Demonstration and Inspection	Finite element analysis will be used on the bulkhead designs in SolidWorks to apply a constant load resembling that of the snatch force of the parachutes on the bulkheads. The bulkheads will be designed by mass so that they do not have displacement of more than 0.01 in under the snatch force load but are still as light as possible.
TDVR 10	Components manufactured must be sanded or filed to prevent injuries to team members during assembly and testing.	WURocketry prioritizes the safety of all team members.	Demonstration	The team will acquire sandpaper and a file from the Student Machine Shop to borrow after each part is delivered, machined, or constructed.

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Table 64 – *Continued from previous page*

Item	Requirement	Justification	Verification Method	Verification Plan
TDVR 11	The bulkheads and ballast must be manufacturable by WURocketry members in the Washington University Student Machine Shop.	The team minimizes extraneous manufacturing expenses and gains valuable hands-on experience by turning design drawings into parts.	Demonstration	The team members will consult the Machine Shop Manager for guidance to construct the bulkheads. All members of the Structures subteam are strongly encouraged to obtain machine shop training and to attend machining hours for the bulkheads.
TDVR 12	All permanent screws are 6-32 Phillips head screws on the launch vehicle.	Standardizing fasteners reduces the required equipment on site and makes transportation, assembly, and repairs simpler.	Inspection	The team members will design and purchase 6-32 size Phillips head screws for the bulkheads for the 2022-2023 season.
TDVR 13	Fin dimensions must be large enough to be above the fin flutter factor of safety of 1.5.	If there is fin flutter in the rocket's flight, the fins could break rendering them unusable and could damage other parts of the rocket	Calculation	The structures subteam will do hand calculations using the fin flutter equations to determine if the dimensions are safe.

8.1.3 Team-Derived Recovery Requirements

Table 65: Team-Derived Recovery Requirements

Item	Requirement	Justification	Verification Method	Verification Plan

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Table 65 – *Continued from previous page*

Item	Requirement	Justification	Verification Method	Verification Plan
TDRR 1	Drogue and Main parachutes must be protected during black powder charge ignition.	Black powder detonations can damage the parachute, potentially threatening a safe recovery. Parachute protection methods can be used to prevent this.	Inspection	The drogue and main parachute deployment systems will be designed to ensure a deployment bag or blanket can be used alongside the parachute. The packing of the parachute will be checked by the R&P Team Lead to ensure the parachutes are properly covered before placed into the rocket.
TDRR 2	Black powder quantity must be less than 5 g.	Too much black powder risks damage to the launch vessel and components within. Ejection canisters can not hold more than 5 g and risk getting blown apart by large enough charge.	Testing and Inspection	In testing and launch preparation, the R&P team lead and WURocketry mentor will ensure that no more than 5g of black powder will be used.
TDRR 3	Black powder charges must properly remove shear pins and separate sections of the rocket.	If black powder charges fail to remove shear pins and separate sections of the rocket, parachute deployment will fail, leading to a high impact velocity, major damage to the rocket, and a potential hazard to observers.	Testing and Inspection	Ground ejection tests will be performed two weeks prior to each launch to ensure the amounts of black powder chosen will successfully remove shear pins and seperate the rocket's sections. The R&P Team Lead and WURocketry Mentor will both conduct, monitor, and verify the testing and results.

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Table 65 – *Continued from previous page*

Item	Requirement	Justification	Verification Method	Verification Plan
TDRR 4	Shock cords used must be three to five times the length of the rocket section attached in the use of nylon shock cords.	Nylon shock cords dampen the snatch force on the rocket due to a greater elastic strength. This elasticity is most effective in greater lengths to disperse energy without causeing the rocket section to bounce back and collide.	Inspection, Testing	The R&P Team lead will verify the length of each shock cord. The R&P Team lead will also inspect the camera footage recorded during launches to determine if bounce or collision occurred.
TDRR 5	Shock cord colors must correlate to their size group.	Color coding aids in the visual analysis of shock cord behavior in the camera footage taken during launch. Additionally, color coding reduces likeliness of incorrect shock cord attachments on launch day.	Inspection	Different colored shock cords will be selected for the main and drogue parachute systems, and will be chosen based on specific size. The shock cords will be visually examined by the R&P Team Lead before launch to ensure the colored shock cords are connected to their respective sections.
TDRR 6	Pressure sensors will be used to verify the ignition of the separation charges within in both separation chambers.	A secondary method of separation verification is necessary to provide crucial information in the event of a recovery failure.	Demonstration	The ported pressure sensors will be mounted such that they are able to read the pressure in the separation chambers. Activation of the Raspberry Pi will provide verification of pressure readouts.

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Item	Requirement	Justification	Verification Method	Verification Plan
TDRR 7	Hardware must be mass-optimized to a reasonable degree.	Mass-optimizing hardware reduces the weight of the overall launch vehicle, allowing for a higher apogee range. Furthermore, ballast may be added to increase weight if necessary, but weight is more difficult to remove at a later date.	Inspection and Analysis	The Recovery and Propulsion subteam selects hardware components of the rocket with their weight in mind and uses a scale to verify their weight.

8.1.4 Team-Derived Payload Requirements

Table 66: Team-Derived Payload Requirements

Item	Requirement	Justification	Verification Method	Verification Plan
TDPR 1	The payload must not exceed 16" in length.	The team has designed the payload bay to be at most 15.5" in length this year.	Design and Analysis	CAD software has been used to model the machined structures and overall assembly of the payload experiment to ensure it does not exceed the length. Post-build measurements will also be taken to verify the physical build does not exceed 16".

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Table 66 – *Continued from previous page*

Item	Requirement	Justification	Verification Method	Verification Plan
TDPR 2	The payload must not exceed 6" in diameter.	The team has designed the launch vehicle with an inner diameter of 6" this year.	Design and Analysis	CAD software has been used to model the machined structures and overall assembly of the payload experiment to ensure it does not exceed the diameter. Post-build measurements will also be taken to verify the physical build does not exceed 6".
TDPR 3	The payload should weigh 5 pounds.	The team has determined launch vehicle stability and conducted Open Rocket simulations with a calculated weight of 5 pounds.	Design and Analysis	CAD software has provided an estimate mass for each model that composes the payload, in addition to component commercial weight specifications.
TDPR 4	The payload imaging camera must be able to rotate	In order to properly take images of the surrounding environment, a servo will be used to rotate the camera left and right at 60 degree intervals.	Test	Test the Full Stop, and Full Speed duty cycle values. From there reduce the Servo speed by changing the duty cycle values and use a spreadsheet and timer to calculate rotation.

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Item	Requirement	Justification	Verification Method	Verification Plan
TDPR 5	The payload will automatically upright itself physically, normal to the ground plane and aligned to the z-axis	In order to properly take images of the surrounding environment, the camera must be deployed upright	Test	The subteam has performed multiple tests on the efficacy of the rotating track design by placing various weights at different CGs on a rotating board to test the orientation of the track. The tests have shown that a ballast weight is capable of self-righting the payload track.
TDPR 6	The payload must be securely retained within the vehicle throughout flight	During flight, the nosecone must not separate and rotating tracks must remain stable, and will only deploy when the vehicle has made a stable landing.	Test and Analysis	On SolidWorks, the team will use a simulation with an added force added in the normal direction to the end of the linear solenoid to ensure there is minimal deflection and that the stress value is not too high.
TDPR 7	The payload deployment must separate the nosecone using the onboard DC separation motor	The payload deployment will involve separation of the nosecone from the payload bay of at least 2” to give the scissor lift enough clearance to be deployed	Test	Test how much torque the rack and pinion can generate. The team will have the rack and pinion plus motor run at various speeds to push into a force sensor. Force will be recorded in newtons and analyses to ensure the nose cone can be separated. In addition we can demonstrate it by pushing a mock or real nose cone.

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Table 66 – *Continued from previous page*

Item	Requirement	Justification	Verification Method	Verification Plan
TDPR 8	The payload camera, radio communication, and deployment mechanisms will be run autonomously by a Raspberry Pi.	It is more efficient to have a system capable of running independently and not relying on external influences.	Test and analyze.	Each phase of the payload mission execution (stand-by, launch, landing, self-righting, separation, deployment, and RAFCO execution) will be all run together to ensure the overall components can run under the single main program without team input.
TDPR 9	The payload software will utilize VHF transceiver hardware to listen for RAFCO on the 2-meter radio frequency band to process and execute camera control and transformation operations.	The USLI launch competition will use a NASA hosted APRS network to communicate RAFCO to the payload experiment.	Inspection and Demonstration	The selected hardware for receiving RAFCO signals has been chosen to listen on the 2-meter band and has been demonstrated to receive APRS transmissions from the local area.
TDPR 10	The team will be capable of maintaining reliable communication with the payload during standby, launch, and operation of the system throughout the flight.	This allows the team more insight into the payload mission as it is being executed in real-time.	Demonstration	The RFM96W transceivers have been demonstrated to communicate over 700ft in direct line of sight of each other. The data sent can be of packets of varying sizes, and specifically ASCII data can be transmitted to send informative strings of the payload operation to the base station

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Item	Requirement	Justification	Verification Method	Verification Plan
TDPR 11	The camera arm scissor lift must raise the camera 2" above the body tube.	This ensures that the images taken of the landing site are of good quality when given enough clearance to view the surroundings.	Test	Various mock weights and servo PWM duty cycles will be tested to determine the weight capabilities of the scissor lift arm and the most efficient amount of power needed to drive the arm.
TDPR 12	The supporting mechanisms of the Payload electronics board must remain stable	When the payload is in a deployed state, the supporting rods should not rotate nor droop to ensure that the camera is stable enough to take images of the surrounding sight and rotate.	Demonstration	The assembled payload will be run as expected of the mission to measure whether the choice of new metal support rods do not deflect, as well as the rotating track remaining stable when the camera is deployed and rotated.

8.2 Budgeting and Timeline

8.2.1 Line Item Budgets

Tables 67 to 76 show the budgets for the different subteams as well as budgets for travel and manufacturing. Recovery and Propulsion was broken out and divided into sub-scale and full-scale budgets for clarity. Table 77 shows the total budget of the team.

Table 67: Structures Budget

Item	Vendor / Manufacturer	QTY	Unit Price	Total Price
6" Diameter, 10' Length G12 Fiberglass Airframe	Madcow Rocketry	1	$366.00	$366.00
4" Diameter, 8' Length G12 Fiberglass Airframe	Madcow Rocketry	1	$211.20	$211.20
6" Diameter, 14" Length G12 Fiberglass Coupler	Madcow Rocketry	1	$93.22	$93.22
4" Diameter, 12" Length G12 Fiberglass Coupler	Madcow Rocketry	1	$41.20	$41.20
6" inch Nosecone Fiberglass 5:1 with rounded aluminum tip	Madcow Rocketry	1	$149.99	$149.99
4" inch Nosecone Ogive 5:1 Goblin & Redmax with rounded composite tip	Madcow Rocketry	1	$90.94	$90.94
Universal AstroCam HD Rocket Camera and Holder	Belleville Hobby	2	$29.49	$58.98
6061 T6 Aluminum 6" x 6" x 3/8"	McMaster-Carr	10	$18.07	$180.70
6-32 Metal Screws 100 count	McMaster-Carr	1	$6.46	$6.46
2-56 Shear Screws 3/16" 100 Pack	McMaster-Carr	1	$8.69	$8.69
2-56 Shear Screws 1/4" 100 Pack	McMaster-Carr	1	$8.74	$8.74
316 Stainless Steel Flange Nuts 3/8"-16 Thread Size 25 Pack	McMaster-Carr	1	$12.65	$12.65
Eyebolt - For Lifting 1/4"-28	McMaster-Carr	8	$6.28	$50.24
Rail Buttons for 1.5" rail	Apogee Components	2	$5.70	$11.40
3/8" lead Screw	Ace Hardware	2	$7.30	$14.60
G10 Fiberglass Sheet 24" x 24" x 1/8"	McMaster-Carr	1	$76.71	$76.71
Total				**$1381.72**

Table 68: Avionics Budget

Item	Vendor / Manufacturer	QTY	Unit Price	Total Price
SparkFun GPS Breakout - NEO-M9N, SMA (Qwiic)	Sparkfun	1	$74.95	$74.95
RockBLOCK External Patch Antenna	RockBLOCK	1	$69.95	$69.95
Easy Mini	AltusMetrum	2	$80.00	$160.00
Micro USB Cord	Apogee Components	2	$6.99	$13.98
3.7V LiPo Battery, 900 mAh	AltusMetrum	2	$12.12	$24.24
Raspberry Pi 4 Model B 2019	Raspberry Pi	1	$135.00	$135.00
Adafruit MCP3008 8-Channel 10-Bit ADC	Adafruit	1	$9.00	$9.00
Adafruit MPRLS Ported Pressure Sensor Breakout - 0 to 25 PSI	Adafruit	2	$14.95	$29.90
USB-C to USB-A Cable (0.5ft)	Cable Creations	2	$7.79	$15.58
USB Battery Pack for Raspberry Pi - 10000mAh - 2 x 5V outputs	Adafruit	1	$39.95	$39.95
Perf Bread Boards	Generic	2	$10.05	$20.10
Base Transceiver (EVK-M91-00)	Mouser Electronics	1	$175.00	$175.00
Quad-band Cellular Duck Antenna SMA	Sparkfun	2	$8.95	$17.90
Rotary Switches	Apogee Components	3	$20.15	$60.45
Zip Ties, 6" Long, Pack of 200	Amazon	1	$8.99	$8.99
Velcro, Pack of 6	Amazon	1	$9.99	$9.99
LiPo Guard Bag	Amazon	2	$7.90	$15.80
Total				**$880.78**

Table 69: Fullscale Recovery Budget

Item	Vendor / Manufacturer	QTY	Unit Price	Total Price
Iris Ultra 120” Standard Parachute	Fruity Chutes	1	$475.71	$475.71
18” Elliptical Parachute	Fruity Chutes	1	$62.89	$62.89
15 ft 5/8” 3,200lb Tubular Nylon Shock Cords	Rocketman	2	$30.00	$60.00
25 ft 5/8” 3,200lb Tubular Nylon Shock Cords	Rocketman	1	$45.00	$45.00
30 ft 5/8” 3,200lb Tubular Nylon Shock Cords	Rocketman	1	$53.00	$53.00
Nomex Cord Protector	Sirius Rocketry	3	$18.95	$56.85
Main Deployment Bag	Fruity Chutes	1	$56.76	$56.76
Drogue Nomex Blanket	Fruity Chutes	1	$17.60	$17.60
”Dog Barf” Recovery Wadding	Rocketry Works	1	$1.99	$1.99
Ejection Canister	McMaster-Carr	4	$1.24	$4.96
9V Batteries, 2 pack	Energizer	1	$7.19	$7.19
FFFFg Black Powder	Goex	1	$21.50	$21.50
Gloves for Packing Black Powder and Motor	Amazon	1	$9.99	$9.99
Baby Wipes for Assembling the Motor	Amazon	1	$9.97	$9.97
Baby Powder for Packing Recovery System	Amazon	1	$6.19	$6.19
Nomex Blanket	Fruity Chutes	2	$34.42	$68.84
Total				**$958.44**

Table 70: Subscale Recovery Budget

Item	Vendor / Manufacturer	QTY	Unit Price	Total Price
Iris Ultra 84" Standard Parachute	Fruity Chutes	1	$326.66	$326.66
12"Compact Elliptical Parachute	Fruity Chutes	1	$67.41	$67.41
10 ft 5/8" 3,200lb Tubular Nylon Shock Cords	Rocketman	1	$25.00	$50.00
15 ft 5/8" 3,200lb Tubular Nylon Shock Cords	Rocketman	1	$30.00	$30.00
25 ft 5/8" 3,200lb Tubular Nylon Shock Cords	Rocketman	1	$45.00	$45.00
13" Nomex Blanket Cord Protector	Sirius Rocketry	1	$17.60	$17.60
4" Deployment Bag	Fruity Chutes	1	$50.60	$50.60
"Dog Barf" Recovery Wadding	Rocketry Works	1	$1.99	$1.99
Ejection Canister	McMaster-Carr	4	$1.24	$4.96
9V Batteries, 2 pack	Energizer	1	$7.19	$7.19
FFFFg Black Powder	Goex	1	$21.50	$21.50
Total				**$622.91**

Table 71: Fullscale Propulsion Budget

Item	Vendor / Manufacturer	QTY	Unit Price	Total Price
L1390G Motor	Aerotech	4	$223.54	$894.16
Aerotech 75/3840 Complete Motor Hardware	Aerotech	1	$503.99	$503.99
6" - 75mm Thrust Plate	SC Precision	1	$68.30	$68.30
Aeropack 75mm Retaining Ring	AeroPack	1	$75.83	$75.83
Motor Shipping and Handling				$50.00
Total				**$1542.28**

Table 72: Subscale Propulsion Budget

Item	Vendor / Manufacturer	QTY	Unit Price	Total Price
K805G-P Motor	Aerotech	1	$151.99	$151.99
54mm 1706 motor kit (Casing, Forward closure, Aft Closure, Forward Seal disk)	Wildman Rocketry	1	$187.99	$187.99
4" - 54mm Thrust Plate	SC Precision	1	$44.87	$44.87
Aeropack 54mm Retaining Ring	AeroPack	1	$46.66	$46.66
Motor Shipping and Handling				$50.00
Total				**$481.51**

Table 73: Payload Budget

Item	Vendor / Manufacturer	QTY	Unit Price	Total Price
Raspberry Pi 4B 4GB RAM	RPI Foundation	1	$152.98	$152.98
SanDisk SD 32GB Pack of 2	SanDisk	2	$13.49	$26.98
TalentCell Rechargeable 12V/5V Pack	TalentCell	1	$39.99	$39.99
DC 5521 Cable Pack of 2	DTV	1	$9.99	$9.99
Drone Power Distribution Board	KK MWC	1	$8.79	$8.79
Adafruit BMP388 Precision Altimeter	Adafruit	1	$9.95	$9.95
Adafruit RFM96W RF	Adafruit	1	$19.95	$19.95
SMA ANT 6.1mm	Adafruit	1	$2.50	$2.50
Smraza 160 Wide-Angle	Smraza	1	$16.99	$16.99
USB RTL-SDR Dongle	RTL-SDR	1	$29.95	$29.95
SG90 360 Degree Servo Pack of 2	Jianniu	1	$8.99	$8.99
Adafruit DC Motor Driver Hat	Adafruit	1	$22.50	$22.50
360* Servo with Angle Feedback	Pollolu	1	$27.99	$27.99
2.54mm Breakaway PCB Board 40Pin Male and Female Header Connector	Orcity	1	$8.99	$8.99
Dual Band VHF UHF Male SMA Antenna	Bingfu	1	$9.99	$9.99
USB Extension Cord	Amazon	1	$2.95	$2.95

Raspberry Pi Camera (Model G)	RPI Foundation	1	$24.99	$24.99
Infrared Thermometer Temp Gun	Etekcity	1	$18.99	$18.99
Handheld Ham Radio UV-S9	BaoFeng	1	$27.99	$27.99
BTECH APRS-K1 Cable	BaoFeng	1	$22.49	$22.49
Lazy Susan Turntable 3.75”	DMSTECH	2	$5.99	$11.98
12V DC Double Shafted Motor	Greartsian	1	$29.99	$29.99
Compact Linear Solenoid	McMaster	2	$82.06	$164.12
6832K74 Steel Rack	McMaster	2	$180.50	$361.00
7880K18 Steel Pinion Gear	McMaster	2	$17.96	$35.92
60355K41 Ball Bearing	McMaster	2	$7.09	$14.18
Ball Bearing, Shielded, Trade No. 608-2Z, for 8mm Shaft Diameter	McMaster	2	$14.33	$28.66
Multipurpose 6061 Aluminum, 8 mm Diameter, 3 Feet Long	McMaster	2	$5.09	$10.18
Multipurpose 6061 Aluminum, 1/8” Diameter, 2 Feet Long	McMaster	2	$2.13	$4.26
Set Screw Shaft Coupling, Black-Oxide Steel, for 8mm Diameter Keyed Shafts	McMaster	2	$10.73	$21.46
Compression Spring, 0.75” Long, 0.210” OD, 0.158” ID, Packs of 12	McMaster	1	$13.40	$13.40
Shipping and Handling				$80.00
Total				**$1269.09**

Table 74: Manufacturing Budget

Item	**Total Price**
Additive Manufacturing	$200.00
Machine Tools	$100.00
Total Cost	**$300.00**

Table 75: STEM Engagement Budget

Item	**Total Price**
Printer Paper	$20.00
Gallon Bags	$20.00
Rubber Bands	$5.00
Paperclips	$5.00
Markers	$20.00
Miscellaneous Other Supplies	$20.00
Hand Sanitizer	$10.00
Total Cost	**$100.00**

Table 76: Travel Budget

Item	**Total Price**
Hotel	$3987.35
Renting Cars/Vans	$1200.00
Gas	$1204.00
Total Cost	**$6391.35**

Table 77: Total Budget

System	**Total Cost**
Structures	$1381.72
Avionics	$880.78
Fullscale Recovery	$958.44
Subscale Recovery	$622.91
Fullscale Propulsion	$1592.28
Subscale Propulsion	$481.51
Payload	$1269.09
Manufacturing	$300.00
STEM Engagement	$100.00
Travel Budget	$6391.35
Total Cost	**$13978.08**

8.2.2 Funding Plan

The budget in Section 8.2.1 is paid for through several avenues in which WURocketry has been seeking to raise money. The major sources of funding are four different Washington University in St. Louis student group grants, which WURocketry has had to write up proposals and give presentations for in order to win prize money. Two of the grants, the Engineering Project Review Board Grant (EPRB) and the McKelvey Grant are awarded on a semester basis, requiring the team to put together two proposals and presentations for each presentation each school year. The EPRB grant is required to be used on a specific set of materials that are indicateed during the grant presentations. This year, EPRB money has and will be used for the development of the payload as well as many structural components like the air frame and nose cone. The McKelvey grant provides more flexibility in spending, and was therefore used for materials not budgeted for in the EPRB and some transportation costs. In the fall semester, the team received $1775 and $2000 from the EPRB and McKelvey grant, respectively. The team has been awarded $1500 and $1850 for the EPRB and the McKelvey grant, respectively, for the spring semester. In addition to the aforementioned engineering school grants, the team was awarded $2375 from the Washington University in St. Louis Student Union. This money may be spent over the course of the school year and is required to be spent on a line-item budget that is proposed the previous year, thereby allowing very little flexibility in how it can be spent. The items that this grant covers include remaining structural components for both the sub-scale and full-scale rocket that were not purchased using the EPRB grant money, all avionics components for the sub-scale rocket and the full-scale rocket, and recovery & propulsion materials including parachutes, hardware, deployment bags, and shock cords. On top of these grants, WURocketry has been awarded a $1400 transportation grant through Washington University in St. Louis that is meant to cover a portion of the costs associated with traveling to Huntsville for the competition in April. Upon receiving less money than anticipated from the aforementioned McKelvey grant, the team was able to secure $3955 from the Washington University Student Union for costs associated with lodging Huntsville, and $1204 for transportation costs. The team will bring 24 members to the competition launch in April. The team has developed a sponsorship brochure that has recently been approved by the school that will serve to market WURocketry to businesses in the St. Louis region and beyond in order to develop relationships that might turn into sponsorships down the road. The goal is to eventually phase out the need for school-related grants so that the team can operate completely on outside investment money. The sponsorship brochure has been included the appendix in section 9.3. The school has indicated that there are leads with Milwaukee Tools and Relativity Space that could prove to help the sponsorship efforts.

All materials that have been purchased or will be purchased have been ordered online and delivered to the engineering office at Washington University in St. Louis. These materials typically come within a week, and the vendors that are being used (see Section 8.2.1) have been reliable in their shipments and deliveries. For materials like motors and black powder, the team mentor, Mike Walsh, who has the proper L2 certification for purchase, will complete the orders and store the materials until they are needed to be used during a launch. Using these processes, the team has found it comfortable to acquire everything that is needed for successful construction of the subscale rocket.

8.2.3 Development Timeline

WURocketry's timeline for the 2022-2023 competition year is split up into five milestones/phases: the proposal phase, preliminary design review phase, critical design review phase, flight readiness review phase, and competition phase. In each of these phases, all necessary tasks were compiled and assigned to a subteam. The leaders of each subteam then assigned individual tasks to subteam members. The tasks and Gantt charts for each milestone were made in Microsoft Project and are shown in Figs. 88, 89, 90, 91. and 92.

The focus for the proposal phase was to absorb the information presented in the USLI Competition Handbook, devise a plan for the rocket and team, and begin research for design considerations. Another large focus in this phase was social media presence and recruitment, as shown in the tasks and Gantt chart for the first month of the competition year.

Task Mode	Task Name	Duration	Start	Finish
	Proposal Phase	**24 days**	**Wed 8/17/22**	**Mon 9/19/22**
	Request for Proposal (RFP) Released	1 day	Wed 8/17/22	Wed 8/17/22
	Team Kickoff Meeting	1 day	Sun 9/11/22	Sun 9/11/22
	Recovery & Propulsion, Structures, and Avionics Research and Preliminary Design Development	14 days	Sun 9/11/22	Wed 9/28/22
	Payload: Research and Design Development	14 days	Wed 8/24/22	Mon 9/12/22
	Safety: Develop Safety Section of Proposal	17 days	Sun 8/21/22	Mon 9/12/22
	STEM Engagement: Develop New Activities for Students	21 days	Sun 9/4/22	Fri 9/30/22
	Social Media: Recruitment-Focused Social Media Posts	30 days	Sun 8/21/22	Thu 9/29/22
	STEM Engagement: Contact Local Schools	35 days	Sun 9/18/22	Thu 11/3/22
	Business/Funding: Request for Funds/Sponsorships	47 days	Sun 8/21/22	Mon 10/24/22
	Recruitment: Engineering Student Group Activities Fair	0.2 days	Mon 8/29/22	Mon 8/29/22
	Recovery & Propulsion, Structures, and Avionics Detailed Design Development	7 days	Sun 9/11/22	Sun 9/18/22
	Develop CAD Model of Subscale and Full-Scale Rockets	7 days	Sun 9/11/22	Sun 9/18/22
	Recruitment: Student Union Student Group In-Person Activities Fair	1 day	Fri 9/2/22	Fri 9/2/22
	Recovery & Propulsion, Structures, and Avionics Develop Technical Design Portion of Proposal	5 days	Sun 9/11/22	Thu 9/15/22
	Payload: Choose Design and Complete Design Validation with Chief Engineer	1 day	Sun 9/4/22	Sun 9/4/22
	Payload: Develop Payload Technical Design Portion of Proposal	5 days	Sun 9/4/22	Thu 9/8/22
	Recovery & Propulsion, Structures, and Avionics Bill of Materials Due	1 day	Sun 9/11/22	Sun 9/11/22
	Proposal Rough Draft Due	1 day	Mon 9/12/22	Mon 9/12/22
	Edit, Compile, and Proofread Proposal	7 days	Sun 9/11/22	Sun 9/18/22
	Build Sub-Scale Rocket	14 days	Sun 10/2/22	Wed 10/19/22
	Payload: Create Detailed Design	22 days	Sun 9/18/22	Mon 10/17/22
	Submit Proposal	0.2 days	Fri 9/16/22	Fri 9/16/22
	Recovery & Propulsion, Structures, and Avionics Design Refinement	7 days	Mon 9/19/22	Tue 9/27/22
	Proposal Due at 8am CDT	1 day	Tue 9/20/22	Tue 9/20/22
	Recovery & Propulsion, Structures, and Avionics Updated Bill of Materials Due	1 day	Tue 9/27/22	Tue 9/27/22

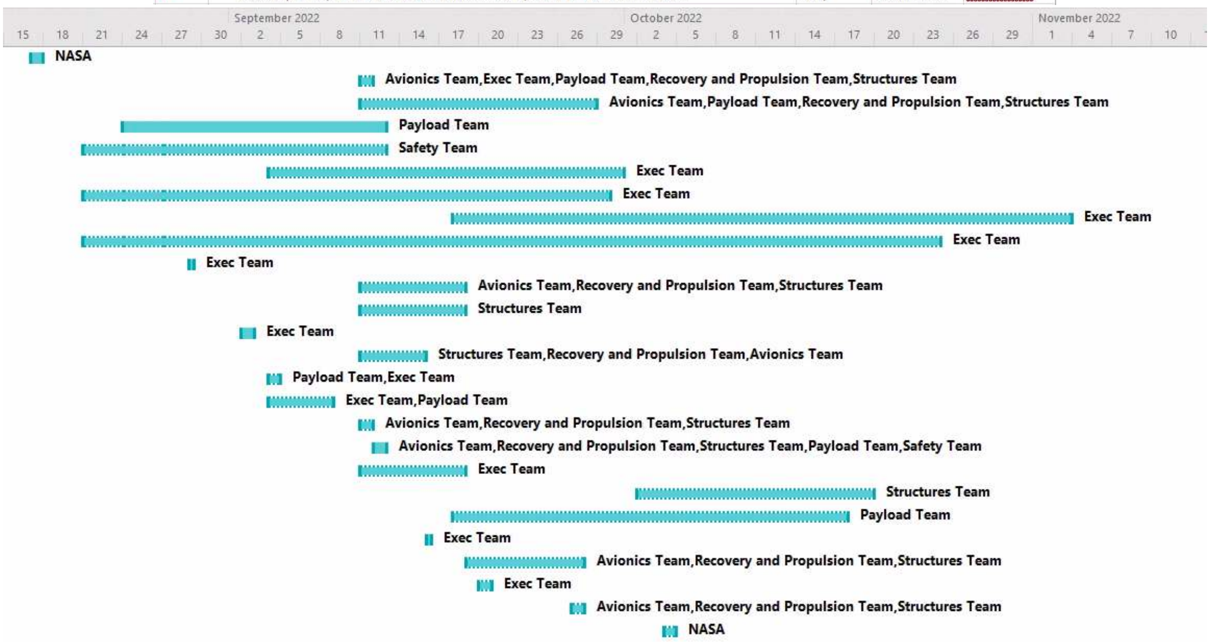

Figure 88: WURocketry Proposal Timeline for the 2022-2023 Competition Year

The focus for the preliminary design review phase was to develop the design considerations and continue to do research into the best alternatives. Sub-teams made their first prototypes and started refining the ideas and designs based on preliminary results. The main focus of the structures sub-team was building the sub-scale rocket, paying special attention to detail to ensure a successful launch.

Task Mode	Task Name	Duration	Start	Finish
	PDR Phase	**34 days**	**Wed 10/5/22**	**Mon 11/21/22**
	Social Media: Update Social Media Weekly	172 days	Wed 10/5/22	Thu 6/1/23
	Social Media: Update Website as Needed for Documentation	172 days	Wed 10/5/22	Thu 6/1/23
	Recovery & Propulsion, Structures, and Avionics Testing	4 days	Wed 10/5/22	Sun 10/9/22
	Payload: Complete CAD and Bill of Materials	11 days	Wed 10/5/22	Wed 10/19/22
	Recovery & Propulsion, Structures, and Avionics PDR Vehicle Section	17 days	Wed 10/5/22	Thu 10/27/22
	PDR Q&A	1 day	Thu 10/6/22	Thu 10/6/22
	Build Full-Scale Rocket	7 days	Sat 10/8/22	Sat 10/15/22
	Payload: Complete Payload Section of PDR	14 days	Sat 10/8/22	Wed 10/26/22
	STEM Engagement: Francis Howell North Engineering Students	1 day	Sat 10/15/22	Sat 10/15/22
	Payload: Manufacture Prototype	7 days	Sat 10/15/22	Sat 10/22/22
	Social Media Handle List sent to project office by 8am CDT	1 day	Fri 10/21/22	Fri 10/21/22
	PDR Rough Draft Due	1 day	Sat 10/22/22	Sat 10/22/22
	Payload: Test Prototype	14 days	Sat 10/22/22	Wed 11/9/22
	Payload: Refine Design Based on Protoype Test Results	17 days	Tue 10/25/22	Wed 11/16/22
	PDR Report, Presentation Slides, and Flysheet Due by 8am CDT	1 day	Wed 10/26/22	Wed 10/26/22
	PDR Teleconferences	20 days	Tue 11/1/22	Mon 11/28/22
	STEM Engagement: North Kirkwood Middle School Engineering Students	1 day	Sat 11/5/22	Sat 11/5/22
	Payload: Build Refined Payload	5 days	Tue 11/8/22	Sun 11/13/22
	Fly Sub-Scale Rocket	1 day	Sun 11/13/22	Sun 11/13/22
	Payload: Validate Refined Payload	5 days	Sun 11/13/22	Thu 11/17/22
	STEM Engagement: Brittany Woods Middle School	0.5 days	Tue 11/15/22	Tue 11/15/22
	Payload Demonstration Flight: Fly Full-Scale Rocket with Payload	1 day	Sun 11/20/22	Sun 11/20/22

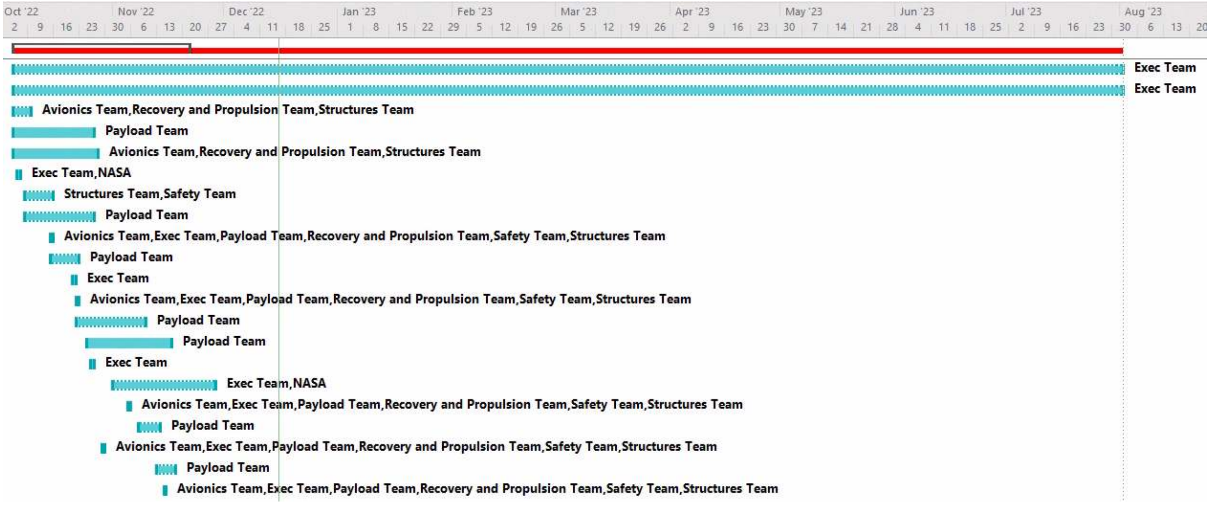

Figure 89: WURocketry Preliminary Design Review Timeline for the 2022-2023 Competition Year

The focus for the critical design review phase was to continue to refine the design of the rocket and payload. In this phase, the sub-scale rocket had already successfully launched, so the focus shifted to building the full-scale rocket and learning from the experiences and shortcomings of the sub-scale launch. For all sub-teams, there was also a shift to testing the final design choices. All tests were compiled and prepared for physical testing. If the tests could be completed in this phase utilizing 3D printing, those tests were performed, analyzed, and a report was written detailing the results and lessons learned.

Task Mode	Task Name	Duration	Start	Finish
	CDR Phase	**58 days**	**Wed 11/30/22**	**Fri 2/17/23**
	CDR Q&A	0.5 days	Thu 12/1/22	Thu 12/1/22
	Recovery & Propulsion, Structures, and Avionics Write Vehicle and Recovery Design Portions of CDR and CDR Presentation Slides	14 days	Wed 11/30/22	Mon 12/19/22
	Payload: Write Payload Design Portion of CDR and CDR Presentation Slides	14 days	Wed 11/30/22	Mon 12/19/22
	CDR Rough Draft Due	1 day	Mon 12/12/22	Mon 12/12/22
	Fly Full-Scale Rocket	1 day	Sun 11/13/22	Sun 11/13/22
	Subscale Flight Deadline	1 day	Mon 1/9/23	Mon 1/9/23
	CDR Report, Presentation Slides, and Flysheet due by 8am CST	0.5 days	Mon 1/9/23	Mon 1/9/23
	CDR Teleconferences	18 days	Fri 1/13/23	Tue 2/7/23

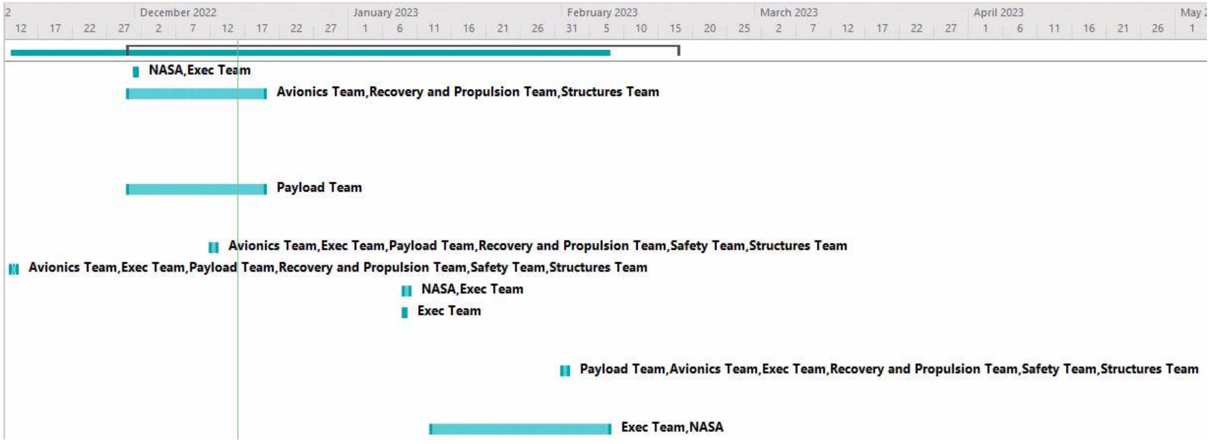

Figure 90: WURocketry Critical Design Review Timeline for the 2022-2023 Competition Year

In the flight readiness review phase, the focus again was mostly on testing and demonstrations. The full-scale rocket was flown with a simulated payload first. In addition, the payload team constructed the payload using the final design choices made in the CDR phase. Once the payload was constructed, more tests and demonstrations were performed to ensure viability of the design and concepts before the payload is launched with the rocket. The payload demonstration flight is also included in this phase, scheduled towards the end of the FRR phase to allow time for the Payload team to build and test their design before flight.

Task Mode	Task Name	Duration	Start	Finish
	FRR Phase	46 days	Fri 1/27/23	Fri 3/31/23
	FRR Q&A	0.5 days	Thu 2/9/23	Thu 2/9/23
	Recovery & Propulsion, Structures, and Avionics Write Vehicle and Recovery Design Portions of FRR and FRR Presentation Slides	18 days	Fri 1/27/23	Tue 2/21/23
	Payload: Write Payload Design Portion of FRR and FRR Presentation Slides	18 days	Fri 1/27/23	Tue 2/21/23
	STEM Engagement: Girl Scouts of Eastern Missouri Rocket Team	0.5 days	Sat 2/4/23	Sat 2/4/23
	FRR Rough Draft Due	1 day	Tue 2/14/23	Tue 2/14/23
	Fly Full-Scale Rocket (Vehicle Demonstraton Try #2)	1 day	Sun 2/26/23	Sun 2/26/23
	STEM Engagement: UCity Kindergarteners: Jackson Park Elementary	1 day	Sat 3/4/23	Sat 3/4/23
	STEM Engagement: UCity Kindergarteners: Flynn Park Elementary	1 day	Sat 3/4/23	Sat 3/4/23
	STEM Engagement: Girl Scouts of Eastern Missouri Rocket Team	1 day	Mon 3/6/23	Mon 3/6/23
	Vehicle Demonstration Flight Deadline	0.5 days	Mon 3/6/23	Mon 3/6/23
	FRR Report, Presentation Slides, and Flysheet due by 8am CST	0.5 days	Mon 3/6/23	Mon 3/6/23
	FRR Teleconferences	18 days	Mon 3/13/23	Wed 4/5/23
	Payload Demonstration Flight and Vehicle Re-flight (Back-up Date: March 26, 2022)	1 day	Sun 3/19/23	Sun 3/19/23
	Payload Demonstration Flight and Vehicle Re-flight deadline	0.5 days	Mon 4/3/23	Mon 4/3/23
	FRR Addendum due by 8am CST	0.5 days	Mon 4/3/23	Mon 4/3/23

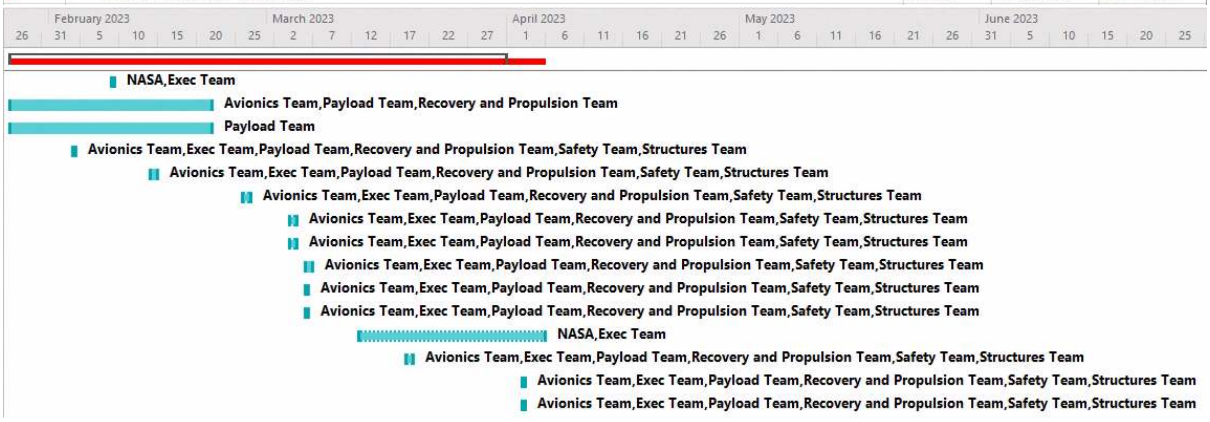

Figure 91: WURocketry Flight Readiness Review Timeline for the 2022-2023 Competition Year

The competition phase will mostly focus on making travel and hotel plans and traveling to Huntsville to launch with the other USLI Competition teams. This consists of final hardware checks, code pushes, and the final competition launch. This phase also entails the Post Launch Assessment Report, in which teams will analyze how the rocket and payload performed on launch day.

Task Mode	Task Name	Duration	Start	Finish
	Competition Phase	22 days	Sat 4/1/23	Mon 5/1/23
	Launch Week Q&A	0.6 days	Thu 4/6/23	Thu 4/6/23
	Teams travel to Huntsville, AL	1 day	Wed 4/12/23	Wed 4/12/23
	Hardware Checks in Huntsville, AL	1 day	Thu 4/13/23	Thu 4/13/23
	Launch Day and Awards Ceremony	0.75 days	Sat 4/15/23	Sat 4/15/23
	Backup launch day	0.75 days	Sun 4/16/23	Sun 4/16/23
	Post-Launch Assessment Review (PLAR) submitted to NASA project management team by 8:00 a.m. CDT.	1 day	Mon 5/1/23	Mon 5/1/23

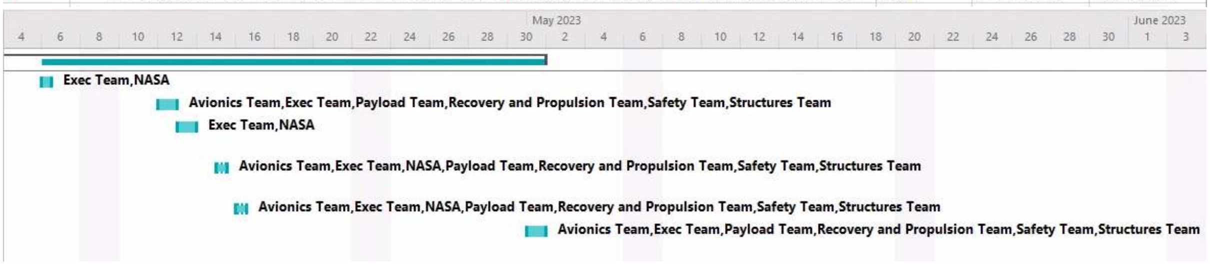

Figure 92: WURocketry Competition Timeline for the 2022-2023 Competition Year

The status of WURocketry's progress throughout the year is being tracked by pivot charts to ensure the project is staying on time and progressing as expected. The overall status of the project is shown in Fig. 93.

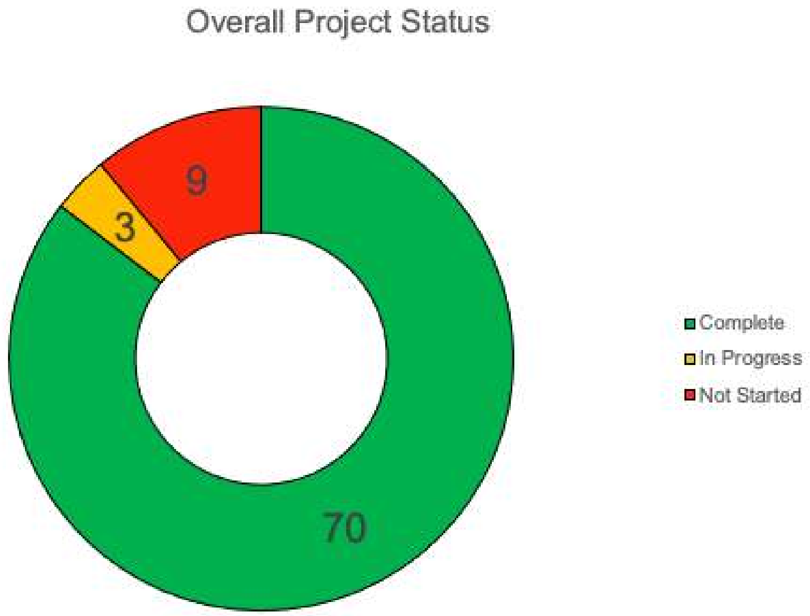

Figure 93: High-Level Status of WURocketry's 2022-2023 Competition Year Tasks.

This figure shows that the team is indeed progressing as expected. This status can also be broken down by phase to determine where most of the work still lies. This is shown in Fig. 94.

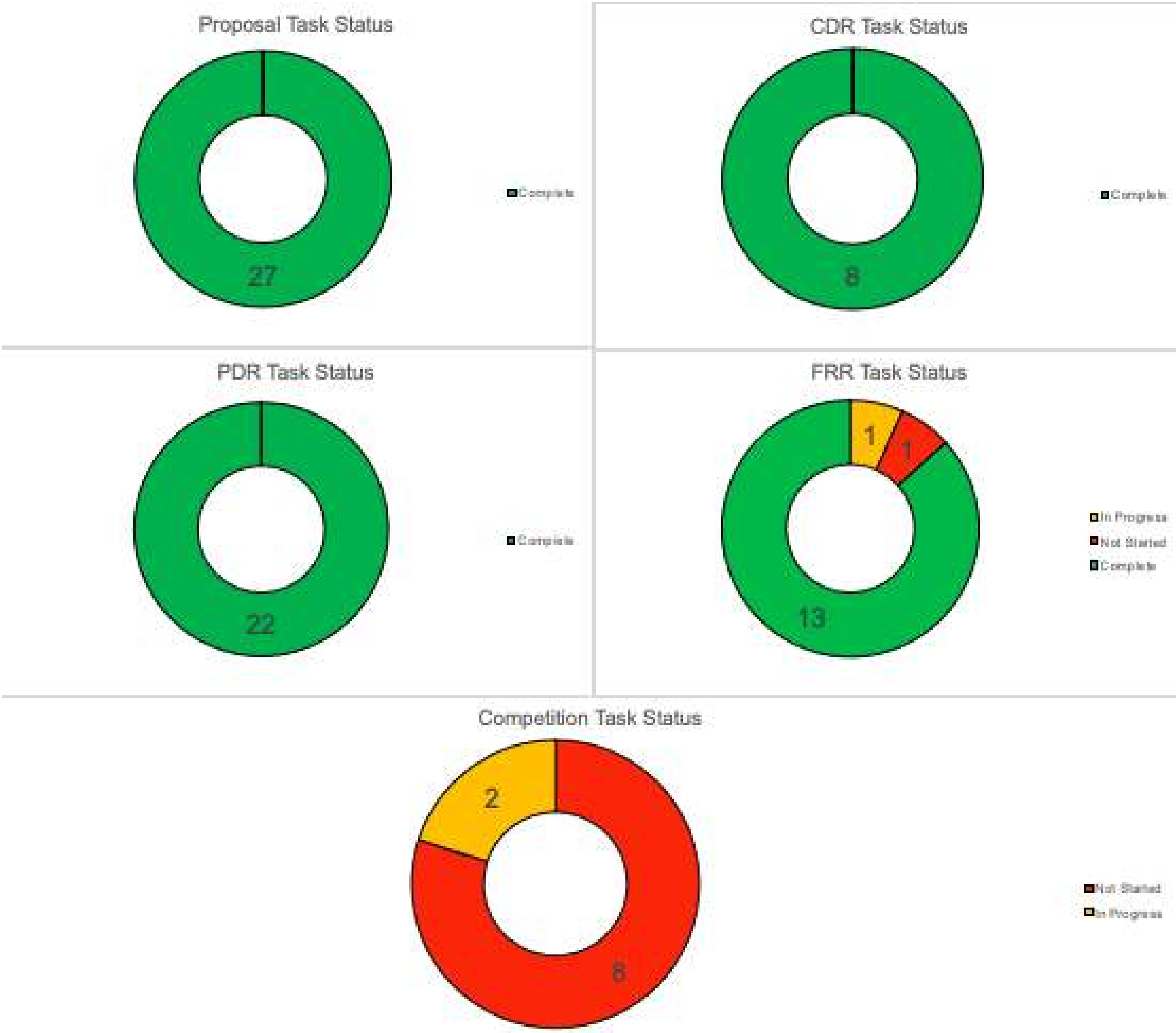

Figure 94: Status of each phase in WURocketry's 2022-2023 competition year.

It can be noted that there is one item in the FRR phase that is "In Progress" and one item that is "Incomplete." These items are the payload demonstration flight and the backup payload demonstration flight. The payload demonstration flight is currently scheduled for March 11, 2023 and is therefore marked as "In Progress." The backup demonstration flight has not been scheduled yet since we do not yet know if we will need this launch. In the event that the payload demonstration flight gets cancelled or does not go as planned, this backup demonstration flight will take place as soon as possible after the first scheduled date.

Figure 93 shows that WURocketry has completed about 80% of the tasks associated with this competition year and Fig. 94 shows that most of these tasks are associated with future phases of the project. This leads the team to believe that the project is on schedule, will progress as expected, and will be ready to present at the final competition.

9 Appendix

9.1 Code for 5.1.1

```
%Everything is in SI units past this point
%Variable Definitions
%y a vector of is the Force in Newtons, x is the time over which the
%varying forces occur
%Aft = 19.24 lb
%Mid = 5.59 lb
%Forward  = 18.012 lb
%% Data Used in Accounting for Thrust and Propellant Burn
motorBurn = burn();
y=thrust();
x=tim();
m=cat(1,motorBurn,0)./1000; %from g to kg

%Effective Cross Sectional Area of Rocket
A=0.0080825645;
%Total Mass of Rocket
weight = 19.43;
%Duration of Flight
dur=2.9;
%air density
ro=1.225;
%total mass lost during flight
propWeight=1.973;
%acceleration due to gravity
g=9.81;
%Drag coefficient
C_d=0.6;

%Equations used:
%Mass lost over time (function n) *assumption, loss of mass over time due
%to propellant burn can be approximated to be linear
%m(t)=weight - (propWeight/dur)*t
%Force over time:
%f(t) (is found using the best fit line tool and saving it to workspace)
%drag force:
%F_d = 1/2(ro)(v^2)(A)(C_d)
%Force due to gravity:
%F_g=m(t)*g


%% Approximating Altitude and Velocity over Time
%terminal velocity = 4.35
%using ode45 to solve the diffeq
%setting up inital conditions and time vectors to use,
x0=[0,0];
tspan2 = [2.91 17.3];
tspan3 = [17.31 51.9];
tspan4 = [51.91 90.7];
%running ode 45 with various conditions based on state of rocket
[t,x] = ode45(@position01, motor,x0 );
```

```
[t2, x2] = ode45(@position2 , tspan2, [x(39,1),x(39,2)]);
[t3, x3] = ode45(@position3 , tspan3, [x2(45,1),x2(45,2)]);
[t4, x4] = ode45(@position4 , tspan4, [x3(57,1),x3(57,2)]);
xFinal = cat(1,x,x2,x3,x4);
tFinal = cat(1,t,t2,t3,t4);
%% Plotting Results

figure;
plot(x,y)
title('Thrust of rocket over time')
xlabel('time (seconds)')
ylabel('Force (Newtons)')

figure;
plot(x,m)
title('Mass of rocket propellant over time')
xlabel('time (seconds)')
ylabel('Mass (kg)')

figure;
subplot(2,1,1);
plot(tFinal, xFinal(:,1));
xlabel('Time')
ylabel('Position (m)')
title('Position and Velocity over Time')
subplot(2,1,2);
plot(tFinal, xFinal(:,2));
xlabel('Time')
ylabel('Velocity (m/s^2)')
%%
%Finding a best fit line
%-444.673048066401*t^10+7861.29244373069*t^9-58789.4063118116*t^8+243586.233686891*t^7
%-614071.424962456*t^6+971874.732925931*t^5-959370.713362109*t^4+
% 565467.299797210*t^3-180670.046352333*t^2+25942.5542978860*t+276.319003851257
%used basic fit data tool, very lengthy, and needs to be recalculated after
%finding net force and divided by m(t)

%lline is the equation put into string form
lline = "";
coe = [-444.673048066401,7861.29244373069,...
    -58789.4063118116,243586.233686891,-614071.424962456,971874.732925931,...
    -959370.713362109,565467.299797210,-180670.046352333,25942.5542978860...
    ,276.319003851257];
for i=0:10
    v=10-i;
    lline = lline + coe(i+1)+"t^"+v+"+ ";

end
%% Function Definitions
function dxdt = position01(t,x)
A=0.0080825645;
weight = 19.43;
coe = [-444.673048066401,7861.29244373069,...
    -58789.4063118116,243586.233686891,-614071.424962456,971874.732925931,...
    -959370.713362109,565467.299797210,-180670.046352333,25942.5542978860,...
    276.319003851257];
dur=2.9;
ro=1.225;
```

```
propWeight=1.973;
g=9.81;
C_d=0.6;
c_1=1/2*ro*A*C_d;
dxdt = [x(2);-g+(coe(1)*t^10+coe(2)*t^9+coe(3)*t^8+coe(4)*t^7+ ...
    coe(5)*t^6+coe(6)*t^5+coe(7)*t^4+coe(8)*t^3+coe(9)*t^2+coe(10)*t ...
    +coe(11)-c_1*(x(2)^2))/(weight-propWeight/dur)];
end

function dxdt = position2(t,x)
A=0.0080825645;
weight = 19.43;
ro=1.225;
propWeight=1.973;
g=9.81;
C_d=0.6;
c_1=1/2*ro*A*C_d;
dxdt = [x(2);-g+((-c_1*(x(2)^2))/(weight-propWeight))];
end

function dxdt = position3(t,x)
A=0.0080825645;
weight = 19.43;
ro=1.225;
propWeight=1.973;
g=9.81;
C_d=0.6;
c_1=1/2*ro*A*C_d;


dxdt = [x(2);-g+((c_1*(x(2)^2)+1.5*x(2)^2*ro*0.5*0.16417322322...
)/(weight-propWeight))];
end

function dxdt = position4(t,x)
A=0.0080825645;
weight = 19.43;
ro=1.225;
propWeight=1.973;
g=9.81;
C_d=0.6;
c_1=1/2*ro*A*C_d;
aftMass = 8.7271172;
c_3 = 1.5*ro*0.5*0.16417322322;
c_4 = 0.5*2.2*ro*7.296587699;

dxdt = [x(2);-g+x(2)^2*((c_1)/(weight-propWeight)+(c_3)/(8.7271172)...
+(c_4)/(weight-propWeight-aftMass))];
end

%% Data Used in Accounting for Thrust and Propellant Burn
function f = thrust()
f=[0
906.203000000000
1249.41000000000
1336.72000000000
1369.84000000000
1402.96000000000
```

```
1411.99000000000
1411.99000000000
1586.61000000000
1649.83000000000
1640.80000000000
1625.74000000000
1628.76000000000
1619.72000000000
1607.68000000000
1601.66000000000
1589.62000000000
1550.48000000000
1499.30000000000
1424.03000000000
1366.83000000000
1312.64000000000
1261.46000000000
1228.34000000000
1213.29000000000
1204.26000000000
1198.23000000000
1198.23000000000
1165.12000000000
1074.80000000000
957.383000000000
839.968000000000
713.522000000000
590.085000000000
427.511000000000
295.043000000000
153.543000000000
69.2450000000000
0];
end
function g = tim()
g=[0
0.0180000000000000
0.0410000000000000
0.0550000000000000
0.0990000000000000
0.173000000000000
0.236000000000000
0.284000000000000
0.678000000000000
0.869000000000000
0.939000000000000
1.10200000000000
1.19700000000000
1.29300000000000
1.37400000000000
1.45500000000000
1.51800000000000
1.59200000000000
1.69100000000000
1.83800000000000
1.96000000000000
2.10000000000000
2.22500000000000
```

```
2.34300000000000
2.41700000000000
2.47900000000000
2.52400000000000
2.56400000000000
2.60100000000000
2.63800000000000
2.66000000000000
2.68900000000000
2.71200000000000
2.73700000000000
2.76300000000000
2.80000000000000
2.84400000000000
2.87700000000000
2.91100000000000];
end
function w = burn()
w= [1973.
1968.92
1956.53
1947.48
1917.71
1866.42
1822.09
1788.21
1492.88
1338.36
1280.78
1147.68
1070.4
992.446
927.099
862.118
811.861
753.777
678.304
570.885
485.774
392.004
311.573
238.133
192.968
155.501
128.476
104.514
82.6561
61.9394
50.7637
37.7345
28.8031
20.6565
14.0429
7.36013
2.42629
0.];
end
```

9.2 Code for 3.3.6

```
%Tomas Collado, 2/15/23
%WURocketry Alternative Parachute Sizing Calculations
clear;
close all;
clc;

syms A_m D_m


format shortg

%%% Parameters %%%
C_d = 1.55; %Drogue Drag Coefficent
D_d = 18; %Drogue Diameter (in)
A_d = []; %Drogue Area (ft^2)
C_m = 2.2; %Main Drag Coefficent
%D_m = []; %Main Diameter (in)
%A_m = 0; %Main Area (ft^2)
shf = .96; %Fudge Factor to account for precense of spill hole
W = 38.492;%Dry Weight of Rocket (lb)
W_ls = 17.762; %Weight of Rocket's Largest Section (lb)
M = []; %Mass of Rocket (slug)
M_ls = []; %Mass of Rocket's Largest Section (slug)
KE = 75; %Kinetic Energy Constraint (ft-lb)
V_t = []; %Maximum Terminal Velocity at Impact (ft/s)
p = 2.376*10^-3; %Air Density Constant (lb/ft^3)

%Conversion from lbs to slugs
%1 slug = 32.174048694867 lbs
M_ls = W_ls/32.174048694867;
M = W/32.174048694867;


%Calculation of Maximum Terminal Velocity at Impact
% KE = 0.5*m*v^2 --> sqrt(2KE/m) = v
V_t = sqrt((2*KE)/M_ls)

%Calculation of Area of Drogue Parachute
A_d = shf*pi*((D_d/2)/12)^2;

%Terminal Velocity Equation
drag = V_t == sqrt((2*W)/(p*(C_d*A_d + C_m*A_m)));

A_m = solve(drag,A_m);

fprintf('Main Parachute Minimum Area = %.2f ft^2\n', A_m)

%Finding Main Parachute Diameter from Area
main = A_m == shf*pi*((D_m/2)/12)^2;

D_m = solve(main,D_m);

fprintf('Main Parachute Minimum Diameter = %.2f in\n', D_m)
```

9.3 Sponsorship Brochure

The below pages are the current draft of the WURocketry sponsorship brochure that will be sent to companies in an attempt to raise money for the team and create partnerships for networking opportunities.

WUROCKETRY

Washington University in St. Louis
James McKelvey School of Engineering

Since 2021

CORPORATE SPONSORSHIP PROPOSAL

OUR MISSION

WURocketry is the Washington University in St. Louis rocket design team. The team designs, documents, and builds an L2, high-powered rocket annually for the NASA Student Launch Competition.

Huntsville, AL

NASA Student Launch Competition

The goal of teams competing in the NASA Student Launch Competition each year is to design and build a rocket to meet NASA-specified criteria.

Teams in the competition are graded on design execution and design report deliveries

PROPOSAL

PDR

CDR

FRR

STEM ENGAGEMENT

WURocketry engages over 300 K-12 students in STEM-related outreach events *EACH YEAR* to provide valuable and accessible educational opportunities

Subteams

- Aerodynamics
- Avionics
- Structures
- Recovery & Propulsion
- Payload
- Safety

GET INVOLVED →

HOW YOU CAN HELP

WURocketry intends on growing the team to the point at which it is able to compete in multiple national competitions focused on high-powered rocketry. This growth and diversification will expose students to more challenging engineering problems on a greater scale.

	Sponsorship Levels		
	Bronze $500	Silver $1000	Gold $1500
Logo on WURocketry Website	x	x	x
Logo on WURocketry Apparel	x	x	x
Logo on WURocketry Rocket	x	x	x
Networking Events with Members		x	x
Access to Resume Database			x

PAST SPONSORS

McDonnell Center for the Space Sciences
McKelvey School of Engineering

Thank You

If you have any questions, please feel free to contact us :

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President

gagefuller@wustl.edu

William Urdahl

Treasurer

u.william@wustl.edu

*All donations are tax deductible and subject to terms and agreements between WURocketry, you (the company/donor), and Washington University in St. Louis.

9.4 Raw Flight Data

The following pages contain the raw flight data from the Full-Scale launch demonstration captured by the Primary Flight Computer.

The following pages contain the raw flight data from the Full-Scale launch demonstration captured by the Redundant Flight Computer.