The Zenith Program

Preliminary Design Review

FAMU-FSU College of Engineering

2525 Pottsdamer Street

Tallahassee, FL 32310

10/27/202

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1 Summary

1.1 Team Summary

1.1.1 Team Information

1.1.1.1 Team Name

This team has dedicated itself to laying the groundwork for continued yearly participation in NASA Student Launch and expansion into experimental liquid-fueled engine development by the parent AIAA chapter. To that end, the team has deemed itself the first year of FAMU-FSU AIAA's rocket development program, called the Zenith Program.

1.1.1.1 Mailing Address

Mail to: FAMU-FSU AIAA

2525 Pottsdamer Street, Suite B111

Tallahassee, FL 32310

1.1.2 Mentor Information

1.1.2.1 Mr. Tom McKeown

- **Title:** Board Member, Spaceport Rocketry Association (NAR #342 / TRA #73)
- **Email:** mckeownt@ix.netcom.com
- **Phone:** 321-266-1928
- **NAR Flyer Number:** 57205
- **TRA Flyer Number:** 01922
- **NAR/TRA Certification Level:** Level 2

1.1.1 PDR Completion Time

The team spent approximately 200 hours working on the PDR document.

1.1.2 Social Media Presence

Table 1-1. Social Media Handles

Social Media Platform	Team Handle
Instagram	@thezenithprogram https://www.instagram.com/thezenithprogram/
Twitter	@ZenithProgram https://twitter.com/ZenithProgram
Facebook	The Zenith Program https://www.facebook.com/profile.php?id=100087080535192

1.2 Launch Vehicle Summary

1.2.3 Target Altitude

The official declared altitude of the Zenith program is 4600 feet. See section 3.3.1 for further detail.

1.2.2 Preliminary Motor Choices

The leading motor choice is the Cesaroni L3200. See section 3.3.2 for further detail.

1.2.3 Vehicle Sections

The leading flight vehicle design is 91 inches in length with a body tube diameter of 6.18 inches a total weight of 34.27 lbs. The static stability margin of the vehicle is 2.26 calibers and the max velocity the vehicle reaches is 682 ft/s. Section 3.1.5 expands further into the leading design of the vehicle and its respective weight distribution.

1.2.4 Recovery System

The recovery system consists of the TeleMega v4 dual-deployment flight computer which is capable of recording altimeter, GPS, and telemetry data. At apogee, a 24” high strength elliptical parachute will deploy. At around 550 feet above ground, a 72” Iris Ultra toroidal main parachute will deploy. The recovery system and all its relevant components are discussed further in Section 3.2.

1.3 Payload Summary

1.3.1 Dual Wheeled Rover Scout

To utilize the most space in the payload section the team decided on a two-wheel system. This allows for the largest possible wheels given the space. The deployment of the rover will utilize the shock cord on parachute deployment to deploy the rover from the payload bay. The rover will be propelled by two DC motors. The team has also set the goal of 3D printing as many parts of the rovers as possible, those being the chassis and the wheels. The mission of the Dual Wheeled Rover Scout, upon successful landing, is to maneuver around the ground terrain capturing video of the surface that will be used to get a topography of the surface. After the rover has retrieved sufficient footage, it has the additional goal of returning to the launch vehicle.

2 Modifications to Proposal

2.1 Modified vehicle criteria

Table 2-1. Vehicle Modifications

Description of Change	Reason for the Change
Projected altitude changes to 4600 feet	The weight of the vehicle increased
Motor changed to a Cesaroni L3200	The change of motor decreased the weight of the motor while also increasing thrust
Rearranged the rocket structure: - Main chute moved to upper payload bay - Avionics bay has its own body section - Payload was moved into the nose cone section	Stability margin and apogee optimization prefer the dual-separation design to the initial single separation. With motor, avionics, and 2 chutes at the base stability was poor and payload remained in the bay. Dual separation allows the main chute to pull rover from retainer on deployment.
Drogue chute increased from 15’’ to 24’’	Decreases the velocity change between the terminal velocity of the drogue and main parachute. This decreases the change of structural damage during main parachute deployment.
CO2 ejection mechanism in place of black powder charges	Removes hazards and regulations of handling, ordering, storing explosive material. Far more easily reusable. Less potential to damage avionics or parachutes.

2.2 Changes made to payload criteria

Table 2-2. Payload Modifications

Description of Change	Reason for the Change
Changed from a four wheeled design to a two wheeled design	This change was made to have the greatest wheel size and best fit in the payload bay. Large wheels provided best mobility on the given terrain
Changed the objective of the rover from planning a flag to using a camera to get terrain topography	This change was made so that the payload would have a scientific purpose. Planting a flag into the ground is not scientific. This change was made to remedy it

2.3 Changes made to project plan

Table 2-3. Project Modifications

Description of Change	Reason for the Change
Projected project budget increased from $3500 to $7000	Refining part selection slightly raised material cost. Original budget did not quote 2 flight computers. Transportation and logistics estimate in proposal was poor, estimate: $500; actual: $2500
Deadlines kept constant. Item durations in work breakdown structure increased. Start times on tasks pushed up by 7-14 days on average.	"Learn as you go." This is the Zenith Program's first time as part of SLI, we determined that the workload for each task far exceeded the time we had estimated and budgeted.
Accommodations plan for competition refined.	Female safety officer. Male team. SO requires a separate hotel room. Team mentor hotel stay also added as component of travel and logistics. Student food stipend added as budget item (ME Dept. Policy).
Sub-scale model initially quoted in budget at 1:10 scale parts. Model is now 50% length scale, 25% impulse scale.	Initial parts quoted do not accurately represent the large-scale vehicle being constructed and do not reach the level of high-power rocketry by impulse class.

3 Vehicle Criteria

3.1 Selection, Design, and Rationale

3.1.1 Launch Vehicle Mission Statement

The mission of the Zenith Program's launch vehicle is to successfully reach the targeted apogee and safely return to the ground to deploy an autonomous rover. Additionally, the vehicle is to be designed with modular and reusable components.

3.1.2 Mission Success Criteria

Table 3-1. Mission Success Criteria

Success Level	Vehicle	Safety
Complete Success	• Vehicle completes full flight and recovery profile • No damages • No off-nominal separations or deployments • RAFCO mission success	• No risk for injury created • No injuries reported
Partial Success	• Vehicle completes full profile • Minor damages • Some off-nominal separations of deployments • RAFCO mission success	• Slight risk of injury created • No injuries reported
Partial Failure	• Vehicle completes full profile • Minor or major damages • Failed separations or deployment events • RAFCO mission failure	• Great risk of injury created • Minor injuries reported
Complete Failure	• Catastrophic failure in flight leading to loss of vehicle • Vehicle inoperable and unable to attempt flight	• Major injuries requiring professional medical attention

3.1.1 Alternate Vehicle Designs and Evaluation

The following alternative designs of the launch vehicle cover specific design selection within the vehicle's major sections.

3.1.1.1 Nosecone Configurations

The nosecone is one of major attributes to the vehicle's aerodynamic characteristics and can be altered to through different geometries to improve the vehicles performance against oncoming airflow. As with most components, the nosecone effects the vehicle's center of pressure by causing pressure variations around the surface of the flight vehicle. The following nosecone designs were considered and evaluated through their geometric characteristics against subsonic flow.

(a) Elliptical Nosecone

The Elliptical Nosecone has an ideal geometry for subsonic flow due to its blunted and rounded nose. This feature increases the drag during flight, which makes it a considerable candidate for low apogee flights. The image below shows a drawing of the model created in SolidWorks.

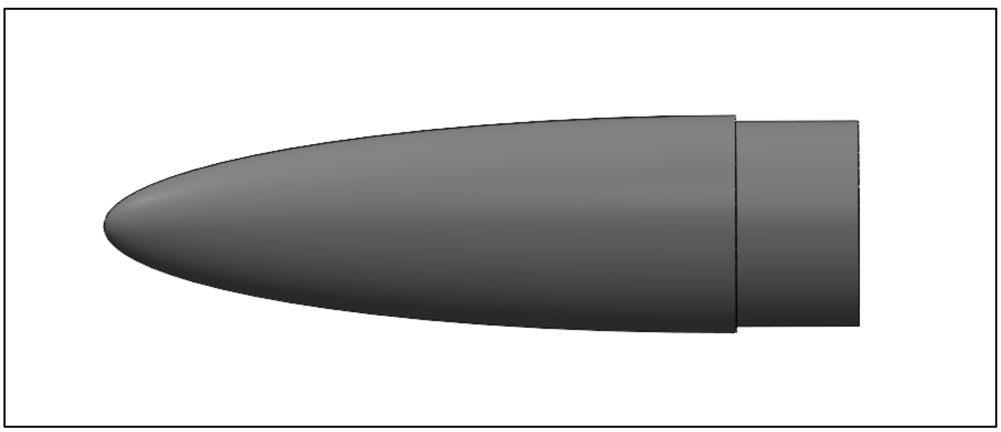


Figure 3-1. Elliptical Nosecone

(b) 3:1 Ogive Nosecone

The Ogive Nosecone is a popular shape in the minds of most rocketry enthusiast. The shape profile is formed by segments of circles to make a tangent relation between the vehicle's body and the base curve of the nosecone. The nosecone tip comes to a sharp pointed end, which is an excellent quality to have at higher for punching through the air during flight. The tangency allows for the opposing airflow to smooth travel across the surface of the vehicle's body without causing swirl airflow at the nosecone base. The image below shows a drawing of the model created in SolidWorks.

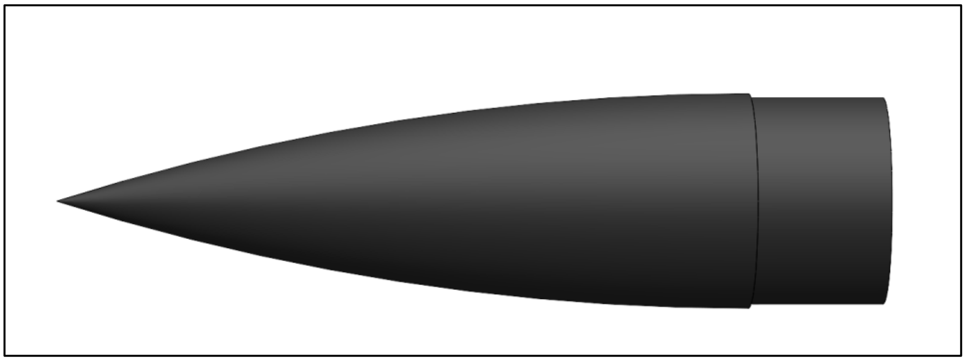


Figure 3-2. Conical Nose

(c) LD – Haack Series

The L-D Haack series is a mixture of Elliptical and Ogive. The Elliptical Nosecone has a more rounded and blunted nose, whereas the L-D Haack Series profile has a slightly rounded nose. As previously mentioned, the Ogive Nosecone has a tangent relation between the base of the nosecone and the vehicles body. The Haack series profile is not perfectly tangent with the body. However, the discontinuous curvature in relation to the vehicle's body is small enough that the development of swirling flow at the nosecone base is negligible. The image below shows a drawing of the model created in SolidWorks.

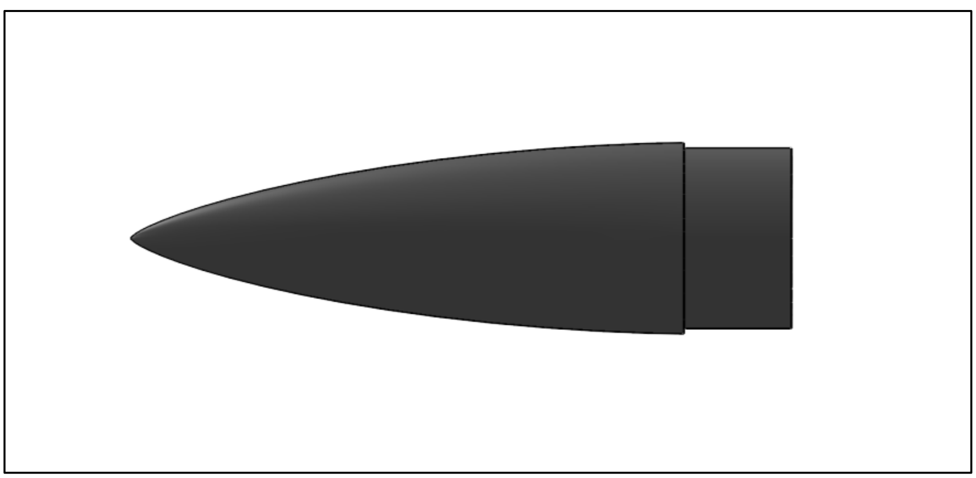


Figure 3-3. LD Haack Nose

The LD-Haack Serie's promising characteristic is the fact that the nose tip does not come to as sharp of a point as the Ogive Nosecone does. Sharp pointed nosecones tend to be useful during sonic or supersonic because it allows the nose to punch through the air at such speeds. In the case of our vehicle, a slightly blunted nosecone is more desirable due to the slight addition in volume of the nose which will help prevent any damage to the tip of the nosecone during flight. The LD-Haack Serie's promising characteristic is the fact that the nose tip does not come to as sharp of a point as the Ogive Nosecone does. Sharp pointed nosecones tend to be useful during sonic or supersonic because it allows the nose to punch through the air at such speeds. In the case of our vehicle, a slightly blunted nosecone is more desirable due to the slight addition in volume of the nose which will help prevent any damage to the tip of the nosecone during flight.

3.1.1.2 Nosecone Camera Housing

To accommodate section 4.2.1 of the NASA Student Handbook, our vehicle will house a camera capable of swiveling 360 degrees and taking pictures of the vehicle's surroundings. Originally, the camera house was designed to be stationed in a clear tube band sitting under the avionics coupler. However, this design caused several issues with the layout of the lower payload bay. The band interferes with the drogue recovery system and U-bolt configuration. Placing the camera house below the avionics coupler would require the housing to have a U-bolt attached to it. The material being used for the camera house was considered between Lexan and PETG clear sheets. The housing would require a material to hold a U-bolt and successfully perform under such loads acting on the house. To resolve this issue, the nosecone will be printed in two parts with a section in between for the camera to swivel and take pictures of the vehicle's surroundings.

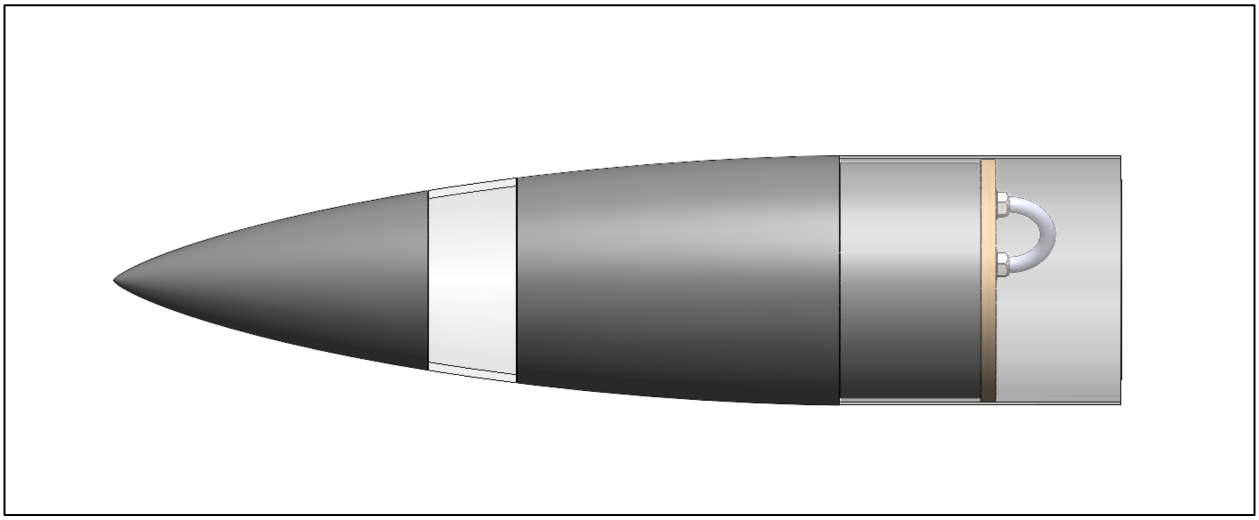


Figure 3-4. Camera Housing

3.1.1.3 Nosecone Bulkhead

To provide a connection point for the shock chord to the payload bay, a bulkhead was placed at the base of the nosecone’s shoulder. The bulkhead will have a U-Bolt for shock chord connection and will have accessibility the camera house for installations/repairs.

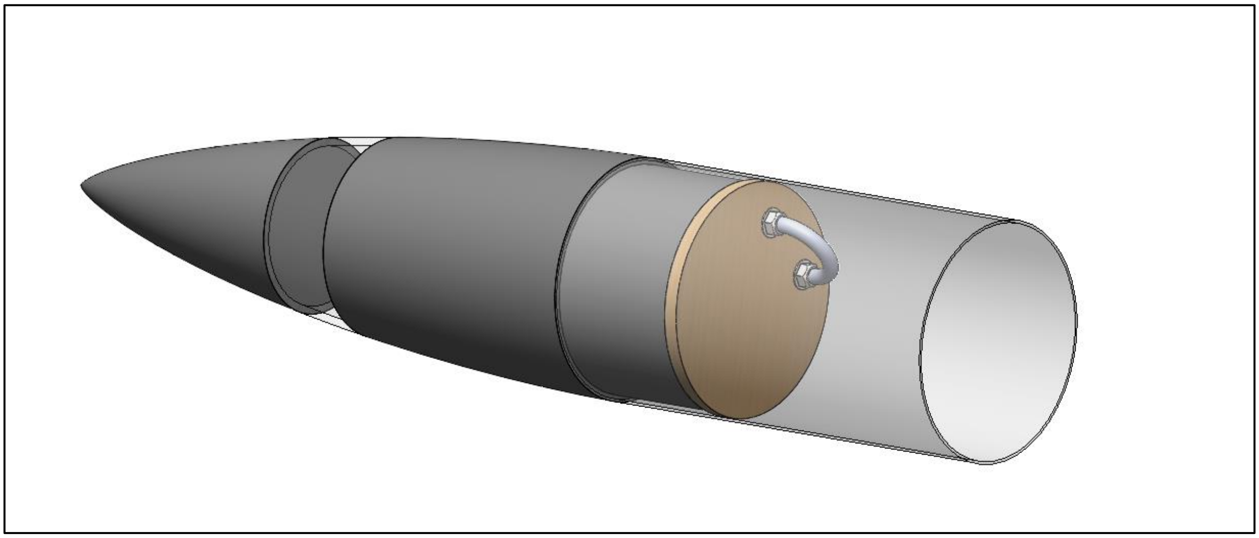


Figure 3-5. Nosecone Bulkhead

Three different methods of positioning are in consideration for the bulkhead of the nosecone. The first was using L-brackets to support the bulkhead and ensure it remains fixed during the flight. The upside of using L-brackets is the ability to remove the bulkhead by simply removing the screws from the L-brackets that were screwed into the bulkhead. The second method is to design a space for the bulkhead to fit against the nosecone base and screw the bulkhead into the nose cone shoulder. However, this method depends highly on the infill and filament of the 3D printed nosecone shoulder. Some 3D filaments can withstand the pulling force of the main parachute opposing the free fall of the vehicle, but in all cases, it depends on how large the opposing force is. The third design considered is creating a hatch door on the bulkhead. This allows easy access to the camera house. However, the bulkhead surface will be crowded enough with the U-bolt for the shock chord connection. The hatch door would have to be large enough for a hand to fit comfortably through and perform tasks inside the camera house. This method would also require epoxying the bulkhead in place. Epoxy provides a strong bond and is ideal for most model rockets. Although epoxy results in the bulkhead remaining fixed unless the adhesive is dissolved, this was not a leading issue to do the quick rebuild time using a 3D printer.

3.1.1.4 Thrust Structure

The thrust structure design went through multiple ideation sessions, as it is one of the trickier sections to design in relation to fin configuration and modularity. Overall, the thrust structure is designed to have the traditional centering rings to center the motor and a bulkhead above the motor separating the thrust structure from the recovery system. The ideation process started with determining whether to include threaded rods. After searching online sources for information on the benefits of threaded rods, it was noticed that the method is not exceedingly popular due to the performance of threaded rods under compression, they are more useful under tension. However, we decided to move forward and design around using threaded rods not only to provide additional support for the recovery system upon deployment, but also support our fin sections and keep the centering rings fixed in place. Traditionally, centering rings are held fixed into the body tube using epoxy. For modularity purposes, our team's ideation and alternative designs revolve around fixing the centering rings using the threaded rods instead of adhesives.

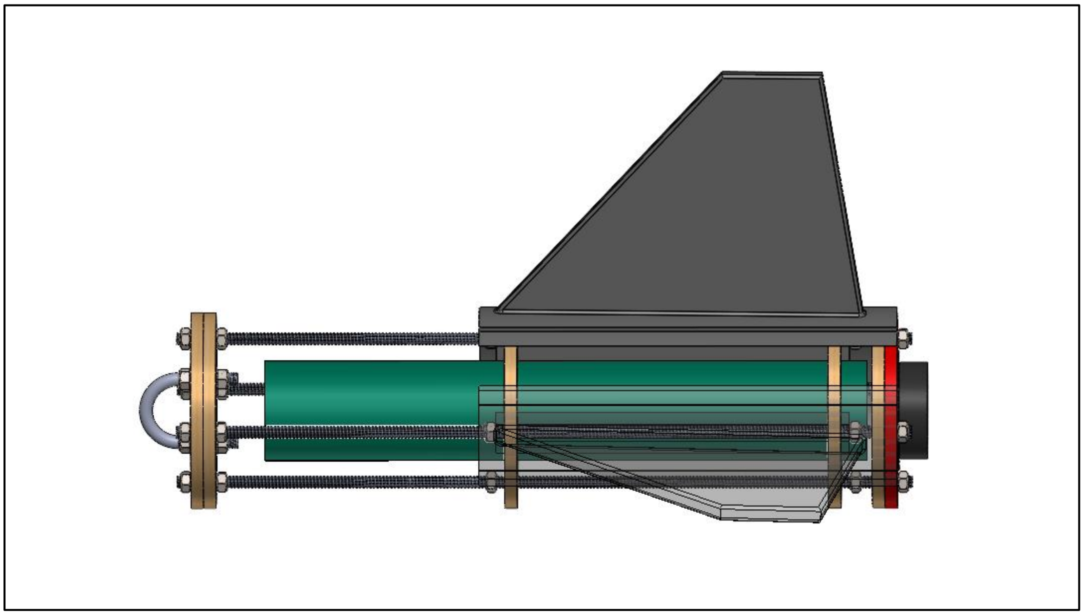


Figure 3-6. Thrust Structure

After running flow simulations on the full vehicle body in SolidWorks, our team noticed the vehicle's aft end was experiencing significant wake drag.

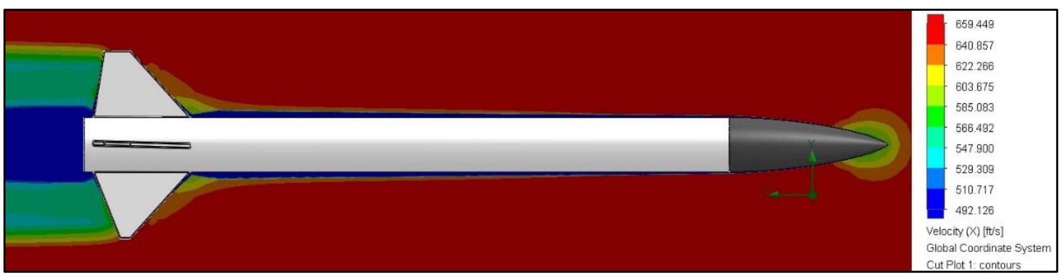


Figure 3-7. Velocity Cut Plot

From the flow simulation above, the abrupt drop in flow velocity at the aft end of the body is shows a characteristic wake formation or separation of the flow from the body at the base of the body tube. Flow separation reduces lift and increases pressure drag. For future design integration, our team has modeled the vehicle with a tail cone.

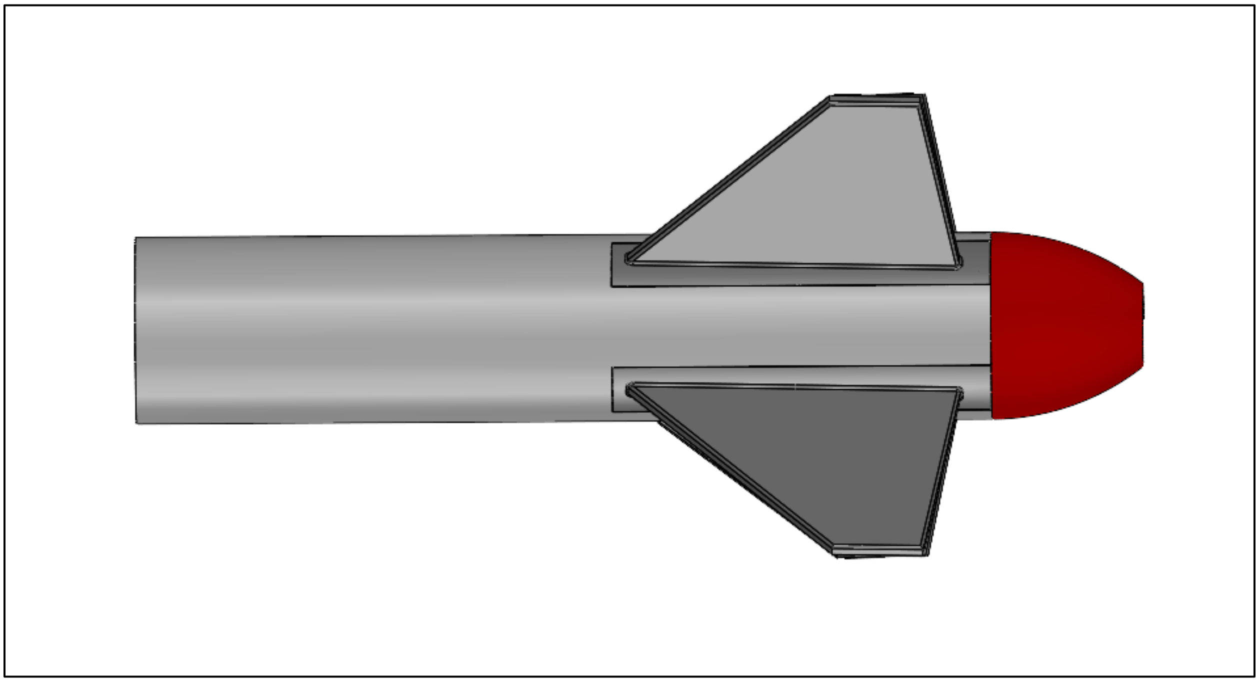


Figure 3-8. Proposed Tailcone

3.1.1.5 Fin Profile

All alternative sizing methods of the fins were created using four fins. Different shapes such as elliptical, symmetrical trapezoid and clipped delta were considered. Elliptical fins are ideal for subsonic speeds because they have a lower induced drag. The clipped delta design is more efficient than symmetrical trapezoid due to the clipped delta having a larger surface area.

3.1.1.6 Fin Configuration

As previously mentioned, much of the thrust structure is designed around using threaded rods. This resulted in a wide range of options for secure fin fitment into the thrust structure. The first design was constructed to allow the fins to slide into a cut-out slot the size of the fin tab dimensions.

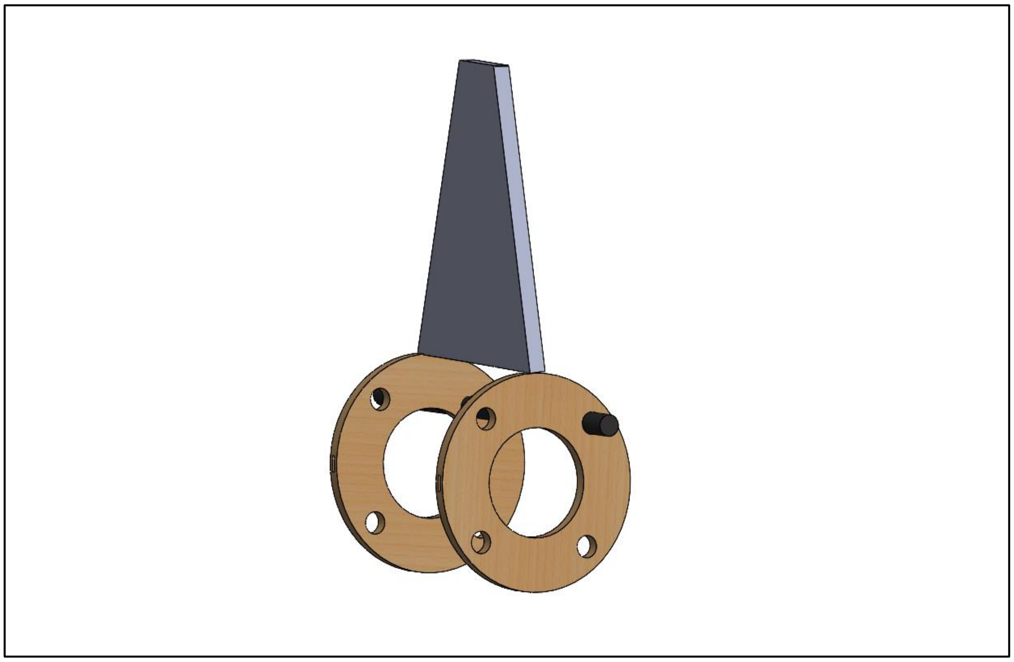


Figure 3-9. Fin Configuration

The fins are fixed to the thrust structure by pushing the fin tabs into cut-out squares on the side of the centering rings and bolted them in. This design was not chosen because the fins are canted, so cut-out squares in the top and bottom centering rings along with the body tube slots would not be aligned and would have to be radially offset, this conflicted with the threaded rod fitment.

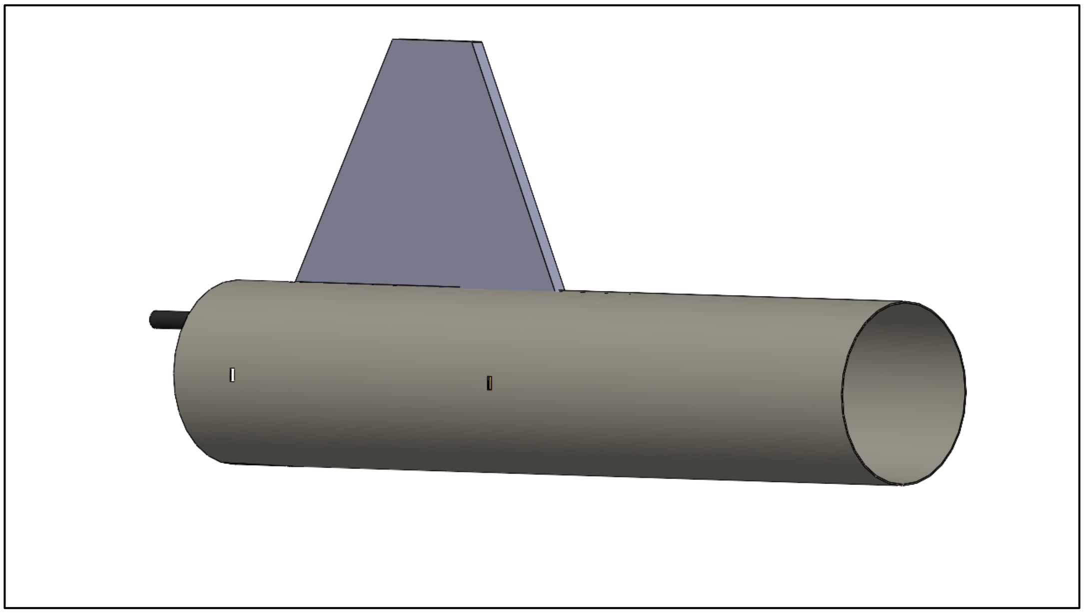


Figure 3-10. Fin Configuration in Body Tube

These issues would not only cause problems in manufacturing, but also increase the chance of failure in the amount of material taken out of the centering rings. This led us to conceptualize a design approach that did not involve cutting out fin tab slots in the centering ring but instead, have the centering ring fit into a slot in the fin tab and then held in place by a bolt. This design was much more feasible because the fins will be 3D printed, which allows the fin model to have specific geometry to appropriately attach to the centering rings. However, again, the canted fins caused issues with the alignment of the fin tabs and having 8 different holes (for the fin tabs and threaded rods) was not ideal for the structural integrity of the centering ring. So, to fix the issue of the unaligned fin tabs and prevent extra holes/slots into the centering rings, a section of the body tube curvature was included in the fin model at the base.

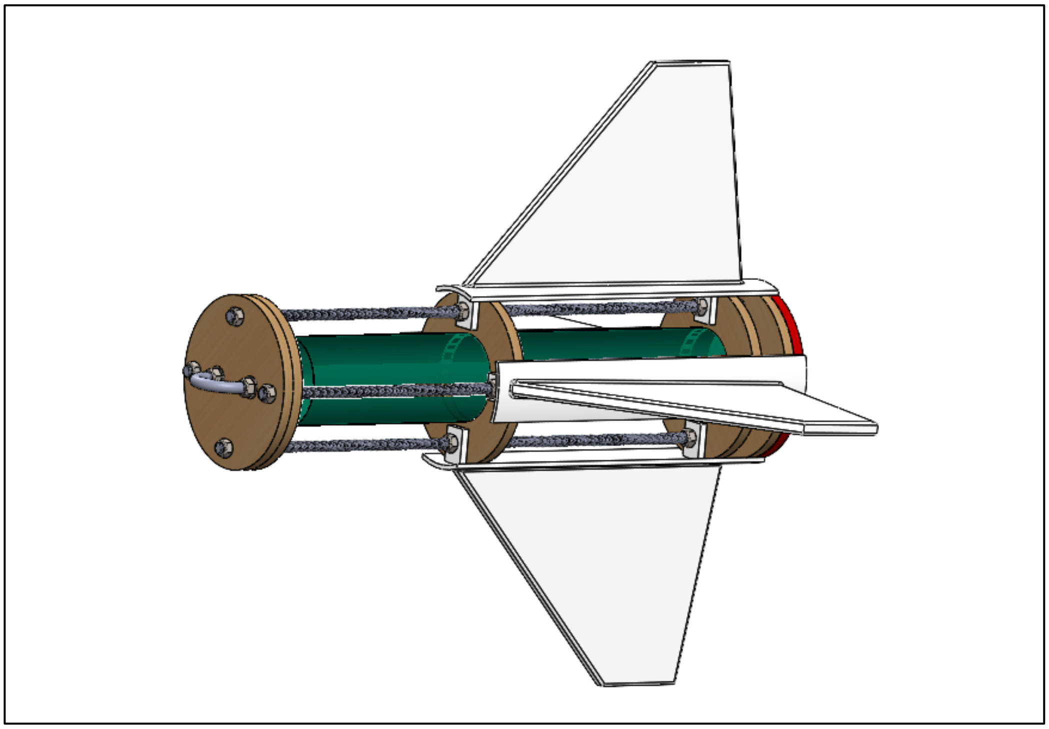


Figure 3-11. Curved Fin Plates Assembly

The curvature will fit flush against the centering rings surface and align with the airframe's surface. The highlight of this design is that the fin tabs are aligned vertically and can clamp onto the centering ring's surface because each tab is modeled on the curved surface rather than the fin root chord. To prevent the usage of extra holes in the centering rings, the threaded rods will be fed through the fin tabs that align with the pre-existing holes in the centering ring for the threaded rod. This design has a sub-alternative that includes a thin extension from the curved surface and longer fin tabs.

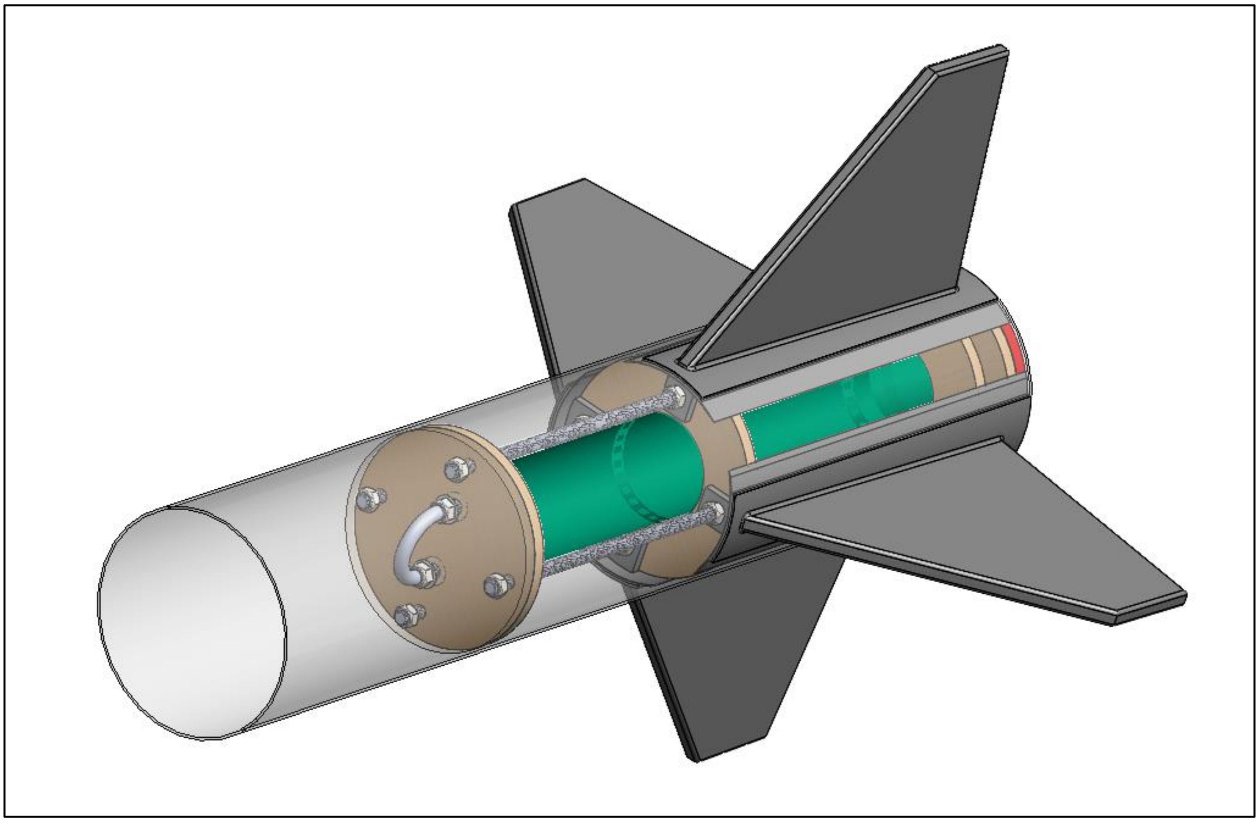


Figure 3-12. Fins and Thrust Structure in Body Tube

The design also has longer fin tabs (in relation to root chord length) to better stabilize and fix the centering rings to the vehicle while distributing the thrust load directly from the rings to the airframe. The nuts holding these two components together will be fixed on the top and bottom of the fin tabs to allow ease of fin removal when taking the threaded rod out of the vehicle. Once the threaded rods are removed, the fins can easily slide out, and vice versa the fins can easily slide into place during assembly.

3.1.2 Nosecone and Fin Material

The nosecone and fins will be 3D printed at our in-house additive manufacturing facility. A small variety of materials were considered for the filament of choice including Acrylonitrile Butadiene Styrene (ABS), Polyethylene Terephthalate Glycol (PETG), and Nylon. All three of these materials were first evaluated in OpenRocket to study their respected weight effects in relation to the vehicle's flight performance. Each material was assessed at the minimum and maximum launch angle and wind speeds at the geographical location of the launch site. The tables below summarize our resulting outputs. All simulations were run on the leading vehicle design covered in section 3.1.5.

Table 3-2. Nosecone and Fin ABS 5 °

ABS Filament		
5 Degree Launch Angle with 0 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	16,066	grams (g)
Stability Margin	2.19	
Velocity off Rod	120	Feet per second (ft/s)
Apogee	4,436	Feet (ft)
Max. Velocity	659	Feet per second (ft/s)
Time to Apogee	15.9	Seconds
Flight Time	91.7	Seconds
Descent Time	75.8	Seconds
Ground Hit velocity	20.1	Feet per second (ft/s)

Table 3-3. Nosecone and Fin ABS 10 °

ABS Filament		
10 Degree Launch Angle with 20 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	16,066	grams (g)
Stability Margin	2.19	
Velocity off Rod	120	Feet per second (ft/s)
Apogee	4,169	Feet (ft)
Max. Velocity	657	Feet per second (ft/s)
Time to Apogee	15.5	Seconds
Flight Time	88.2	Seconds
Descent Time	72.7	Seconds
Ground Hit velocity	20.1	Feet per second (ft/s)

From the two tables above, ABS filament is a prime candidate for staying above an apogee of 4,000 feet and under a descent time of 80 seconds. ABS is a high-level tensile strength material and has optimal heat resistance that would serve well with its purpose of our vehicle.

Table 3-4. Nosecone and Fin PETG 5 °

PETG Filament		
5 Degree Launch Angle with 0 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	16,748	grams (g)
Stability Margin	2.23	
Velocity off Rod	121	Feet per second (ft/s)
Apogee	4,260	Feet (ft)
Max. Velocity	631	Feet per second (ft/s)
Time to Apogee	15.8	Seconds
Flight Time	87.7	Seconds
Descent Time	71.9	Seconds
Ground Hit velocity	20.6	Feet per second (ft/s)

Table 3-5. Nosecone and Fin PETG 10 °

PETG Filament		
10 Degree Launch Angle with 20 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	16,748	grams (g)
Stability Margin	2.23	
Velocity off Rod	121	Feet per second (ft/s)
Apogee	4,002	Feet (ft)
Max. Velocity	629	Feet per second (ft/s)
Time to Apogee	15.2	Seconds
Flight Time	84.1	Seconds
Descent Time	68.9	Seconds
Ground Hit velocity	20.6	Feet per second (ft/s)

Comparing PETG to ABS, PETG has a better stability margin and descent time. However, this is due to one of the leading concerns with using PETG, weight addition. Weight addition increases the opposing downward force acting on the vehicle and decreases the vehicle's apogee.

Table 3-6. Nosecone and Fin Nylon 5 °

Nylon Filament		
5 Degree Launch Angle with 0 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	16,357	grams (g)
Stability Margin	2.21	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4,361	Feet (ft)
Max. Velocity	647	Feet per second (ft/s)
Time to Apogee	15.8	Seconds
Flight Time	90.4	Seconds
Descent Time	74.6	Seconds
Ground Hit velocity	20.4	Feet per second (ft/s)

Table 3-7. Nosecone and Fin Nylon 10 °

Nylon Filament		
10 Degree Launch Angle with 20 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	16,357	grams (g)
Stability Margin	2.21	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4,099	Feet (ft)
Max. Velocity	645	Feet per second (ft/s)
Time to Apogee	15.4	Seconds
Flight Time	87.1	Seconds
Descent Time	71.7	Seconds
Ground Hit velocity	20.4	Feet per second (ft/s)

Comparing Nylon to both PETG and ABS, Nylon's output values are better than PETG's, but a little less satisfactory than ABS's. Although Nylon has a better stability margin than ABS, ABS has the safer choice for staying above the minimum apogee of the competition. Something that was considered during this simulation testing was the infill of the print. In OpenRocket, the part is estimated as a whole object with 100% infill. The upside with 3D printing is that it gives our team the ability to change the infill percentage, allowing us to change the weight of the vehicle to improve performance. Another factor is the material properties of Nylon versus ABS. Nylon has a higher melting point and tensile strength than ABS, but this does not suppress the fact that ABS is cheaper and easier to manufacture. PETG has a lower melting point than both materials, but it is easier to manufacture than both ABS and Nylon. PETG is made of softer polymer plastics which minimizes warping issues during the printing process, an issue that is more likely to occur during an ABS print. Overall, ABS has the performance outcomes our team desires, but PETG is more feasible with respect to production. In either case, 3D printing these components is a promising manufacturing method that will decrease the rebuild time and save the organization money.

3.1.3 Leading Vehicle Design

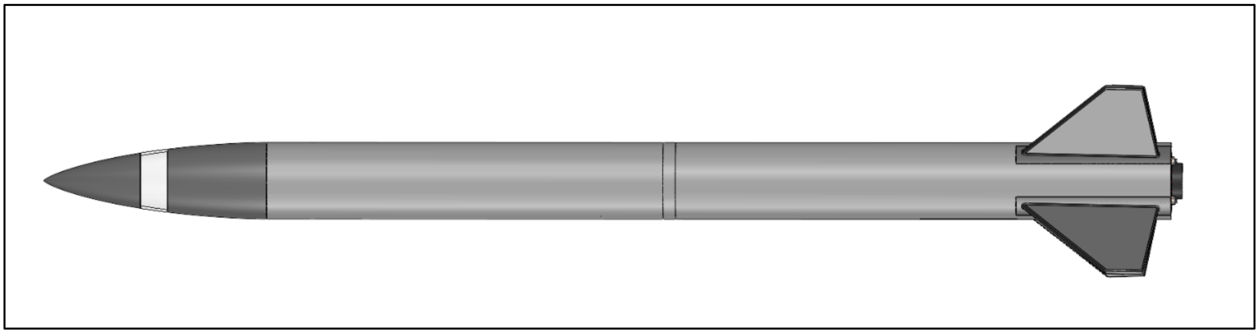


Figure 3-13. Leading Vehicle Design

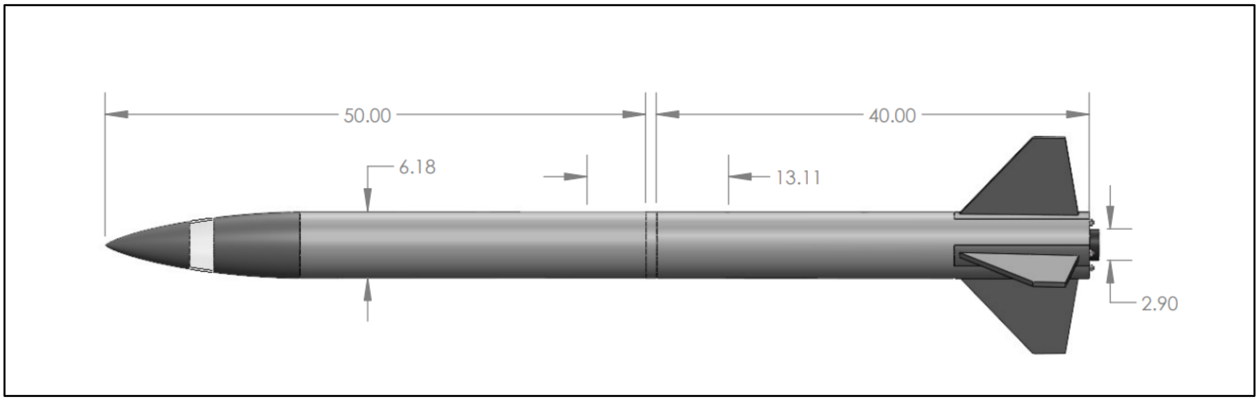


Figure 3-14. Leading Vehicle Dimensions

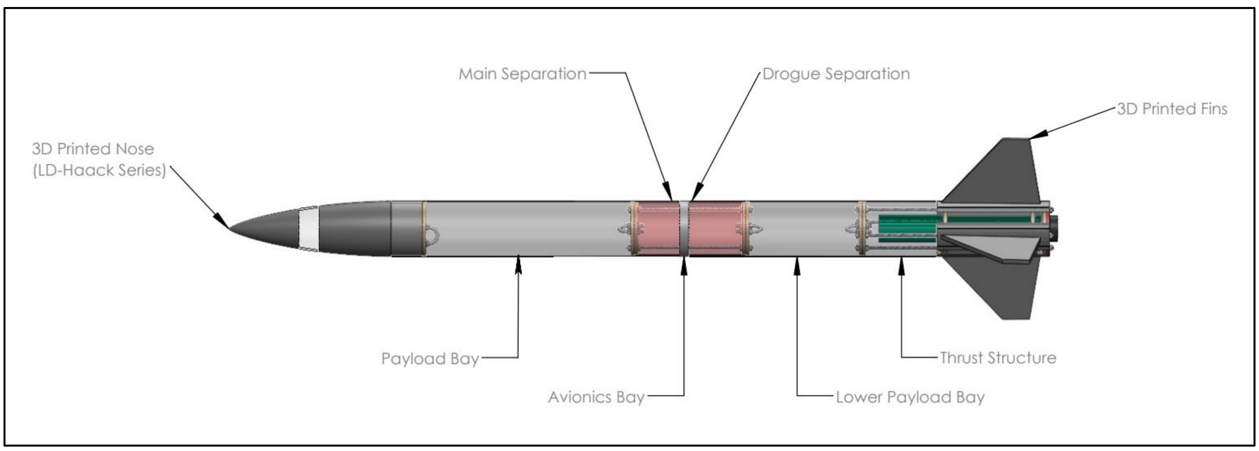


Figure 3-15. Leading Vehicle Sections

3.1.3.1 Nosecone Design and Configuration

From the comparisons in section 3.1.3.1, the LD-Hack Series profile has the characteristics our team desires to meet our goals. The leading issues with the Ogive and Elliptical nosecone designs are their nose tip profile. The Ogive nosecone has a sharp point at its nose and the elliptical has a medium blunt point at its nose. The LD – Haack Series has a shape that combines these two characteristics into one. To create the LD-Haack Series nose profile, a MATLAB code was written to plot out the coordinates of the curve given length and diameter inputs. The following equation was used to plot these coordinates:

$$y = \frac{R\sqrt{\theta - \frac{\sin(\theta)}{2} + Csin^3(theta)}}{\sqrt{\pi}}$$

(Eqn. 3-1)

Where R is the base radius of the nose cone and the variable C is the optimized for the nose cone profile to minimize drag given certain inputs. In our case, C is equal to zero, which defines the LD-Haack Series profile for minimizing drag given an initial nosecone length and base diameter. The variable θ is defined by:

$$\theta = \ cos^{-1}\left(1 - \frac{2x}{L}\right)$$

(Eqn. 3-2)

Where L is the length of the nosecone and x is a range of value from 0 to L. The coordinates of the curve were uploaded to SolidWorks to model the nosecone around its respective governing equations. The MATLAB code is attached in Appendix C.

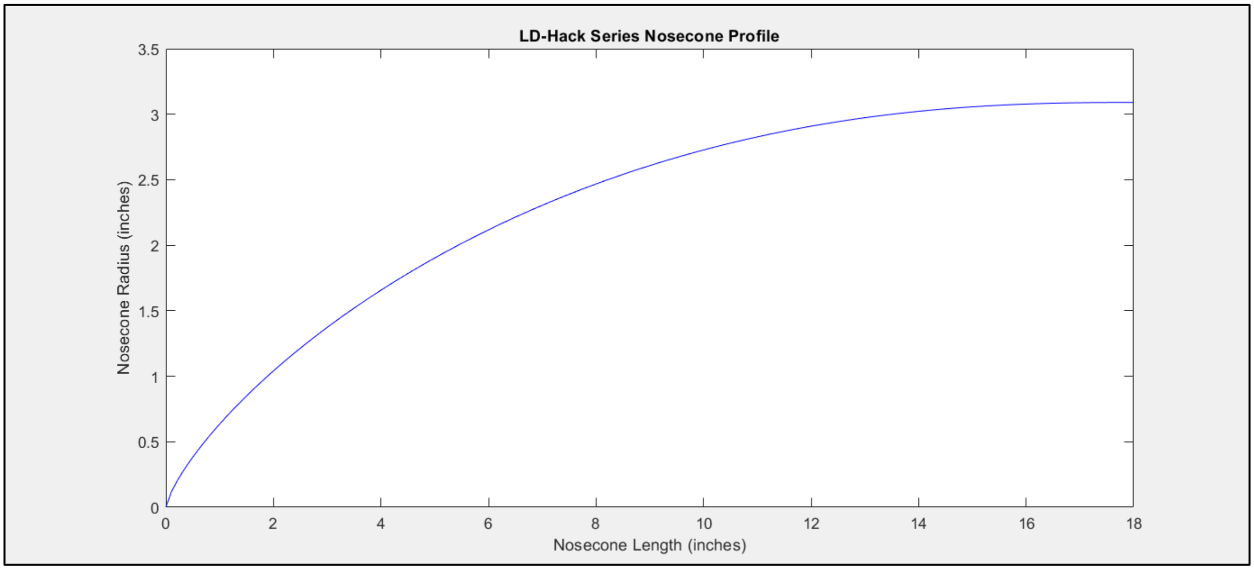


Figure 3-16. Derived MATLAB Nosecone Curve

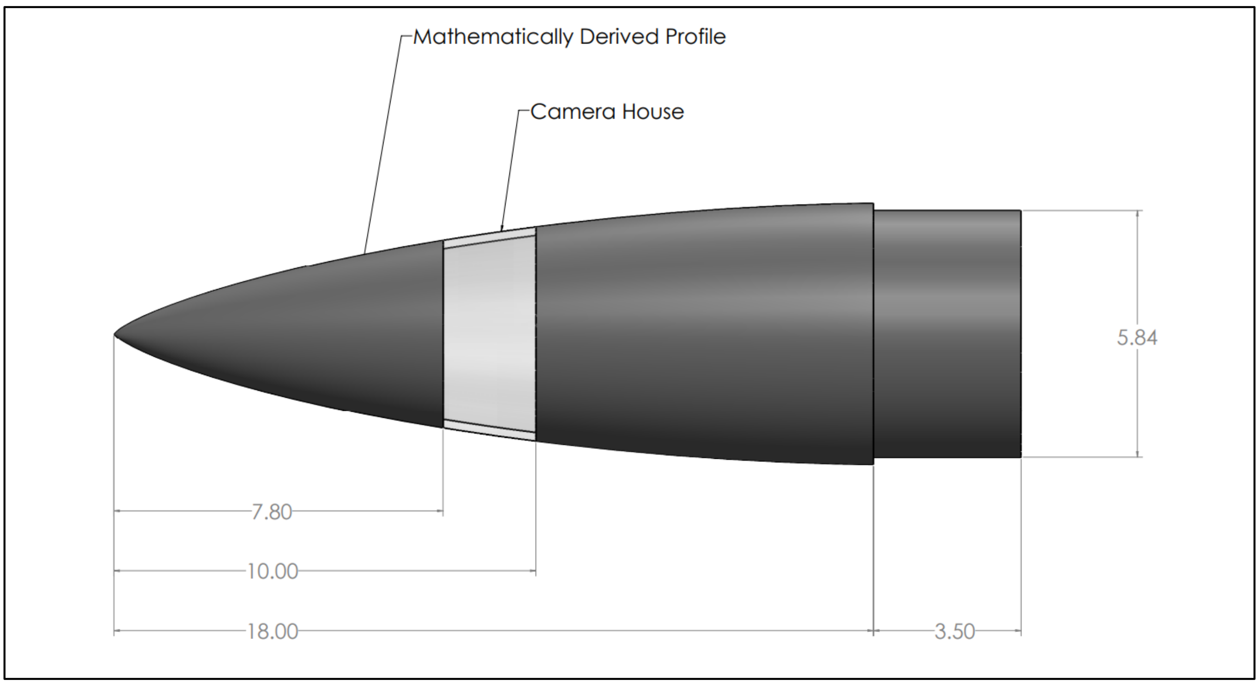


Figure 3-17 .Nosecone Measurements

The leading material selection for the upper and lower portions of the nosecone will be ABS filament. ABS filament was chosen due to its high heat resistance and material strength compared to PETG. Nylon is on the bottom of the alternatives list because the difficulty of the manufacturing process outweighs the pros.

3.1.3.2 Upper Payload Bay

The upper payload bay, or the upper airframe body tube, will be 32 inches of Blue Tube material. The upper payload bay will contain a payload housing that stores the vehicle's deployable rover, along with the main parachute recovery system. The payload housing will be 3D printed from ABS material to fit snug inside the body and kept in place with a mechanical device until the main parachute deploys which is covered in depth in section 4.5

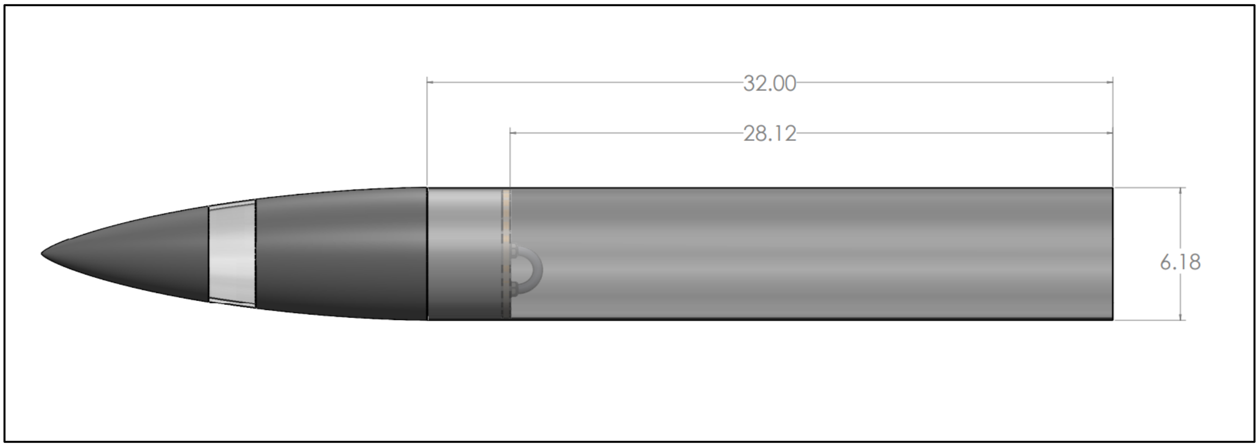


Figure 3-18. Upper Payload Bay

3.1.3.3 Avionics Bay

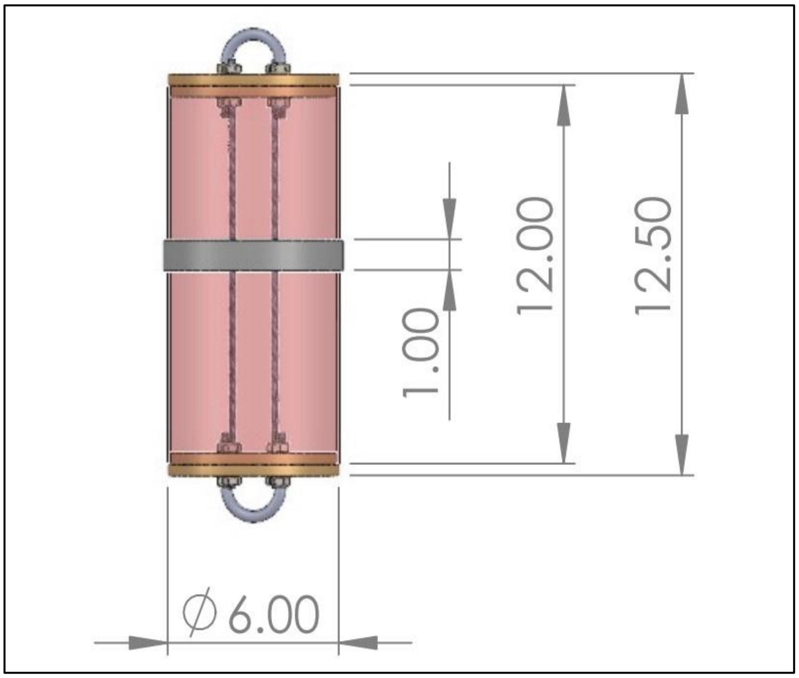


Figure 3-19. Avionics Bay

The avionics bay is a 12-inch long, 6-inch outer diameter, coupler sized section intended to house the flight computers, antenna, and power systems, as well as function as a coupler between the upper and lower vehicle sections prior to separation. Threaded rods run the length of the bay, attaching two U-bolts, which will attach to the main and drogue parachutes. Connecting the bolts and mounting them through two sandwiched bulkheads is intended to distribute load through the bay without catastrophic failure of the end bulkheads upon parachute deployment.

Wood or fiberglass plates are used as a baseplate or “sled” for avionics components, although an interesting option determined while working on the CAD model of the bay would be to 3D print an ABS feature which can slide down the threaded rods. The feature would include holes through which zip ties could be routed to fix the avionics components in place. This adds modularity to the design as the ABS feature can be used in any bay, and features can be easily and readily switched.

An34 ejection option also researched was a CO2 ejection system which is meant to mount inside of the avionics bay. The ABS feature for mounting avionics components may also prove useful in creating a mount for the complex geometry of the machined aluminum CO2 ejector.

3.1.3.4 Lower Payload Bay and Fin Can

The lower payload bay, located between the avionics bay and thrust structure, will be 40 inches of blue tube material with a 6” inner diameter. The avionics bay, as mentioned previously discussed, will acts as the coupler between the lower and upper portions of the vehicle. The first ejection event in the flight sequence will separate the lower payload bay from the avionics bay.

When the flight computer commands separation, a simultaneous command is sent to a Jolly Logic parachute release housed in the upper payload bay. The Jolly Logic is an electronic mechanism for releasing parachutes from their protective retaining bag and is discussed in detail in Section 3.2. In this case, the Jolly Logic retains the drogue parachute to be deployed at apogee inside the upper payload bay. Since this parachute release presents a single-point-failure, a second parachute release may be required to cross-thread the leads of the retaining bands between the two. This incurs another $300+ expenditure which is a factor that must be weighed.

The fin can refer to the section of body into which the fins are mounted. Seeking a highly modular and rapid-iteration capable vehicle, the team has designed removeable fins which mount into the thrust structure. The fin roots sit against a curved plate of the same curvature as the main body, which will sit flush with the curved body in a CNC machined slot in the base of the lower body tube.

3.1.3.5 Thrust Structure

As mentioned in section 3.1.3.4, the thrust structure has gone through many unique design iterations. The leading design chosen to function as the thrust structure is the threaded rod thrust assembly.

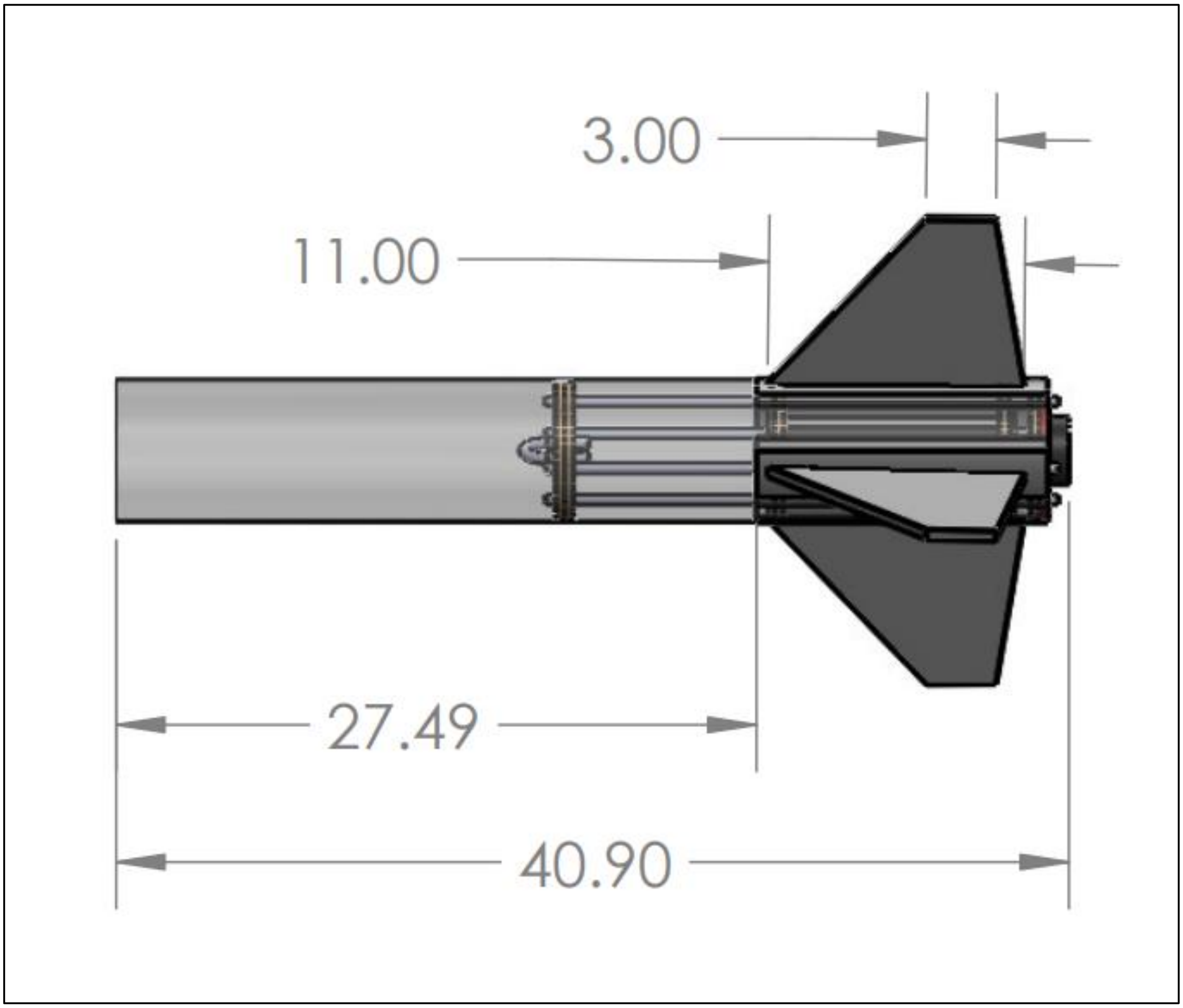


Figure 3-20. Thrust Structure

The threaded rod structure is another design choice in favor of modularity. Rather than fix the centering rings, motor case, retaining ring, and thrust plate in place, the threaded rods allow for this entire assembly to press-fit into the body tube, but slide out when necessary. The upper bulkhead is a sandwiched double bulkhead which is fixed in the body tube permanently with epoxy.

The threaded rod assembly pushes centering rings, motor case, thrust plate, and motor retainer into the body from the bottom, with the rods passing through tabs on in inner side of each fin baseplate, on to holes in the upper double bulkhead. This effectively holds the centering rings rigidly in place, pins the fin assemblies to the body tube, and smoothly transfers the thrust force up the rods to the double bulkhead.

3.1.3.6 Fin Design and Configuration

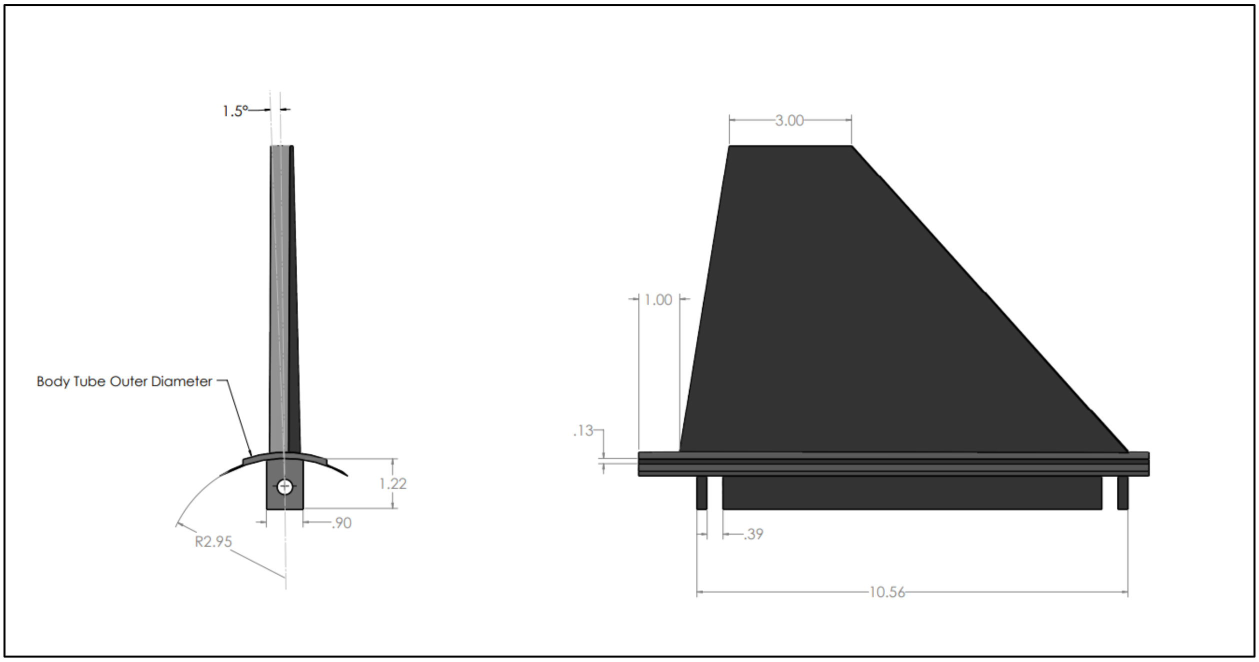


Figure 3-21. Fin Model

As mentioned in the thrust structure discussion, the aim of the fin design is to rigidly attach the fin to the body tube while ensuring the fin root seamlessly integrates with the body surface. To this end, a curved plate with the same curvature as the 6” inner diameter blue tube was created as a baseplate for the fin. On the inner surface, a mounting block with a hole running the long axis of the fin plate allows the threaded rods of the thrust structure to be passed through the fin base.

Slots cut at end of the mounting block allow the fin to press-fit over the centering rings. The fins are intended to be pressed into the pre-cut slots in the body tube, pressing over the centering rings, at which point a threaded rod running through both will fix them rigidly in place inside the body tube. With the curved fin baseplate now fixed in place, the fin geometry for flight can be discussed. The fin plate is wider than the fin to both accommodate the plate curvature and to allow for a cant angle to be applied to the fins. The fins are canted at 1.5 degrees clockwise off vertical and exhibit a clip-delta shape produced by the OpenRocket parameter optimization tool.

A leading concern for the team was fin failure due to the speed of the vehicle and the structure of the fin configuration in relation to their material. To account for this, the fin flutter speed was calculated and compared to maximum simulated vehicle velocity to determine if any instabilities would arise from the fin model. The fin fluttering speed defines the aerodynamic stability of fins under elastic and inertial forces and can be determined by the following equation:

$$V_f = a\sqrt{\frac{\frac{G}{1.337AR^3P(l+1)}}{2(AR+2)\left(\frac{t}{c}\right)^3}}$$

(Eqn. 3-3)

The variables in the equation are defined below along with their calculated values. The MATLAB code used to calculate the flutter speed is attached as Appendix C.

Table 3-8. Fin Flutter Speed Parameters

Fin Flutter Speed			
Parameter	**Symbol**	**Value**	**Unit**
Speed of Sound	a	1098.9	ft/s
Shear Modulus	G	151920	lb/in^2
Aspect Ratio	AR	1.0714	
Pressure	P	12.44	Lb/in^2
Taper Ratio	l	0.2727	
Fin Thickness	t	0.47	inches
Root Chord	c	11	inches
Fin Flutter Speed	V_f	1837.2	ft/s

Table 3-9. Fin Flutter Speed Results

Max Vehicle Speed:	683 ft/s
Fin Flutter Speed:	1837 ft/s
Percent Flutter Speed Achieved:	37%
Factor of Safety:	2.7

3.1.3.7 Vehicle Weight Estimates

Table 3-10. Vehicle Component Weights

Component	Weight (lbs.)
Nosecone	4.47
Nosecone Bulkheads	0.231
Camera housing with camera	0.388
U-Bolt with 4 Nuts/Washers	0.121
Quick link	0.050
Ballast Mass	0.551
Payload Bay	6.73
Main Parachute	0.838
Shock Chord	0.119
Kevlar Blanket	0.250
Payload Housing	3.50
Avionics Bay	3.41
Airframe Coupler	0.741
Avionics Sled	0.882
Inner Bulkhead x 2	0.291
Outer Bulkhead x 2	0.308
Threaded Rods x 2	0.732
U-Bolt 4 Nuts/Washers x 2	0.242
Quick link x 2	0.100
C02 Canister x 2	0.071
Flight Computer	0.055
400mAh Lithium-Ion Polymer Battery	0.021
160mAh Lithium-Ion Polymer Battery	0.009
RF Tracker/Transmitter	0.012
Switches	0.013
Fin Can	12.46
Motor Mount Tube	0.278
Centering Ring x 2	0.419
Fin x 4	3.673
Bulkhead x 3	0.842
Threaded Rod x 4	3.016
Thrust Plate	0.789
Drogue Parachute	0.137
Kevlar Blanket for Drogue	0.125
Quick Link	0.050
U-Bolt 4 Nuts/Washers	0.121
1515 Rail Button x 2	0.0424

3.1.3.8 Motor Alternatives

The motor selection process started with evaluating alternatives to accommodate our vehicle design goals and the requirements per the 20222-2023 NASA Student launch Handbook.

Table 3-11. Motor Options

Motor	Manufacturer	Total Impulse (Ns)	Initial Thrust (N)	Max Thrust (N)	Burn Time (s)	Weight (g)
L3200	Cesaroni Technology	3,300.3	3,283.6	3,723.0	1.0	3,264
L850W	AeroTech	3,646.2	1,000.9	1,866.2	4.4	3,742
L820	Cesaroni Technology	2945.6	690.6	984.8	3.59	3420.0

3.1.3.8.1 Cesaroni L820

The first solid propellant motor evaluation began with analyzing the Cesaroni L820. The Cesaroni L820 was a good selection in powering our previous 72-inch flight vehicle covered in the project proposal. However, with the weight addition that has been designed to the vehicle since the proposal was submitted has required us to study and analyze different motors for optimal performance.

Table 3-12. Cesaroni L820 Performance

Parameter	Value	Units
Total Vehicle Weight	15,700	grams
Stability Margin	2.23	
Velocity off Rod	53.6	ft/s
Apogee	3671	feet
Max. Velocity	501	ft/s
Time to Apogee	16.1	seconds
Flight Time	83.3	seconds
Descent Time	67.2	seconds
Ground Hit velocity	19.8	ft/s

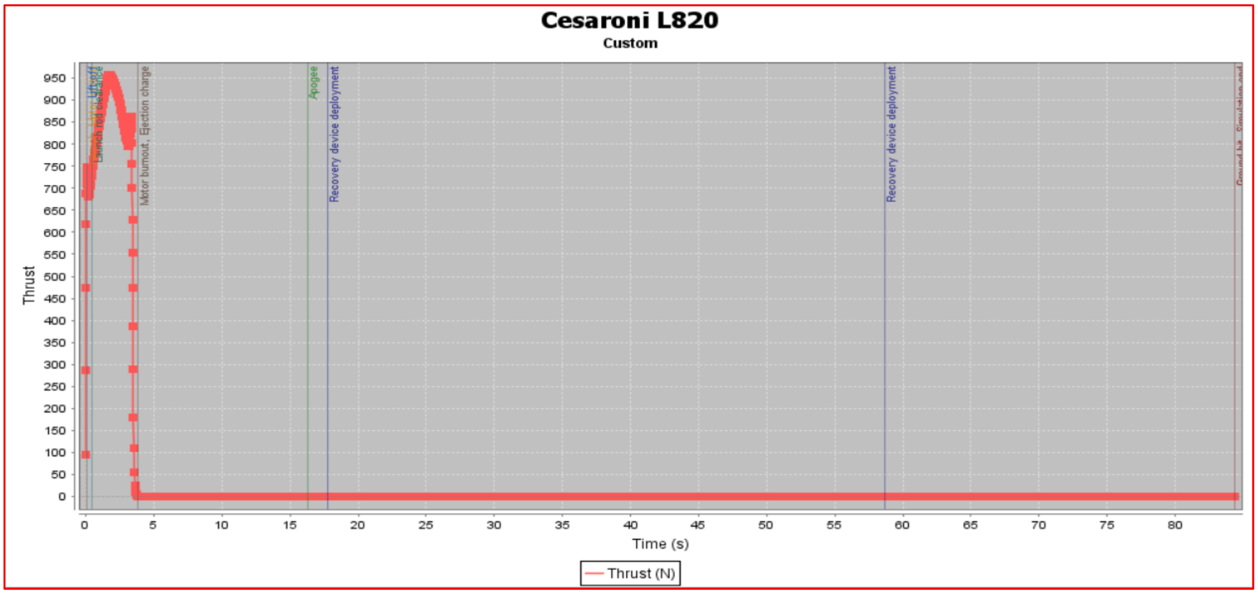


Figure 3-22. Cesaroni L820 Thrust Curve

3.1.3.8.2 AeroTech L850W

The AeroTech L850 was originally evaluated with the leading design with the intent of having a motor with a longer burning time than the leading motor (Cesaroni L3200). A longer burning time results in a smaller thrust force which prevents the vehicle from experiencing too much thrust at once. The thrust of a slow burning motor is also optimal for moving the vehicle in a stable, vertical direction.

Table 3-13. Aerotech L850 Performance

Parameter	Value	Units
Total Vehicle Weight	15,544	grams
Stability Margin	2.2	
Velocity off Rod	68.3	ft/s
Apogee	5016	feet
Max. Velocity	601	ft/s
Time to Apogee	18.1	seconds
Flight Time	104	seconds
Descent Time	85.9	seconds
Ground Hit velocity	19.8	ft/s

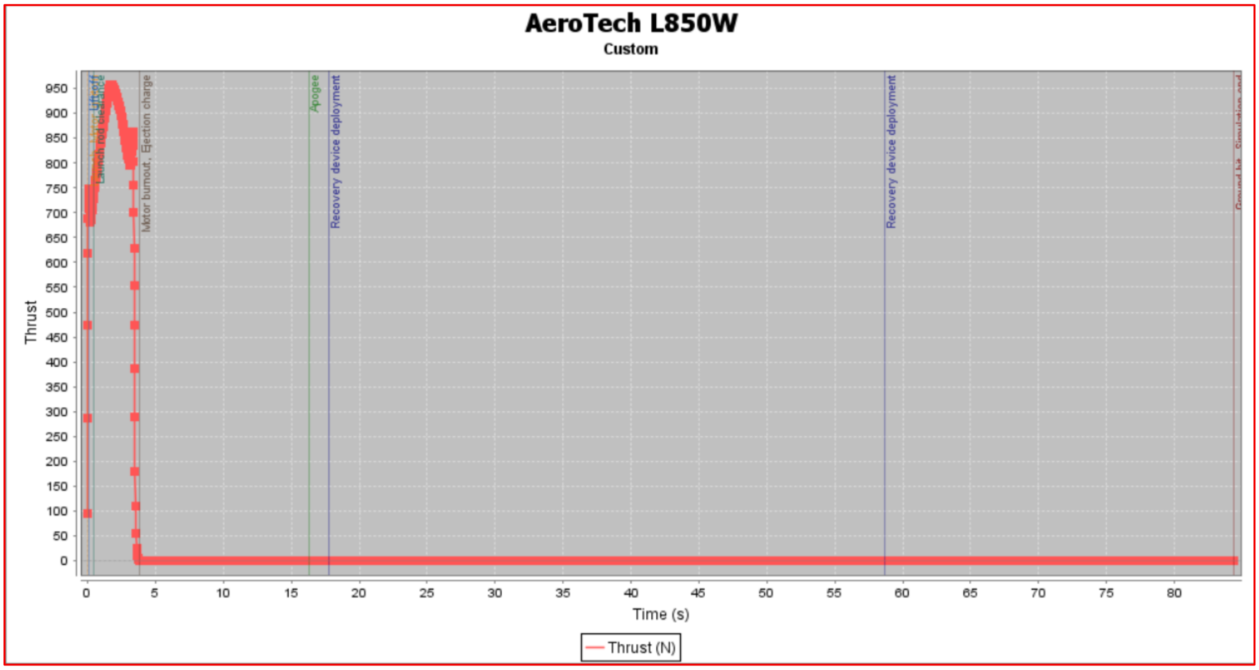


Figure 3-23. AeroTech L850W Thrust Curve

3.1.3.8.3 Cesaroni L3200

The Cesaroni L3200 has been outperforming all of our motor selections in overall goals. With a total weight of 8.25 pounds and a max thrust of 3,724 newtons (837 lbf), the L3200 has proved its ability to reach over 4,000 feet and optimize our descent time. One of the motor's features that works especially well with our design is its burn time of 1 second. As mentioned in section 2.1.4, our fins that are attached to the flight vehicle will be 3D printed. A shorter burn time prevents the fin's filament from experiencing all the heat from the motor for an extended period of time and decreases the amount of time that thrust loads are applied to the vehicle's structure.

Table 3-14. Cesaroni L3200 Performance

Parameter	Value	Units
Total Vehicle Weight	15,953	grams
Stability Margin	2.26	
Velocity off Rod	75.3	ft/s
Apogee	4549	feet
Max. Velocity	682	ft/s
Time to Apogee	16.1	seconds
Flight Time	95.8	seconds
Descent Time	79.7	seconds
Ground Hit velocity	19.8	ft/s

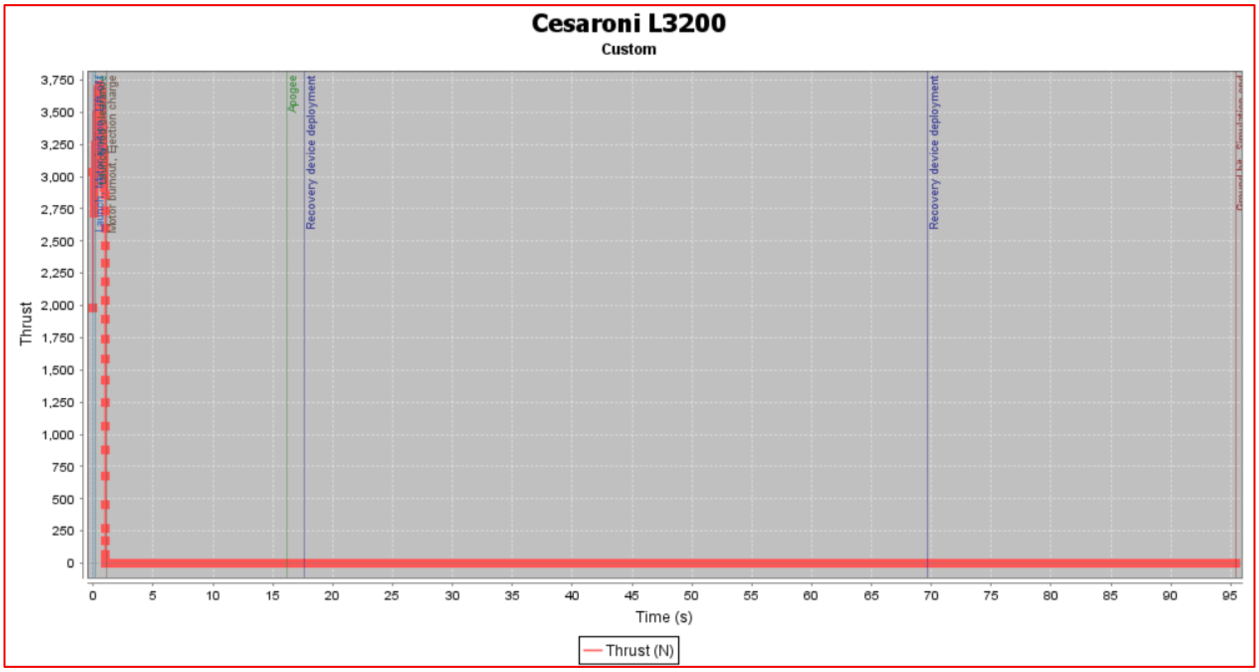


Figure 3-24. Cesaroni L3200 Thrust Curve

3.2 Recovery Subsystem

3.2.1 Description of Recovery Event

For safety measures, the altimeter will be turned on after the flight vehicle is in launch configuration. In addition, the activation of the altimeters will take place before the ignitor is placed into the motor of the vehicle, to ensure the recovery system is operative in the unlikely event of an accidental launch. Once the altimeters are powered on, the transmission of data to the ground station will be verified. The altimeters power source will be verified to be capable of keeping the vehicle in a launch-ready configuration for at least two hours without losing functionality of any recovery electronics. The preprogrammed ejection altitude will also be checked to be within an allowable range. If at any moment during the launch sequence the recovery system malfunctions, the launch procedure will be stopped, and all recovery units will be assessed until proven functional, then launch procedures will resume.

At apogee, the pressure inside of the avionics bay will be at its lowest. The altimeter's barometric sensor will detect this low pressure and send a direct current to an e-match that will ignite the ejection charge for the drogue parachute. Once the charge is ignited, the released gas will build up enough pressure in the section to shear the pins that hold the fin can to the avionics bay. All separation points on the launch vehicle will be held together with small nylon shear pins that can withstand all aerodynamic forces during flight, but not the force from the ejection charge. During descent, the sections will be tethered together with some length of shock cord tied to a U-bolt on the bulkhead of each, and the drogue chute will also be attached to the cord with the use of a quick link. Shock cord selection is discussed in Section 3.2.2.8 below. A secondary charge will go off 1-2 seconds after apogee to ensure that the sections are properly separated, and that the drogue parachute is deployed. The reason for the secondary charge delay is to avoid over pressurizing the inside of the flight vehicle which can cause any structural damage. The drogue parachute will be released from its packed arrangement with the use of the Jolly Logic Chute Release 5X, which has a barometric sensor that will be set to detect when the vehicle reaches apogee.

After the drogue has deployed, the vehicle will descend at a higher speed than what is required for it to safely land. However, this descent speed will be just enough to ensure the vehicle recovers in a timely manner that satisfies the time constraint. The vehicle will continue to descend at this rate until around 550 feet above ground level. This altitude will be sensed by the altimeter, and it will send another direct current to the ejection canister of the main parachute section. Like the drogue parachute, the main will be connected to some length of shock cord with the use of a quick link. As the separation occurs, the payload housing will slide out of the upper bay of the vehicle while remaining connected to the main parachute shock cord. This shock cord will be tethered to the top bulkhead of the avionics bay, run through the payload housing, then tethered to the bulkhead in the nosecone. For redundancy, if the first charge does not separate the vehicle sections, there will be a second charge set to ignite approximately one second after the primary charge of the main chute. The main parachute will slow down the vehicle's descent to a safe speed for landing. The sizing and selection of the drogue and main parachutes are discussed in further detail below in Sections 3.2.2.6 and 3.2.2.7, respectively.

The primary recovery system will rely on the barometric pressure sensors of the primary altimeter to send the initial charge for parachute ejections. The secondary charges will rely on a timed ignition that will be configured into the second altimeter. Throughout the recovery process, team members on the ground will track the vehicle's position and location with the use of a GPS and transmitter.

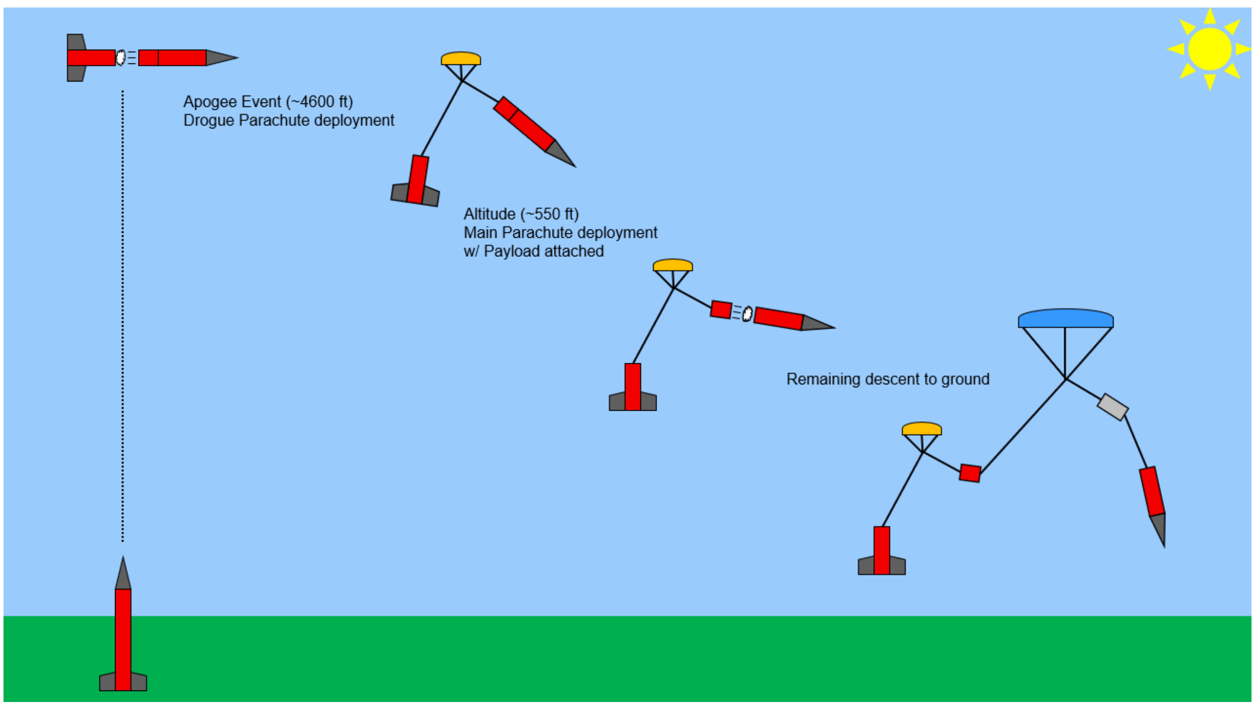


Figure 3-25. Recovery Profile

3.2.2 Component Selection

3.2.2.1 Altimeter Alternatives

There are currently four altimeters under consideration for the recovery system. The Altus Metrum: EasyMini v2.0, TeleMega v4.0, Entacore: AIM 3, and Missile Works: RRC3. All of them are dual deployment capable and are commercially available. Precision, reliability, and size are the factors in consideration of which altimeter to use.

Table 3-15. Specifications for Altimeter Options

	EasyMini v2.0	TeleMega v4.0	AIM 3	RRC3
Manufacturer	Altus Metrum	Altus Metrum	Entacore	Missile Works
Dimensions (weight)	1.5"L x 0.8"W x 0.6"H (6.52 g)	3.25"L x 1.25"W x 0.625"H (24.95 g)	2.56"L x 0.98"W x 0.59"H (12.81 g)	3.92"L x 0.925"W (17.01 g)
Logged Data	Altitude, Velocity, Total flight time, and Temperature	Altitude, Velocity, Acceleration, Time (total flight, burn, and ground to apogee), and Temperature	Altitude, Velocity	Altitude, Velocity, Time to Apogee
Measurement Units	Imperial / Metric	Imperial / Metric	Imperial / Metric	Imperial
Max Altitude (ft)	100,000	100,000	38,615	40,000
Sampling Rate (Hz)	100 (ascent), 10 (descent)	100 (ascent), 10 (descent)	10	20
Minimum Altitude for arming (ft)	N/A	N/A	N/A	300
# of Flights Stored	Varies (10 min)	Varies (40 min)	Varies (30 min)	15 (28 min each)
# of Pyro Channels	2	6	2	3
Battery (V)	3.7 - 12	3.7 - 12	3.7 - 14	3.7 - 10
Price ($ USD)	96.93	484.62	121.15	96.50

Additional Info	Consists of a barometric pressure sensor only	Built-in GPS/telemetry unit. Downloadable data via USB cable and AltOS software. Extra accessories required for ground station. Requires HAM license.	Consists of a barometric pressure sensor only	Consists of a barometric pressure sensor only. Telemetry and other advanced functions are optional add-ons.

The Missile Works RRC3 is most used by student teams for its simplicity and affordability. Although it is priced at a low value compared to most dual-deployment altimeters, it has some key features of high-end flight computers. The RRC3 also allows you to record and store multiple flights without having to download or process data in between flights. The device also allows for the user to switch the deployment mode with built-in dip switches and pushbutton. It also offers advanced operations such as flight telemetry and auxiliary outputs, with an optional LCD terminal accessory or a USB connection to a PC with the mDACS Software application. The main deployment altitude of the RRC3 can only be adjusted by increments of 100 feet, which can hinder the redundant secondary charges from deploying at our desired heights.

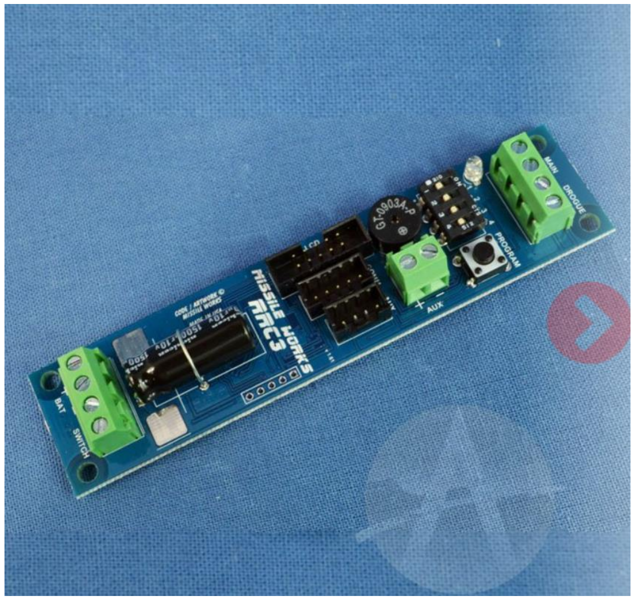


Figure 3-26. RRC3 Altimeter

The AIM 3 has similar features to the RRC3 with a slightly lower sampling rate and maximum altitude. The AIM3 can record and store more than 30 minutes of flight data per use. It can also be connected to a PC or laptop for downloading data or modifying settings. Deployment settings can be configured to be based on apogee, time, accent altitude, decent altitude, or peak velocity. The option of configuring the deployment setting could prove to be beneficial for ejection redundancy.

Figure 3-27. AIM 3 Altimeter

The EasyMini has a significantly higher sampling rate than the previously mentioned altimeters. The altimeter also has the smallest volume compared to all the alternatives, which makes it a viable option for its sizing. One of the main disadvantages of the EasyMini is its data storage capacity. The device can store a little more than 10 minutes of flight data, which does not meet our team needs.

Figure 3-28. EasyMini v2.0

The TeleMega is the most complex of the altimeter options. It is a high-end altimeter that has a built-in accelerometer, telemetry, and GPS tracking unit. In addition, it has the highest sampling rate and data processing capabilities. Like the AIM 3, deployment settings can be configured based on a variety of flight events or time for redundancy. The TeleMega requires additional ground station equipment for transmitting and receiving flight data. It can store up to 40 minutes of flight data and reach a maximum altitude of 100,000 feet. In addition, it consumes a low amount of power when the vehicle is in a stationary non-flight mode, which allows the vehicle to be launch-ready for more than 2 hours. The only challenge with using the TeleMega is that it may require a HAM Radio License to operate. However, one of our members plans to get this certification before any flight testing or use of this altimeter. An image of the TeleMega flight computer is shown below.

Figure 3-29. TeleMega v4.0

3.2.2.2 <u>Locator and Transmitter Alternatives</u>

There are four GPS trackers under consideration for use in the launch vehicle. All of the trackers are commercially available technology that are commonly used in high-power rocketry. The specification for each tracker is listed below.

Table 3-16. GPS Tracker Options

	Featherweight GPS Tracker	Eggtimer TRS GPS	RTx/GPS System	TeleMega v4.0
Manufacturer	Featherweight Altimeters	Eggtimer Rocketry	MissileWorks	Altus Metrum
Transmission Power	60 mW	100 mW	250 mW	N/A
Transmission Frequency	915 MHz	915 MHz	900 MHz	435MHz
Range (ft)	164,042	30,000	47,520	101,706
Price ($ USD)	365	90	330	484.62
Additional Info	Can link to iPhone	N/A	Easily meshes w/ RRC3 altimeter	Requires HAM License

The Eggtimer TRS GPS consists of a transmitter centered about a GPS telemetry system which sends a stream of formatted data that is received from the rocket and sent back to the receiver located on the ground as well as sending position updates on the rocket every second, providing its exact latitude and longitude. This transmitter must be paired with Eggfinder LCD receiver. Transmission frequency stands at about 915 MHz, with a Transmission power of 100 mW and smaller range of 30,000 ft.

The Featherweight GPS Tracker is a simpler GPS option that still proves to be useful. The Featherweight GPS tracker is made up of an antenna that is powered by a LiPo battery and GPS tracker. The Transmission power of this Tracker is 60 mW and has a Transmission Frequency standing at the same value as the Eggtimer GPS transmitter with a wide range of 164,042 ft. This tracker can be connected to the user's smartphone that can provide live readings of the rocket's location and flight path.

The RTx GPS System is one of the alternatives that is ready to use once bought off the shelf, and require little time to completely, as well performing about the same as the other transmitters in terms of transmitting coordinates back to a receiver. The RTx GPS system has a competitive Transmission Frequency of 900 MHz and of 250 mW, but has very low range of 47,520 ft, being second in comparison to the Eggtimer TRS GPS, but will still be an alternative to consider. The Transmitter can also be link with an RRC3 altimeter to collect telemetry data.

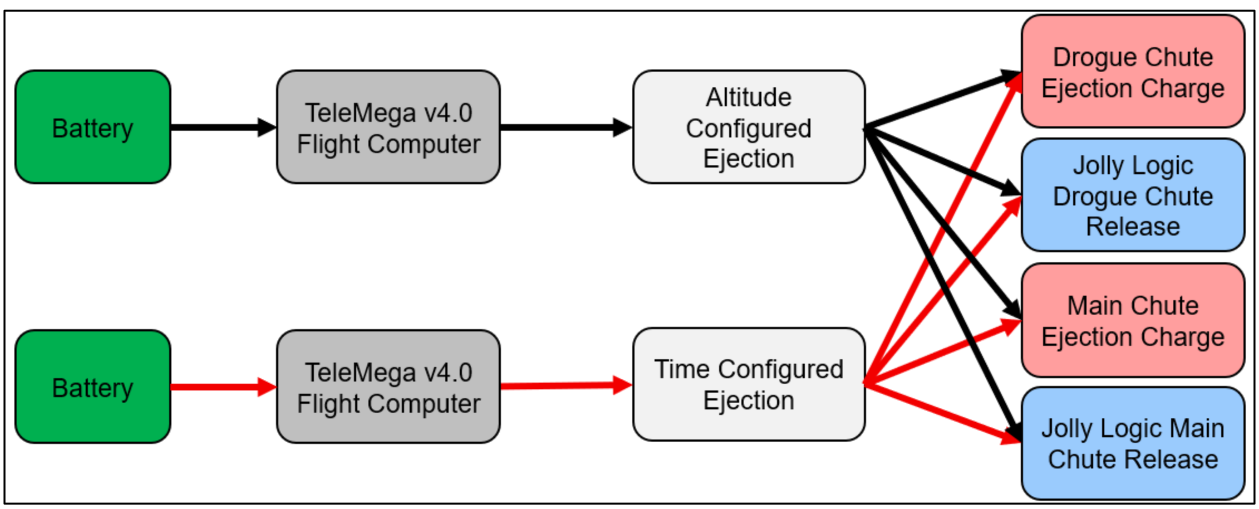
TheTeleMega v4.0 has already been addressed intricately in the altimeter section of the report, but The Telemega also serves as a GPS transmitter with a large competitive range of 101,706 ft and lower Transmission Frequency of 435 MHz and having a highest price in comparison to all the alternatives. However, the Telemega v4.0 being to serve multiple purposes and being decently versatile proves to be a viable transmitter alternative that is still worth considering.

3.2.2.3 Recovery Electronics Diagram

The entire recovery system will be controlled by two flight computers that are capable of accurately igniting the ejection system. The primary ejections of both the drogue and main will rely on the barometric pressure sensor of the primary altimeter, which will detect apogee and main deployment altitude, then send a direct current to ignite the ejection charge. The secondary ejections will be programmed to rely on times set in the secondary altimeter that are 1-2 seconds after the primary ejections. In the unlikely event that the primary altimeter fails to sense the desired ejection altitudes of the primary charges, then the secondary charges will be ignited by the secondary altimeter, nonetheless. In addition, each altimeter will also be electronically routed to the Jolly Logic release mechanism on each parachute to unravel it. A block diagram of the avionic system is shown below.

Figure 3-3 illustrates how the redundant avionics systems are independent of each other. The diagram flow with the black arrows is the primary altimeter system and the red one is the secondary altimeter. The two systems will be physically separated from one another. In the unlikely event that one of them fails, the other will not be affected and can still ignite both charges while safely recovering the vehicle.

Figure 3-30. Recovery System Block Diagram



3.2.2.4 Drogue Parachute Sizing

The drogue parachute selection was influenced by the descent rate and drift distance of the launch vehicle. The descent rate is significant, because if it is too high the rapid deceleration of the main parachute deployment can cause structural damage to the vehicle. The drogue parachute should slow the vehicle down enough to prevent this from happening. The challenges that arise when mitigating the descent rate issue, is that of the descent time and recovery area constraints stated in the Student Launch Handbook. The drogue parachute chosen must satisfy each of these requirements, while maintaining a safe descent rate. The equation that governs the descent speed of the vehicle while under a parachute is shown below

$$v = \sqrt{\frac{2mg}{AC_D\rho}}$$

(Eqn. 3-3)

Where m is the burnout mass of the launch vehicle, g is the gravitational acceleration constant, A is the projected area of the parachute, C_D is the drag coefficient of the parachute and ρ is the density of air.

The table below shows the options considered for the drogue parachute. Out of the four options listed, the Fruity Chutes 15-in Classic Elliptical is eliminated from consideration because the descent speed is too high for a safe main parachute deployment. The other three parachutes are all viable options that will be considered.

Table 3-17. Drogue Parachute Alternatives

Parachute	Drag Coefficient	Projected Area (ft^2)	Descent Speed (ft/s)	Descent Time from Apogee to Main Deployment (s)	Wind Drift from Apogee to Main Deployment at 20 MPH (ft)
Fruity Chute 15" Classic Elliptical	1.5	1.1781	121.3116	33.3851	979.297
Fruity Chute 18" Classic Elliptical	1.5	1.6965	101.0919	40.0626	1175.168
Fruity Chute 24" Classic Elliptical	1.5	3.0159	75.8202	53.4159	1566.865
Fruity Chute 30" Classic Elliptical	1.5	4.7124	60.6558	66.7702	1958.593

3.2.2.5 <u>Main Parachute Sizing</u>

The main parachute selection is primarily affected by the maximum kinetic energy requirement stated in the Student Launch Handbook. This requirement ensures that the launch vehicle sections safely land. The time and recovery area constraint are also factors of the main parachute sizing. The descent speed of the vehicle under the main parachute is governed by the same equation used for the drogue parachute. Consequently, the main parachute sizing is determined by the launch vehicle performance requirements.

Table 3-18. Main Parachute Alternatives

Parachute	Drag Coefficient	Projected Area (ft^2)	Descent Speed (ft/s)	Descent Time from Main Deployment to Ground (s)	Wind Drift from Main Deployment to Ground at 20 MPH (ft)	Kinetic Energy of Heaviest Recovered Section (ft-lb)
Fruity Chute 60" Iris Ultra Standard	2.2	19.0267	24.9256	22.0657	647.259	83.5662
Fruity Chute 72" Iris Ultra Standard	2.2	27.3985	20.7713	26.4788	776.712	58.0319
Fruity Chute 84" Iris Ultra Standard	2.2	37.2924	17.8040	30.8919	906.164	42.6357
Fruity Chute 96" Iris Ultra Standard	2.2	48.7084	15.5785	35.3051	1035.615	32.6430

3.2.1.1 Shock Cord Selection

The separate descending sections of the vehicle will be held together with some length of shock cord. The shock cord must be able to withstand the force it would induce during parachute deployment and deceleration of the vehicle. The length of the cord should be enough to ensure that separate sections of the vehicle do not collide during descent. The two material options for the shock cord are Nylon and Kevlar. Both materials have shock cords that can withstand up to 1500 lb or higher. If black powder is to be used for ejection, then Kevlar may be more beneficial due to its heat resistant properties. A good rule-of-thumb for shock cord sizing is that it should be between 3-5 times the length of the rocket. Therefore, our 91-inch-tall vehicle should have a shock cord length anywhere between 23-38 feet. Currently, the team is leaning toward using two 30 ft braided Kevlar shock cords. The drogue and main parachutes attachment points to the shock cord will be specifically placed in a way that prevents the descending sections of the vehicle from colliding.

3.2.1.2 Ejection Charge Sizing

The sizing of the ejection charge is dependent on which type of ejection system is utilized. Black powder charges are the most used ejection systems, but the use of black powder introduces a good amount of risk being that it can scorch or damage any of the internal components of the flight vehicle. In addition, the purchase and handling of black powder requires approval from the FAMU-FSU College of Engineering, FSU Police Department, FSU Health & Safety Office, and the federal government. For these reasons, the team is leaning towards using CO2 ejection charges to mitigate these concerns. CO2 ejection systems require less formalities and are more affordable and safer, compared to black powder systems.

3.2.2 Leading Design

All the electronics for recovery will be stored inside the avionics bay. The components will be mounted onto a 3-D printed ABS sled that will have threaded rods running through it. This was chosen because of the ease of integrating the sled design into the avionics bay. Since the sled will be 3-D printed any changes that might need to be made can be easily adjusted by the team.

The Fruity Chutes 24-inch Classic Elliptical is the selected drogue parachute for the design. Although it has a high drift distance, the descent speed was the ultimate deciding factor. This decision was made to ensure that the rapid change in speed from the main parachute deployment does not cause any structural damage to the flight vehicle nor any other safety hazards. The drogue parachute remains well underneath the descent time and recovery area constraints, therefore making it a satisfactory choice.

The main parachute chosen for the leading design is the Fruity Chutes 72-inch Iris Ultra Standard. The descent time and kinetic energy were the two main deciding factors for the main parachute. Combined with the descent time from the drogue parachute it results in a total descent time of approximately 80 seconds, which satisfies the time constraint stated in the Student Launch Handbook.

All the deployment events will be controlled by two TeleMega v4.0 flight computers that will be mounted to the avionics sled. This altimeter was chosen for its high functionality and GPS tracking capabilities. Since the altimeter comes with its own telemetry unit it eliminates the need to purchase a separate GPS tracker for the launch vehicle, which further simplifies the avionics system. Both altimeters will be powered and wired independently of each other for redundancy and safety concerns.

3.3 Mission Performance Predictions

3.3.1 Declared Target Altitude

Based on extensive simulations and design iteration conducted by the Zenith Program the flight vehicle target apogee is 4,600 feet. This number was reach by taking the average apogee reached in OpenRocket/MATLAB for launch angles (5, 7, and 10 degrees) and windspeed conditions (0, 5, 10, 15, and 20 mph). Our team predicts the flight vehicle to change in weight as the design selection narrows in. To account for this factor, an error margin of five percent of the average altitude was added to the apogee and rounded to the nearest whole number.

3.3.2 Flight Simulation Data

The flight vehicle was modeled and evaluated through OpenRocket simulation software. The software uses the general dimensions of the flight vehicle to output desired parameters. The simulation result tables for various wind speeds and launch angles are attached as Appendix D. Appendix E contains relevant values vs. flight time plots for each of the simulation results presented in Appendix D.

3.3.3 Apogee Calculations

The declared target altitude was chosen based on a convergence of many simulations in OpenRocket, verified with a MATLAB code to output apogee and fin flutter speed. The flight vehicle's apogee was calculated using the basic equations of rocket motion equations presented in Apogee Peak of Flight Newsletter, Issue 320. Where the total altitude, H_{total}, can be express as:

$$H_{total} = H_{coasting} + H_{burnout}$$

(Eqn. 3-4)

Where $H_{coasting}$ is the coasting altitude and $H_{burnout}$ is the altitude at burnout. Both of these altitudes can be calculated using the following equations:

$$H_{burnout} = \frac{1}{2}(v_{max} + v_{rest})t$$

(Eqn. 3-5)

Where v_{max} is the maximum velocity that the vehicle reaches during flight and v_{rest} is the initial velocity while the vehicle is at rest (0 ft/s). After the vehicle has reached its peak altitude, the velocity at that altitude becomes zero. Giving the resulting altitude equation:

$$H_{coasting} = \frac{v_{rest} - v_{max}}{2a}$$

(Eqn. 3-6)

Where v_{rest} is the velocity of the flight vehicle at its peak altitude (0 ft/s). The following table is a comparison of all the relevant values obtained in OpenRocket versus MATLAB using a launch angle of 5 degrees and a wind speed of 0 mph.

Table 3-19. Apogee Calculation Comparison

Parameter	OpenRocket	MATLAB	Units	Error Percentage
Max. Velocity	682	662	ft/s	3%
Burnout Altitude	372	330	feet	11%
Coasting Altitude	4193	6790	feet	61%
Total Altitude	4565	7121	feet	55%

Looking at the table above, the maximum velocity values have a smaller error percentage because the speed aspect between the two objects is almost identical: a body of mass experiencing an upward thrust force with an opposing gravitational force. The coasting altitude and total altitude values have a much larger error. This is likely due to the equations used in the MATLAB code ignoring the aerodynamic effects/forces on the flight vehicle during flight. The calculations in the code are loosely based around an object with a fixed weight launching directly upward with no environmental or stability effects acting on it. All simulations were conducted in varying wind conditions and launch configurations. These results are presented in The MATLAB code is attached as Appendix C, while the flight simulation result for all launch angle and windspeed conditions are attached as Appendix D. Appendix E provides relevant values vs. flight time for all simulations conducted.

3.3.5 Vehicle Stability Margin Calculations

To simulate the flight vehicle's stability, OpenRocket software simulation was used to plot the stability margin of the team's vehicle versus time.

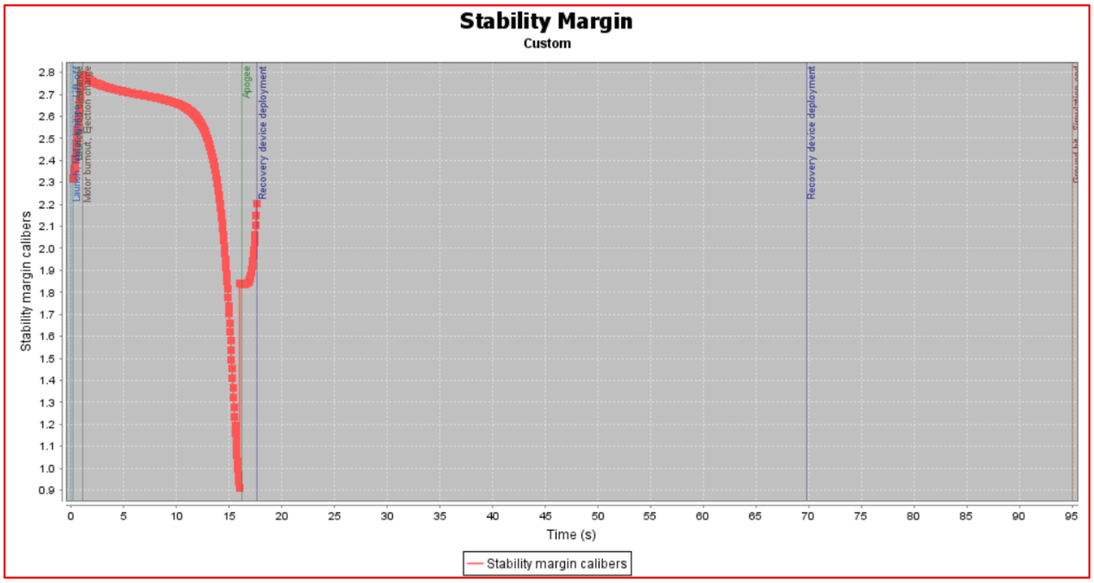


Figure 3-31. Vehicle Stability Margin vs. Flight Time

From the figure shown above, the flight vehicle satisfies the stability margin listed per NASA Student Launch Handbook. The stability magrin can be defined as the distance between the center of gravity and the center of pressure. The figure shows that the maximum stability margin is about 2.8 calibers and the static stability margin at the point of rial exit is about 2.31 calibers

3.3.6 Kinetic Energy

The kinetic energy of each section of the vehicle during descent is governed by the mass and velocity of each. The equation used to determine the kinetic energy of each section is stated below:

$$KE = \frac{1}{2}mv^2$$

(Eqn. 3-75)

Where m is the mass, and v is the velocity of the section. The maximum kinetic energy set by the requirement in the Student Launch Handbook is 75 ft-lb, which can be used to derive the maximum velocity for each descending section. The maximum velocity of each descending section is shown below.

Table 3-20. Maximum Descent Velocity

Section	mass (g)	mass (slug)	Maximum Descent Velocity (ft/s)
Nosecone + upper payload bay	3321.6	0.2276	25.6719
Payload + housing	1589	0.1089	37.1167
AV bay	1547	0.1060	37.6172
Fin can	3925.9	0.2690	23.6136

Once the maximum velocity is known, the descent velocity and subsequent kinetic energy of each section can be determined using the 72-inch Iris Ultra Standard main parachute.

Table 3-21. Maximum Kinetic Energy

Section	mass (g)	mass (lbm)	mass (slug)	Descent Velocity (ft/s)	Kinetic Energy (ft-lb)
Nosecone + upper payload bay	3321.6	7.3229	0.2276	20.77	49.093
Nosecone + upper payload bay + payload	4910.6	10.8260	0.3365	20.77	72.578
Payload	1589	3.5031	0.1089	20.77	23.485
AV bay	1547	3.4106	0.1060	20.77	22.865
Fin can	3925.9	8.6551	0.2690	20.77	58.024

The table above shows the maximum kinetic energy for each section of the vehicle. The second row of the column highlights the worst-case scenario of the payload not exiting the upper payload bay when the main parachute is deployed. In this worst-case scenario the maximum kinetic energy is 72.58 ft-lb, which is under the requirement of 75 ft-lb stated in the Student Launch Handbook. This verifies that the 72-in Iris Ultra Standard parachute is a good selection for the main parachute.

3.3.7 Descent Time and Drift

The descent time is determined by the descent velocity of each parachute and the altitudes at which they are deployed. The drift can be calculated, but a few assumptions must be made. The first assumption is that the launch vehicle reaches apogee directly above the launch pad. The second is that at apogee and main deployment altitude, the terminal velocities are reached instantaneously. Lastly, the wind speeds are applied uniformly on the vehicle and it all drifts in one direction. Although these assumptions make the calculations not entirely accurate, it still gives a good understanding of how severe wind conditions can affect the vehicle's descent. To determine the total descent time of the vehicle the equation below was used:

$$t = \frac{h_a - h_m}{v_d} + \frac{h_m}{v_m} \qquad \textbf{\textit{(Eqn. 3-8)}}$$

where h_a is the apogee altitude, h_m is the main deployment altitude, v_d is the descent velocity underneath the drogue parachute, and v_m is the descent velocity underneath the main parachute. For the declared altitude of 4600 ft, the calculated descent time is 79.9 seconds.

Table 3-22. Descent Time and Drift

Wind Speed (mph)	Apogee (ft)	Descent Time (s)	Wind Drift (ft)
0	4600	79.9	0
5	4600	79.9	585.9333
10	4600	79.9	1171.867
15	4600	79.9	1757.8
20	4600	79.9	2343.733

4 Payload Criteria

4.1 Payload Objective

The objective of the payload upon landing is to autonomously receive RF commands and perform a series of tasks with an on-board camera system. Our team has also added the self-goal of making the components of the payload out of 3d printed parts. After going out to achieve its mission goal the payload will return to the launch vehicle.

4.2 Payload Success Criteria

Table 4-1. Payload Success Criteria

Success Level	Payload	Safety
Complete Success	The payload goes out gathers data and returns to the rocket	No one was injured or harmed, all risks mitigated
Partial Success	The payload only drives out and returns to the rocket without collecting data	Near miss incidents involving team members and/or spectators related to operational or non-operational factors
Partial Failure	The payload does not move but records data	Minor Injury to team member and/or spectator
Complete Failure	Deployment system fails in a manner that leads to severe airframe damage Unrecoverable rover	Severe team member and/or spectator injury due to operational or non-operational factors

4.3 Payload Design

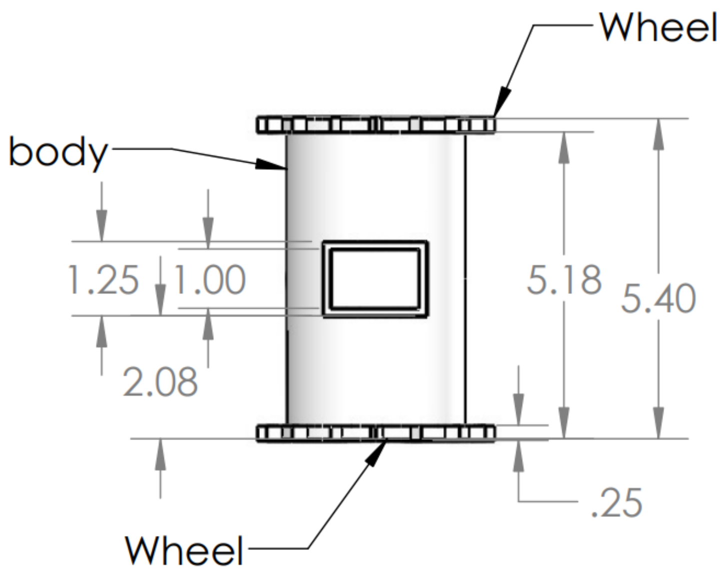


Figure 4-1. Rover Dimensions

4.3.1 Dual Wheeled Rover Scout

Since the limited space in the rocket body and the rougher terrain at the launch site, the team felt that a larger wheeled rover would make for more mobility over the rough terrain. This led to a coaxial wheeled design, where the wheels are larger than the rover body. The rover can be divided into 4 main systems stability, wheel, drivetrain, and control hardware.

4.3.1.1 Stability Design

The stability system was made so that the motor would not just spin the body. These are the following options for stability:

(a) Vehicle tether

4.3.1.1 The vehicle tether is where the rover is connected to the rocket during the duration of its mission. This would make it so the rover would not flip over whilst driving. A benefit of the tether is that if the rover can get over the terrain, the tether will not get caught and cause the rover to stop its motion. The tether is being pulled by the rover so this adds additional weight to the rover as it drives, which will add to the decision for the motor.

(b) Spring loaded wheel

The spring-loaded wheel will be folded up during the flight. Once the rover is released from the housing the wheel will fold and provide the same responsibility as the tether, except it riding in front of the rover. This will keep the rover's weight the same allowing the motor to be. The only concern is with the uneven soil terrain that front wheel can get caught impeding the movement of the rover.

4.3.1.2 Wheel Design

These are the following options for the wheels:

(a) Spiked Wheel

The spiked wheel provides more traction into the soft terrain allowing the rover to dig into the ground and propel itself forward. It allows for easier travel over different densities easily.

(b) Round Wheel
Traversing over changing density terrain can cause these wheels to slip losing traction and lessening the performance. These wheels would also be bought instead of 3D printed which would take away from our team's goal on the payload

4.3.1.3 <u>Drivetrain Design</u>

The number of motors used will affect how much power is available to the wheels to allow them to traverse obstacles, as well as the increase the weight of the vehicle with each motor added. These are the following options for the drive train:

(a) Single DC Motor with Mechanical Differential
Having a single motor would decrease the weight of the rover and the price of the vehicle. If the single motor were to fail, there would be not backup power to complete its intended mission. It would also not allow steering of the rover.

(b) Independent Motor Control
Having the two motors allows for somewhat of a failsafe. Since each of the motors would be on their own wheels respectively if one of the motors were to fail the vehicle would still be able to rotate and captures images around its 360-degree view. The 2-motor system would require more power, adding more weight to the rover.

4.3.1.4 <u>Control Hardware</u>

Both of the following devices are capable of all the tasks that are needed to be done by the rover. These are the following options for the control hardware:

4.3.1.4.1 Arduino Mega

The Arduino Mega uses the C# programing language, therefore it cannot make its own decision. All the capabilities are those which can be coded into it. C# is one of the simpler coding languages which allows for the program to be executed quickly and therefore make decisions quickly. Through our engineering program we have used an Arduino mega and are familiar with it.

4.3.1.4.2 Raspberry Pi

Unlike the Arduino mega the raspberry pi is a computer that not only executes a code but makes decisions. This would have the ability to do everything that needs to be done. None of the group's members have worked with a raspberry pi.

4.3.2 Data collection

As part of the mission objective, the rover will take video to collect data of the terrain.

Table 4-2. Camera Alternatives

Camera	Price	Field of View (deg.)	Form Factor (mm)
Arducam 5MP	$39.39	60	34x24
ArduCam 8MP	$29.99	175 x 155 x 115	24x25
Arducam Mini	$25.99	60	34 x 24

4.4 Payload Leading Alternatives

Table 4-3. Payload Alternative Solutions

System	Choice
Stability	Tether
Wheel	Spiked
Drivetrain	Independent motor
Control Hardware	Arduino Mega

For the Dual Wheeled Rover Scout, the main priority is providing the means for rover movement without inhibition. The choices that were selected for the final design kept this in mind. The tether provides the least impingement to movement. Since it is held behind the rover there is no issues with it getting cause on upcoming terrain. The tether system can also assist in returning the rover to launch vehicle, which is one of our group's set objectives. The spiked wheels allow for more traction to the surface, allowing full utilization of the motors power. The independent motor follows the same trend, providing more power to each of the individual wheels. This also allows for more steering control as it can be used in tandem with the camera to avoid obstacles. For control hardware the team decided to stick with more familiar equipment, such as the Arduino Mega for the control interface of the rover.

4.5 Payload – Launch Vehicle Interface

The rover is going to be encased in a 3D printed housing that is the inner diameter of the rocket body. That housing with the rover will be able to lock into place with a ring embedded inside of the rocket.

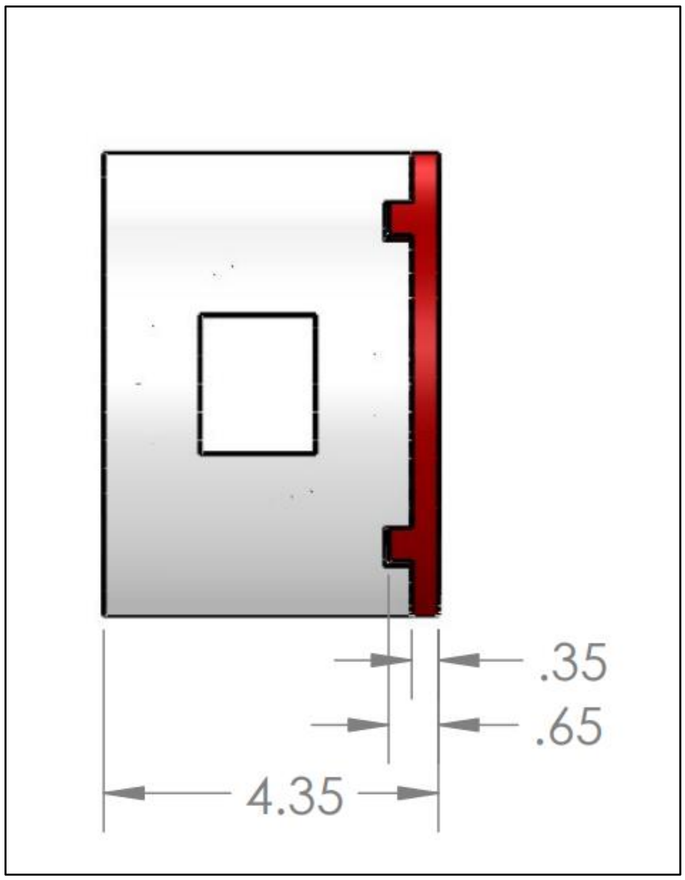


Figure 4-2. Payload Rocket Interface

The red ring shown in the figure above will be connected to the tube of the rocket body. The housing that is shown in white above in the white will slide into the red ring whilst holding the rover inside it. This was made in this way to aid in the rover deployment system. During the main chute deployment phase, the rover housing shown in white will be connected in the middle of the shock cord between the main chute and the upper payload bay. Upon landing the while housing will open allowing the rover to exit and go to complete its mission. To keep payload from sliding away from the red section during the flight the avionics section will have a piece that payload bay and rest against the white part holding it against the fixed red retainer.

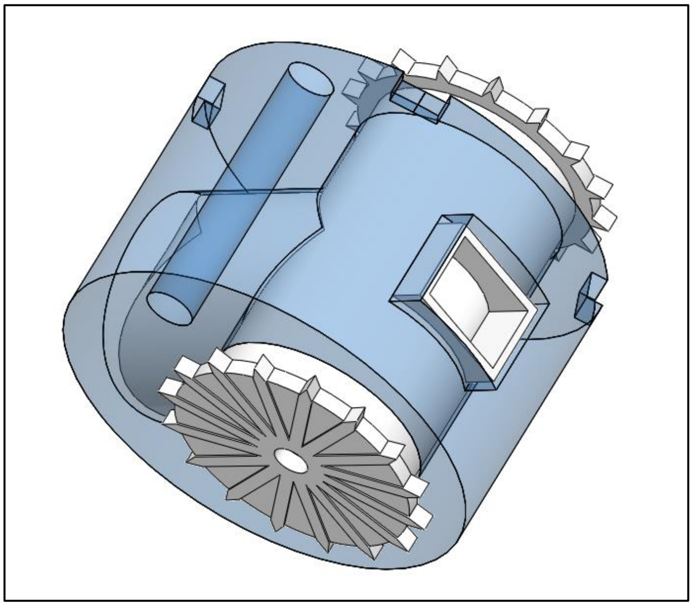


Figure 4-3. Rover Inside Housing

4.5.1 Payload deployment Alternatives

As said previously the rover will be attached to the housing and the housing to the shock cord until it has touched down. After the touchdown event the housing will open. The rover will still need to remove itself from the housing, these are the current alternatives:

4.5.1.1 Extended Rover Housing

The extended rover housing will extend to the bottom of the rover wheels providing a ramp system for the wheels to ride on out of the housing. This alternative makes it so that there is no need for extra equipment to be added. Using the power of the rover's motor to disembark.

4.5.1.2 Spring System

The spring will be embedded in the bottom of the rover housing. Upon opening the spring will push the rover from the bottom out of the housing. Allowing the rover to clear the housing

4.5.1.3 Gear System

The gear would have to be powered by a separate motor. This would add some extra mass to the vehicle. When the motor turns the gear, it moves a rack that then pushes the rover out of the housing.

5 Safety

5.1 Risk Assessment Matrix and Definitions

To conduct a Failure Mode and Effects Analysis for each vehicle system, environmental risk assessment, and personnel risk assessment, the risk classification matrix in Table 5-1 was used. Tables 5-1 and 5-2 on the following page define each severity and likelihood class.

Table 5-1. Risk Classification Matrix

<table>
<tr><th colspan="3" rowspan="3"><u>Risk Classification Matrix</u></th><th colspan="4">Event Likelihood</th></tr>
<tr><td>Possible</td><td>Plausible</td><td>Probable</td><td>Highly Probably</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td>D</td></tr>
<tr><td rowspan="4">Event Severity</td><td>Marginal</td><td>1</td><td>1A</td><td>1B</td><td>1C</td><td>1D</td></tr>
<tr><td>Significant</td><td>2</td><td>2A</td><td>2B</td><td>2C</td><td>2D</td></tr>
<tr><td>Major</td><td>3</td><td>3A</td><td>3B</td><td>3C</td><td>3D</td></tr>
<tr><td>Catastrophic</td><td>4</td><td>4A</td><td>4B</td><td>4C</td><td>4D</td></tr>
</table>

Table 5-2. Severity Classification Definitions

Severity	Vehicle Outcomes	Personnel Outcomes
Marginal	Little to no impact to vehicle integrity. Flight profile consistent with expectation. Safe recovery. Payload intact and deployed. Vehicle can be reused.	No potential for injury created.
Significant	Vehicle integrity compromised. Minor repair required. Deviation from expected flight profile. Safe recovery. Payload intact and deployable. Vehicle can be reused.	Minor risk of injury created. No injuries.
Major	Vehicle integrity compromised. Substantial repair required. Large deviation from expected flight profile. Recovery may endanger personnel. Payload and deployment mechanism damaged. Vehicle can be reused.	Great risk of injury created. Injuries reported. Injuries are manageable with basic first-aid.
Catastrophic	Vehicle breakup in flight. Irreparable damage. Unarrested descent. Recovery not possible. Payload destroyed. Complete loss of vehicle and payload.	Great risk of injury created. Injuries reported. Injuries require professional medical attention.

Table 5-3. Likelihood Classification Definitions

Likelihood	Definition
Possible	Within the set of all conceivable outcomes. Not likely to occur.
Plausible	Reasonable chance of occurrence due to uncertainty bounds.
Probable	Likley to occur. Uncertainty is now in whether the event will **not** occur.
Highly Probable	Near certainty. Statistical chance of occurrence far outweighs the chance of no occurrence.

5.2 Vehicle Systems Failure Mode and Effects Analysis

Table 5-4. Avionics and Power Systems FMEA

Failure Mode	Cause(s)	Hazard Category
(PS.1) Power loss on pad	• Dead battery • Disconnection of leads	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of power to flight computer	• Vehicle launch cannot be commanded • Battery replacement required • Personnel must approach cold vehicle – minimal risk	• Ensure battery is charged pre-flight • Have flight computer transmit battery condition • Firm lead attachment • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(PS.2) Power loss in flight	• Dead battery • Disconnection of leads	4A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of power to flight computer	• Loss of vehicle control • No control authority over recovery system • Unable to measure altitude • Unable to command deployment events • Unarrested descent • Risk to personnel	• Ensure battery is charged pre-flight • Have flight computer transmit battery condition • Firm lead attachment • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(PS.3) Power loss after recovery	• Dead battery • Disconnection of leads	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of power to flight computer	• Loss of control authority over payload deployment mechanism • Unable to deploy payload	• Ensure battery is charged pre-flight • Have flight computer transmit battery condition • Firm lead attachment • Redundant power/avionics

Failure Mode	**Cause(s)**	**Hazard Category**
(AV.1) In-flight barometer failure	• Bad component • Poor component calibration • Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Altitude cannot be determined from atmospheric pressure	• Vehicle relies on double integration of accelerometer data for altitude • Large compounding errors in integration may cause off-nominal main deployment • Nominal drogue deployment using accelerometer	• Purchase components from reputable dealer • Test components extensively before flight • Firm electrical lead attachments • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.2) In-flight accelerometer failure	• Bad component • Poor component calibration • Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Altitude and velocity cannot be determined by integration of acceleration data	• Vehicle relies on inflection of barometric data to determine apogee (pressure begins increasing) • Potential off-nominal drogue deploy • Nominal main chute deployment using barometer	• Purchase components from reputable dealer • Test components extensively before flight • Firm electrical lead attachments • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.3) Simultaneous in-flight accelerometer/barometer failure	• Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Altitude and velocity cannot be determined	• Recovery events reliant on time-commanded backup charges • Off-nominal drogue deploy • Off-nominal main deploy	• Purchase components from reputable dealer • Test components extensively before flight • Firm electrical lead attachments • Redundant power/avionics

Failure Mode	**Cause(s)**	**Hazard Category**
(AV.4) In-flight/post-flight GPS unit failure	• Bad component • Poor component calibration • Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Vehicle landing site cannot be precisely determined	• Sonic beacon becomes primary locator • Visual tracking to ground aids in recovery	• Purchase components from reputable dealer • Test components extensively before flight • Firm electrical lead attachments • Redundant power/avionics
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.5) Flight computer failure (pre-flight)	• Bad component • Power loss	2A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over vehicle	• Vehicle launch cannot be commanded • Personnel must approach cold vehicle – minimal risk	• Same as previous
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.6) Flight computer failure (in-flight)	• Bad component • Power loss	4A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over vehicle	• No control authority over recovery system • Unable to measure altitude • Unable to command deployment events • Unarrested descent • Risk to personnel	• Same as previous
Failure Mode	**Cause(s)**	**Hazard Category**
(AV.7) Flight computer failure (post-flight)	• Bad component • Power loss	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over vehicle	• Loss of control authority over payload deployment mechanism • Unable to deploy payload	• Same as previous

Failure Mode	Cause(s)	Hazard Category
(AV.8) Wire leads disconnect	• Excessive vehicle vibration • Poor terminal connections	4D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Any combination of AV.1 – AV.4, AV.6, and AV.7 failure modes	• Loss of control authority over vehicle • No control authority over recovery system • Unable to measure altitude • Unable to command deployment events • Unarrested descent • Risk to personnel • Loss of control authority over payload deployment mechanism • Unable to deploy payload	• Ensure proper soldering of terminal leads • Extensively test robustness of connections to tension and vibration • Implement vibration damping measures for electrical components • Redundant power/avionics

Table 5-5. Avionics and Power Systems Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	PS.1 1A AV.7 PS.3	1B	1C	1D
	Significant	2	AV.1 AV.4 AV.2 2A AV.3 AV.5	2B	2C	2D
	Major	3	3A	3B	3C	3D
	Catastrophic	4	PS.2 4A AV.6	4B	4C	AV.8 4D

Table 5-6. Energetics and Pyrotechnics FMEA

Failure Mode	Cause(s)	Hazard Category
(PRO.1) Failed motor igniter	• E-match fails to ignite • Black powder pellet fails to ignite after E-match	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Vehicle remains on launchpad in unknown state	• E-match/igniter replacement required • Personnel must approach warm vehicle – significant risk • Dud ignition converts vehicle cold • Random ignition in time following dud – significant risk to personnel approaching	• Redundant e-matches • E-match close proximity to black powder pellet
Failure Mode	**Cause(s)**	**Hazard Category**
(PRO.2) Ejection charge initiation failure	• E-match fails to ignite	2B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Body sections do not separate	• Separation dependent on backup charge (time initiated) • Off-nominal parachute deployment	• Redundant e-matches
Failure Mode	**Cause(s)**	**Hazard Category**
(PRO.3) Ejection charge fails to separate sections	• Insufficient black powder load • Excessive friction in coupler • Shock cord entanglement	2B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Body sections do not fully separate	• Structural damage between colliding body sections • Separation dependent on backup charge (time initiated) • Off-nominal parachute deployment	• Redundant ejection charges: • Time-commanded backup charge

Failure Mode	Cause(s)	Hazard Category
(EN.1) Unintentional motor ignition	• Static Discharge • Human Error	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Launch vehicle departs launch rails unexpectedly	• Flight computer not prepared to execute profile • Unable to command recovery sequence • Burns and hearing damage to personnel in immediate vicinity of vehicle	• Ensure vehicle is grounded in prep area and on pad • Ensure proper communication during count sequence
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.2) Unintentional ejection charge initiation (pre-flight)	• Static Discharge • Human Error	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Unexpected black powder detonation	• Creation of large audible signature and expulsion of hot exhaust gasses • Great injury to personnel standing in line with and near charge. Medical emergency • Burns and hearing damage to personnel in immediate vicinity of vehicle • Body section(s) are ejected • Body sections impact nearby personnel. Minor to significant injuries	• Ensure vehicle is grounded in prep area and on pad • Ensure proper communication during count sequence • Implement CO_2 ejection system

Failure Mode	Cause(s)	Hazard Category
(EN.3) Uneven combustion in solid fuel	• Poor mixing of fuel and oxidizer • Poor distribution of propellant in case	4C
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Asymmetric thrust about vehicle z-axis	• Deviation from expected flight path • Loss of vehicle stability • In-flight break up of vehicle. Loss of vehicle • Unarrested descent. Risk to personnel	• Purchase motor from reputable dealer (Cesaroni is the current selection)
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.4) Motor exhaust in body tube	• Motor case rupture • Nozzle foreword of thrust plate	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Damage to body tube • Loss of vehicle integrity	• Mid-flight fin detachment • Catastrophic body rupture • Vehicle in-flight breakup • Loss of vehicle	• Aluminum motor case, thrust plate, and motor retainer • Extensive sealing in motor compartment
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.5) Motor jettison	• Thrust plate or motor retainer failure	3A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Motor and casing separate from launch vehicle after burnout	• Changes to stability margin as Cg shifts towards nose • Deviation from projected flight profile • Risk to personnel from uncontrolled, unarrested descent of metal motor casing	• Aluminum thrust plate and motor retainer to ensure dynamic loading margins are not exceeded

Failure Mode	Cause(s)	Hazard Category
(EN.6) Avionics damage	• Hot/corrosive ejection charge exhaust gasses	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Development of any AV.1 – AV.4 and AV.6 Failure Modes	• No control authority over recovery system • Unable to measure altitude • Unable to command deployment events • Unarrested descent • Risk to personnel	• Insulate void space in body • Implement CO2 ejection system
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.7) Burned parachute(s)	• Hot/corrosive ejection charge exhaust gasses	4D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Drogue and/or main parachute unable to provide sufficient drag to slow descent	• Partially or fully unarrested descent • Fire inside body tube • Fire in canopy on descent	• Kevlar blankets to retain chutes • Insulate void space • Implement CO2 ejection system
Failure Mode	**Cause(s)**	**Hazard Category**
(EN.8) Chain detonation of ejection charges	• Hot/corrosive ejection charge exhaust gasses	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Multiple separation event at apogee • Simultaneous deployment of drogue and main chute	• Deviation from intended flight profile • Risk to personnel from (4) and (5) • structural damage to colliding body sections • Parachute entanglement. Increased descent rate Uncontrolled descent. • Decreased descent rate. Increased wind drift. Vehicle exits recovery zone	• Insulate void space in body • Implement CO2 cooling system to black powder ejection charges

Table 5-7. Energetics and Pyrotechnics Risk Matrix

<u>**Risk Classification Matrix**</u>			**Event Likelihood**			
			Possible	Plausible	Probable	Highly Probably
			A	**B**	**C**	**D**
Event Severity	Marginal	**1**	1A	1B	1C	1D
	Significant	**2**	2A	**PRO.2** 2B **PRO.3**	2C	2D
	Major	**3**	**EN.5** 3A	**PRO.1** 3B **EN.8**	3C	**3D**
	Catastrophic	**4**	4A	**EN.1** **EN.4** 4B **EN.2** **EN.6**	**EN.3** 4C	**EN.7** **4D**

Table 5-8. Recovery System FMEA

Failure Mode	Cause(s)	Hazard Category
(RS.1) Drogue parachute entanglement	• Poor shock cord stowage in body • Snag hazards in deployment path	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• High descent rate after apogee • Main parachute deployment at higher speed	• Main parachute canopy damaged in high-speed deployment • Main parachute cords tear or rupture • Partially or fully unarrested vehicle descent • Over tensioning of vehicle shock cord. Cord tearing or rupture • Unarrested descent of body sections • Risk to personnel • Major repair needed	• Design for no snag hazards in deployment path of parachute • Reeve loose shock cord • Implement cord routing solutions
Failure Mode	**Cause(s)**	**Hazard Category**
(RS.2) Main parachute entanglement	• Poor shock cord stowage in body • Snag hazards in deployment path	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• High descent rate after main deployment • High ground impact velocity	• Partially arrested descent • Damage to vehicle structures • Damage to internal components • Major repair required	• Design for no snag hazards in deployment path of parachute • Reeve loose shock cord • Implement cord routing solutions
Failure Mode	**Cause(s)**	**Hazard Category**
(RS.3) Single electronic chute release failure	• Bad component • Power loss • Debris in latch mechanism	2B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Parachute remains retained in body	• Chute deployment contingent upon second release (timed event) • Off-nominal chute deployment	• Cross connection of retaining cord ends between two chute releases • Reputable distributor

Failure Mode	Cause(s)	Hazard Category
(RS.4) Double electronic chute release failure	• Power loss	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Parachute deployment rendered impossible	• Unarrested descent • Loss of vehicle • Risk to personnel	• Cross connection of retaining cord ends between two chute releases • Reputable distributor
Failure Mode	**Cause(s)**	**Hazard Category**
(RS.5) Shock cord rupture	• Excessive tension on cord	3A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Tether between body sections compromised	• Unarrested descent of body section(s)	• Extensive simulation pre-flight • Select shock cord with large factor of safety
Failure Mode	**Cause(s)**	**Hazard Category**
(RS.6) Shock cord entanglement	• Poor shock cord stowage in body • Snag hazards in deployment path	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Shock cord unable to extend to full length	• Collision of body sections on descent • Very minor damage to structure	• Reeve loose shock cord • Implement cord routing solutions

Table 5-9. Recovery System Risk Matrix

Risk Classification Matrix			**Event Likelihood**			
			Possible	Plausible	Probable	Highly Probably
			A	**B**	**C**	**D**
Event Severity	Marginal	**1**	**RS.6** 1A	1B	1C	1D
	Significant	**2**	2A	**RS.3** 2B	2C	2D
	Major	**3**	**RS.5** 3A	**RS.2** 3B	3C	**3D**
	Catastrophic	**4**	4A	**RS.1** 4B **RS.4**	4C	**4D**

Table 5-10. Vehicle Structures FMEA

Failure Mode	Cause(s)	Hazard Category
(STR.1) Melting of fin assembly during motor burn	• Heat transfer from motor case • Lack of heat resistance in fin material	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of flight stability	• Vehicle breakup in-flight • Loss of vehicle • Unarrested descent of body sections • Risk to personnel	• Use heat resistant print material • Treat for heat resistance • Minimize heat transfer
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.2) Fins shear off	• Fin flutter • Aerodynamic loading	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of flight stability	• Vehicle breakup in-flight • Loss of vehicle • Unarrested descent of body sections • Risk to personnel	• Extensive simulation pre-flight • Ensure flutter speed >> max vehicle velocity
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.3) Body tube zippering	• Shock cord contact with body on deployment	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of vehicle integrity	• Vehicle damage on descent • Major repair needed	• Implement “bumpers” to avoid cord contact • Implement cord routing
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.4) Damaged motor retainer	• Defect in part • Excessive dynamic loading	3A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Potential motor jettison after burnout	• Unarrested descent of motor casing • Risk to personnel • Minor repair required	• Aluminum motor retainer to absorb far larger loads than necessary

Failure Mode	Cause(s)	Hazard Category
(STR.5) Bulkhead or U-bolt torn loose	• Excessive loading during chute deployment • Late chute deployment	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Body section(s) disconnected from parachute	• Unarrested descent of body section(s) • Risk to personnel • Major repairs required	• Extensive pre-flight simulation • Extra thick bolts and wide bracing on bulkheads
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.6) Dislodged centering ring(s)	• Defect in part(s) • Excessive dynamic loading • Poor connection to threaded rods	3A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Motor long axis no longer colinear with vehicle z-axis	• Deviation from flight profile • Minor loss of stability • Risk to personnel	• Fix centering rings to threaded rods with hex nuts • Use thread lock to fix nuts
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.7) Damaged rover retainer	• Defect in part(s) • Poor 3D print • Excessive dynamic loading • Excessive ground impact velocity	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Rover sits loose in payload bay	• Minor decrease in vehicle stability • Minor rover damage • Improper or impossible rover deployment	• Extensive pre-flight testing • Minimize ground impact velocity • Cushion landing
Failure Mode	**Cause(s)**	**Hazard Category**
(STR.8) Damaged avionics sled retainer(s)	• Defect in part(s) • Poor 3D print • Excessive dynamic loading • Excessive ground impact velocity	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Avionics sleds sit loose in av bay	• Potential for AV.8 failure mode • Loss of control authority over vehicle	• Extensive pre-flight testing • Minimize ground impact velocity • Cushion landing

Table 5-11. Vehicle Structures Risk Matrix

Risk Classification Matrix			**Event Likelihood**			
			Possible	Plausible	Probable	Highly Probably
			A	**B**	**C**	**D**
Event Severity	Marginal	**1**	STR.7 1A	1B	1C	1D
	Significant	**2**	2A	STR.4 2B	2C	2D
	Major	**3**	STR.6 3A	STR.3 3B STR.8	3C	3D
	Catastrophic	**4**	4A	STR.1 4B STR.5 STR.2	4C	4D

Table 5-12. Payload FMEA

Failure Mode	Cause(s)	Hazard Category
(RVR.1) 3-D printed rover body damaged	• High ground impact velocity • Defects in 3D print	1C
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Structure of rover compromised	• Loose components dig into terrain • Loss of propulsion • Internal wiring shifted. Leads torn from Arduino	• Extensive pre-flight testing • Minimize ground impact velocity • Cushion landing
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.2) 3-D printed rover wheels damaged	• High ground impact velocity • Defects in 3D print	1C
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Traction and/or propulsion negatively impacted • Physical immobilization	• None	• Extensive pre-flight testing • Minimize ground impact velocity • Cushion landing
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.3) Electronic latch fails to release quick link on shock cord	• Power loss • Debris in latch mechanism	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Payload remains tethered to recovered flight vehicle	• Rover can only move as far from vehicle as slack in shock cord will allow	• Ensure firm lead connections • Clean latch mechanism
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.4) Wheels become entrenched in loose terrain	• Insufficient wheel diameter • Insufficient tread on tires	1D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Physical immobilization	• None	• Extensive pre-flight testing

Failure Mode	Cause(s)	Hazard Category
(RVR.5) Rover becomes stuck in furrow of plowed field	• Cylindrical rover geometry	1D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Physical immobilization	• None	• Outrigger/arm in design phase to recover from this condition
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.6) Power loss	• Dead battery • Electrical lead disconnection	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over rover	• Physical immobilization • RAFCO Mission failure	• Charge battery pre-flight • Firm electrical connections
Failure Mode		**Hazard Category**
(RVR.7) Propulsion failure	• Dead battery • Electrical lead disconnection • Bad motor	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Physical immobilization	• None	• Charge battery pre-flight • Firm electrical connections
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.8) Antenna disconnection from GNC	• Excessive vibration in flight • Excessive ground impact velocity	1D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over rover	• Physical immobilization • RAFCO Mission failure	• Firm electrical connections • Pad landing, reduce velocity
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.9) GNC unit failure	• Bad component • Power loss	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of control authority over rover	• Physical immobilization • RAFCO Mission failure	• Firm electrical connections

Failure Mode	Cause(s)	Hazard Category
(RVR.10) Foreword looking camera failure	• Broken lens during ground impact • Power loss	1A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of ability to see terrain ahead of rover	• Technical immobilization • RAFCO Mission failure	• Padding around camera assembly • Firm electrical connections
Failure Mode	**Cause(s)**	**Hazard Category**
(RVR.11) Camera actuation system failure	• Motor failure • Obstructed gears • Power loss	1B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Camera cannot swivel camera	• RAFCO Mission failure	• Firm electrical connections • Clean gear mechanism

Table 5-13. Payload Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	RVR.7 1A RVR.9 RVR.1	RVR.3 1B RVR.6 RVR.1	RVR.1 1C RVR.2	RVR.4 1D RVR.5 RVR.8
	Significant	2	2A	2B	2C	2D
	Major	3	3A	3B	3C	3D
	Catastrophic	4	4A	4B	4C	4D

Table 5-14. Environment FMEA

Vehicle Risks to Environment		
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.1.1) Launch pad/recovery area fire (energetic initiated)	• Dry vegetation in vicinity of motor ignition	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Danger to wildlife • Danger to habitat • Danger to personnel	• Potential for fire growth if left unmitigated	• Clear launch area of vegetation
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.1.2) Launch pad/recovery area fire (LiPo battery initiated)	• Battery overcharge, over discharge, overtemp	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Danger to wildlife • Danger to habitat • Danger to personnel • HazMat release	• Pollution of crops with HazMat • Pollution of groundwater with HazMat	• Clear launch area of vegetation • Do not use battery improperly
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.1.3) Interstage insulation littered in launch/ recovery area	• Insulation used in body tube to minimize void space and insulate parachutes from ejection charge gasses	1C
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Ingestion of insulation by wildlife	• Disrespectful to property owners to eject litter on their land	• Biodegradable insulation (popcorn)
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.1.4) Litter spread over launch site by personnel	• Lack of trashcans • Poor team leadership	1D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Ingestion of litter by wildlife	• Disrespectful to property owners to litter on their land	• Bring trash bags • Firm leadership. Zero tolerance for littering

Environmental Risks to Vehicle		
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.2.1) Vehicle touches down in nearby trees	• Excessive wind drift	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Difficulty in or inability to recover launch vehicle • Minor damage to vehicle components	• Loss of vehicle • Repairs required	• Extra-long shock cord to bring components closer to ground
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.2.2) Vehicle touches down in nearby body of water	• Excessive wind drift	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Damage to body tube structure • Damage to avionics or payload electronics	• Major repairs required	• Extensive sealing of avionics bay and rover GNC unit
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.2.3) In-flight Collision	• Tall infrastructure (power lines) • Bird strike	4A
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Loss of stability • Damage to animal or object impacted	• Loss of vehicle • Repair to damaged infrastructure required	• Ensure vehicle is launched away from all infrastructure • Await clear skies
Failure Mode	**Cause(s)**	**Hazard Category**
(ENV.2.4) Vehicle or components dropped	• Uneven launch site terrain causes personnel tripping	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Damage to vehicle structures • Damage to payload structures • Damage to avionics • Damage to payload electronics	• Inability to launch • Repairs required	• Practice extreme caution while handling vehicle components

Table 5-15. Environmental Risk Matrix

Risk Classification Matrix			**Event Likelihood**			
			Possible	Plausible	Probable	Highly Probably
			A	**B**	**C**	**D**
Event Severity	Marginal	**1**	1A	1B	ENV.1.3 1C	ENV.1.4 1D
	Significant	**2**	2A	2B	2C	2D
	Major	**3**	3A	ENV.1.1 3B ENV.2.2 ENV.2.4	3C	**3D**
	Catastrophic	**4**	ENV.2.3 4A	ENV.1.2 4B ENV.2.1	4C	**4D**

5.3 Personnel Risk Assessment

Personnel risk assessment was conducted using the same FMEA format as was used for vehicle systems and environmental risk assessment.

Table 5-16. Personnel FMEA

Failure Mode	Cause(s)	Hazard Category
(PPL.1) Skin contact with APCP solid propellant	• Improper material handling • Lack of PPE	3D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Chemical burns • Eye irritation	• None	• Provide safety training • Provide PPE
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.2) Electrocution	• Improper safety procedures followed • Live electrical while wiring	2D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Discomfort/pain • Burns	• Greater or grave injury with prolonged exposure	• Provide safety training
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.3) Proximity to high-pressure burst event (CO2 charge)	• Overpressure in pressure vessel • Pressure vessel tipping • Human error	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Hearing damage • Struck/Impaled by flying object(s)	• None	• Provide safety training • Do not overfill pressure vessels • Pressure vessels chained to walls • Declare all testing and clear area prior to initiation

Failure Mode	Cause(s)	Hazard Category
(PPL.4) Proximity to explosive event (Black powder charge)	• Accidental initiation (human error, static discharge)	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Hearing damage • Burns from expanding hot gasses	• Severity increased with proximity • Severity increased with decreased angle-off-bore of charge	• Ground vehicle components • Minimize personnel handling charges • Isolate firing mechanism until range clear
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.5) Proximity to combustion event	• Motor ignition (intentional) • Motor ignition (unintentional) • Loose black powder burn	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Hearing damage • Burns from expanding hot gasses	• Severity increased with proximity • Severity increased with decreased angle-off-bore of charge	• Ground vehicle components • Minimize personnel handling motor • Isolate ignition mechanism until range clear
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.6) Injury: slip and fall, minor cuts, accidental collisions	• Uneven terrain • Tripping hazards on flat ground • Improperly stored sharp objects	3B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Pain/discomfort • Bruises • Small lacerations	• Infection of lacerations not immediately treated	• Situational awareness • Clean lab spaces • Proper safety procedures
Failure Mode	**Cause(s)**	**Hazard Category**
(PPL.7) Dehydration, heat exhaustion, heat stroke	• Lack of water • Lack of adequate sun protection or shade	4B
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Thirst • Disorientation • Loss of consciousness	• None	• Provide ample water • Bring portable awning/tent • Bring sunscreen, hats, etc.

Failure Mode	Cause(s)	Hazard Category
(PPL.8) Soldering iron burns	• Improper use or stowage of soldering iron	3D
Primary Effect(s)	**Secondary Effect(s)**	**Mitigations**
• Minor burns	• Increased severity with prolonged contact	• Proper training in use of soldering iron • Minimize personnel involved

Table 5-17. Personnel Risk Matrix

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	B	C	D
Event Severity	Marginal	1	1A	1B	1C	1D
	Significant	2	2A	2B	2C	PPL.2 2D
	Major	3	3A	PPL.3 3B PPL.6	3C	PPL.1 3D PPL.8
	Catastrophic	4	4A	PPL.4 4B PPL.7 PPL.5	4C	4D

5.4 FMEA Summary

The risk classification matrix is overlayed with the number of risk items and percentage of total items that appear in each risk category. Our assessment identified a total of 63 risk items, with 40% of these items falling into the 3B and 4B categories. These categories represent substantial consequences in the event of failure with only a minor chance of failure, thus we can conclude that the bulk of our risk can be considered tolerable. 30 items fall into the 3D and 4D categories. These risks present substantial consequences and a substantial chance of failure. Mitigation strategies for items in these risk categories must be numerous, effective, and well-implemented by the team to ensure safety and mission success.

All 1-series (~30% of items) and A-series (~30% of items) risks can be considered tolerable risks. 1-series are the most tolerable because regardless of their likelihood of occurrence, the outcomes have marginal impact to safety and mission success. The 3A and 4A risk categories present substantial risk to safety and mission success but have an exceptionally low probability of failure. The entire A-series can be effectively considered negligible with the implementation of mitigation measures discussed.

Table 5-18. Overall Risk Item Distribution

Risk Classification Matrix			Event Likelihood			
			Possible	Plausible	Probable	Highly Probably
			A	**B**	**C**	**D**
Event Severity	Marginal	**1**	1A 8 Items 12.7%	1B 3 Items 4.8%	1C 3 Items 4.8%	1D 4 Items 6.3%
	Significant	**2**	2A 5 Items 7.9%	2B 4 Items 6.3%	2C 0 Items 0.0%	2D 1 Item 1.6%
	Major	**3**	3A 3 Items 4.8%	3B 10 Items 15.9%	3C 0 Items 0.0%	**3D** 2 Items 3.2%
	Catastrophic	**4**	4A 3 Items 4.8%	4B 14 Items 22.2%	4C 1 Item 1.6%	**4D** 2 Items 3.2%

5.5 Project Plan Risk Assessment

Project planning risk assessment was conducted using a similar format as the systems, personnel, and environment failure mode analysis, although for the case of impact to project timeline and budget the severity definitions which define the risk matrix were modified. Project plan risk severities are defined below, which also reiterates the likelihood definitions of previous sections.

Table 5-19. Project Plan Risk Severity Definitions

Severity	Timeline Outcomes	Budget Outcomes
Marginal	All milestones can be met without corrective action.	The project will proceed with no cost overruns. Project is viable.
Significant	Milestones may not be met without minor corrective action.	Cost overruns incurred amount to less than $100 per milestone. Project is viable.
Major	Milestones will not be met without substatial corrective action.	Cost overruns incurred range from $100 to $500 per milestone. Long term viability becomes questionalbe.
Catastrophic	Milestones will be missed entirely with no chance of timely completion.	Cost overruns exceed $500 per milestone. Sponsors and investors doubt viability.

Likelihood	Definition
Possible	Within the set of all conceivable outcomes. Not likely to occur.
Plausible	Reasonable chance of occurrence due to uncertainty bounds.
Probable	Likley to occur. Uncertainty is now in whether the event will **not** occur.
Highly Probable	Near certainty. Statistical chance of occurrence far outweighs the chance of no occurrence.

Using these new definitions, the analysis in the following table was performed. Risk level and mitigation strategies are assessed on a 1-5 scale with 5 suggesting that:

a) The risk to the timeline, budget, or project is substantial, and likelihood of occurrence rises above possible
b) The mitigation strategies are an excellent countermeasure to the risk item, while 1 suggests the mitigation measures have little to no effect.

And 1 suggesting that:

a) The risk to the project is marginal and the likelihood of occurrence is significant or below
b) The mitigation strategy does a poor job of effectively managing the risk to the project

Table 5-20. Project Plan Risk Assessment

Code	Risk Item	Effects	Risk Cat.	Mitigations	Mit. Effect
(PLN.1)	Broken parts and/or tools	• Replacement parts required • Cost incurred • Time delays pending new tools/parts	2	• Handle all parts on steady surfaces • Transport parts carefully and in teams • Use tools within specified operating ranges	3
(PLN.2)	Shop injuries	• Suspension of shop work for safety review • Major time delays • Threat to investor confidence	5	• Provide safety training • Emphasize personal responsibility • Clean shop environment	2
(PLN.3)	Poor meeting attendance	• Slower than projected progress • Inter-department miscommunications	2	• Iterate on meeting date and time to work best for all • Facilitate channels for communication outside of meetings	1
(PLN.4)	Poor communication between departments	• Slower development of interlinked systems • Slower test campaigns • Poor equipment sharing or resource management	3	• Facilitate channels for communication outside of meetings • Ensure communication is documented referenceable	4

Code	Risk Item	Effects	Risk Cat.	Mitigations	Mit. Effect.
(PLN.5)	Insufficient design documentation. Lost documentation	• Poor resource management • People repeating completed tasks or analyses • Time wasted on discarded concepts, ideas, solutions	3	• Facilitate shared team storage (Teams, drop box, slack) • Keep all leads and members appraised of current iteration	5
(PLN.6)	Weeks of increased university coursework	• Reduces availability of team members • Decrease in team attendance	3	• Discuss exam schedules with students, members, and professors • Work exam/project week delays into timeline	1
(PLN.7)	Saturday home football games	• Reduced team member availability on 1 of 2 potential test launch days in each week • Large delays in event of launch failure pending scheduling a re-flight • Reduced team attendance and availability on Saturdays	2	• Plan for launches on away game weekends • Plan for Sunday launches • Explore mid-week launches with professor coordination	3
(PLN.8)	Low stock of commercially sourced items	• Build or testing delayed pending restock • Higher fees for expedited shipping	3	• Purchase items well in advance of deadlines • Source alternative items or distributors	4

Code	Risk Item	Effects	Risk Cat.	Mitigations	Mit. Effect.
(PLN.9)	Test launch weather scrubs	• Large delays pending re-flight scheduling • Cost of new motor incurred • Missed milestones	3	• Use yearly weather patterns for launch facility to anticipate conditions • Monitor conditions week of launch • Schedule backup launch days • Schedule test launches well ahead of time	2
(PLN.10)	Catastrophic test launch failure	• Loss of vehicle • Massive time delays pending full rebuild • Missed milestones • Massive cost incurred • Threat to investor confidence	5	• Extensive simulation and testing before flight • Plan test launches well ahead of milestones in event of failure	2
(PLN.11)	Non-catastrophic test launch failure	• Considerable time delays pending scheduling re-flight • Cost of new motor incurred • Missed milestones	4	• Plan test launches well ahead of milestones in event of failure • Include "padding" in budget to accommodate partial failures resulting in $200-300 expenses	5

6 Project Plan

6.1 Requirements Verification

Table 6-1. Safety Team Derived Verification Matrix

Safety Team Derived Requirements				
Number	**Description**	**Justification**	**Success Criteria**	**Verification Method**
1	Proper safety equipment shall be provided to all personnel	The use of PPE helps to reduce the likelihood of injury while working	Entrances to all team shops are stocked with all necessary PPE	Inspection
2	Launch day attendees shall keep a reasonable pace during all aspects of activities	Maintaining a steady pace reduces the likelihood of falling or tripping	Team members are to walk, meaning having one foot on the ground at a time	inspection
3	All major hazards identified in the risk assessment matrix shall be decreased to yellow or green by CDR through mitigations	Mitigating potentially dangerous/frequent hazards creates a more robust system	All hazards identified in the CDR document fall in the yellow or green zones after the mitigation.	inspection

Table 6-2. Launch Vehicle Team Derived Verification Matrix

Launch Vehicle Team Derived Requirements				
Number	**Description**	**Justification**	**Success Criteria**	**Verification Method**
1	The launch vehicle shall not exceed 16Gs of acceleration during ascent	Acceleration higher than 16Gs could cause problems for the payload or vehicle structure	Simulations are done in OpenRocket	Analysis
2	The launch vehicle shall have symmetrical fins	This ensures that the launch vehicle is aerodynamic and ensures the CG is on center by causing equal aerodynamics on both sides and equal weight distribution	The launch vehicle has four fins equally spaced from each other around the airframe along with one camera positioned at the center of the nosecone	Inspection
3	The lower payload bay shall have at least 6 inches of interior length	This is to give the payload team enough space for any lower payload electronics	The lower payload bay is designed to have 6 inches of interior length	Inspection
4	The airframe shall be capable of launching in temperatures between 20- and 100-degrees Fahrenheit	The launch vehicle is planned to operate in a variety of launch fields and seasons	The airframe material is rated to not be damaged or deformed under these temperatures	Inspection/Analysis
5	The launch vehicle shall not go above Mach 0.7	Higher speeds and accelerations are not necessary they endanger the payload and other structural components	Simulations are done is OpenRocket to confirm the launch vehicles maximum velocity	Analysis
6	The launch vehicle shall use at least 2 centering rings to support the motor tube	This ensures that the motor tube has the adequate support to experience the high force caused by the motor	Two centering rings along with the engine block will be used to support the motor tube	Inspection

Number	Description	Justification	Success Criteria	Verification Method
7	The launch vehicle shall have a stability margin between 2.5 and 3.5 calibers	Stability margins lower than 2 are probhibited by NASA. Margins of stability greater than 2.2 are more stable	The aerodynamics lead designs the launch vehicle such that minimun stability margin of 2.5 calibers.	Analysis/Inspection

Table 6-3. Recovery Team Derived Verification Matrix

Recovery Team Derived Requirements				
Number	**Description**	**Justification**	**Success Criteria**	**Verification Method**
1	New batteries shall be used for the altimeters before every flight	Insufficient voltage supply can lead to the altimeter powering off	New batteries will be chosen and verified to be full before being placed on the AV sled	Inspection/Analysis
2	U-bolts shall be used for all shock cord connections	U-bolts provide two points where shock can go through the bulkhead to increase stability	U-bolts are installed on the bulkheads as anchor points for the recovery harness	Inspection
3	All electronic components in the launch vehicle shall be removable.	Removable electronics allow for easier changes and adjustments to design	None of the electronic components in the launch vehicle are permanently fixed in place	Inspection/Test
4	There shall be no more than 4 sections of the vehicle recovered	NASA gives a requirement that there can be no more than 4 of the vehicle	The vehicle will be designed to have only 4 sections	Inspection/Test
5	The secondary ejection charges shall be based off a configured time set on the redundant altimeter	This will guarantee proper parachute deployments, if the primary altimeter fails	Both altimeters are completely independent of each other	Analysis/Test

Table 6-4. Payload Team Derived Verification Matrix

Payload Team Derived Requirements				
Number	**Description**	**Justification**	**Success Criteria**	**Verification Method**
1	The payload vehicle SHALL have a diameter of less than 4.5 inches.	The Inner diameter of the launch vehicle is already limited to 6 inches. The extra space is needed for the rover housing	The Payload fits inside of its housing.	Inspection
2	The payload shall resist getting stuck during its motion	The rover will be subjected to rough terrain at Bragg Farm. It is important that the rover can work in many different conditions	The payload maintains traveling over rough terrain	Test
3	The payload shall be supported within the launch vehicle	The rover is subjected to the different forces during the launch. To limit the movement during the launch it must be supported from all sides.	The payload integration system supports the payload so that it is not dislodged before deployment	Inspection
4	The payload integration system shall be a maximum of 7 inches long	Limiting the length of the integration system also limits the payload length. This all lends to a more favorable static stability margin	The payload integration system is less than 7 inches	Test

6.2 Budgeting and Timeline

6.2.1 Amended Project Budget

Table 6-5 shows the updated project budget which now includes accurate vehicle component selections, shipping and handling charges, and amendments to the logistical expenses for the team. The full line-item budget is attached as Appendix A for review.

Table 6-5. Project Budget Summary

Project Component	Expected Cost
Sub-scale airframe and propellant	$660.00
Full-scale airframe and propellant	$1390.00
Avionics system	$1,250.00
Recovery system	$900.00
General materials	$450
Transportation and logistics	$2,350
Full Project Cost:	**$7,000**

6.2.2 Funding and Material Acquisition

6.2.2.1 <u>Funding Sources</u>

Funding for this year's project team is being graciously provided through two sources: the Aero-Propulsion, Mechatronics, and Energy (AME) center has diverted $2,000 of their NASA MUREP Grant funding to Zenith Program to facilitate Florida A&M student involvement with a complex aerospace project, and to facilitate FAMU student relations with NASA at large, in hopes of creating a firm feeder pipeline of underrepresented minority students to NASA. The FAMU-FSU COE Mechanical Engineering Department has generously offered to cover the difference in project costs in tranches with disbursement contingent on progression through the Student Launch competition. Once the initial AME Center funding is depleted, Mechanical Engineering will continue funding for parts and material, transportation to the test launch facility, and transportation and lodging for Launch Week.

6.2.2.2 Funding Allocation

Based on the revised project budget, the expected funding allocation is presented in Figure 6-1.

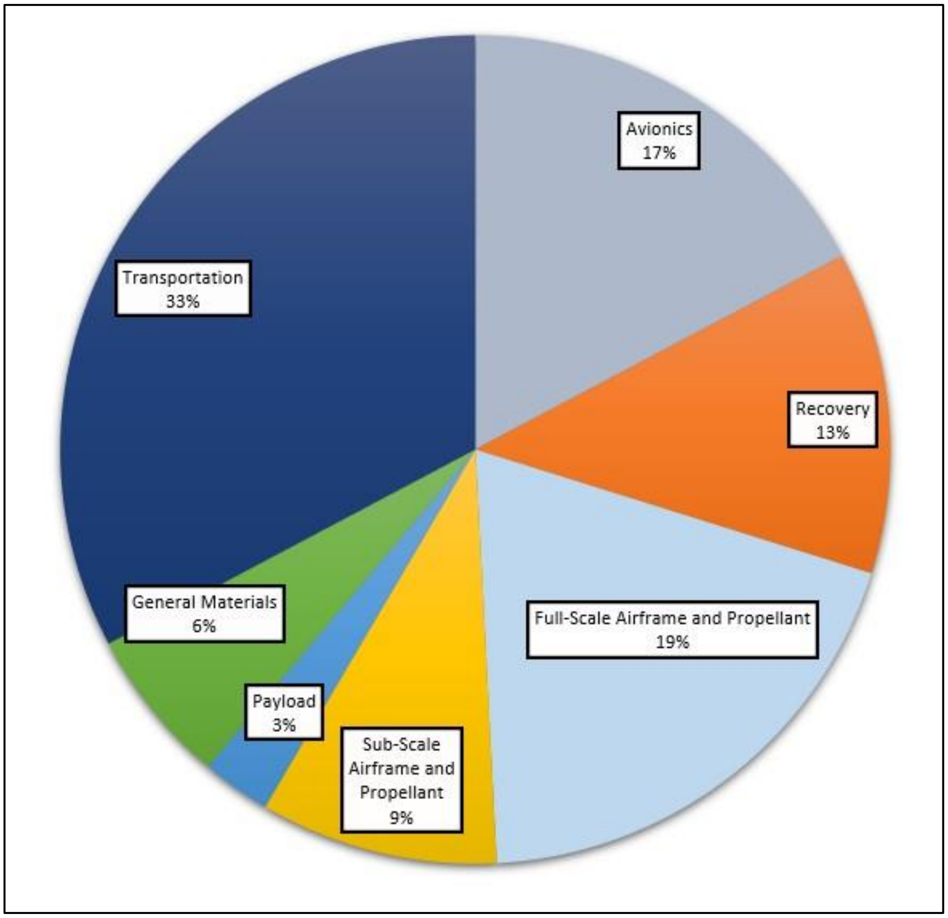


Figure 6-1. Funding Allocation by % of Total Budget

Figure 6-1 demonstrates most of the project cost is related to the full-scale vehicle build and transportation, of which all is related to the accommodation and other logistics for the trip to Launch Week. The recovery and avionics systems will be common to both the sub-scale and full-scale vehicles and require much investment to create a fully redundant system of acceptable quality. The disparity in cost, then, is due to the exponential scaling of price of Blue Tube 2.0 airframe material, propellant, and motor hardware.

Using the updated budget, a determination of project cost vs. time (or milestones) was made, shown in Figure 6-2. These expenditures to achieve each milestone will be used to coordinate with the project sponsors for funding disbursement and to monitor the whether the project is on-budget when reaching each milestone.

Item	Item Cost		Flight Expenditure
Sub-scale airframe + TF1 propellant	$664.68		
Avionics + Recovery	$1,797.89		
General Materials	$436.74		Test Flight 1
Logistics TF1	$103.60	→	$3,002.91
Full-scale airframe + TF2 propellant	$1,278.26		
Logistics TF2	$103.60		Test Flight 2
add:	$1,381.86	→	$4,384.77
Payload and TF3 propellant	$418.08		
Logistics TF3	$103.60		Test Flight 3
add:	$521.68	→	$4,906.45
Competition propellant	$224.95		
Comp. Logistics	$2,038.40		Comp. Flight
add:	$2,263.35	→	$7,169.80

Figure 6-2. Expenditures per Flight Milestone

6.2.2.3 Material Acquisition Plan

Materials for the vehicle(s) and payload will be procured differently according to their classification, with the distinctions described in Table 6-6.

Table 6-6. Material Classification

Class	Hardware Type	Component(s)	Notes
1	Specialized (Boutique)	Avionics unit, recovery systems, telemetry transmission, airframe	Limited stock across few distributors. Small windows to place order before components are sold out.
2	Specialized	Imaging, actuators, electric motors, 3D-print material, chute bags	Special order required. In-stock from various distributors.
3	General Purpose	Shock cord, links, bolts, glues, tools, etc.	Readily available. Can be purchased locally.
4	Hazardous	Solid Propellant Motor	Special order. Mentor cert # needed. Special storage considerations.

Class 1 materials are difficult to procure due to the limited number of distributors and low stock at said distributors. The Zenith team has determined the most feasible method for purchasing these components is to quote the price for a bulk order and request the funding in the form of a check to be deposited in the FAMU-FSU AIAA bank account. The organization debit card will be used to purchase the components as they become available from distributors which the avionics and recovery teams are actively monitoring.

Class 2 material orders are a less time-sensitive matter as these items are mass produced and available from many distributors. These materials will be procured by submitting a line-item material request from a single distributor to either the AME Center or Mechanical Department, who will complete the purchase order and provide the materials to the Zenith team upon delivery.

Class 3 materials are the simplest in terms of procurement and will be treated as a single bulk purchase. This is to say that the expected cost of Class 3 material will be estimated across the entire project and provided in a single payment to the FAMU-FSU AIAA account, which will function as the operating account for the Zenith team. Class 3 materials will be purchased on an as-needed basis with the organization account, and any substantial funds remaining after project completion will be returned to the AME Center and Mechanical Department or donated to FAMU-FSU AIAA with the permission of the donors.

Class 4 material will be purchased similarly to Class 2 materials, through AME Center or Mechanical Department purchase order, with the constraints that the project NAR/TRA mentor will also approve the purchase by providing their flyer number(s), and these materials will not be purchased more than 1-2 weeks prior to their expected use. The time constraint may be lifted if low stock causes concern that the propellant would not be available for launches should it not be purchased and stored well ahead of time. The time constraint on Class 4 material purchasing is intended to reduce the time that COE Facilities is required to store hazardous material (APCP Propellant – flammable, explosive, oxidizer).

6.2.3 Project Timeline

The Gantt chart created during the proposal process has been adhered to without major modification thus far and is expected to hold true for the remainder of the project. Minor modifications, such as adding longer durations to tasks, have been implemented to hold milestone deadlines firm. The project Gantt chart has been attached as Appendix B.

From the Gantt chart, major project milestones and their corresponding completion dates and expected durations are summarized in Table 6-7, which lists activities through the subscale test flight, submission of CDR, and completion of project phase 2.

The team intends to dedicate time during the full-scale build in phase 3 to inspect adherence to the Gantt chart and budget through phases 1 and 2, and make any modifications to phases 3, 4, and 5 deemed necessary when new university class schedules are in hand and early semester workloads are determined.

Table 6-7. Project Timeline Summary through CDR

Goal Owner	Milestone or Deliverable	Expected (*Required) Completion Date	Estimated Activity Duration
Zenith	Proposal acceptance	10/4/2022	N/A
Zenith	Establish social media	10/6/2022	2 days
Zenith	Finalize preliminary design	10/19/2022	22 days
Zenith	Complete updated budget sheet	10/26/2022	7 days
NASA SLI	Submit PDR report and slides	*10/26/2022	14 days
Zenith	Establish points of contact with proposed institutions for STEM Engagement	10/31/2022	Est. POC: 14 days Plan Evt: +30 days
Zenith	Prepare PO sheets for material acquisition	11/2/2022	7 days
NASA SLI	PDR Presentation	*11/9/2022	Activity: 1 day Window: 26 days
Zenith	Begin avionics and recovery system assembly and testing	11/16/2022	23 days
Zenith	Begin subscale airframe assembly and testing	11/16/2022	23 days
Zenith	Subscale test flight	12/10/2022	1 day
NASA SLI	Submit CDR Report and slides	*1/09/2023	30 days

7 Late PDR Submission – Failure Analysis

The Zenith Program PDR was submitted past the deadline of 10/26/2022, 8am CDT. The team was able to complete the deliverable within the 72-hour period in which submissions are accepted, submitting on 10/27/2022. Considering that flight milestones over the course of the project do not include such a submission grace period, a failure analysis must be conducted to determine what went wrong leading to this missed milestone and how to mitigate this possibility in future.

7.1 Causes

Table 7-1. PDR Missed Milestone Cause/Effect Chart

Item #	Item	Effect on PDR Submission
1	Program director did not budget the team enough time to complete PDR to the required standard	PDR was started far later than it should have been. Once the scope of the report was realized, corrective action was taken, and the senior design team began working through the nights to meet the deadline. Exhaustion led to brain-drain, and a less polished product than would otherwise be expected.
2	Core senior design team members failed to integrate the underclassmen Zenith Program members in writing the PDR report	The senior design team of 4 members were responsible for the creation of the PDR without the assistance of the larger team available.
3	Senior design team members failed to train underclassmen in programs such as OpenRocket and SolidWorks, and did not verify their abilities in MATLAB	The senior design team was responsible for all CAD designs, MATLAB programs, and OpenRocket designs/simulations, which needed to be completed for discussion during PDR
4	Too much emphasis was placed on trying to perfect the vehicle design, and not enough on comparing alternatives as a part of the PDR	The senior design team, already task loaded, spent far too much time generating design concepts, making their CAD models, and simulating them. Far more alternatives than were required by PDR were generated and dismissed.

7.2 Future Mitigation Strategies

Table 7-2. Missed Milestone Mitigations to be Implemented for CDR

Item #	Mitigation Strategy	Action Items
1	Apply knowledge gained. Use records of time spent on proposal and PDR, both design work and report writing, to determine how many hours per person future reports will require.	1. Discuss with each senior design team member. Create task list completed by each with approximate durations. 2. Create chronological task list with expected durations for future years of the project to utilize 3. Take total time spent on proposal and PDR per person. Factor PDR time per person into the Gannt chart for CDR and FRR. Add several days padding for conservatism.
2	Engage the underclassmen members in the design process, design reviews, and writing of technical reports	1. Provide copies of Proposal and PDR to each underclassmen 2. Familiarize underclassmen with requirements for the project 3. Familiarize underclassmen with the requirements for the proposal and PDR they have been given 4. Ensure underclassmen are clear on the quality of work required 5. Assign small chunks of future reports to groups of 3-4 underclassmen. Monitor progress. Mentor the writing process.
3	Ensure underclassmen are being provided basic or advanced training in CAD programs, coding, and specialty programs such as openrocket	1. Develop training curriculum for solidworks 2. Develop curriculum for MATLAB 3. Develop curriculum for openrocket 4. Develop in-meeting tasks or quizzes to verify quality of training 5. Find and provide online tools or videos to assist in the learning or refinement of skills 6.

Item #	Mitigation Strategy	Action Items
4	Requirements of the document must be firmly adhered to. Example: develop 2-3 concepts, select leading design, create CAD models and flight simulations, create PDR report. Then use extra time to continue 114valuating and improving leading design	1. Review the requirements for PDR 2. Create a workflow chart that must be adhered to 3. Set firm date early to begin writing report 4. Expect to finish report before deadline and use spare time to evaluate and improve vehicle design based on sub-scale flight result

Appendix A. Line-Item Budget

	Total Projected Cost:	$6,976.67		
Part Name		**Quantity**	**Cost**	**Quantity Cost**
Avionics System				
TeleMega		2	$484.00	$968.00
TeleBT Ground Module		1	$150.00	$150.00
Arrow Antenna 3E Yagi		1	$74.99	$74.99
900 mAh LiPo Battery		2	$12.12	$24.24
SMA-BNC Connector		2	$9.99	$19.98
			Subtotal:	**$1,237.21**
Recovery System				
24" Fruity Chutes: Drogue Chute		1	$75.33	$75.33
72" Fruity Chutes: Iris Ultra Main Chute		1	$265.71	$265.71
Jolly Logic Chute Release 5X-series		2	$139.95	$279.90
Tinder Rocketry Eagle CO2 Ejection System		1	$270.00	$270.00
CO2 Canister - 21g - 2pk		1	$10.78	$10.78
			Subtotal:	**$901.72**
Full-Scale Vehicle				
ID = 6.0", L = 48" Airframe - Blue Tube 2.0		2	$77.42	$154.84
6" to 75mm Centering Ring - Baltic Birch		3	$9.50	$28.50
6" Airframe Bulkhead		6	$8.95	$53.70
OD = 6", L = 12" Avionics Bay w/ Hardware		1	$72.00	$72.00
2-56 Nylon Shear Pins - 20 ct.		1	$3.00	$3.00
1515 Rail Button (large)		2	$4.00	$8.00
AeroPack 75mm retainer (flanged)		1	$75.83	$75.83
Cesaroni P75-2G Motor Casing		1	$201.95	$201.95
Cesaroni L-3200		3	$224.95	$674.85
MJG Igniter		3	$1.50	$4.50
3-d Print Section		**1kg spool - ABS**	--	--
Fins		3	--	--
Nosecone		1	--	--
Camera housing		1	--	--
	Sum of Spools:	5	$21.99	$109.95
			Subtotal:	**$1,387.12**

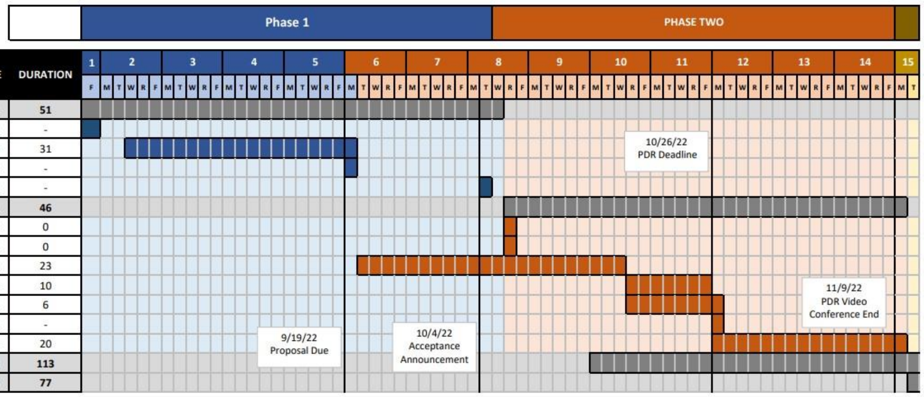
Sub-Scale Vehicle			
ID = 3.0", L = 48" Airframe - Blue Tube 2.0	1	$31.00	$31.00
3" to 38mm Centering Ring - Baltic Birch	3	$3.49	$10.47
3" Airframe Bulkhead w/ eyebolt	4	$3.69	$14.76
OD = 3", L = 8" Avionics Bay w/ Hardware	1	$40.00	$40.00
38mm aft closure	1	$54.79	$54.79
RMS-38/1080 Casing w/ foreword closure	1	$119.08	$119.08
Aerotech J575FJ-14, 38mm propellant kit w/ igniter	1	$115.21	$115.21
15" Fruity Chutes: Drogue Chute	1	$63.41	$63.41
48" Fruity Chutes: Class Elliptical Main Chute	1	$149.99	$149.99
3-d Print Section	**1kg spool - ABS**	--	--
Fins	2	--	--
Nosecone	1	--	--
Camera housing	1	--	--
Sum of Spools:	3	$21.99	$65.97
		Subtotal:	**$664.68**
Payload			
12V DC brushed motor	2	$9.10	$18.20
Arducam Mini	1	$39.99	$39.99
Arduino Meda	1	$48.40	$48.40
900 mAh LiPo Battery	1	$12.12	$12.12
Jumper Wire F-2-M (20 ct.)	1	$2.10	$2.10
Jumper Wire M-2-M (28 ct.)	1	$1.95	$1.95
Jumper Wire F-2-F (40 ct.)	1	$4.40	$4.40
3-d Print Section	**1kg spool - ABS**	--	--
Frame + wheels	1	--	--
Housing	1	--	--
Retaining ring	1	--	--
Sum of Spools:	3	$21.99	$65.97
		Subtotal:	**$193.13**
General/Uncategorized Components			
3/8" Stainless Steel Quick Link	4	$13.47	$53.88
1/4in x 1in Stainless Steel U-Bolt w/ Plate (5 pack)	4	$16.48	$65.92
#1500 Kevlar Shock Cord ($/ft)	30	$1.30	$39.00
LipoCharger V2	1	$19.99	$19.99
2-56 Drill and Tap Set (for shear pins)	1	$7.95	$7.95
Shipping and handling - all budget bulk estimate	1	$250.00	$250.00
		Subtotal:	**$436.74**
Transportation and Logistics			
Gas reimbursement - SRA test launches (Orlando)	3	$103.60	$310.80
Gas reimbursement - NASA MSFC (Huntsville)	1	$118.40	$118.40
Student IHG Hotel Rooms (4 days, $90/day)	2	$360.00	$720.00
Food Stipend (4 comp. days, $35/day/student)	6	$140.00	$840.00
Mentor IHG Hotel Room (4 days, $90/day)	1	$360.00	$360.00
		Subtotal:	**$2,349.20**

Appendix B. 2022/2023 Zenith Program Gantt Chart

Part 1 – Proposal to PDR

The Zenith Program - NASA Student Launch

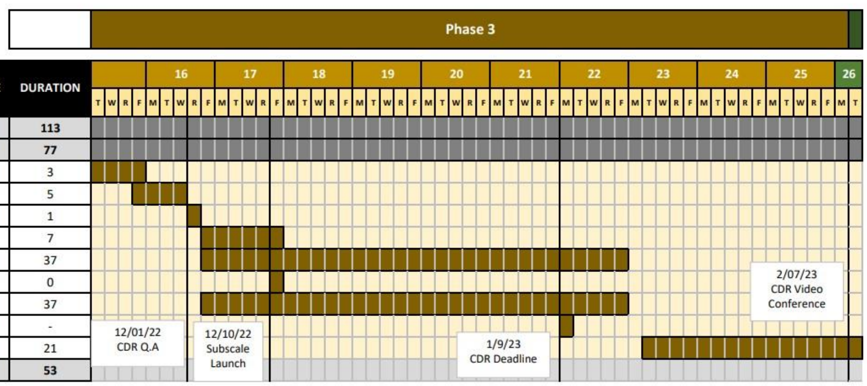
WBS NUMBER	TASK TITLE	START DATE	END DATE	DURATION
1	**Proposal**	08/14/22	10/04/22	**51**
1.1	RFP Released	08/19/22	08/19/22	-
1.1.1	Proposal Work	08/19/22	09/19/22	31
1.2	Completed Proposal Submission	09/19/22	09/19/22	-
1.3	Awarded Proposals Announced	10/04/22	10/04/22	-
2	**PDR**	10/06/22	11/21/22	**46**
2.1	PDR Q&A	10/06/22	10/06/22	0
2.2	Establish Social Media Accounts	10/07/22	10/07/22	0
2.3	Finalize Preliminary Design	09/19/22	10/12/22	23
2.4	Write PDR Report	10/09/22	10/19/22	10
2.5	Create PDR Presentation	10/19/22	10/25/22	6
2.5.1	PDR Deadline	10/26/22	10/26/22	-
2.6	PDR Video Conference	11/01/22	11/21/22	20
3	**STEM Engagement**	10/17/22	02/07/23	**113**
4	**CDR**	11/22/22	02/07/23	**77**



Part 2 – PDR to CDR

The Zenith Program - NASA Student Launch

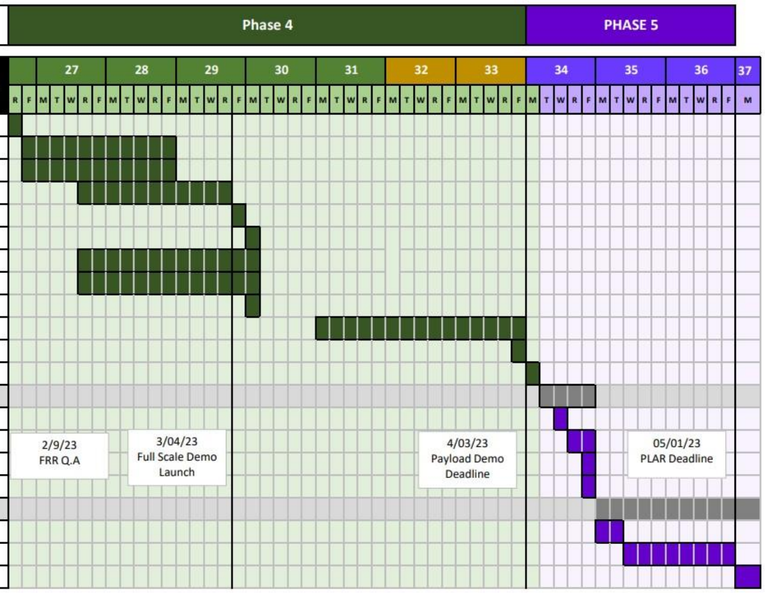
WBS NUMBER	TASK TITLE	START DATE	END DATE	DURATION
3.00	**STEM Engagement**	10/17/22	02/07/23	**113**
4	**CDR**	11/22/22	02/07/23	**77**
4.1	Assess PDR Feedback	11/22/22	11/25/22	3
4.1.1	Implement Design Improvements	11/25/22	11/30/22	5
4.2	CDR Q&A	12/01/22	12/01/22	1
4.3	Manufacture Subscale Model	12/02/22	12/09/22	7
4.4	Write CDR Report	12/02/22	01/08/23	37
4.5	Subscale Model Launch Test	12/10/22	12/10/22	0
4.6	Create CDR Presentation Slides	12/02/22	01/08/23	37
4.6.1	CDR Deadline	01/09/23	01/09/23	-
4.7	CDR Video Conference	01/17/23	02/07/23	21
5	**FRR and Flight Demonstration**	02/09/23	04/03/23	**53**



Part 3 – CDR to FRR, Competition, and PLAR

The Zenith Program - NASA Student Launch

WBS NUMBER	TASK TITLE	START DATE	END DATE	DURATION
5.1	FRR Q&A	02/09/23	02/09/23	0
5.2	Manufacture Full-Scale Vehicle	02/10/23	02/25/23	15
5.2.1	Manufacture Payload	02/10/23	02/25/23	15
5.2.2	Pre-flight Testing	02/16/23	03/02/23	14
5.3	Vehicle Demonstration Flight	03/04/23	03/04/23	1
5.3.1	Vehicle Demonstration Flight Deadline	03/06/23	03/06/23	0
5.4	Write FRR Report	02/16/23	03/02/23	14
5.5	Create FRR Presentation Slides	02/16/23	03/02/23	14
5.5.1	FRR Report Deadline	03/06/23	03/06/23	0
5.6	FRR Video Conference	03/13/23	03/31/23	18
5.7	Payload Demonstration Flight	04/01/23	04/01/23	1
5.7.1	Payload Demonstration Flight Deadline	04/03/23	04/03/23	-
6a	**Competition**	04/12/23	04/16/23	**4**
6.1	Travel to Marshall SFC	04/12/23	04/12/23	1
6.2	Launch Readiness Review	04/13/23	04/14/23	1
6.3	Launch Day	04/15/23	04/15/23	1
6.3.1	Backup Launch Day	04/16/23	04/16/23	1
6b	**PLAR**	04/17/23	05/01/23	**14**
6.4	Analyze competition flight data	04/17/23	04/19/23	2
6.5	Write PLAR Report	04/19/23	04/30/23	11
6.5.1	PLAR Report Deadline	05/01/23	05/01/23	-



Appendix C. MATLAB Programs

Velocity of Rocket (Motor --> Cesaroni L3200)

```
% Defining initial parameter

Impulse_total_SI = 3300; % Total Impulse in Newton-seconds
Burn_time = 1; % Seconds
g_SI = 9.81; % m/s^2
W_grams = 15559; % grams
W_avg = W_grams*0.001*g_SI; % kg
Vi = 0; % m/s
theta = 5; % degrees


% The following equations will calculate the flight vehicle's Apogee
 with a
% launch angle of 5 degrees and windspees of 0 mph

Thrust = Impulse_total_SI/Burn_time; % Newtons
Vm = ((Thrust/W_avg)-1)*9.81*Burn_time; % m/s
Vm = Vm*cosd(theta);
Burnout_ALT= (1/2)*(Vm + Vi)*Burn_time; % feet
Coasting_Alt = (Vm^2 - 0)/(2*9.81); % feet
Total_Altitude_meters = Coasting_Alt + Burnout_ALT; % feet
Total_Altitude_Feet = Total_Altitude_meters*3.281; % feet


% The follwing code is written simply to output the answers on the
 script
% publication

fprintf('The flight vehicle has a maxium velocity of %.3f ft/s. \n\n',
 Vm*3.281)
fprintf('The altitude at motor burnout is %.3f feet. \n\n',
 Burnout_ALT*3.281)
fprintf('The coasting altitude is %.3f feet. \n\n',
 Coasting_Alt*3.281)
fprintf('The flight vehicle''s peak altitude is %.3f feet. \n\n',
 Total_Altitude_Feet)
```

The flight vehicle has a maxium velocity of 661.174 ft/s.

The altitude at motor burnout is 330.587 feet.

The coasting altitude is 6790.893 feet.

The flight vehicle's peak altitude is 7121.480 feet.

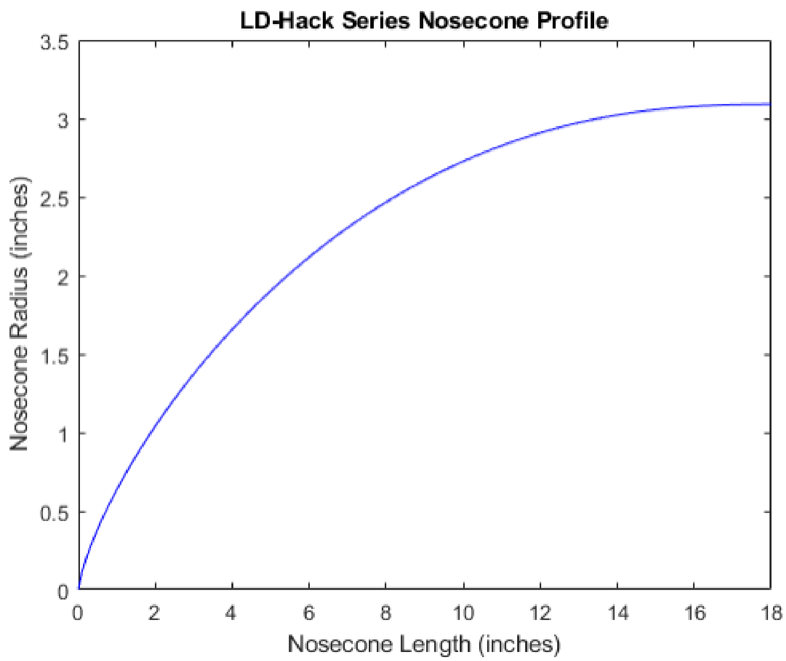
Flutter Speed (Material --> ABS Fialment)

```
% Defining Initial parameters

E = 416258.3; % Young's Modulus  (psi)
v = 0.37; % Poisson's Ratio (unitless)
Cr = 11; % Root Chord in inches
Ct = 3; % Tip Chord in inches
t = 0.47; % Thickness in inches
b = 7.5;  % Fin Height relative to the root chord in inches


% The following equations will calculate the fin flutter speed for the
% leading design's fin configuration using ABS filament as the
 material of
% choice

G = E/(2*(1+v));
h = 4558; % Max height the rocket will reach in feet
S = (1/2)*(Cr + Ct)*b; % Wing Area (inches squared)
AR = (b.^2)/S; % Aspect Ratio (unitless)
lambda = Ct/Cr; % Taper Ratio (unitless)
T = 59 - 0.00356*h; % Temp (Fahrenheit)
P = (2116/144)*((T + 459.7)/518.6).^5.256; % Pressure (also converts
 to lb/in^2)
a = sqrt(1.4*1716.59*(T + 459.7)); %Speed of sound (ft/s)
Vf = a*sqrt((G/(1.337*(AR.^3)*P*(lambda+1)))*(2*(AR+2)*((t/
Cr).^3))); % Fin Flutter Speed


% The follwing code is written simply to output the answers on the
 script
% publication

fprintf('The flutter speed of the fin is %.4f ft/s. \n\n', Vf)
```

The flutter speed of the fin is 1836.9724 ft/s.

L-D Hack Series Equations

```
L = 18;
R = 3.09;
C = 2/3;

x = (0:0.1:18);
theta = acos(1 - ((2*x)/L));

y = (R*sqrt(theta - ((sin(2*theta))/2) + (C)*(sin(theta).^3)))/
sqrt(pi);

% (3.09*sqrt(arccos(1-(2*x)/19) - ((sin(2*(arccos(1-(2*x)/19))))/2) +
 (1/3)*(sin((arccos(1-(2*x)/19))^3))))/sqrt(pi)

figure(1)
plot(x, y, 'b')
hold on
xlabel('Nosecone Length (inches)')
ylabel('Nosecone Radius (inches)')
title('LD-Hack Series Nosecone Profile')

% xlswrite('L-VHackSeries.xlsx',transpose(x),'PTS','A1:A191');
% xlswrite('L-VHackSeries.xlsx',transpose(y),'PTS','B1:B191');
```



Appendix D. Flight Simulation Result Tables

Flight Simulation		
5 Degree Launch Angle with 0 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4575	Feet (ft)
Max. Velocity	683	Feet per second (ft/s)
Time to Apogee	16.1	Seconds
Flight Time	95.2	Seconds
Descent Time	79.1	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
5 Degree Launch Angle with 5 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4554	Feet (ft)
Max. Velocity	683	Feet per second (ft/s)
Time to Apogee	16.1	Seconds
Flight Time	95.6	Seconds
Descent Time	79.5	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
5 Degree Launch Angle with 10 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4518	Feet (ft)
Max. Velocity	681	Feet per second (ft/s)
Time to Apogee	16.1	Seconds
Flight Time	93.9	Seconds
Descent Time	77.8	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
5 Degree Launch Angle with 15 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4494	Feet (ft)
Max. Velocity	682	Feet per second (ft/s)
Time to Apogee	16	Seconds
Flight Time	93.57	Seconds
Descent Time	77.57	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
5 Degree Launch Angle with 20 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4457	Feet (ft)
Max. Velocity	679	Feet per second (ft/s)
Time to Apogee	15.9	Seconds
Flight Time	93.8	Seconds
Descent Time	77.9	Seconds
Ground Hit velocity	5.95	Feet per second (ft/s)

Flight Simulation		
7 Degree Launch Angle with 0 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4543	Feet (ft)
Max. Velocity	681	Feet per second (ft/s)
Time to Apogee	15.9	Seconds
Flight Time	93.8	Seconds
Descent Time	77.9	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
7 Degree Launch Angle with 5 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4534	Feet (ft)
Max. Velocity	208	Feet per second (ft/s)
Time to Apogee	15.9	Seconds
Flight Time	94.4	Seconds
Descent Time	78.5	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
7 Degree Launch Angle with 10 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4472	Feet (ft)
Max. Velocity	681	Feet per second (ft/s)
Time to Apogee	15.6	Seconds
Flight Time	92.9	Seconds
Descent Time	77.3	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
7 Degree Launch Angle with 15 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4433	Feet (ft)
Max. Velocity	680	Feet per second (ft/s)
Time to Apogee	15.4	Seconds
Flight Time	92	Seconds
Descent Time	76.6	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
7 Degree Launch Angle with 20 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4389	Feet (ft)
Max. Velocity	679	Feet per second (ft/s)
Time to Apogee	15.2	Seconds
Flight Time	93.1	Seconds
Descent Time	77.9	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

Flight Simulation		
10 Degree Launch Angle with 0 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4467	Feet (ft)
Max. Velocity	682	Feet per second (ft/s)
Time to Apogee	16	Seconds
Flight Time	94	Seconds
Descent Time	78	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

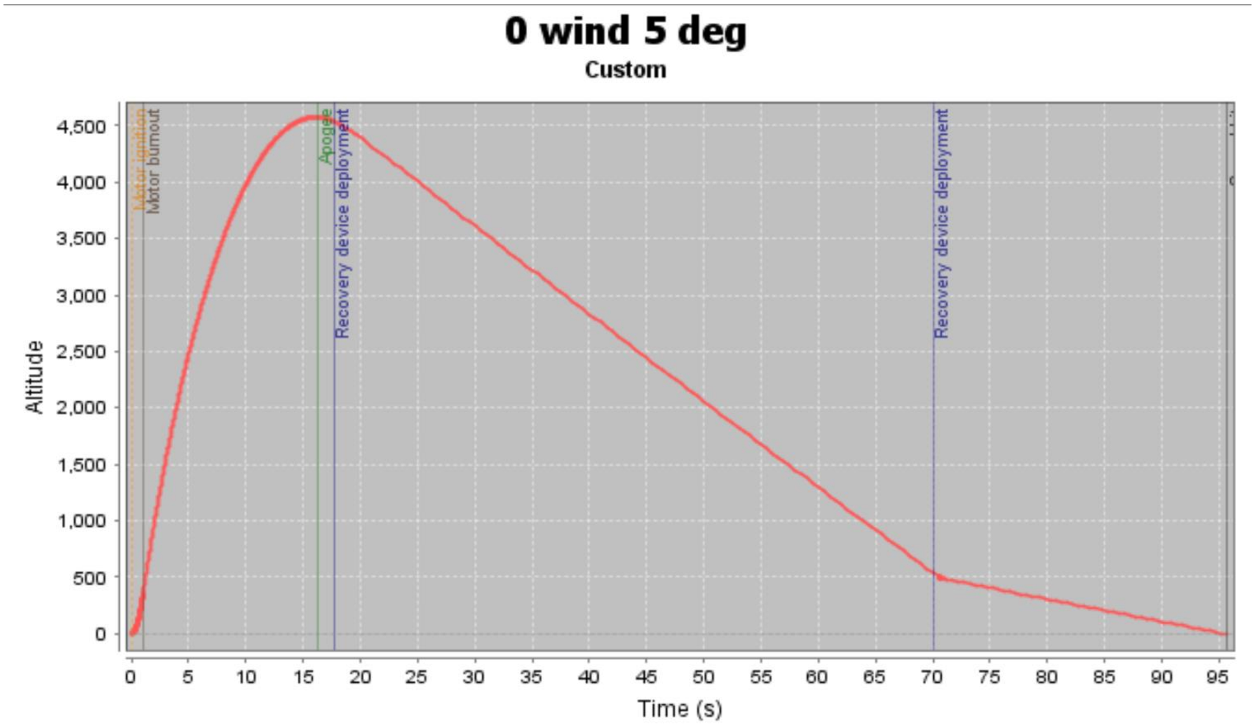
Flight Simulation		
10 Degree Launch Angle with 5 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4428	Feet (ft)
Max. Velocity	682	Feet per second (ft/s)
Time to Apogee	15.9	Seconds
Flight Time	93.3	Seconds
Descent Time	77.4	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

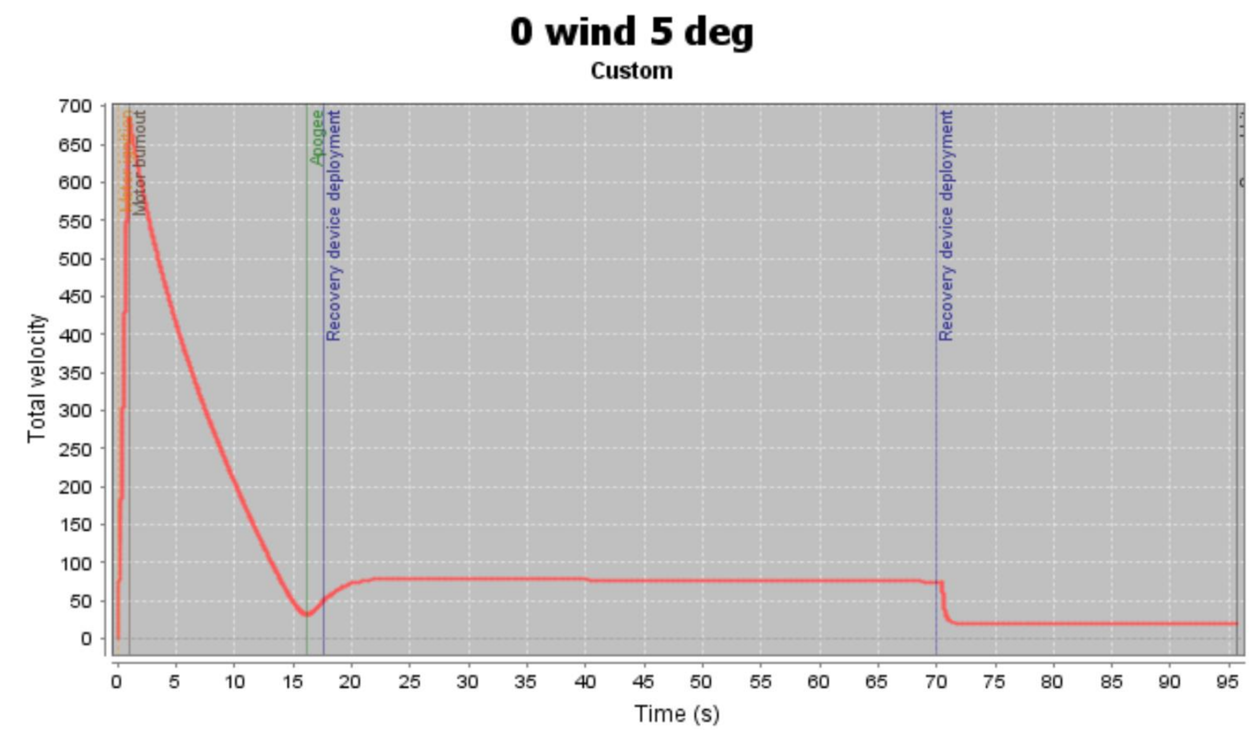
Flight Simulation		
10 Degree Launch Angle with 10 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4348	Feet (ft)
Max. Velocity	681	Feet per second (ft/s)
Time to Apogee	15.8	Seconds
Flight Time	91.9	Seconds
Descent Time	76.1	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

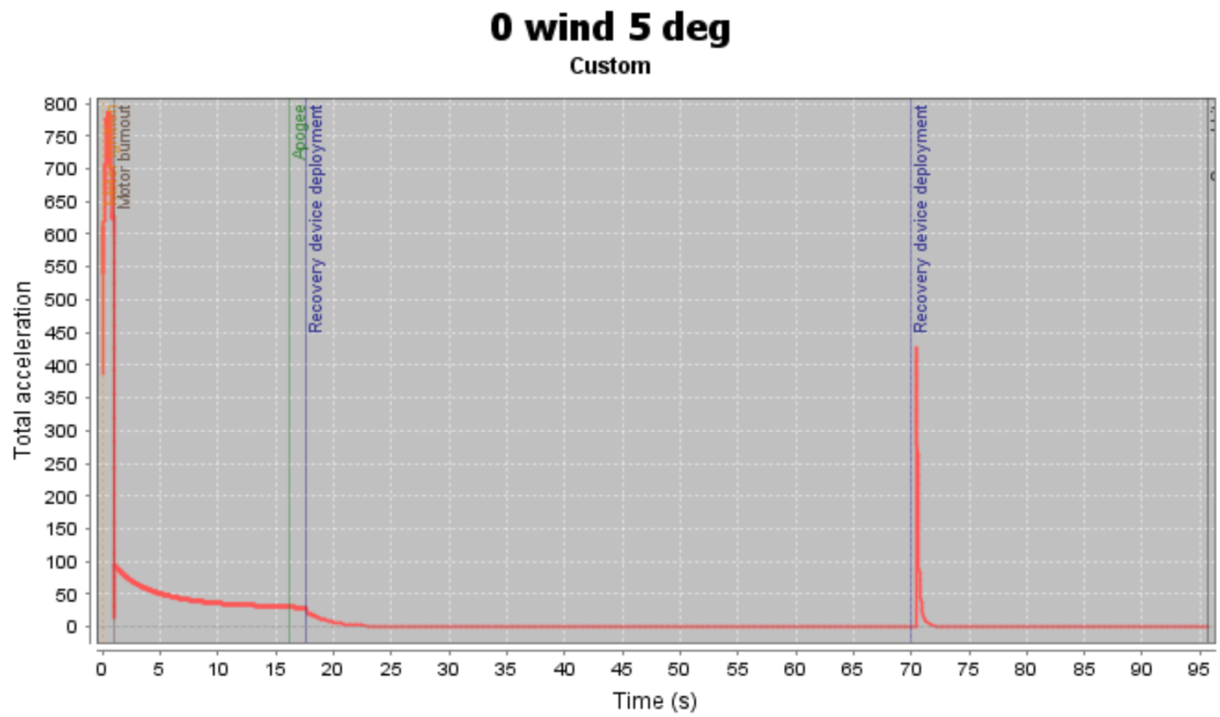
Flight Simulation		
10 Degree Launch Angle with 15 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4336	Feet (ft)
Max. Velocity	681	Feet per second (ft/s)
Time to Apogee	15.7	Seconds
Flight Time	91	Seconds
Descent Time	75.3	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

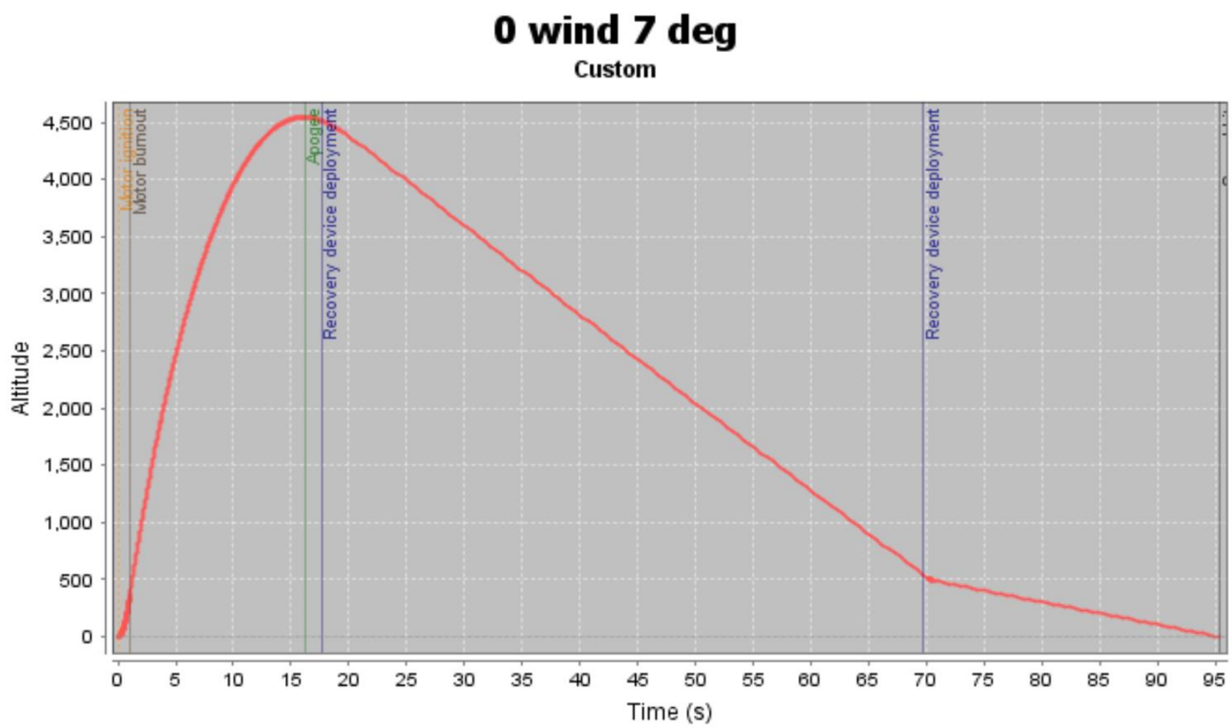
Flight Simulation		
10 Degree Launch Angle with 20 MPH Wind Speeds		
Parameter	**Value**	**Units**
Total Vehicle Weight	15,516	grams (g)
Stability Margin	2.26	
Velocity off Rod	124	Feet per second (ft/s)
Apogee	4285	Feet (ft)
Max. Velocity	680	Feet per second (ft/s)
Time to Apogee	15.6	Seconds
Flight Time	91.7	Seconds
Descent Time	76.1	Seconds
Ground Hit velocity	19.8	Feet per second (ft/s)

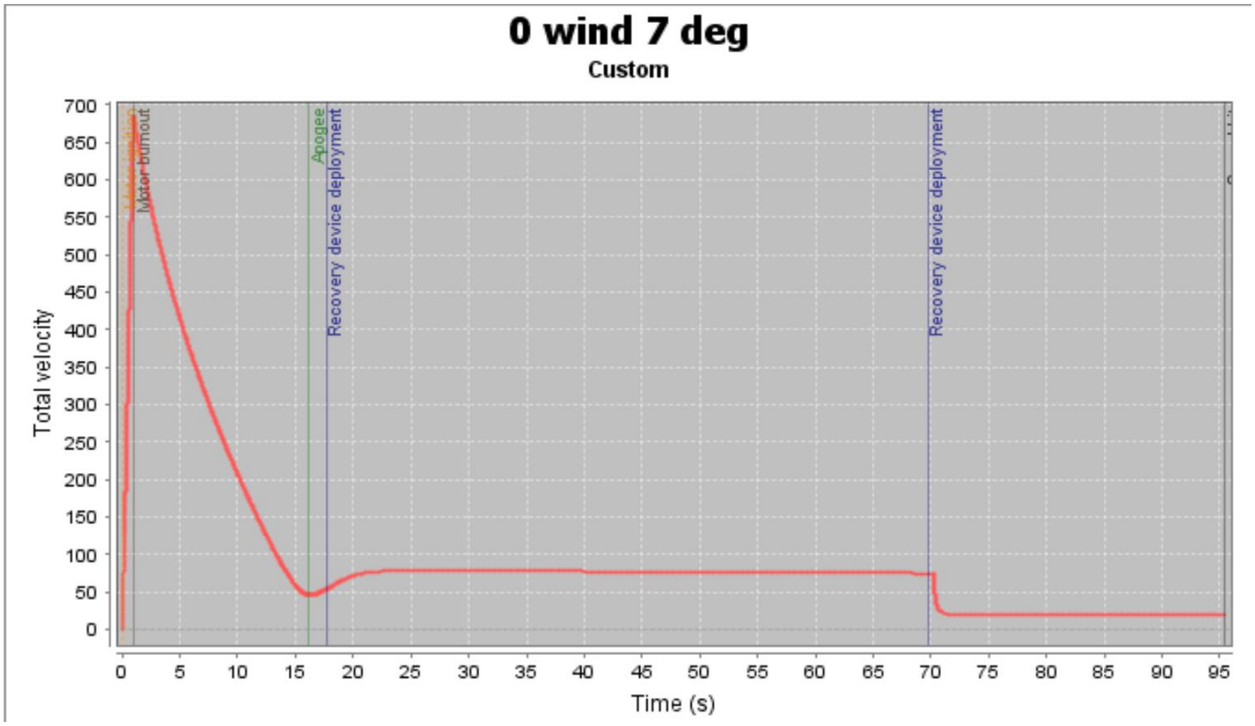
Appendix E. Flight Simulation Result Plots

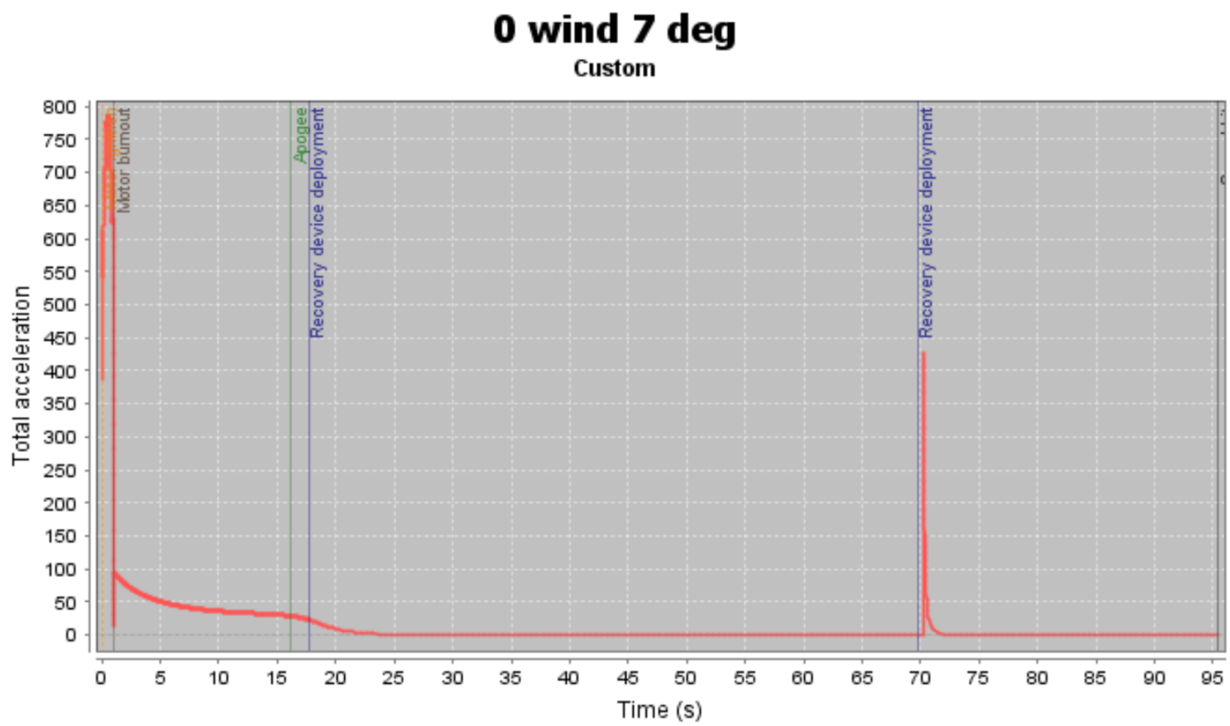





0 wind 5 deg
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment


0 wind 7 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment


0 wind 7 deg
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95


0 wind 7 deg
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
0
5
10
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20
25
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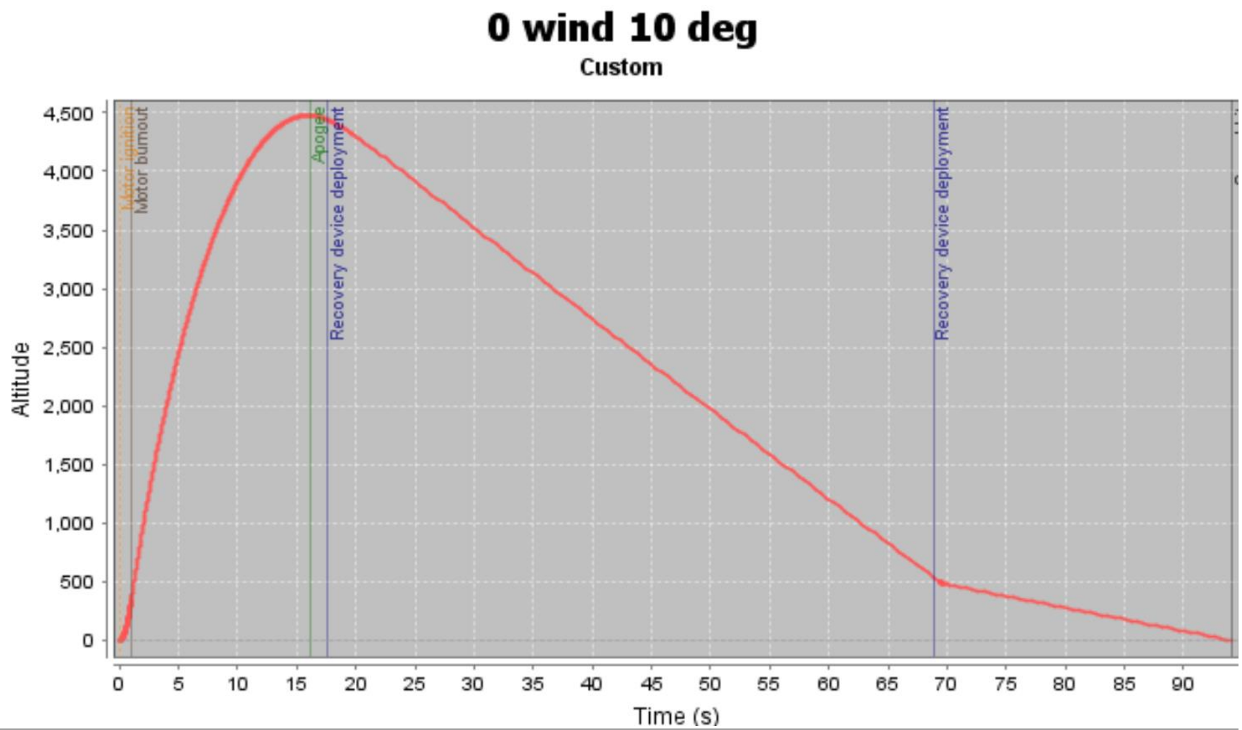
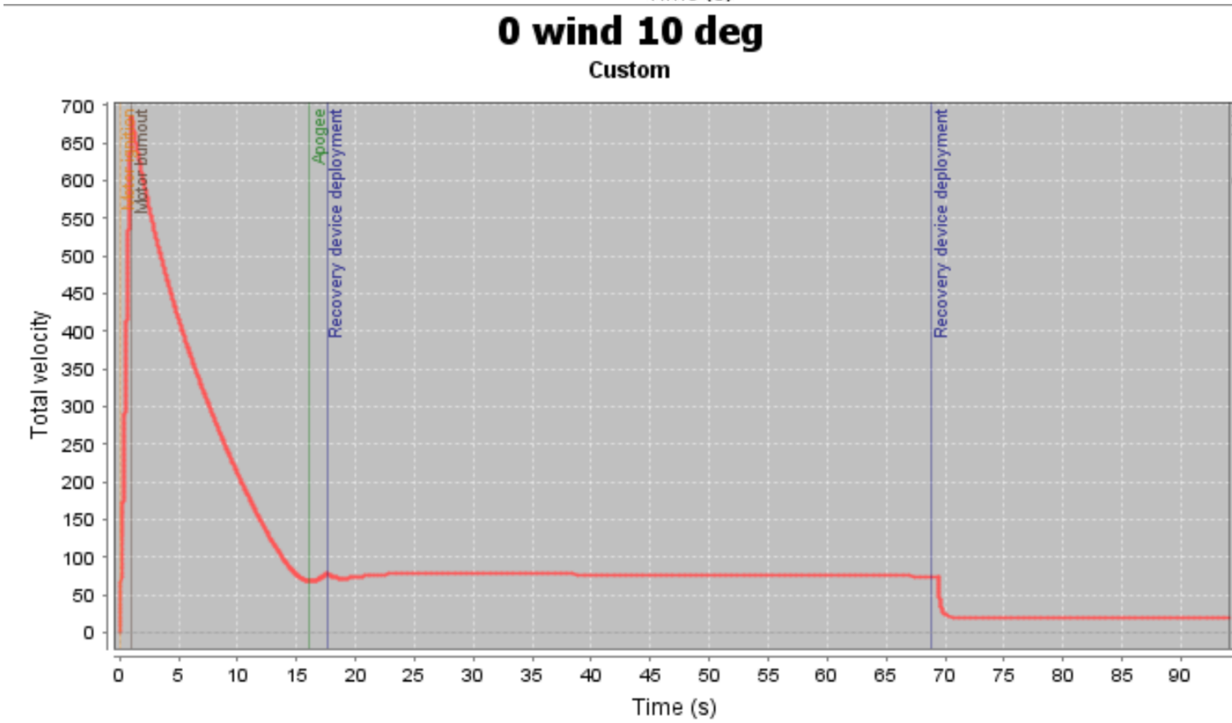
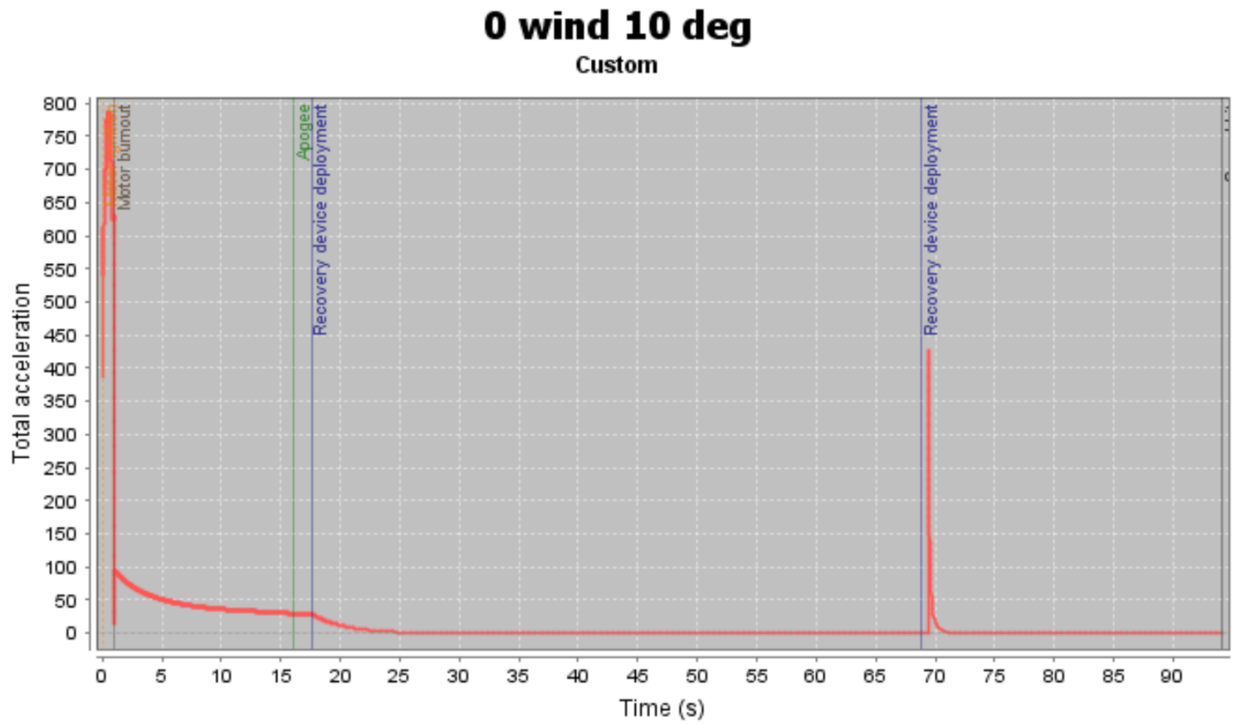
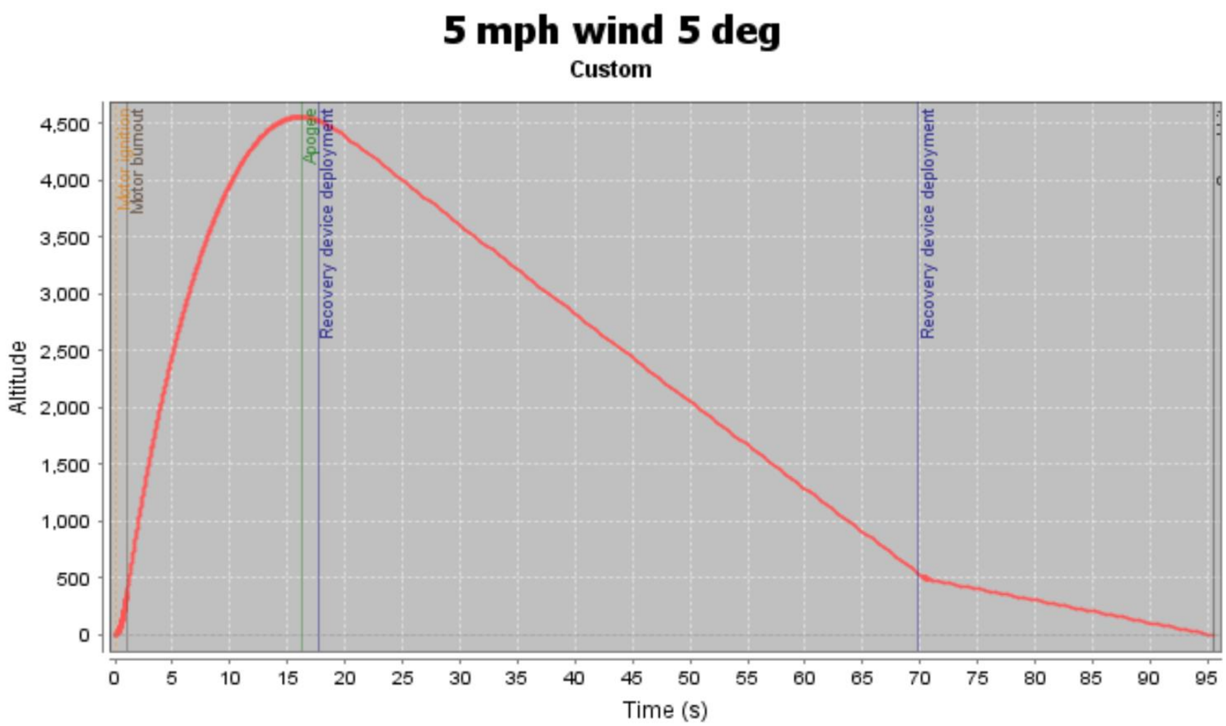
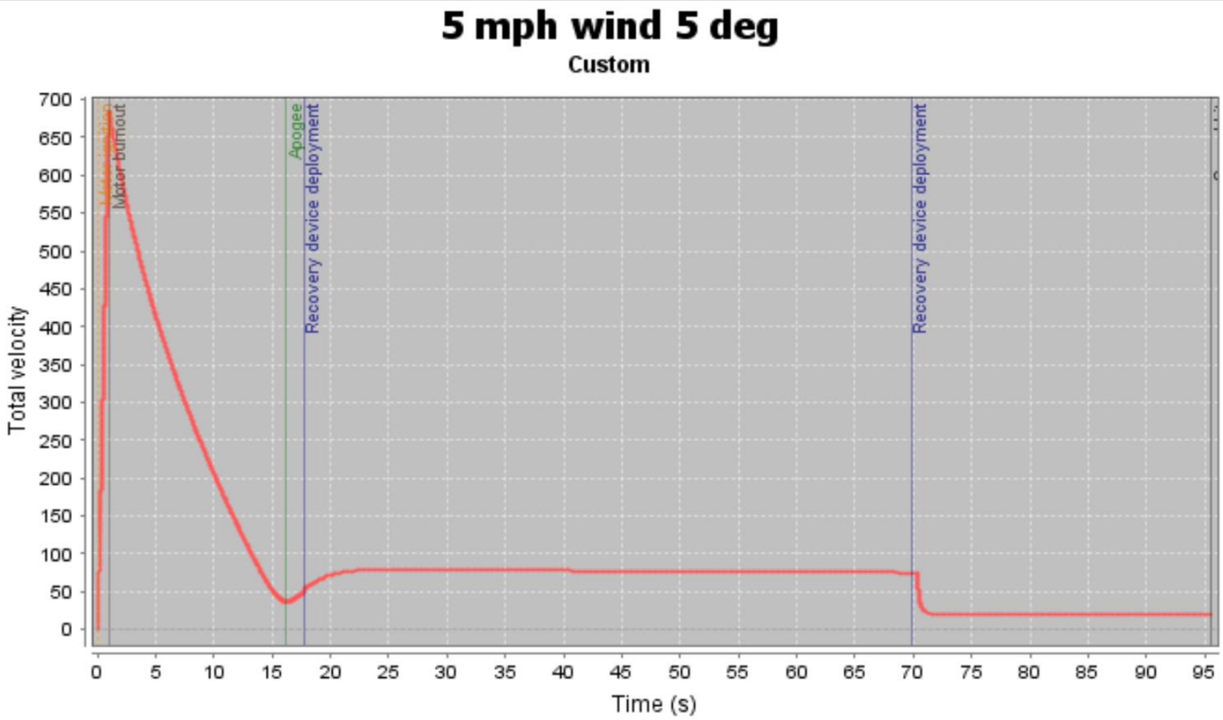
35
40
45
50
55
60
65
70
75
80
85
90
95

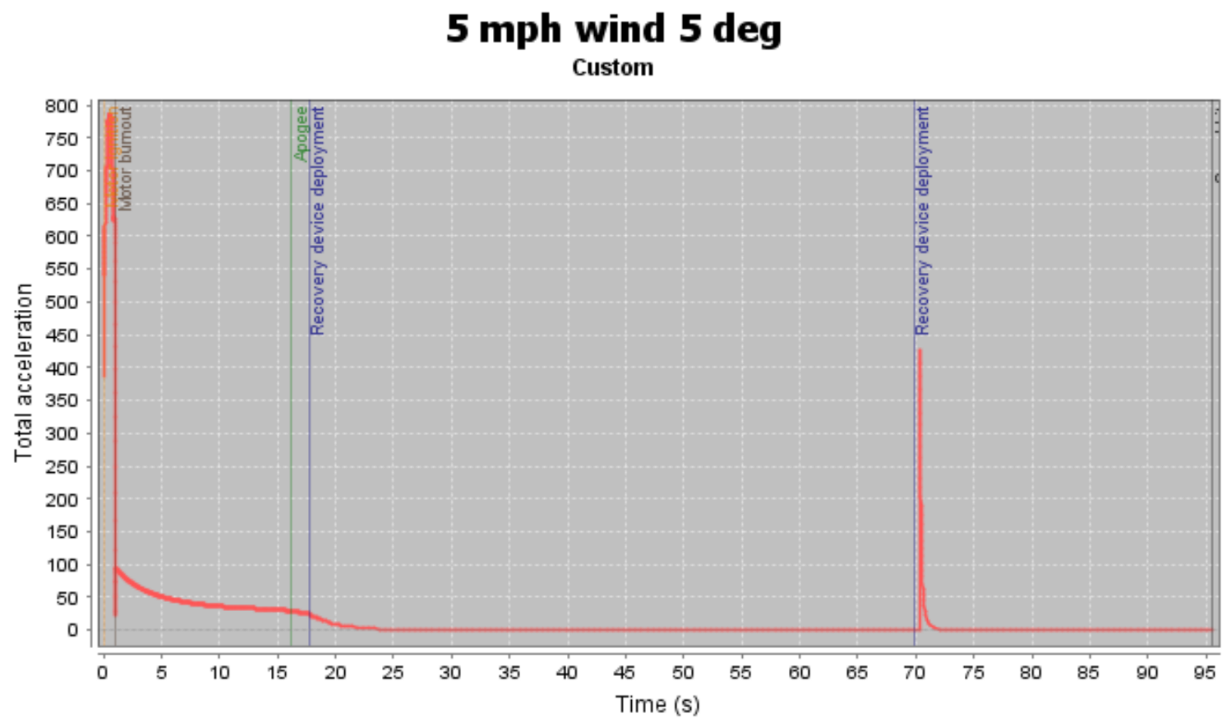

0 wind 10 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment


0 wind 10 deg
Custom
Total velocity
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment


0 wind 10 deg
Custom
Total acceleration
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
Time (s)


5 mph wind 5 deg
Custom
Altitude
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
Time (s)


5 mph wind 5 deg
Custom
Total velocity
Time (s)
Apogee
Motor burnout
Recovery device deployment
Recovery device deployment
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95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Custom
Total acceleration
Time (s)
Apogee
Motor burnout
Recovery device deployment
Recovery device deployment
0
50
100
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200
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300
350
400
450
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650
700
750
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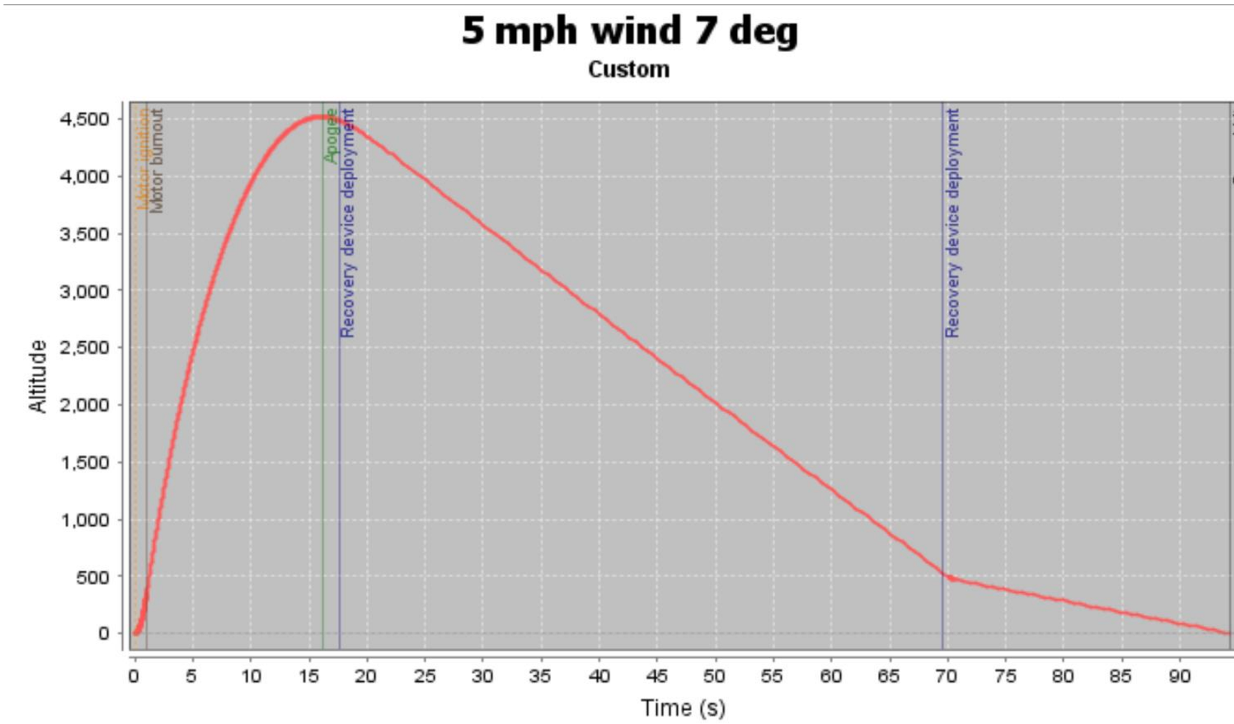
95


5 mph wind 7 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
4,500
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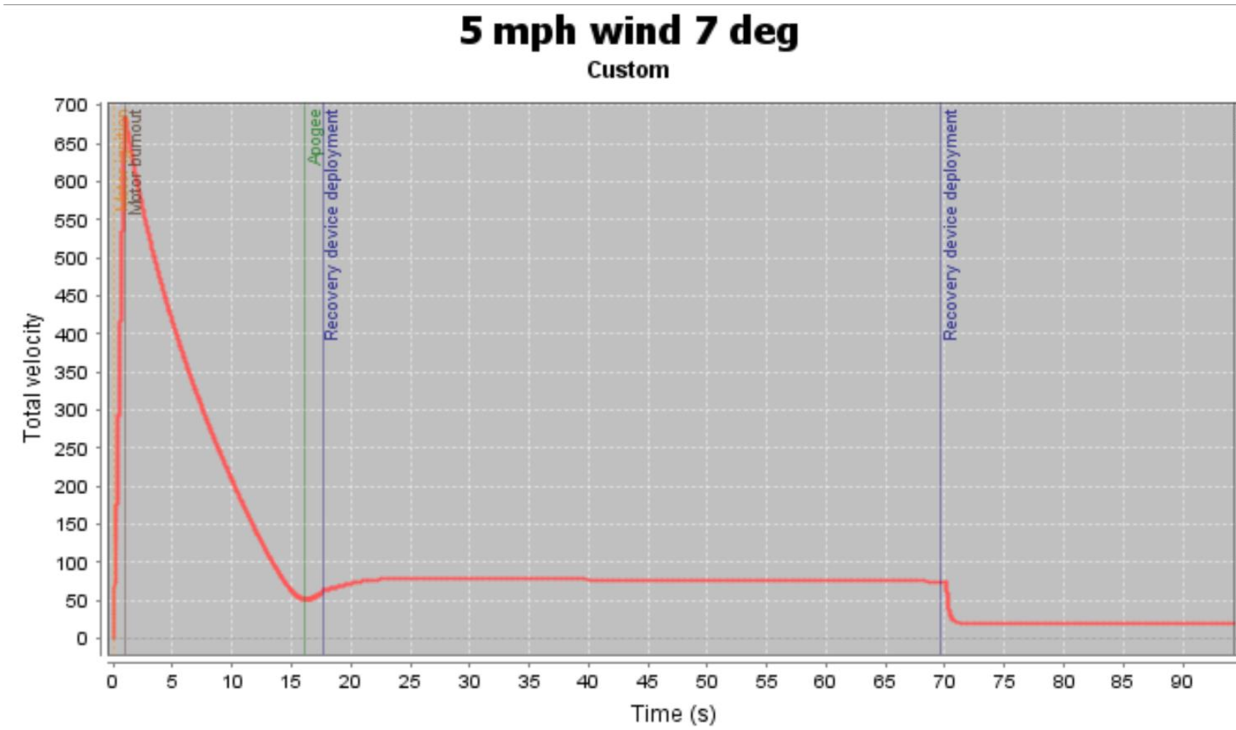
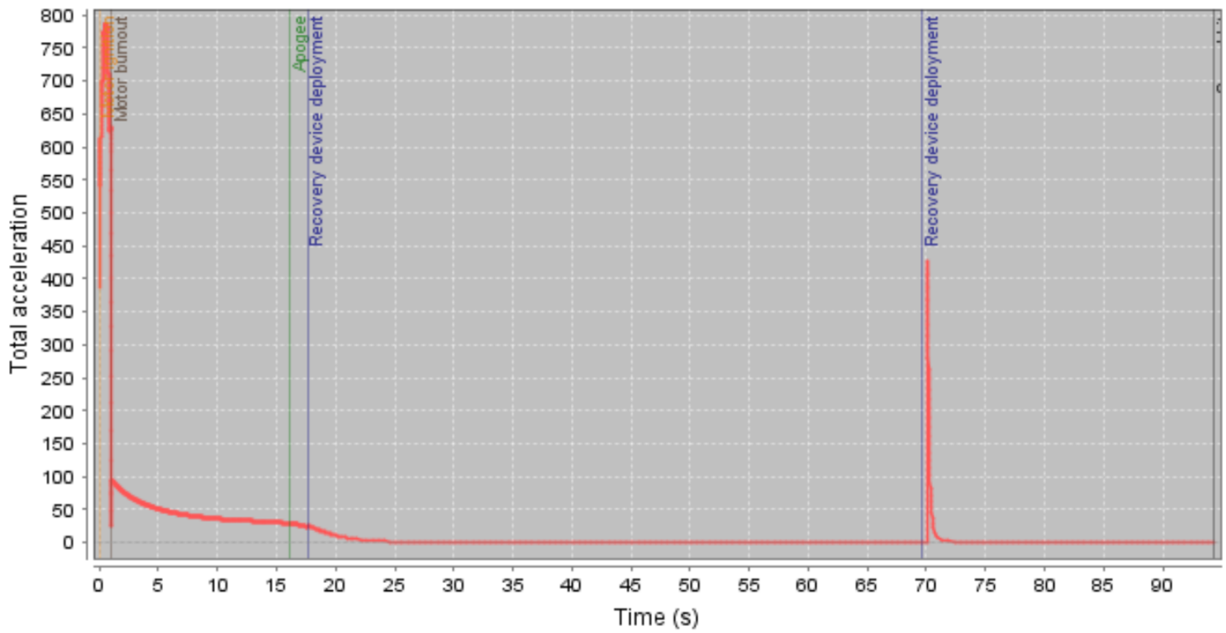
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90


5 mph wind 7 deg
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90

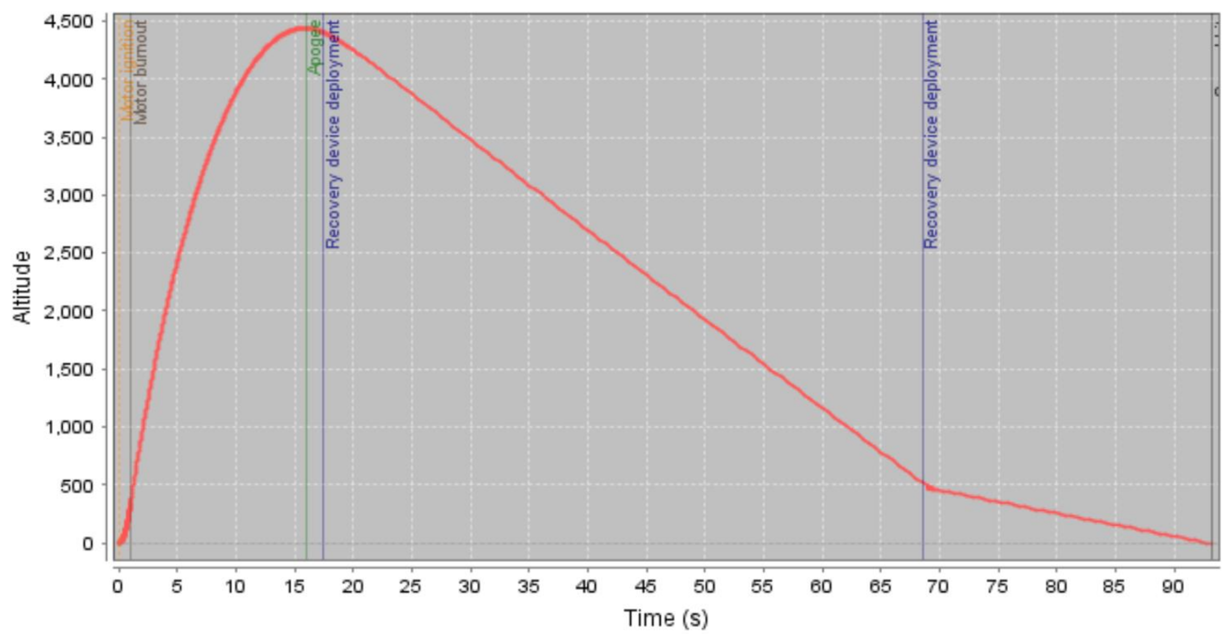
5 mph wind 7 deg

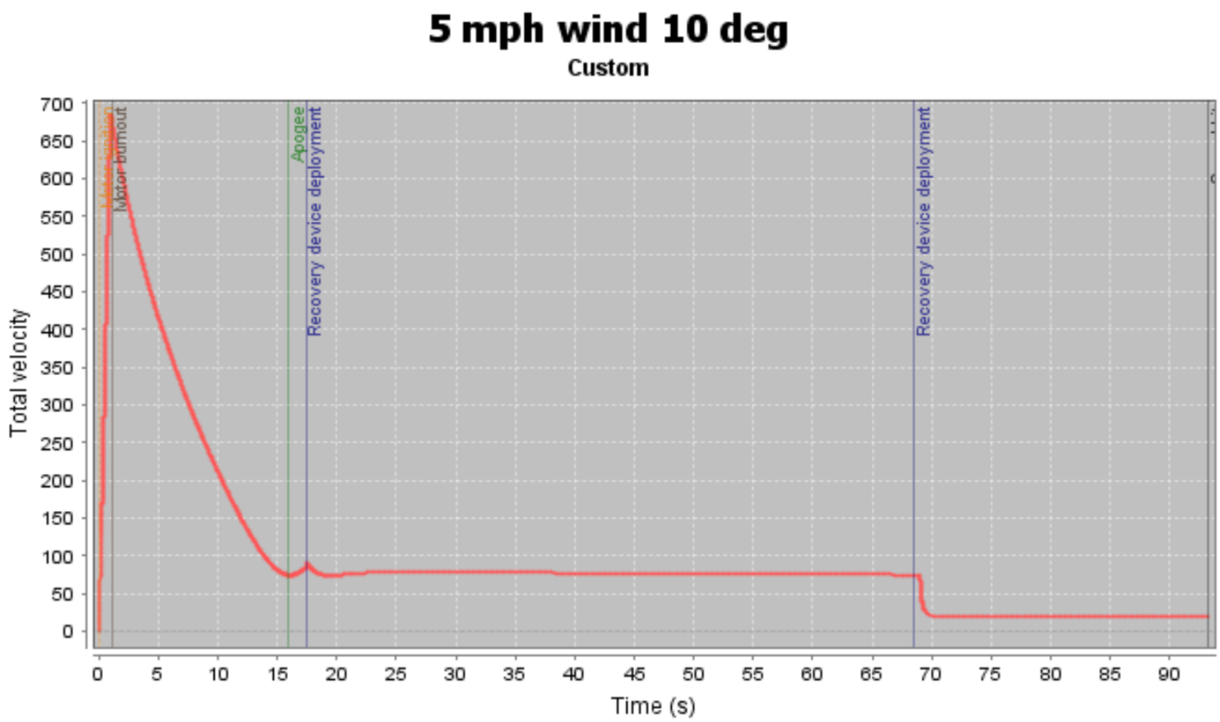
Custom



5 mph wind 10 deg

Custom

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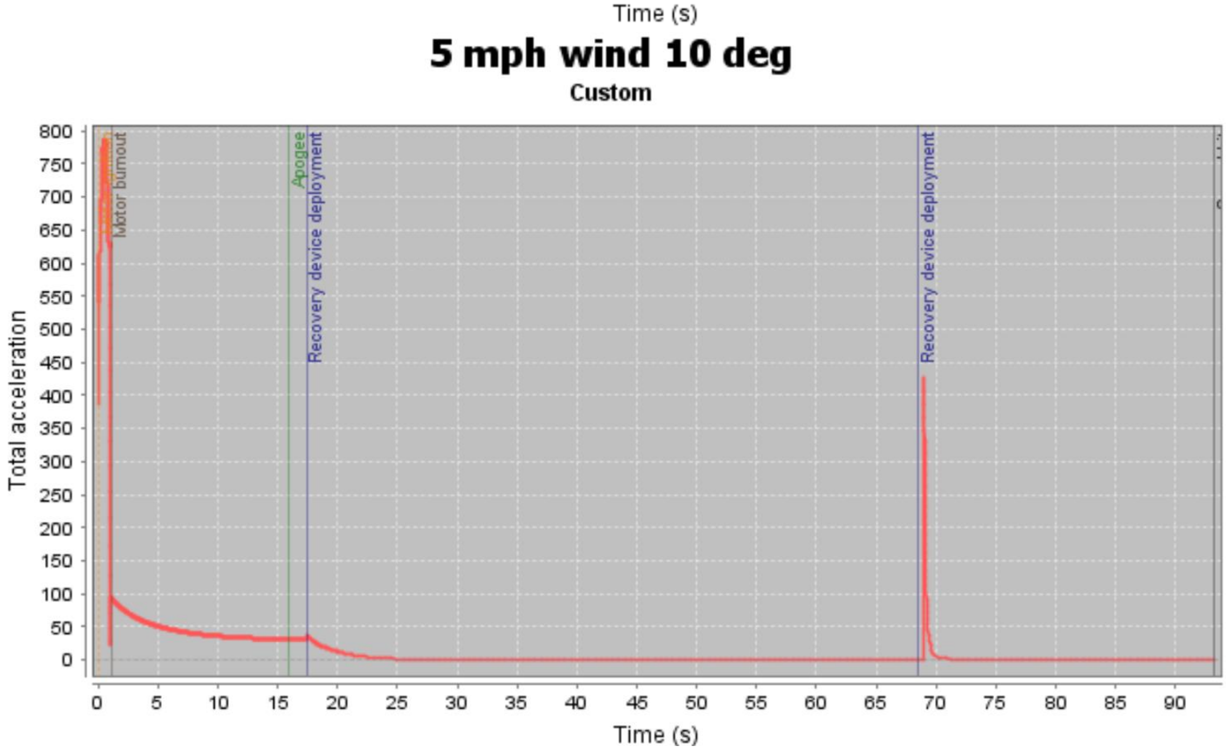
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment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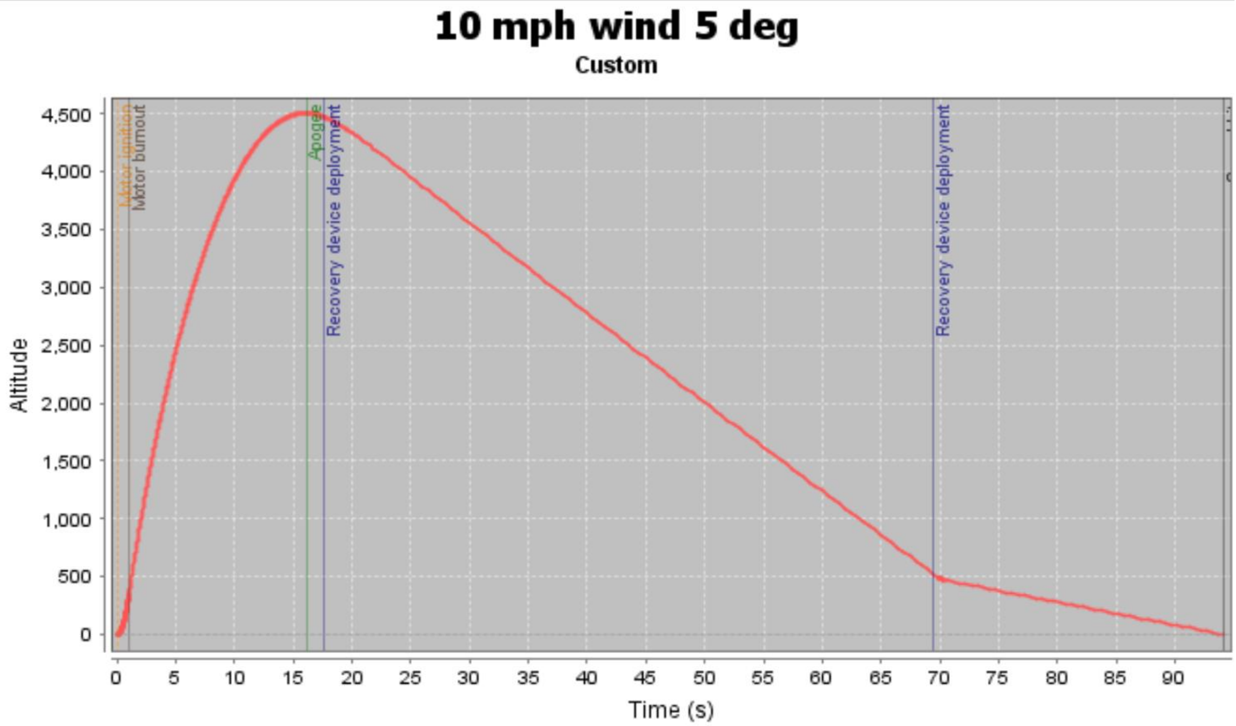
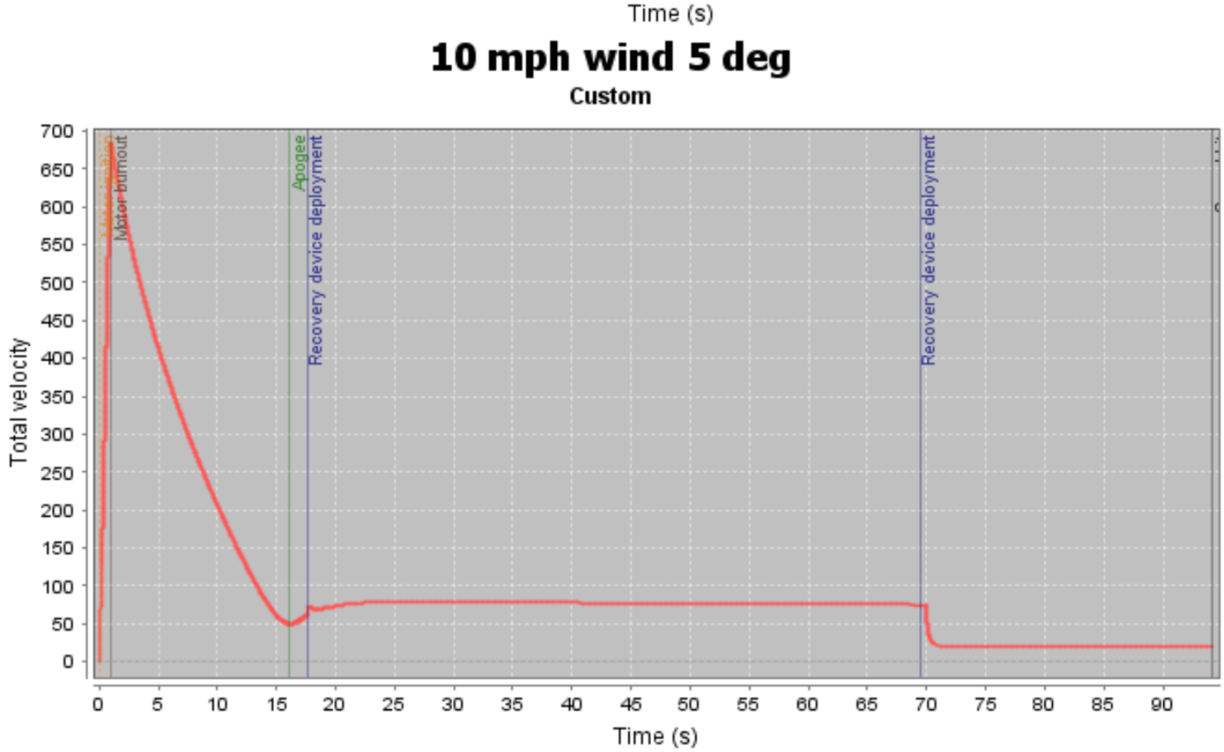
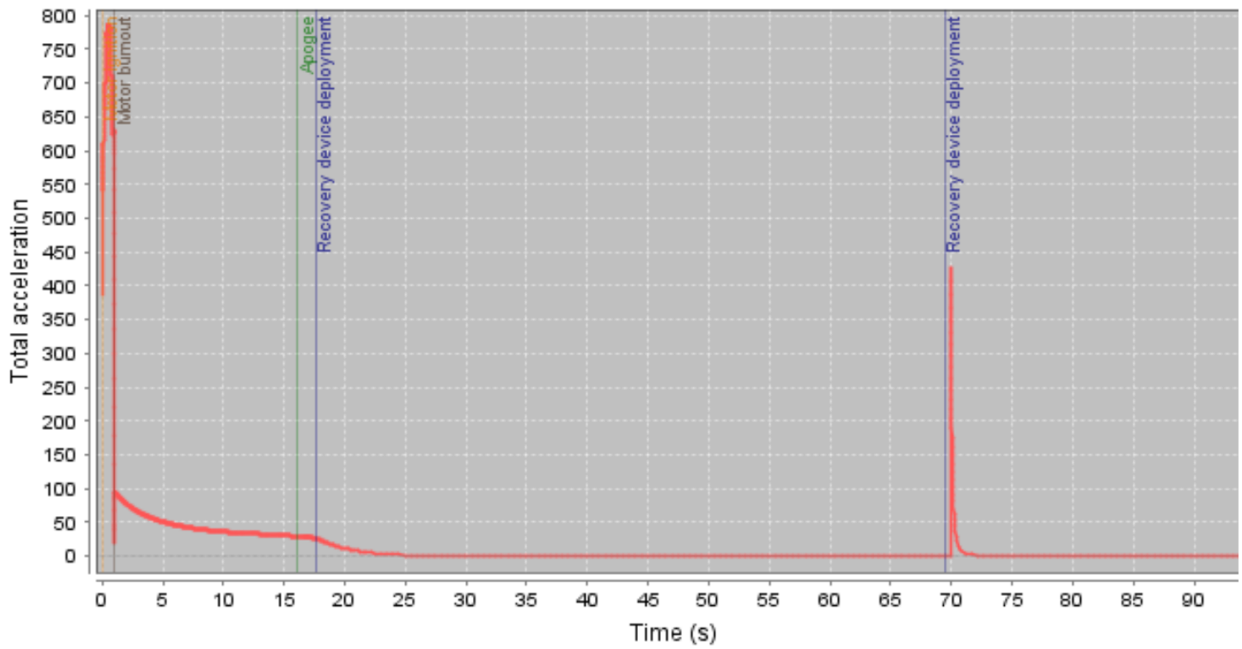
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment


10 mph wind 5 deg
Custom
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
Altitude
Time (s)
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90


10 mph wind 5 deg
Custom
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
Total velocity
Time (s)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90

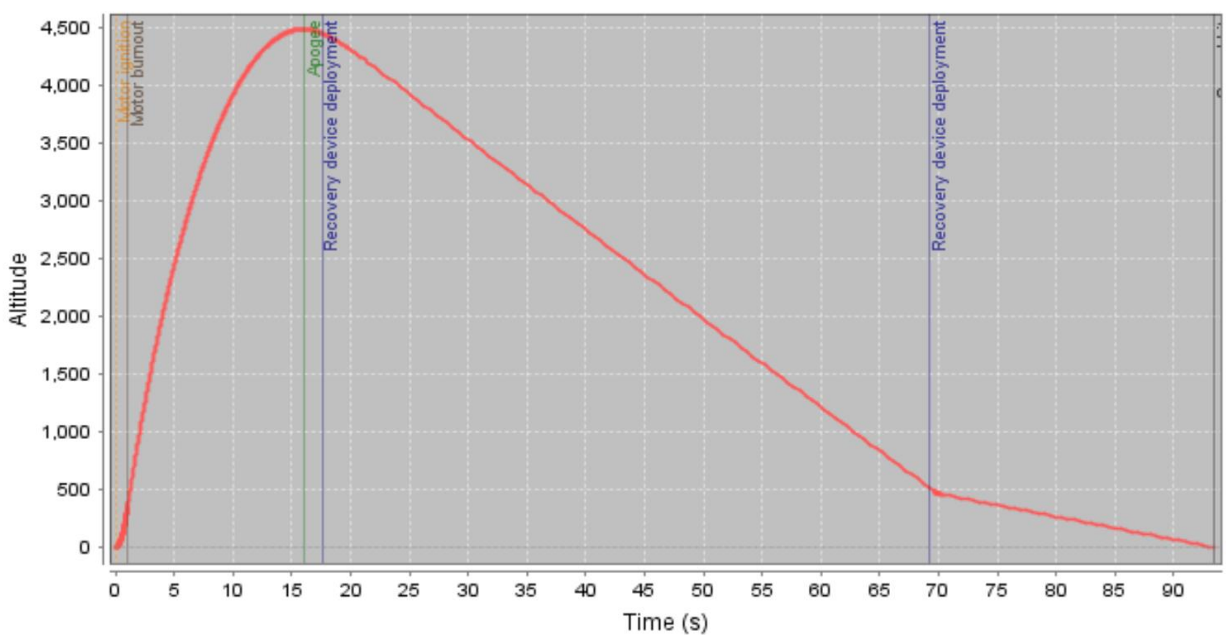
10 mph wind 5 deg

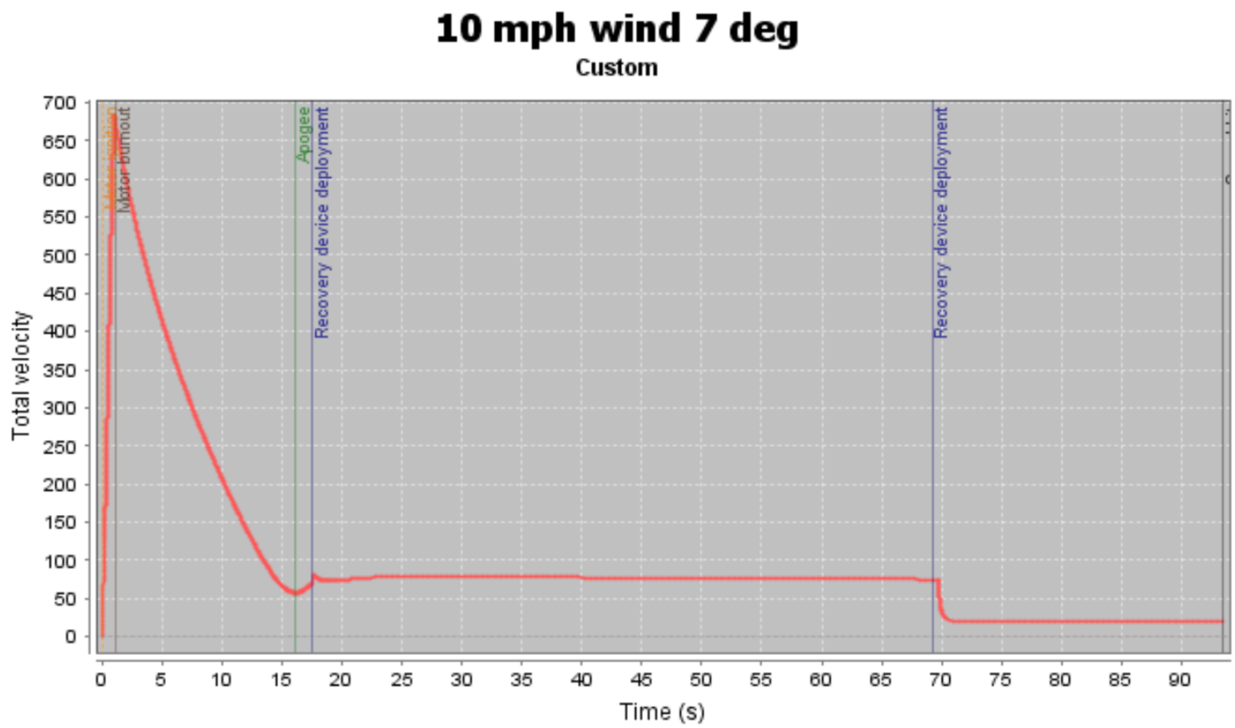
Custom



10 mph wind 7 deg

Custom




10 mph wind 7 deg
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
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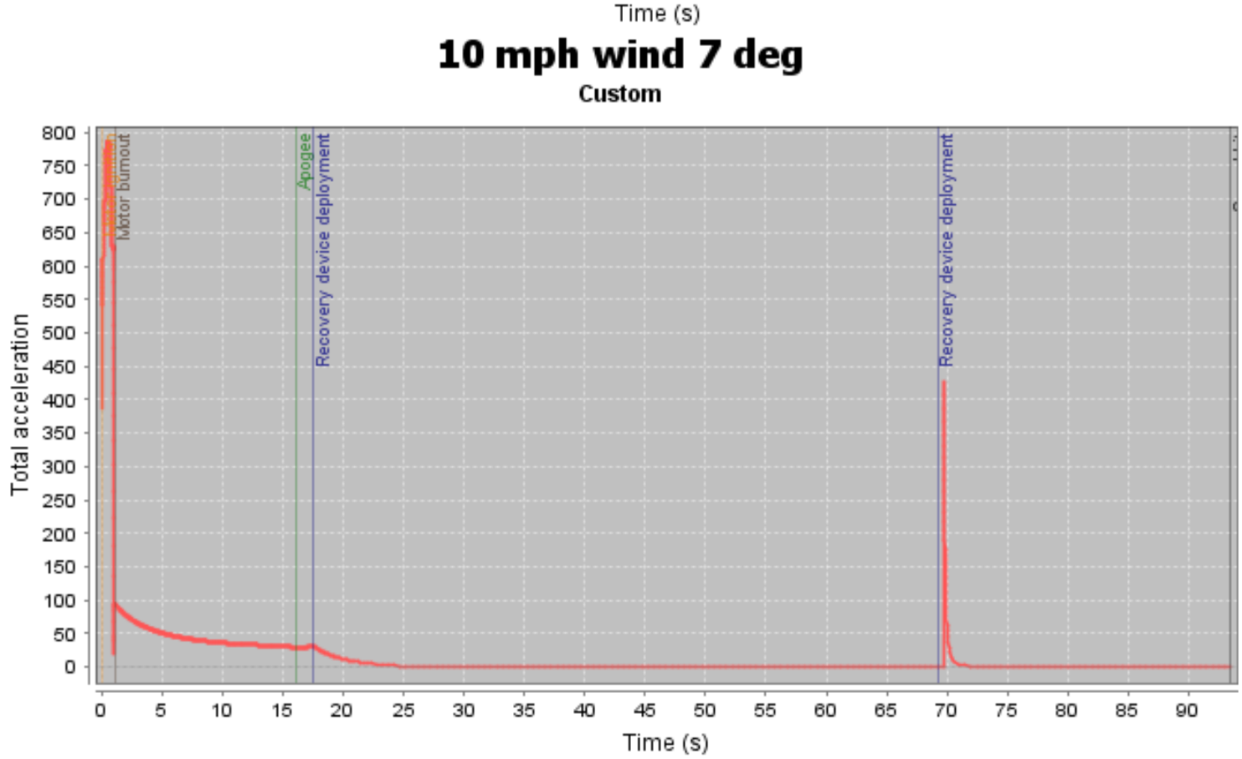
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90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Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
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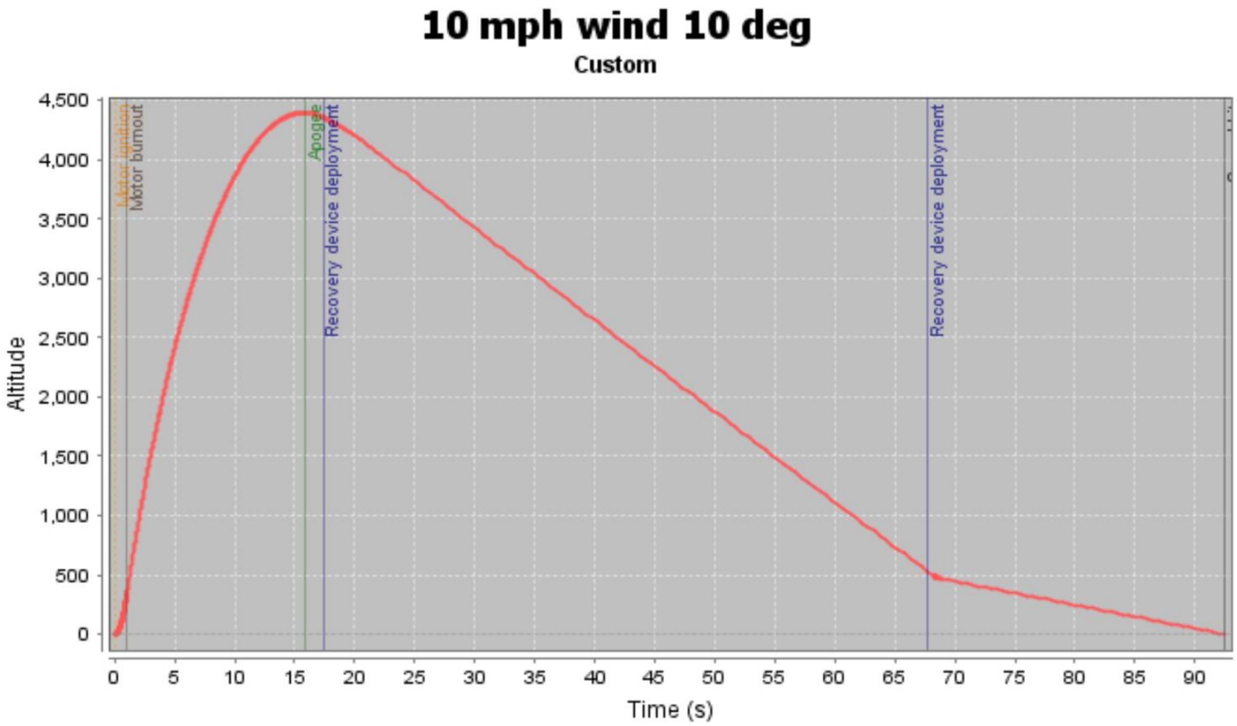
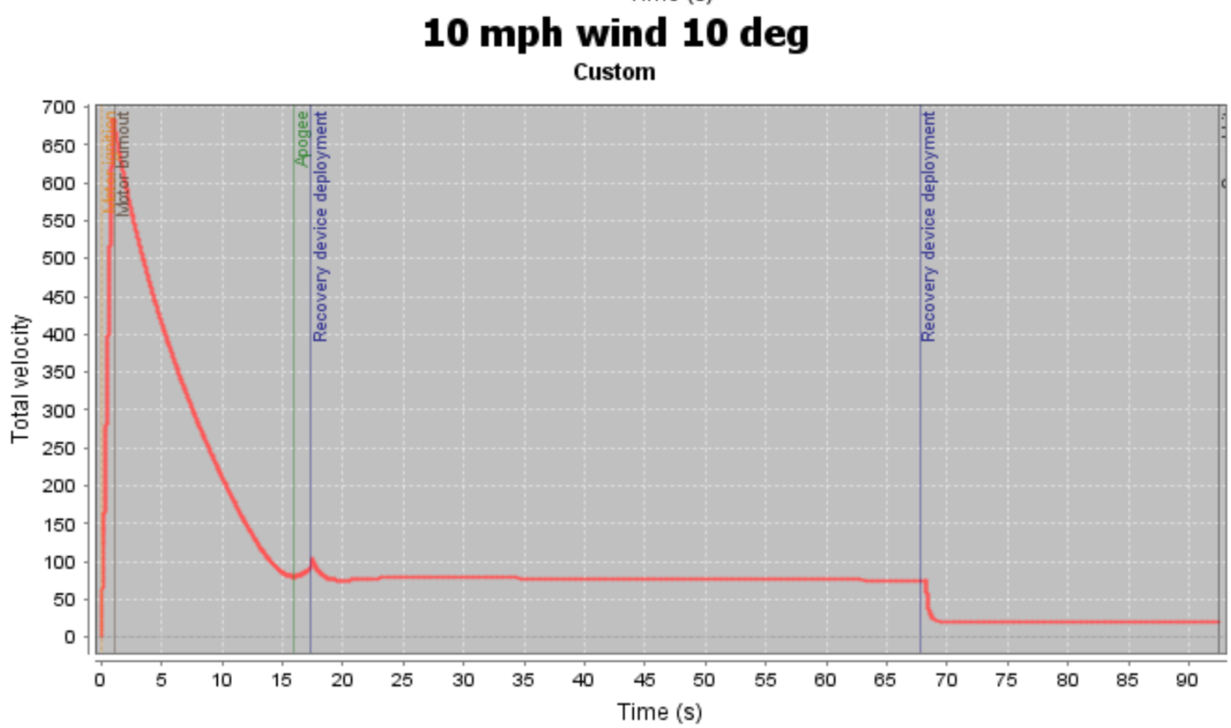
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90


10 mph wind 10 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90


10 mph wind 10 deg
Custom
Total velocity
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
5
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15
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30
35
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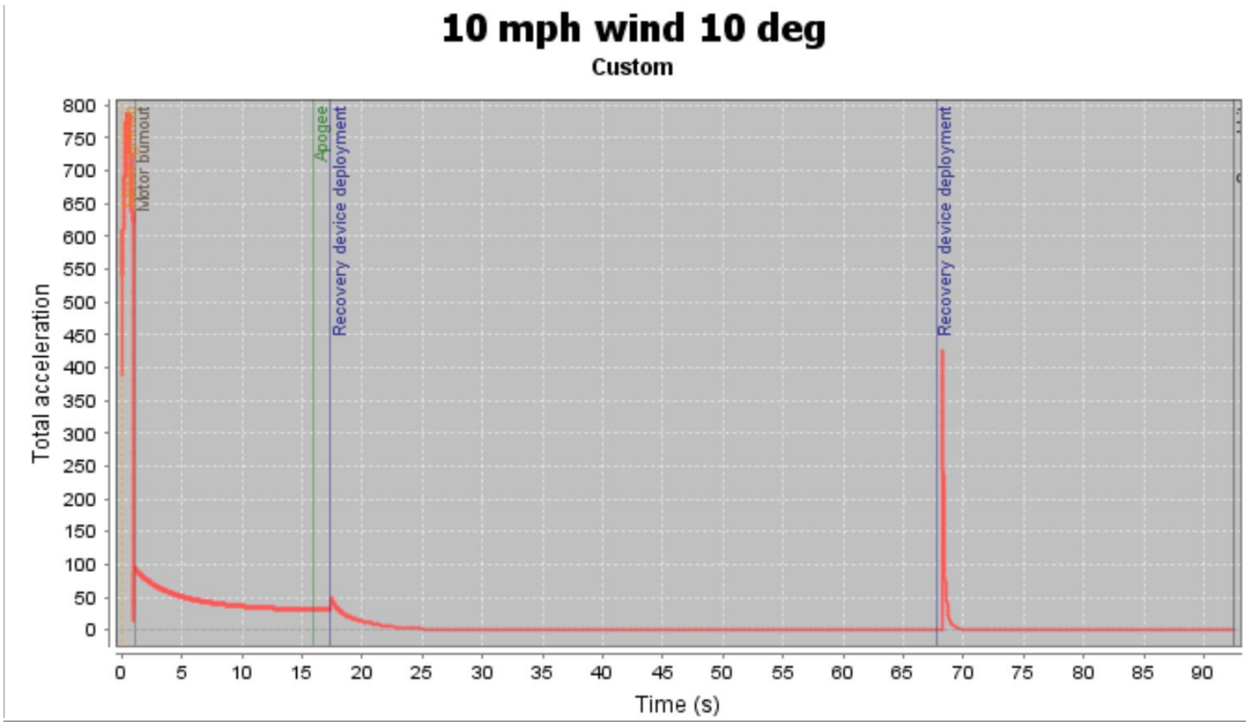
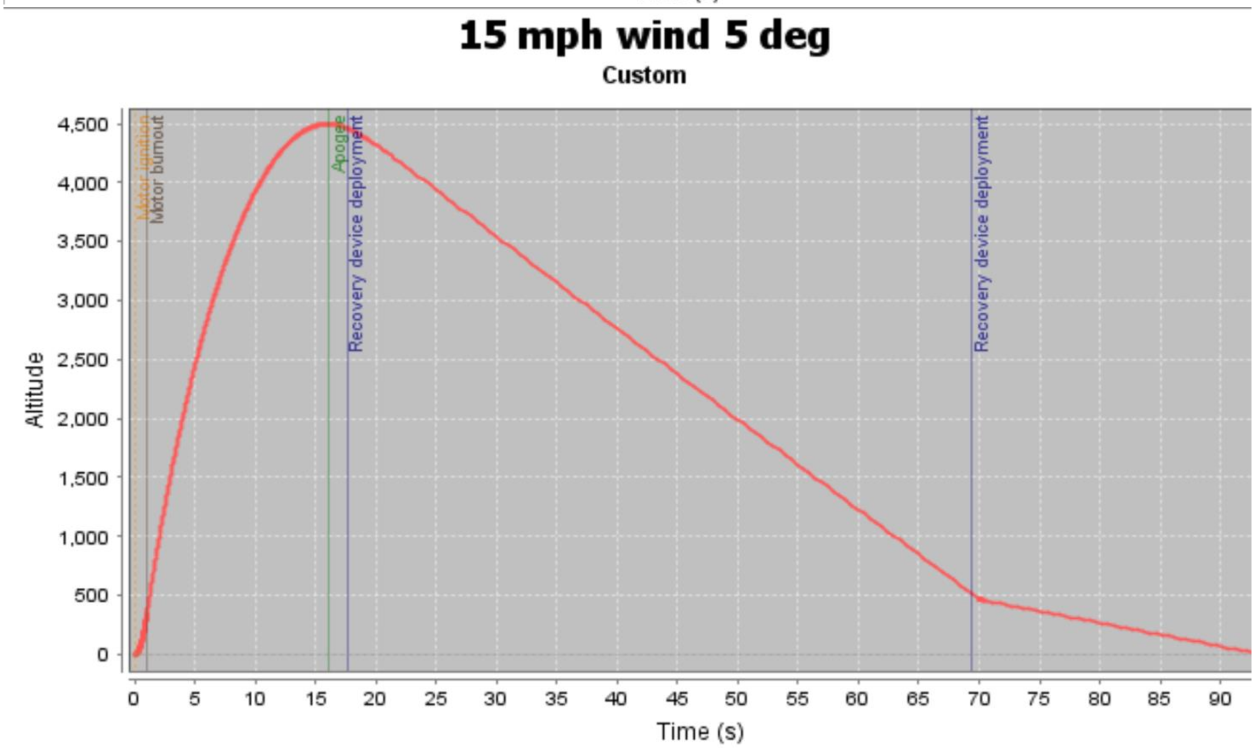
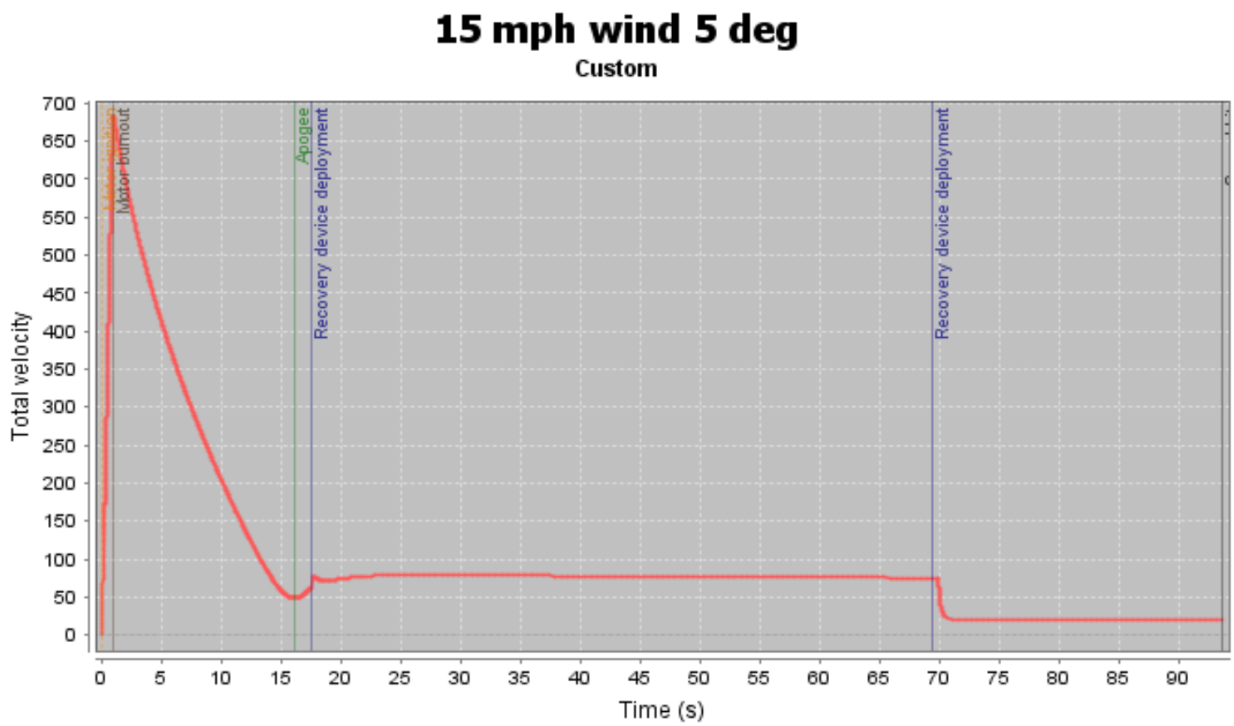
45
50
55
60
65
70
75
80
85
90

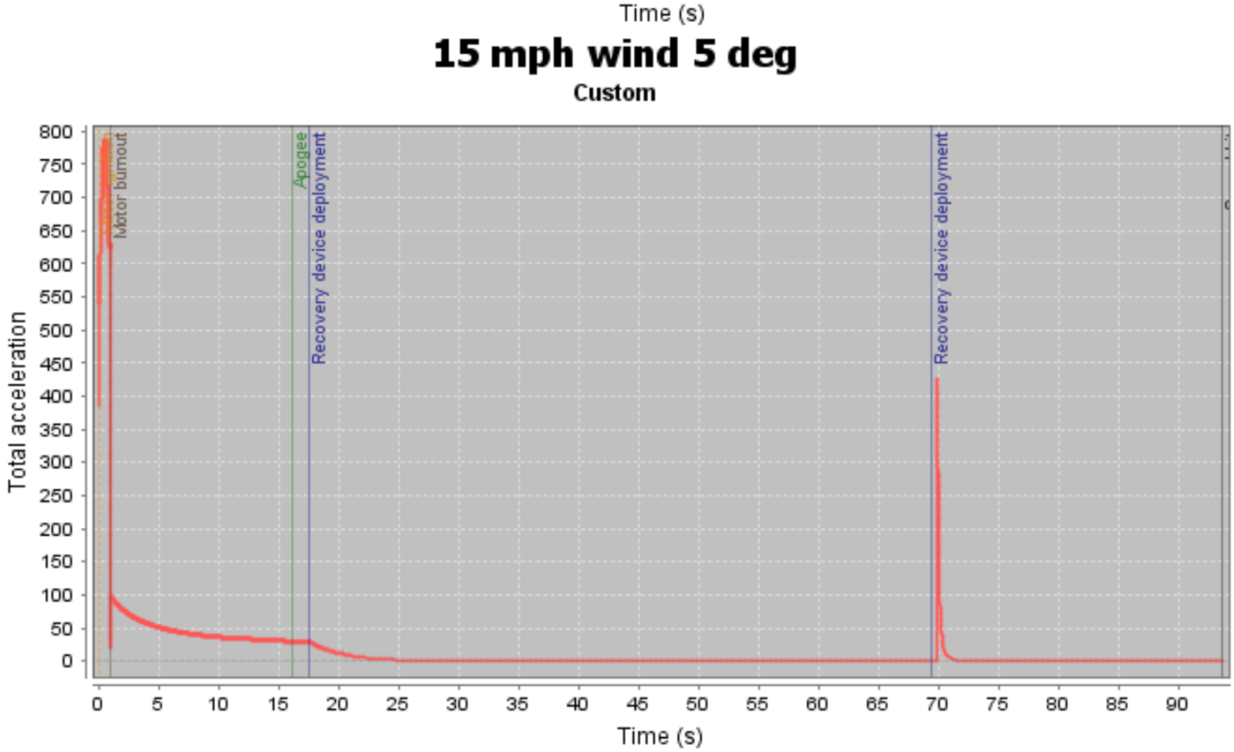


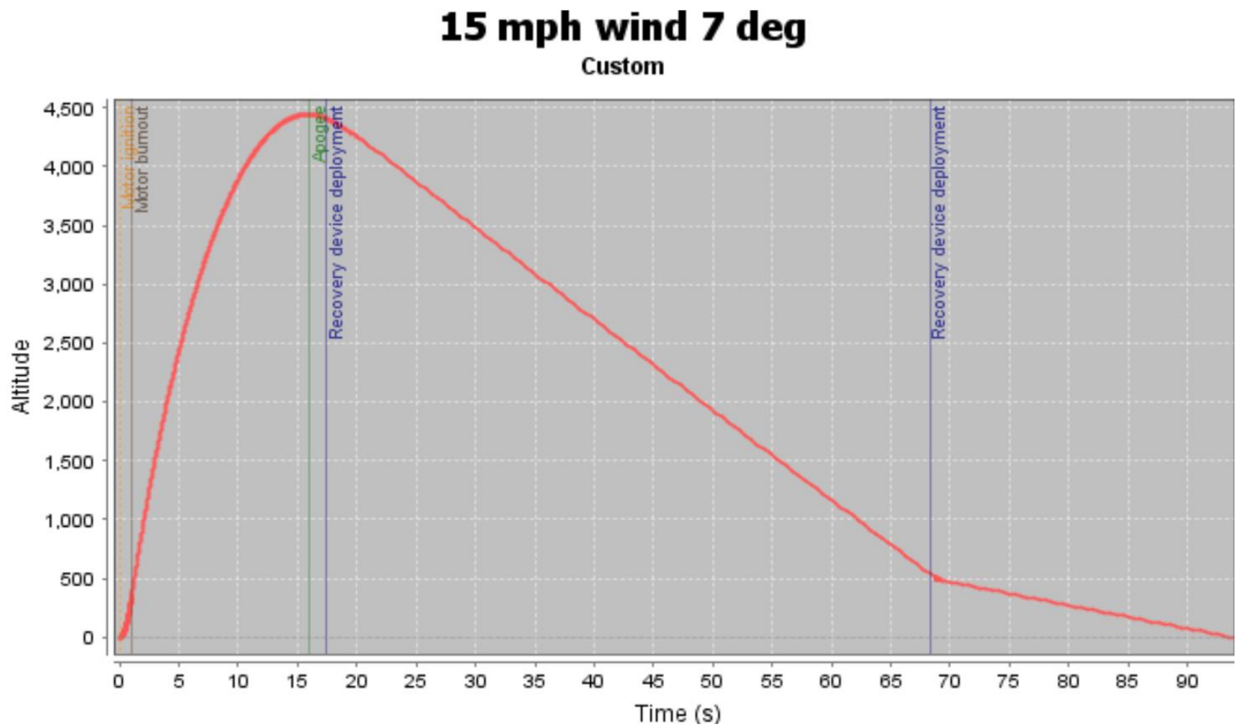
10 mph wind 10 deg
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

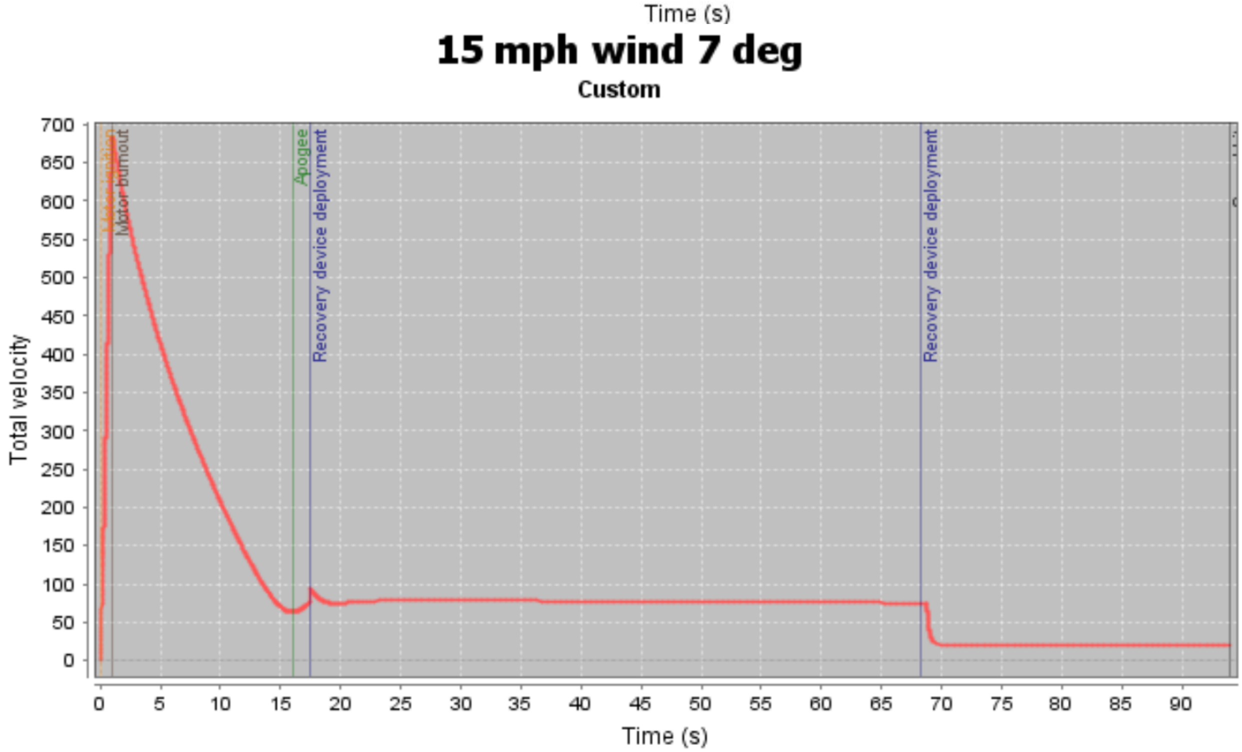


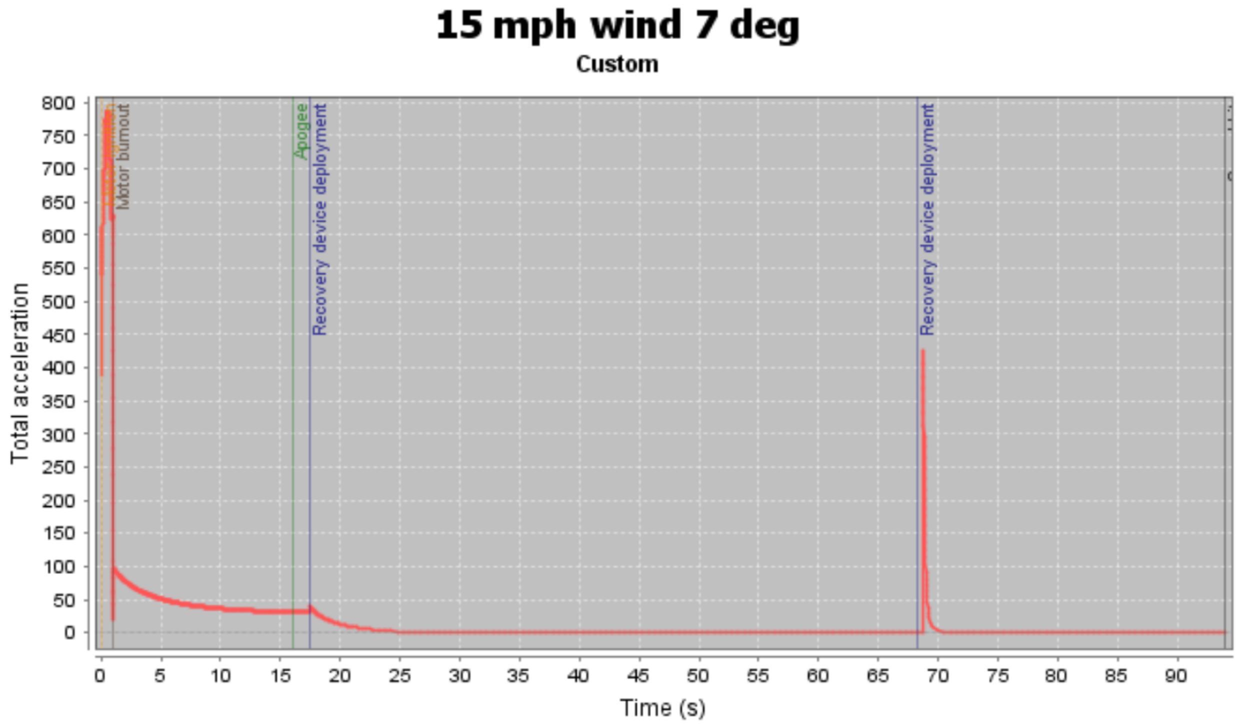
15 mph wind 5 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

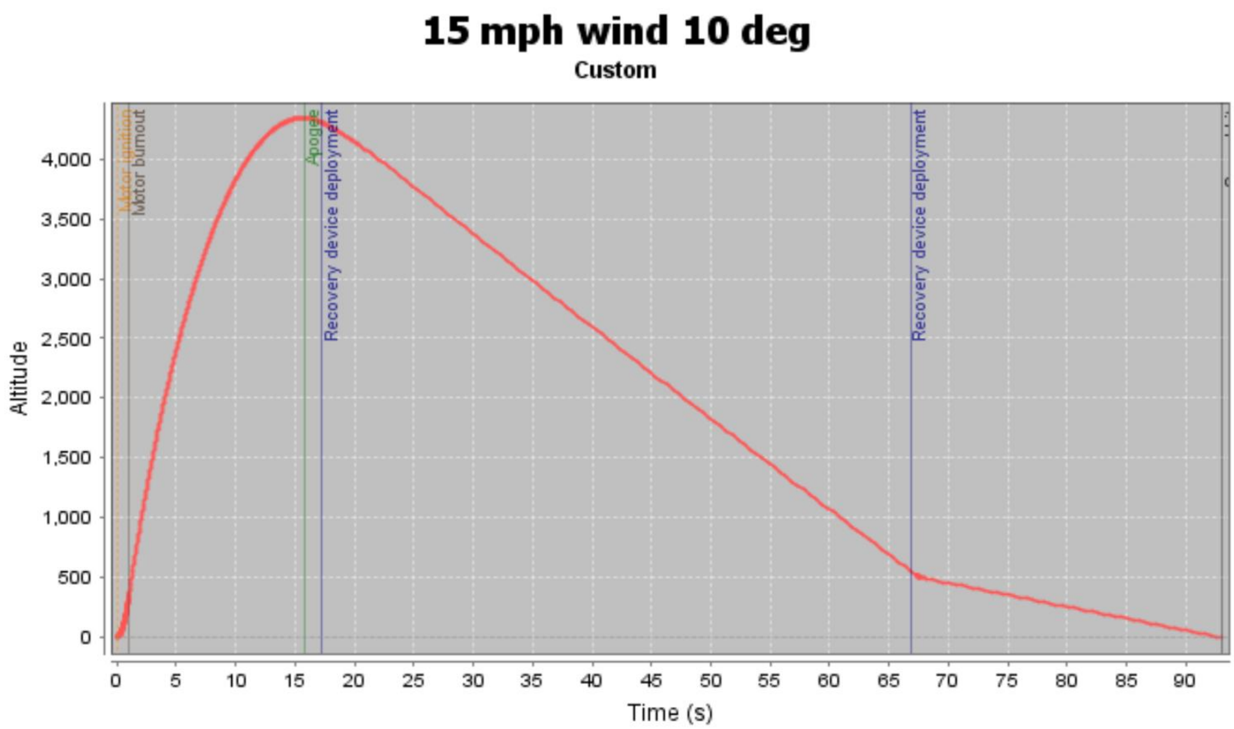

15 mph wind 5 deg
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

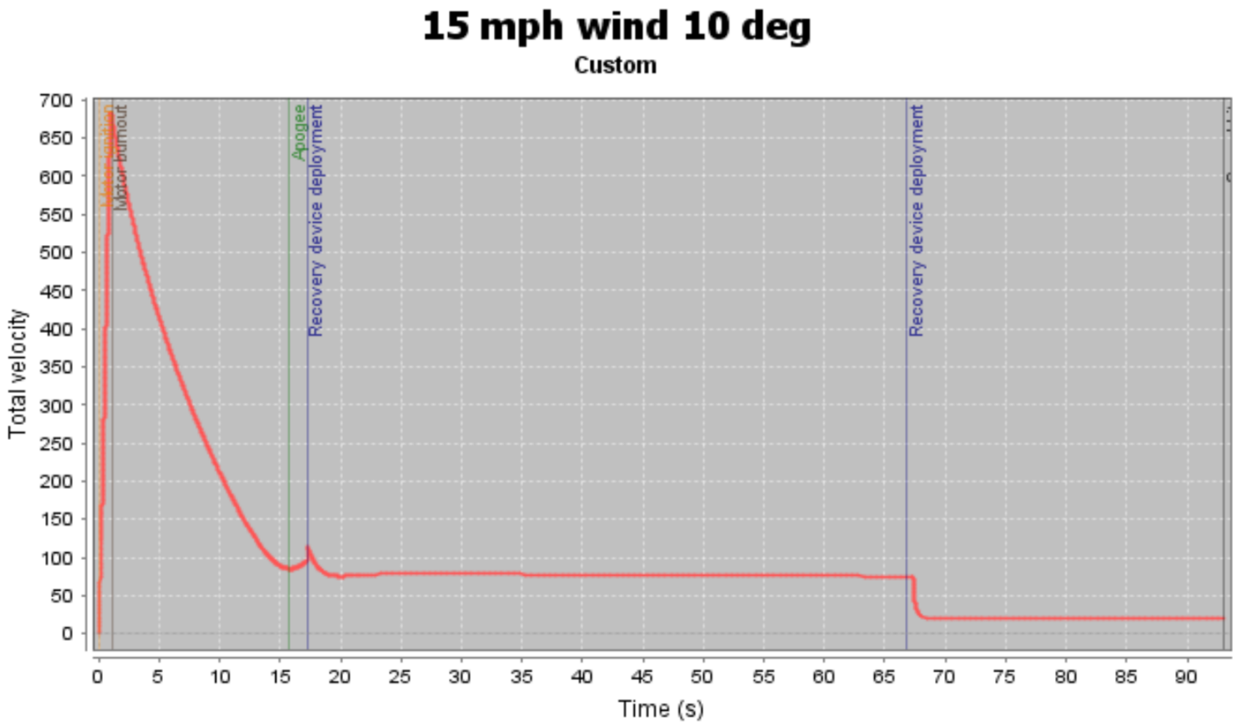

15 mph wind 5 deg
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

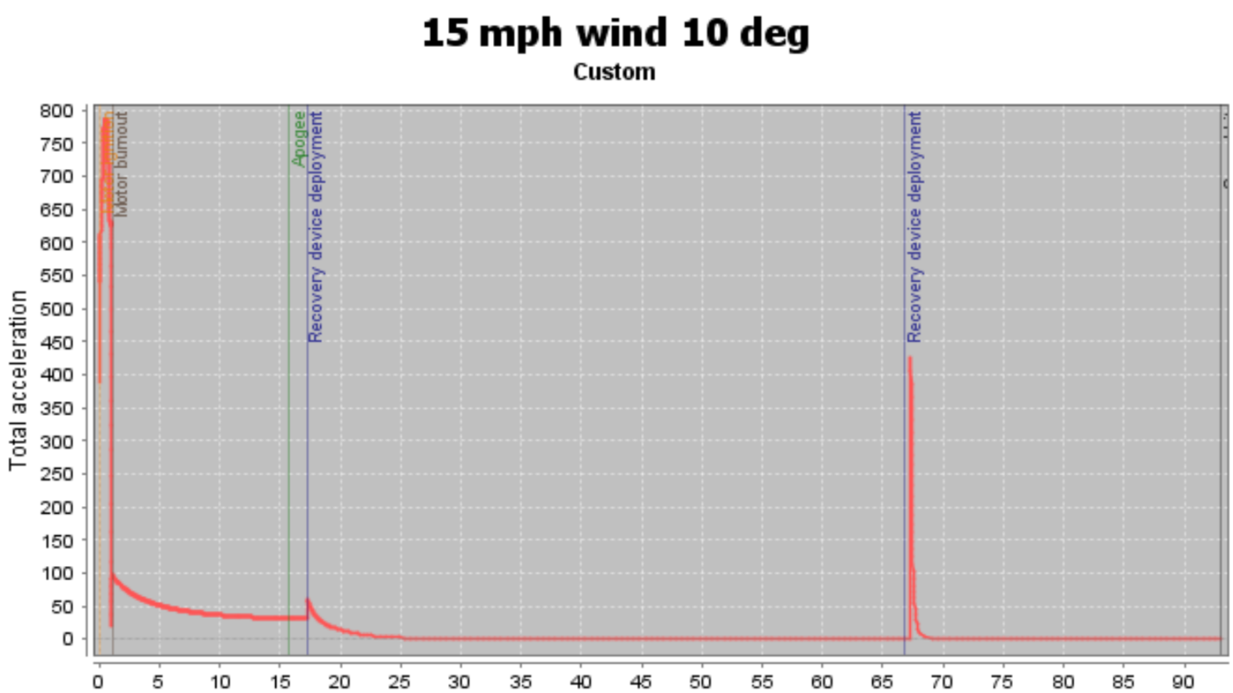

15 mph wind 7 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

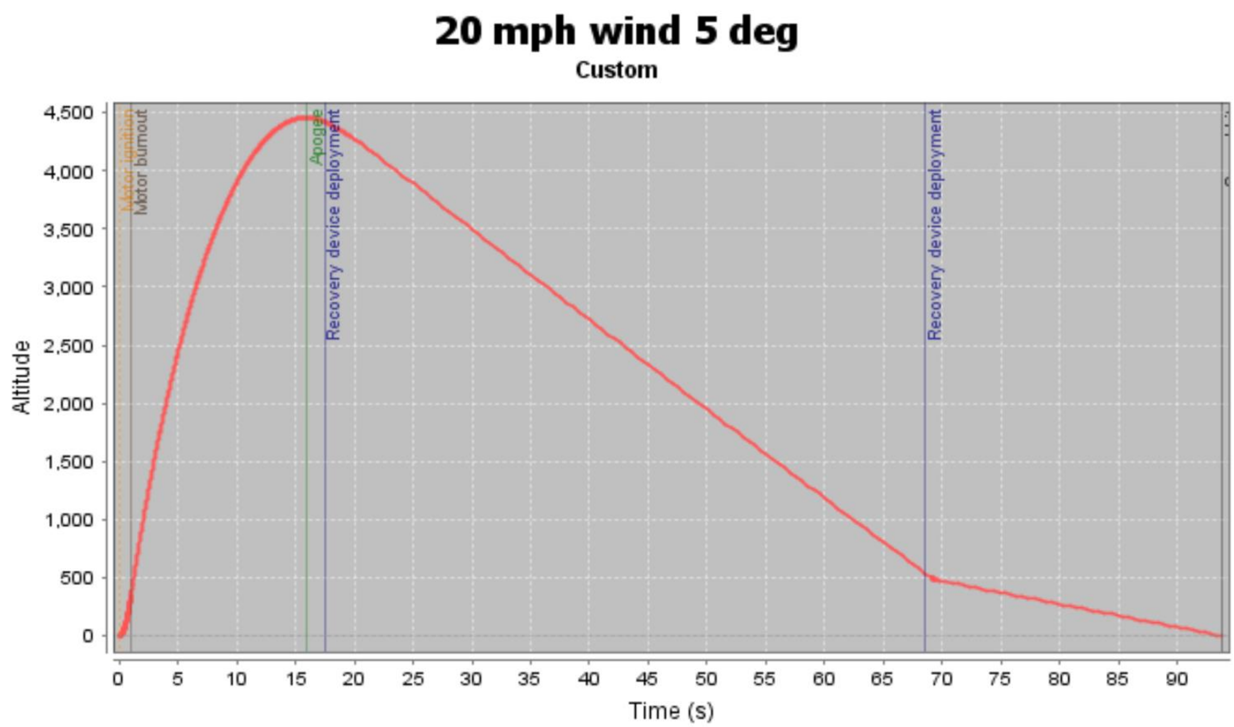

15 mph wind 7 deg
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

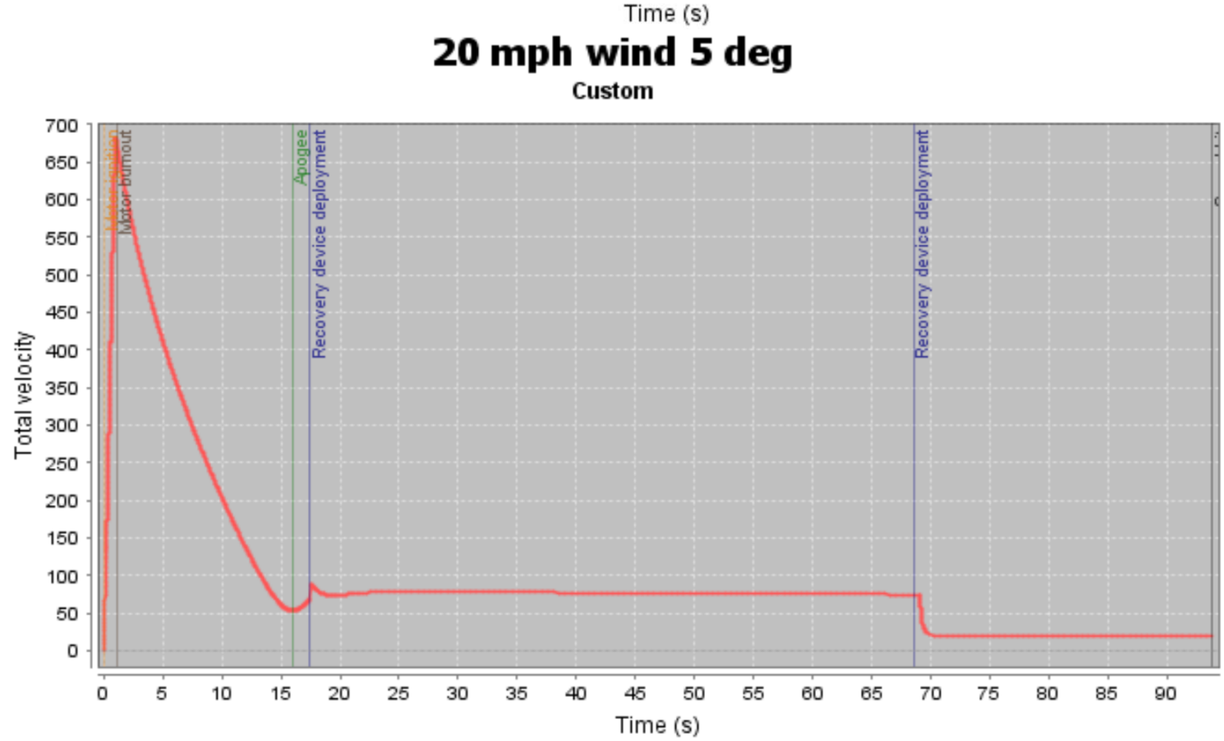

15 mph wind 7 deg
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

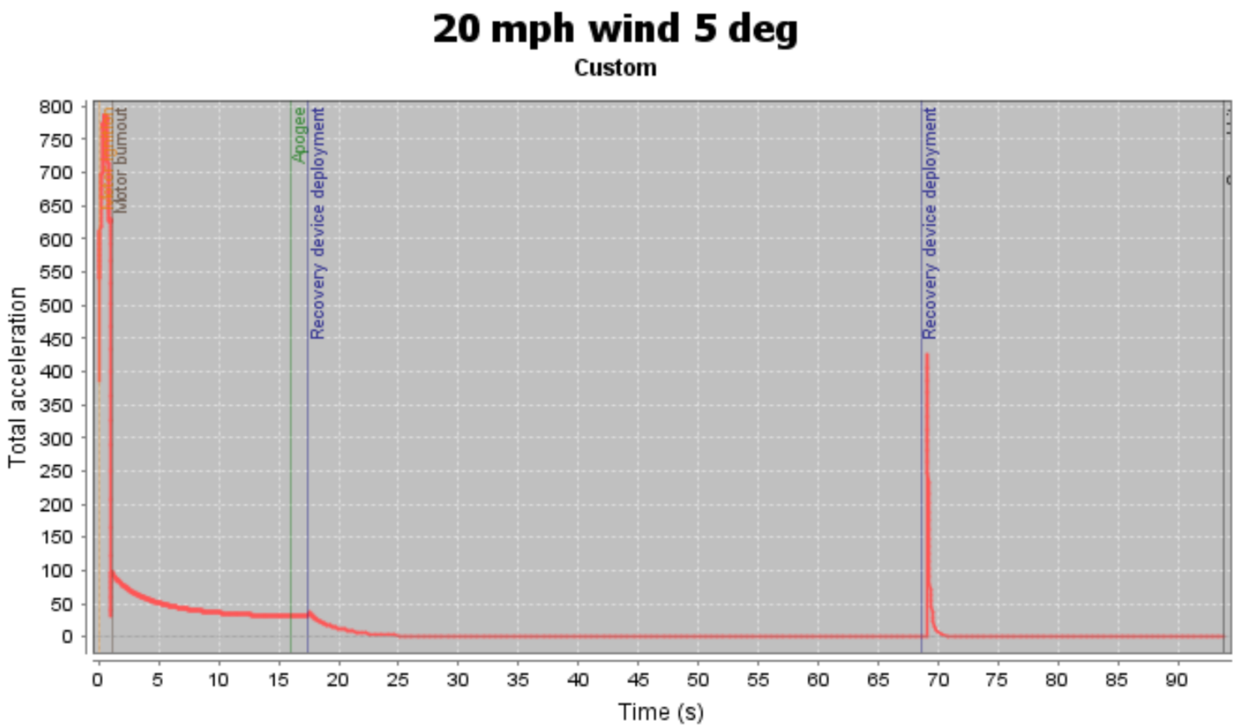

15 mph wind 10 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

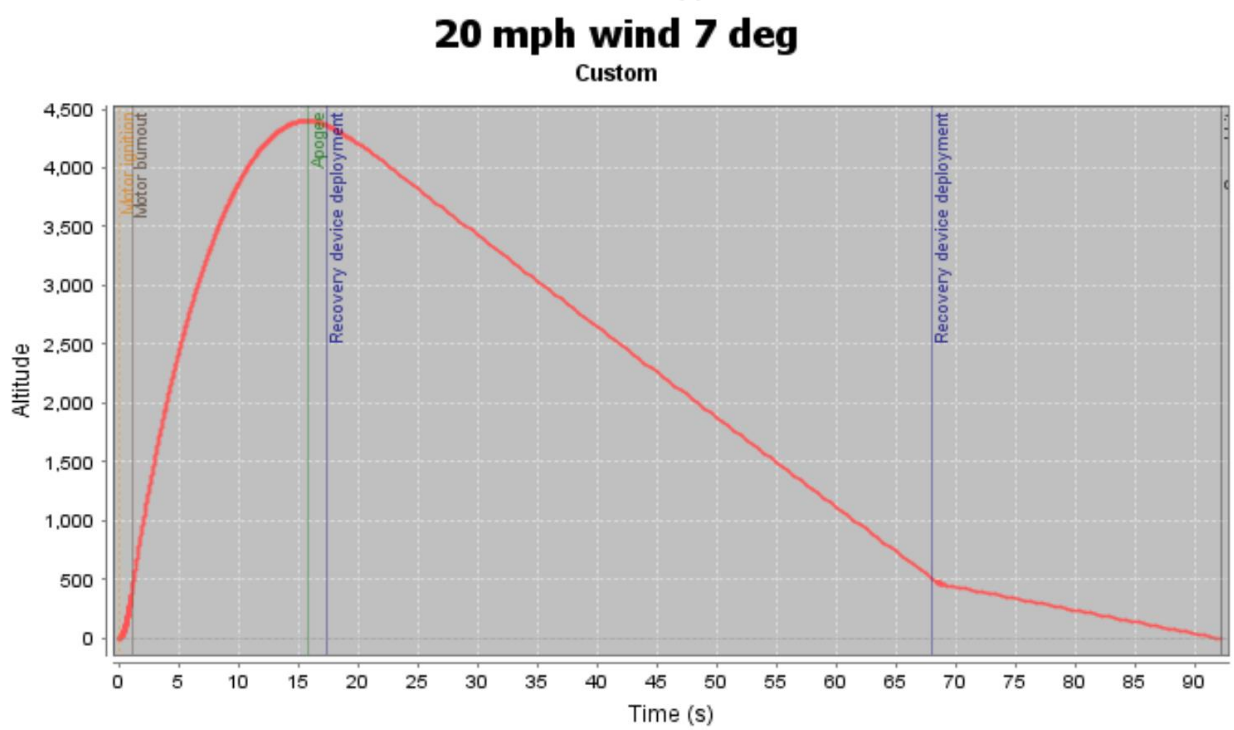

15 mph wind 10 deg
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment

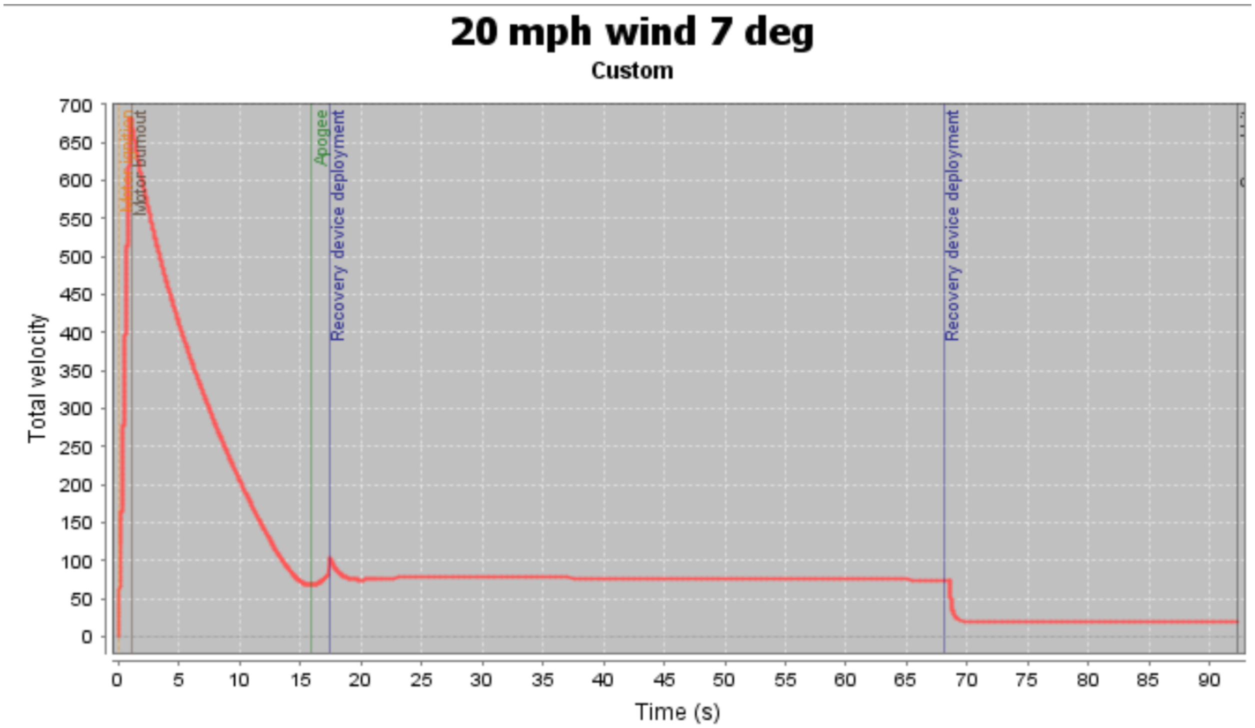

15 mph wind 10 deg
Custom
Total acceleration
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment


20 mph wind 5 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90


20 mph wind 5 deg
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90


20 mph wind 5 deg
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90


20 mph wind 7 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90


20 mph wind 7 deg
Custom
Total velocity
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
0
5
10
15
20
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45
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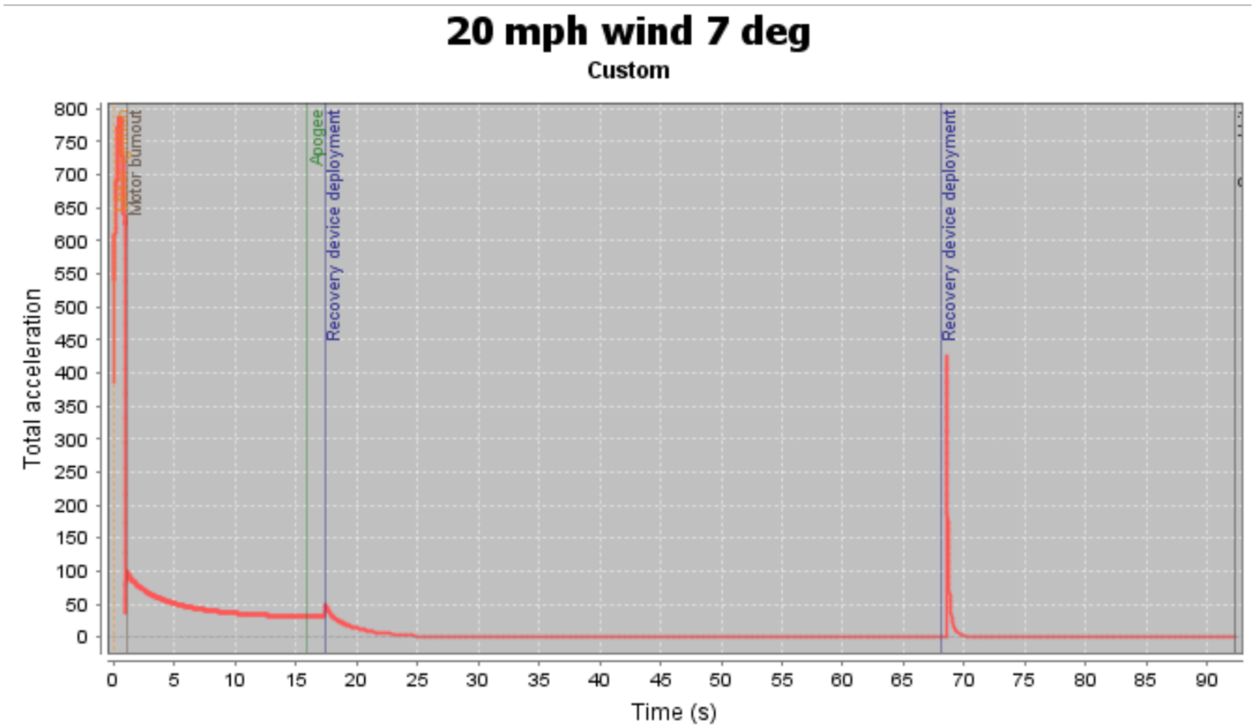
60
65
70
75
80
85
90


20 mph wind 7 deg
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
0
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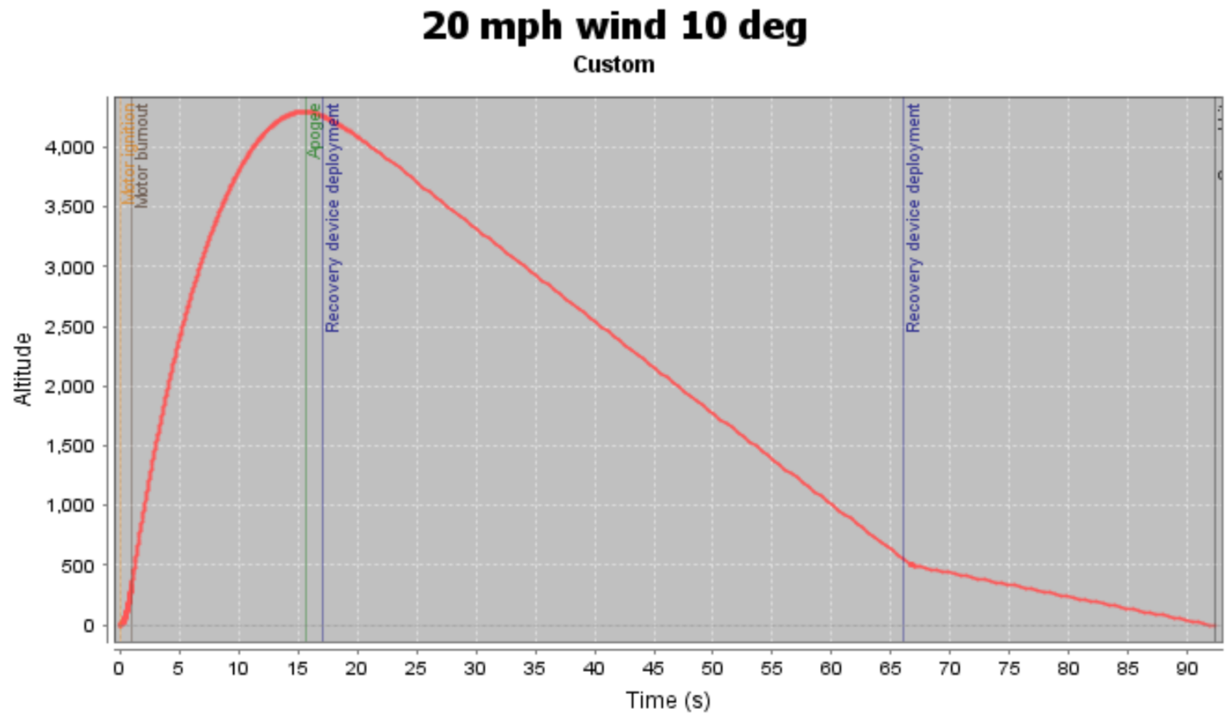
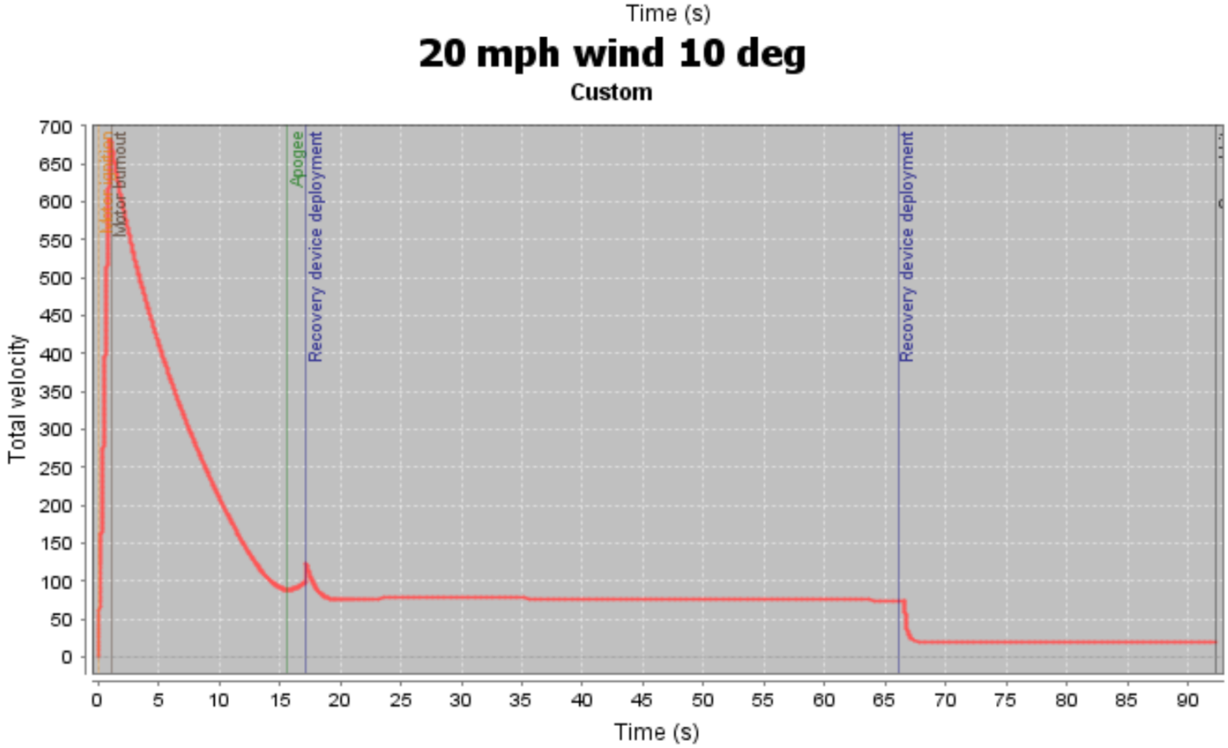
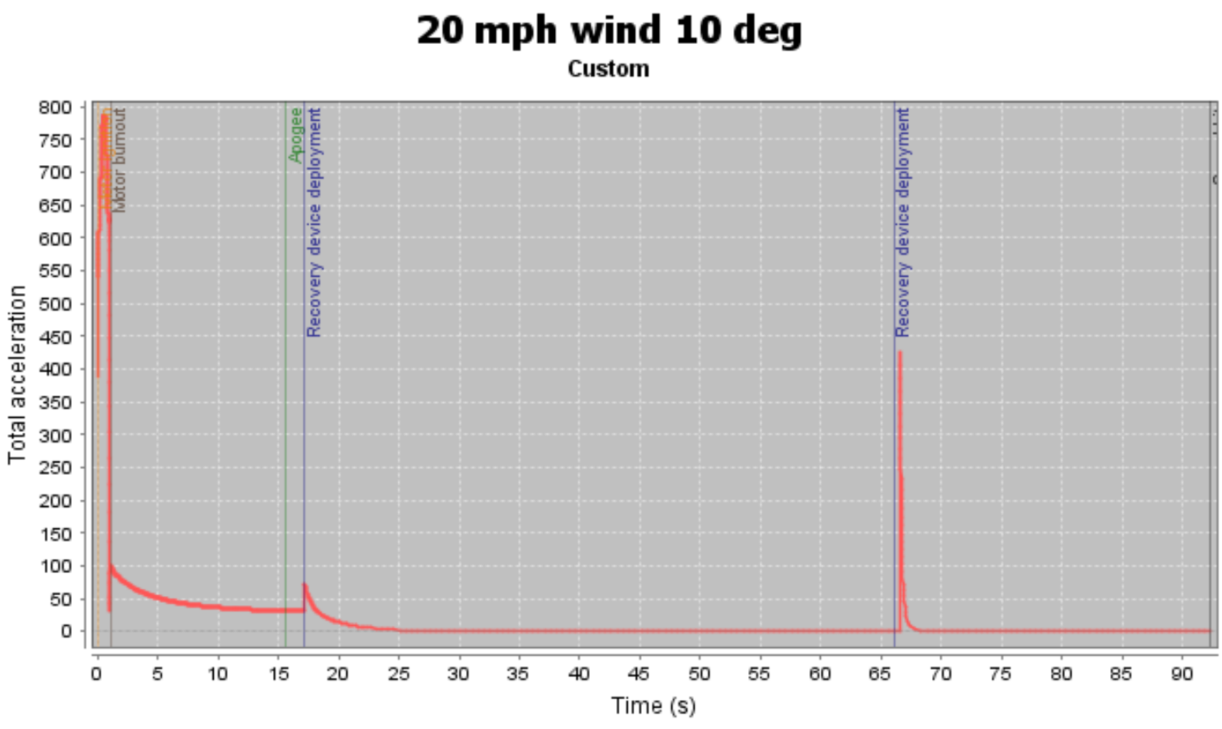

20 mph wind 10 deg
Custom
Altitude
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment


20 mph wind 10 deg
Custom
Total velocity
Time (s)
Motor ignition
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment


20 mph wind 10 deg
Custom
Total acceleration
Time (s)
Motor burnout
Apogee
Recovery device deployment
Recovery device deployment
800
750
700
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550
500
450
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85
90