The Pennsylvania State University

LionTech Rocket Labs

2017-2018 USLI Project Nimbus

Flight Readiness Review

046 Hammond Building, University Park, PA 16802
March 05, 2018

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List of Acronyms

A&R	Avionics and Recovery
CFD	Computational Fluid Dynamics
EIT	Electronic and Information Technology
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
EHS	Environmental Health and Safety
GPS	Global Positioning System
HPCL	High Pressure Combustion Lab
LTRL	LionTech Rocket Labs
MDRA	Maryland Delaware Rocketry Association
MSDS	Material Safety Data Sheet
NAR	National Association of Rocketry
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
PPE	Personal Protective Equipment
PSC	Pittsburgh Space Command
PSU	The Pennsylvania State University
RSO	Range Safety Officer
SDS	Safety Datasheet
STEM	Science Technology Engineering and Mathematics
STTR	Small Business Technology Transfer
TRA	Tripoli Rocket Association
UPAC	University Park Allocation Committee
USLI	University Student Launch Initiative

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1. Summary of Report

1.1 Team Summary

Team Name and Address

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1.2 Vehicle Summary

Size and Mass

The launch vehicle was designed to incorporate a rover payload while minimizing weight and providing sufficient strength. A diameter of 5.5 inches was chosen to give sufficient space for the payload. The overall length of the vehicle is 112 in. The dry weight of the launch vehicle is 27.75 lb, while the wet mass, which includes the motor and casing, is 36.3 lb. An OpenRocket rendering of the final flight vehicle is shown in Figure 1.

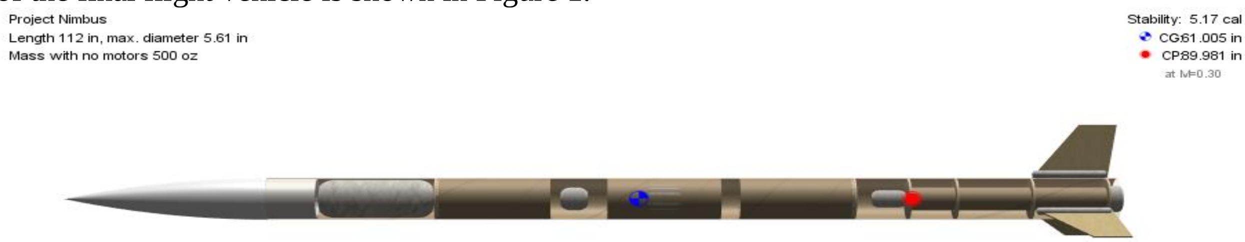


Figure 1. OpenRocket Rendering of Fullscale

Motor Choice

The motor selection process is based on the mission performance criteria outlined in the NASA USLI 2017-18 Handbook and preliminarily uses OpenRocket to simulate flight characteristics. Through this motor selection process, the Aerotech L1390 was selected.

Recovery System

The avionics bay will be fully redundant, consisting of two independent Stratologger CF altimeters with corresponding independent power sources, switches, and charges. The redundant altimeter will be at a one-second delay so that the body of the rocket is not overwhelmed when the ejection charges detonate. The redundant charge will have a slightly larger black powder charge to ensure that the shear pins are broken. The rocket will have dual-deployment parachute recovery where drogue parachute will deploy at apogee and main parachute will deploy at 700 ft above ground level (AGL). The drogue parachute will be a 12" Fruity Chutes Classical Elliptical and the main parachute will be an 84" Fruity Chutes Iris Ultra Compact. These parachutes guarantee that the rocket will land under the NASA kinetic energy requirement of 75 ft-lbs.

1.3 Payload Summary

The payload challenge chosen this year is build a remotely deployable autonomous rover. The rover will be deployed from the launch vehicle and then autonomously move at least 5 feet away from all parts of the rocket. After the rover has reached its destination, it will deploy a set of foldable solar panels.

1.4 Milestone Review Flysheet

Milestone Review Flysheet 2017-2018			
Institution	Pennsylvannia State University	Milestone	FRR

Vehicle Properties	
Total Length (in)	112
Diameter (in)	5.63
Gross Lift Off Weigh (lb.)	36.3
Airframe Material(s)	Carbon Fiber Wrapped Blue Tube
Fin Material and Thickness (in)	G10 FR4 Fiberglass 3/16
Coupler Length/Shoulder Length(s) (in)	12/6

Motor Properties	
Motor Brand/Designation	Aerotech/ L1390
Max/Average Thrust (lb.)	371/309
Total Impulse (lbf-s)	887
Mass Before/After Burn (lb.)	137 oz/ 67 oz
Liftoff Thrust (lb.)	1375
Motor Retention Method	Plywood centering rings

Stability Analysis	
Center of Pressure (in from nose)	89.98
Center of Gravity (in from nose)	69.98
Static Stability Margin (on pad)	3.6
Static Stability Margin (at rail exit)	2.6
Thrust-to-Weight Ratio	8.56
Rail Size/Type and Length (in)	1515 / 120 in
Rail Exit Velocity (ft/s)	71.5

Ascent Analysis	
Maximum Velocity (ft/s)	684
Maximum Mach Number	0.61
Maximum Acceleration (ft/s^2)	303
Predicted Apogee (From Sim.) (ft)	5347

Recovery System Properties – Drogue Parachute				
Manufacturer/Model	Fruity Chutes Elliptical			
Size/Diameter (in or ft)	12" Diameter			
Altitude at Deployment (ft)	5280			
Velocity at Deployment (ft/s)	-			
Terminal Velocity (ft/s)	105			
Recovery Harness Material	Kevlar			
Recovery Harness Size/Thickness (in)	0.5			
Recovery Harness Length (ft)	40			
Harness/Airframe Interfaces	3/8" Steel U-Bolt			
Kinetic Energy of Each Section (Ft-lbs)		Nose/Payload	Avionics Bay	Booster
		1784	987.6	2284

Recovery System Properties – Main Parachute				
Manufacturer/Model	Fruity Chute Iris Ultra Compact			
Size/Diameter (in or ft)	84" Diameter			
Altitude at Deployment (ft)	700			
Velocity at Deployment (ft/s)	105			
Terminal Velocity (ft/s)	18			
Recovery Harness Material	Kevlar			
Recovery Harness Size/Thickness (in)	0.5			
Recovery Harness Length (ft)	30			
Harness/Airframe Interfaces	3/8" Steel U-Bolt			
Kinetic Energy of Each Section (Ft-lbs)		Nose/Payload	Avionics Bay	Booster
		47.54	26.4	60.91

Recovery Electronics	
Altimeter(s)/Timer(s) (Make/Model)	Stratologger Cf
Redundancy Plan and Backup Deployment Settings	Single level redundancy for drogue and main event
Pad Stay Time (Launch Configuration)	2 hours

Recovery Electronics		
Rocket Locators (Make/Model)	Americaloc GL300W	
Transmitting Frequencies (all - vehicle and payload)	Cell Phone Service (AT&T): 850 mHz	
Ejection System Energetics (ex. Black Powder)	Black Powder	
Energetics Mass - Drogue Chute (grams)	Primary	1.5
	Backup	2.5
Energetics Mass - Main Chute (grams)	Primary	2
	Backup	3
Energetics Masses - Other (grams) - If Applicable	Primary	25g CO2 cartridge
	Backup	N/A

Milestone Review Flysheet 2017-2018

Institution	Pennsylvannia State University	Milestone	FRR

Payload	
Payload 1 (official payload)	**Overview** The payload challenge chosen this year is build a remotely deployable autonomous rover. The rover will be deployed from the launch vehicle and then autonomously move at least 5 feet away from all parts of the rocket. After the rover has reached its destination, it will deploy a set of foldable solar panels.
Payload 2 (non-scored payload)	**Overview** N/A

Test Plans, Status, and Results	
Ejection Charge Tests	The ejection charges will be tested before all flights. The charges used will be sufficiently large to ensure deployment of the corresponding parachute without causing damage to the body tube. To complete the ground test, the ejection charges must be loaded and the initiators must be connected to a 40 ft wire extender. Then, the rocket must be assembled and the shear pins must be installed. From a safe distance, a 9V battery can be connected to the wire extender. (Safety note: make sure that everyone is a safe distance away from the rocket and that no one is standing in line with the nose cone or booster section of the rocket.) This will cause the charge to detonate and should separate the rocket. If the rocket does not separate, then the amount of black powder will need to be increased on that section. If the the ejection charge test for the drogue parachute charge also separates the main parachute section, then the amount of black powder in the drogue parachute section will need to be decreased. (Safety note: If any charges do not detonate, then only the lead and safety officer can approach the rocket with the utmost care to disarm the rocket.) This procedure was performed prior to the fullscale test launch to verify the chosen black powder charges of 1.5 and 2 grams. The test was successful and those size echarges were then used for fullscale test flight which performed as expected.
Sub-scale Test Flights	We launched on a Cesaroni J280 and acheived an apogee of 3733 ft. During descent, parachute deployment appeared to be nominal and the rocket touched down at a safe impact velocty. Upon landing, the airframe and major components of the rocket were inspected and no physical damage was observed.
Full-scale Test Flights	A fullscale test flight was performed on February 18th. Weather conditions on the day of launch were very favorable. The air temperature was 47º F, the wind was averaging 7 mph primarily from the West, and there was little to no cloud cover. The fullscale rocket launched with the compeition motor, an Aerotech L1390 and achieved an apogee of 5472 ft. All systems of the rocket performed as expected including downbody camera footage, airframe structural components, ejection charges, and rover retention during flight. During main deployment, the booster coupler experienced some zippering which is planned to be mitiagted through the addition of fireballs to the recovery harness.

2. Changes Made Since CDR

Flight Vehicle

No design changes were made to the structure of the final flight vehicle since CDR. Fullscale test flight sufficiently verified the strength of all structural components and prior design decisions. However, changes to the recovery system have been made to further mitigate possible issues. The addition of carbon fiber this year mitigates zippering issues on the body tube but does not account for section of blue tube coupler. Therefore, multiple fireballs will be added to the recovery harness to further mitigate possible zippering during competition flight.

Payload

Slight changes were made to the inside of the rover body to allow for more space. The solar panel deployment mechanism was changed from a spring-loaded system to a rotating servo arm system. A rotating servo arm is a more functional design because it is now retractable. The previous system could only be deployed once, but now the rover can bring its solar panels in and out multiple times during a single mission.

Project Plan

Since the Critical Design Review, LTRL has made minor changes ensuring this club’s success. During CDR, the club was only under budget by $99.98, therefore requiring inquiry into additional funding sources. Many potential sponsors were contacted, and several have agreed to financially support the club. The new donors are the Penn State College of Engineering, Pennsylvania Space Grant, and the Boeing Company. With these three means of funds the club has brought in an additional $5,465.62. The club is also expecting another $1,000.00 from the University Park Allocations Committee. With these added means of revenue, the club has been able to be more flexible with its outflow. Since the Critical Design Review, the club has made $409.06 of fullscale purchases. With having a greater inflow, the club decided to upgrade to a more convenient location and this caused travel expenses to increase by $732.55. Also, outreach costs have been reduced to $150.00. Lastly, miscellaneous expenditures have increased by $31.00. Overall, the club is much better off financially since the Critical Design Review.

3. Vehicle Criteria

3.1 Design and Construction of Vehicle

Airframe Design

Blue tube wrapped in carbon fiber was selected as the material for the airframe for this year's launch vehicle. This decision was made based on the scores given in the weighted design matrix shown in Table 1.

Table 1. Airframe material selection matrix

		Fiberglass		**Blue Tube**		**Carbon Fiber**		**Carbon Fiber Wrapped Blue Tube**	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Strength	0.25	4	1	1	0.25	5	1.25	5	1.25
Cost	0.15	2.5	0.375	5	0.75	1	0.15	2.5	0.375
Workability	0.1	2	0.2	3.5	0.35	1	0.1	3	0.3
Weight	0.25	1	0.25	4	1	5	1.25	4	1
Appearance	0.05	5	0.25	3	0.15	5	0.25	5	0.25
Legacy	0.1	5	0.5	5	0.5	1	0.1	2	0.2
Hazardousness	0.1	1	0.1	5	0.5	1	0.1	2	0.2
Total			**2.675**		**3.5**		**3.2**		**3.575**

The scores for each category are justified below.

Strength
Yield strength is determined to be the primary factor when discussing strength. The ratings for yield strength for each material are show below in Table 2.

Table 2. Material Strength Comparison

	Yield Strength (KSI)
Fiberglass (G70)	30
Blue Tube	5.07
Carbon Fiber	610-700

Cost
The cost for each material was measured by dollars per foot for 5.5 in. diameter and approximately ⅛ in. thickness body tube is shown in Table 3.

Table 3. Material Cost Comparison

	Cost ($ / ft)
Fiberglass	43.75
Blue Tube	14.25
Carbon Fiber Tube (5.26 Diameter)	165.40
Carbon Fiber Wrapped Blue Tube	14.25 (blue tube) + 18.42 (carbon fiber weave) + 9.9 (epoxy)= 42.58

Weight
The densities of each material considered are shown in Table 4. The material with the lower density received a higher score for weight.

Table 4. Density Discrepancy between manufacturer and OpenRocket

	OpenRocket Density (oz / in^3)	Website Density (oz / in^3)
Fiberglass	1.07	1.03
Blue Tube	0.751	0.583
Carbon Fiber	1.03	0.923

Final Selection and Construction
After the scores were weighed and summed, blue tube wrapped in carbon fiber had the highest score and was selected as a result. The team wrapped the body tube in two layers of carbon fiber weaving to ensure structural integrity which was verified during fullscale test flight as there was no structural damage to the carbon fiber wrapped body sections. The carbon fiber weaving was coated with industrial epoxy and resin. This coated carbon fiber weaving was then hand wrapped around the blue tube. The carbon fiber blue tube was then wrapped with heat shrink tape to compress the epoxy and carbon fiber weaving around the body tube. The process of wrapping the body tube with heat shrink tape is shown below in Figure 2. Finally, the heat shrinking tape was heated using a heat gun and hair dryer to shrink the tape tightly around the body tube which was left to cure for 48 hours. A few methods of wrapping the blue tube with carbon fiber were attempted by the team to yield the best result possible. The carbon fiber was wrapped with the weaving parallel and perpendicular to the longitudinal axis to determine what would yield the smoothest wrap. The first piece of blue tube that was wrapped was re-wrapped after the team had become more comfortable with the measuring, cutting, and wrapping of the carbon fiber.

Figure 2. Wrapping the carbon fiber blue tube in heat shrink tape

Camera Cover

As part of the team derived requirements, a down body camera has been included to supply visual data of flight performance and monitor fin flutter. The exterior portion of the camera is cylindrical with a diameter of 0.75 in and length of 4 in. To securely seat the larger camera on the exterior of the rocket, a 3D printed cover was designed to tightly hold the camera to the body while also providing aerodynamic efficiency. This cover was printed in PLA material due to its lightweight characteristics. Figure 3 shows the more spatially efficient design for this year’s competition on subscale. Figure 4 shows the camera cover on the fullscale rocket during fullscale test flight.

Figure 3. Refined camera cover design on subscale rocket (3” body tube)

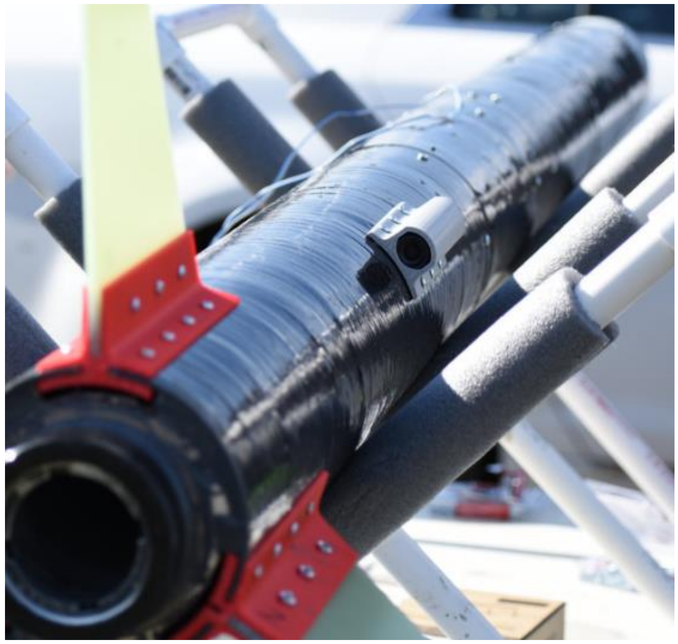


Figure 4. Camera cover design on fullscale rocket (5.61” outer diameter body tube)

Fullscale flight has verified that this design feature can withstand all stresses during flight while securing the down body camera. Fullscale flight results has also shown that the camera cover’s effect on drag did not render the vehicle unstable at any point during flight. Figure 5 contains dimensioned representation of the camera cover used on fullscale.

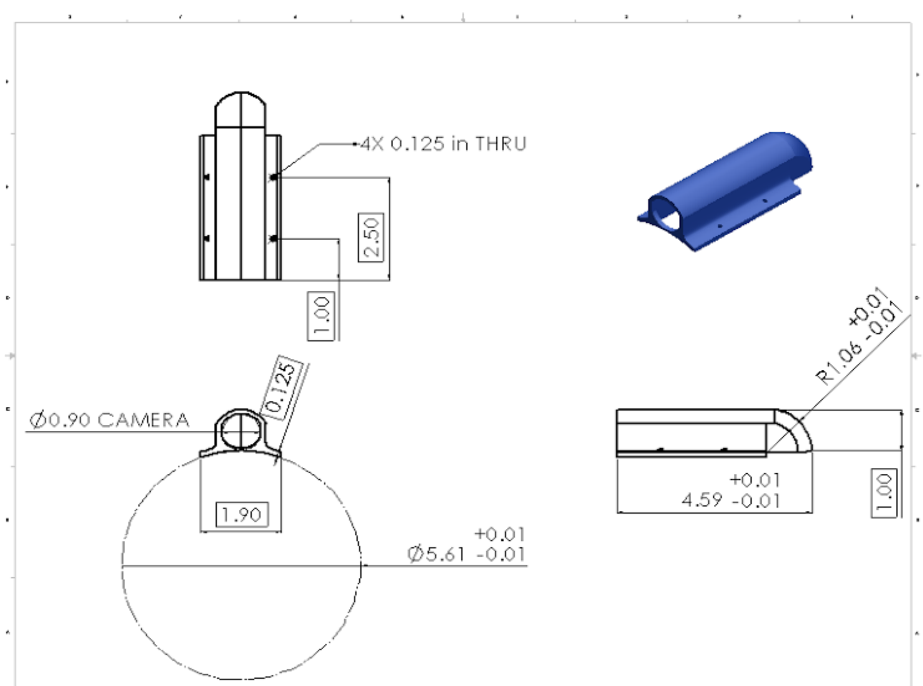


Figure 5. Camera cover specifications

The camera cover is designed to hold a cylindrical camera of 0.90 in. diameter and a length of approximately 4.25 in. including the portion of wire bending into the vehicle.

Fin Retention

Fin retention was accomplished this year using removable fin brackets. The fin brackets lay both on the exterior and interior of the body tube to provide extra structural integrity. The body tube was cut straight from the end to allow the brackets to be inserted from the bottom of the rocket in one piece and lay flush to the bottom of the body tube. Figure 6 contains an image of the brackets attached to that tube.

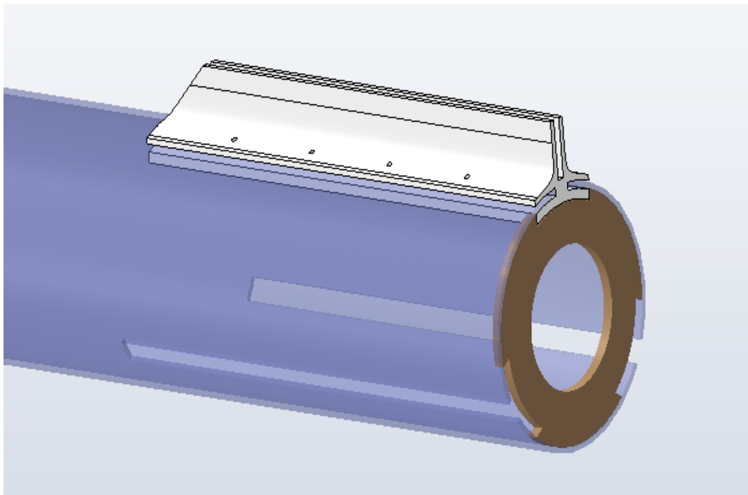


Figure 6. Fin Bracket Model

Eight bolts were placed equally along the length to be secured through use of nuts placed on the interior of the fin bracket. The fins were fastened via nuts and bolts through the top section of the brackets. A conic rho fillet was chosen to decrease stress concentrations throughout the length of the bracket. This filet also allows the screws to be aligned perpendicular to the body tube to maximize contact. A secondary purpose of the bracket is to mitigate much of the fin flutter that may be encountered for larger fins. Figure 7 shows the fin brackets on the fullscale rocket during fullscale test flight.

Figure 7. Fin Bracket on Fullscale Launch Vehicle

This concept was chosen by using a concept selection matrix. Table 5 shows the fin retention selection matrix.

Table 5. Fin Retention Selection Matrix

		3D Printed, Epoxied		Epoxied (reference)		3D Printed, Bolted	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Cost	0.15	2	.30	3	0.45	2	0.30
Strength	0.20	3	.60	3	0.60	3	0.60
Simplicity of Implementation	0.20	4	.80	3	0.60	5	1.00
Lead Time	0.15	2	.30	3	0.45	2	0.30
Replaceability	0.30	3	.90	3	0.90	5	1.50
Total			2.90		3.00		3.70
Rank		3		2		1	

Using these scores, the design that was shown in Figure 7 was chosen. These fin bracket specifications can be observed in Figure 8.

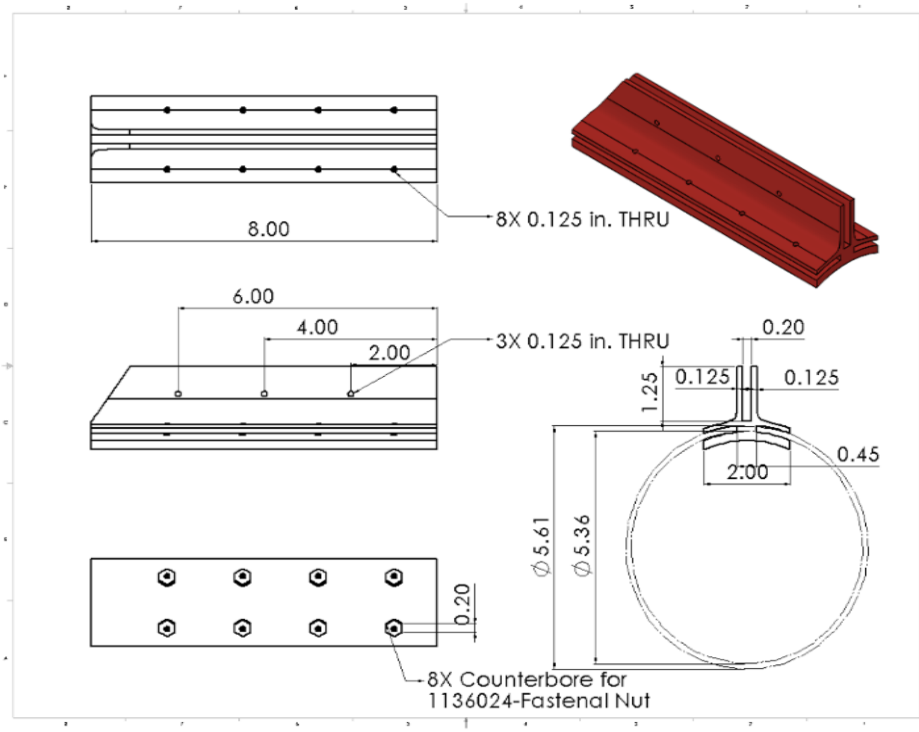


Figure 8. Fin bracket dimensional drawing

The brackets are counterbored for a Fastenal nut used with a ⅛ in. bolt. The nut was epoxied into the counterbore prior to assembly. This securing method ensures sufficient compression between the bracket and airframe and provide additional integrity. Since the fin brackets were a key structural component, they were 3D printed using ABS instead of PLA due to ABS's superior strength. The fin brackets withstood all flight and impact forces during fullscale test flight.

Fins

Three fins were designed to shift the center of pressure towards the aft end of the aircraft and increase the stability of the rocket. The fins will have a thickness of 3/16 in. to combat fin flutter, assist vehicle stability, and ensure structural integrity. These fins were fastened via nuts and bolts through the top section of the brackets. Figure 9 details the dimensions of the fin design.

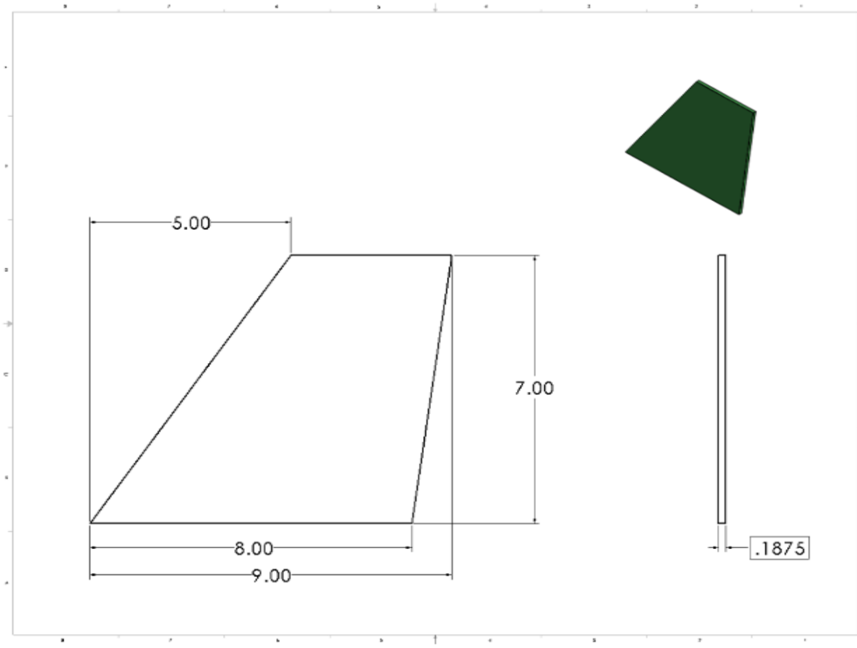


Figure 9. Fin Dimensions

The fins are composed of G10 Fiberglass due to its strength and aerodynamics. The fins were constructed by measuring the fins out on 3/16" fiberglass sheets. The measured fins were then cut out of the fiberglass sheets using a dremel with a cutting wheel accessory. Four fins were cut so that the best three fins could be chosen, and so that there was a spare fin in case of fin failure. These four fins were then sanded down to make them identical and bring them to exact specifications. The three chosen fins performed as expected during the fullscale test flight and absorbed direct impact forces during landing with no failure.

Fin Flutter Calculations

To maximize stability of the launch vehicle and prevent flight catastrophe, the vehicle fins must not flutter at any point during flight. The addition of fin brackets mitigates this issue by reducing the length of the fins that will experience bending. Using the fin flutter calculations from Apogee Components located in Appendix D: Apogee Rockets Fin Flutter, LTRL evaluated the critical airspeed that would result in fluttering of the fins. If the launch vehicle does not exceed this airspeed, the fins will not flutter. Using the geometry of the fin and bracket assembly, along with the material properties of 3/16 in G10 Fiberglass, the minimum airspeed to cause fin fluttering is V_f = 1032.5 ft/sec. The maximum velocity of the launch vehicle will not exceed 684 ft/s, thus fin fluttering will not occur.

Nose Cone Design

The nose cone is the forward most part of the rocket and is the first thing to experience drag. The nose cone should be as light as possible but also be as aerodynamic as possible. Two nose cone shapes were considered: 4:1 ogive and Von Karman. To decide which concept would be selected, a trade study was conducted. The full comparison of the ogive vs Von Karman can be seen in Table 6.

Table 6. Nose Cone Selection Matrix

		Ogive 4:1		Von Karman	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score
Availability	0.15	5	0.75	5	0.75
Cost	0.35	4	1.40	2	0.70
Drag	0.20	3	0.60	5	1.00
Mass	0.20	4	0.80	3	0.60
Total			3.55		3.05
Rank		1		2	

The ogive 4:1 nose cone with a metal tip was chosen and purchased from Apogee Rockets. There was a discrepancy between the actual measured weight of the nose cone and the weight of the nose cone given by the manufacturer's website. The actual weight of the nose cone ended up being 17 ounces heavier than the advertised weight. The nose cone withstood all aerodynamic stresses and impact forces during fullscale flight.

Separation Points

Separation points are where the rocket will separate during flight to deploy parachutes and the rover payload. There will be three separation points: two for parachute deployment and one for rover deployment. The separation point for drogue parachute is located between the booster and drogue body tube sections. The separation point for main parachute will be located between the main and payload body tube sections. These separation points were chosen so that one avionics bay would be sufficient for both drogue and main deployment. Attachment point strength was another huge factor, in which couplers were used to secure the attachment points. This allows for the force during deployment to be easily transferred to the body tube, which is preferred over relying upon the shear strength of epoxy to hold a bulkhead in place. The separation points chosen allows for the parachutes to be shot out of the body tube rather than shot into the body tube to further ensure proper separation and parachute deployment. The final separation point occurs at the nose cone to open a section of the rocket for the rover to exit. The rover deployment will separate the entire nose cone from the body tube instead of separating the nose cone from the nose cone shoulder.

An added benefit to the sectioning scheme that has been chosen is that each subsystem will have a dedicated section of the rocket to work on during launch day while being independent of the other subsystems. This will increase the efficiency of each subsystem and reduce assembly time on launch day.

Bulkheads

Bulkheads are used for attachment points of the parachutes and to contain the avionics bay within a coupler. ¼" plywood were used for attachment point bulkheads due to their cheap cost but reliable strength. Fiberglass bulkheads were also considered because of their superior strength but the drawback of the extra cost and mass of fiberglass bulkheads outweighed the benefit of their strength.

A selection matrix was created in which the plywood bulkhead was set to be the reference and the other option was compared to these values. Table 7 lists the scores and final rankings of these two options.

Table 7. Bulkhead selection matrix (plywood reference)

		Plywood (ref)		**Fiberglass**	
Attributes	**Weight**	Score	Weighted Score	Score	Weighted Score
Cost	0.30	3	.90	1	0.30
Mass	0.30	3	.90	1	0.30
Strength	0.40	3	1.20	5	2.00
Total			3.00		2.60
Rank		1		2	

The ¼" thick plywood bulkheads were chosen and purchased from Apogee Rockets. Attachment point bulkheads feature both an inner and outer bulkhead to both keep the assembly aligned concentrically with the tube and increase strength. One of these bulkheads lay on the outer edge of the coupler and the other bulkhead was sanded down to fit tightly within the coupler. The bulkheads are then attached together by the U-bolt attachment point and epoxied into the coupler using JB-Weld. The two bulkheads together help withstand parachute deployment forces and allow for more epoxy to be used in between the bulkheads and coupler. All bulkheads performed as expected without failure during fullscale test flight.

Centering Rings

The motor of the rocket must be held in place during flight to allow proper thrust of the vehicle. The motor tube is used to provide a space for the motor to be placed and must be properly secured in the rocket. Centering rings are used to attach the motor tube to the body of the vehicle to keep the motor in place during its operation. All motor retention designs that were considered use three centering rings placed equidistant from each other along the motor tube. These centering rings will act as an attachment between the motor tube and the body tube. The three materials considered for centering rings were plywood, fiberglass, and machined aluminum. The material of the centering rings was chosen through a weighted design matrix.

The following objectives listed in Table 8 are the criteria that will be used to compare the various centering ring designs. These criteria will be rated by the measures listed.

Table 8. Selected Criteria with appropriate weights

Objectives	Measures	Weight (1-5)
Structural Strength	Yield Strength (KSI)	3.5
Overall Weight	Density (oz/in^3)	2
Total Cost	$	2.5
Manufacturability	Time per centering ring (hrs)	3.5
Motor Retention strength	Available thicknesses of material in inches	4.5

Table 9 details the scores each material received for each objective on a scale of 1-5.

Table 9. Centering Ring Selection Matrix

		Plywood			**Fiberglass**			**Machined aluminum**		
Attributes	**Weight**		Score	Weighted Score		Score	Weighted Score		Score	Weighted Score
Structural Strength	3.5	4.5-6 ksi	2	7	30 ksi	5	17.5	40 ksi	5	17.5
Weight	2	.321 oz/in^3	3.5	7	.149 oz/in^3	4.5	9	1.5607 oz/in^3	1	2
Cost	2.5	$6.78	5	12.5	$8.98	3	7.5	$10.33	2	5
Manufacturability	3.5	0	5	17.5	0	5	17.5	.67 hours	2	7
Motor Retention strength	4.5	.25”	4	18	.14”	2	9	.25”	4	18
				62			60.5			49.5

There are three centering rings attached to the motor tube and to the body of the rocket with epoxy to keep the motor tube in place. The inner edge of the centering rings are epoxied onto the motor tube using JB-Weld, and the outer edge of the centering rings were then epoxied onto the body of the rocket using JB-Weld. The three centering rings are located 1 inch, 9 inches, and 17 inches from the aft of the motor tube. These equidistant positions allow the three centering rings to absorb equal amounts of force. The material used for the centering rings is plywood based on the trade study detailed above. This motor retention design was verified through fullscale test flight where the design performed as expected with no structural failures.

3.2 Recovery Subsystem

The components of the recovery system are the avionics board, the avionics bay structure, the parachutes and their corresponding harnesses, the altimeters, the faraday cage, and the method of parachute deployment.

Avionics Board

The avionics board is a 3D printed sled that slides into the avionics bay structure. It contains the altimeters and their independent corresponding power supplies. The avionics board is secured to the avionics bay structure when the door to access the avionics board is closed. This door ensures that the avionics board will not slide out of place. The avionics board and avionics bay structure have been printed from PLA. The club has successfully used this material for avionics boards and avionics bay structures for many flights. This avionics bay design was used and was successful in the fullscale test flight.

The avionics sled is shown in Figure 10. This is the first year that A&R will use an avionics bay that is accessible without having to completely disassemble the rocket. This will allow A&R to access the avionics bay easily to secure any loose wires or check any connections. This avionics bay was much faster to assemble that previous avionics bays during the fullscale test flight.

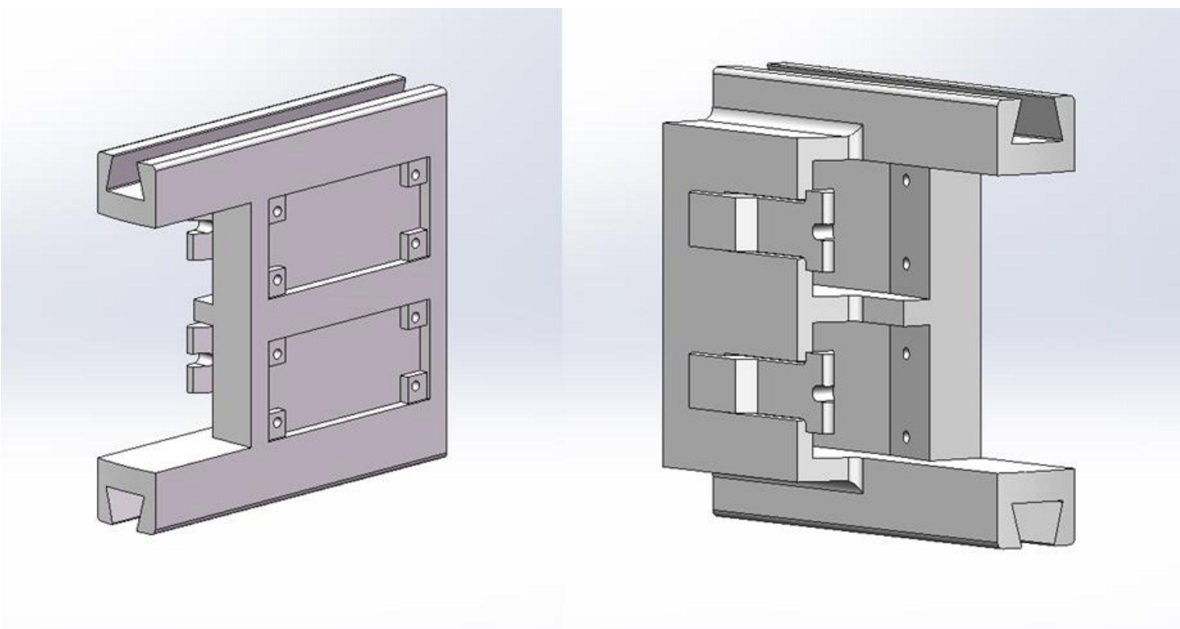


Figure 10. Altimeter Placement Area (Left), Battery Placement Area (Right)

Avionics Bay Structure

The avionics bay is situated within the coupler below the main parachute and above the drogue parachute. As shown in Figure 11, the avionics bay is the combination of the avionics board and the avionics bay structure. The AV bay is entirely 3D printed, using PLA filament. The AV bay is 6 inches tall, and the outer diameter of the AV bay will be the same as the inner diameter of the coupler. The AV bay has been epoxied and screwed into the coupler to ensure that it does not move during flight. The AV bay has a door that makes the interior accessible from outside the rocket without disassembling the AV bay. The door is cut from the outside body of the rocket, and can be screwed into the coupler, so that it is flush with the body of the rocket. The switches to turn on the altimeters are accessible interiorly. The door allows us to pull out the avionics board during assembly and when necessary. A full assembly of the AV bay is shown in Figure 11.

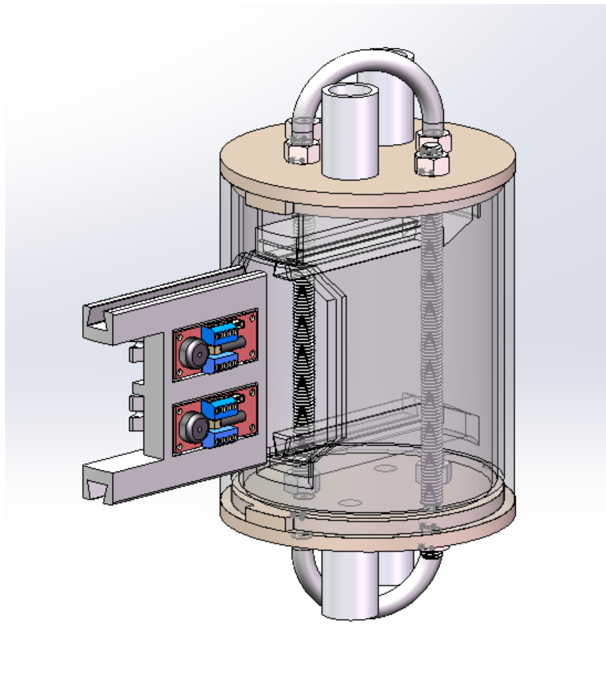


Figure 11. SolidWorks Rendering of Avionics Bay

The AV bay is also designed to hold a faraday cage, which is continuous around the sides, on the bulkheads, and in the door. The faraday cage slides between the anterior and interior walls of the AV bay. It is secured to the door and bulkheads so when they are screwed in, the parts of the cage on them will contact the part of the cage within the AV bay.

The bulkheads are made of plywood. While laser cut red oak would have been preferred, A&R was unable to do testing to verify the strength of the red oak. Plywood bulkheads have been used often in the past and have always been successful. Additionally, the plywood bulkheads were used during the fullscale test flight and were able to withstand the forces from the parachutes.

Avionics Bay Electronics and Charges

The avionics bay will feature two fully independent Stratologger CF altimeters. These altimeters have been successfully used for several flights and are commercially available. Each altimeter will be connected to an internally accessible switch.

The ejection charges will be black powder. Black powder has been used for every rocket flight for two years now and it has detonated every time. The reliability of black powder is what makes it so appealing to A&R. Each parachute has a primary ejection charge and a redundant ejection charge.

The primary drogue parachute charge will be 1.5 grams and the redundant charge will be 2.5 grams. The primary main parachute charge will be 2 grams and the redundant charge will be 3 grams. The redundant charges will detonate one second after the primary charges. The redundant charges have addition black powder to ensure the shear pins break at apogee or 700 ft ABG.

Parachutes and Recovery Harnesses

The drogue parachute will be a 12” Fruity Chutes Classical Elliptical and the main parachute will be an 84” Fruity Chutes Iris Ultra Compact. These parachutes were chosen using LTRL’s MATLAB code and verified using OpenRocket. The drogue parachute will deploy at apogee and the main parachute will deploy at 700ft ABG.

The parachutes are attached to each section of the rocket using 0.5” Kevlar cord. This cord is heat and fire resistant and more than sufficiently strong enough to withstand the forces of the parachutes and rocket during descent. The Kevlar cord is attached to each attachment point in the rocket and parachutes using ⅜” quicklinks. Both the Kevlar cord and the quicklinks were used in the USLI competition last year and were successful.

The main parachute will have a recovery harness of 27ft from the avionics bay coupler to the main parachute and 10ft from the main parachute to the forwards bulkhead. The drogue parachute will have a recovery harness of 24ft from the avionics bay coupler to the drogue parachute and 7ft from the drogue parachute to the booster section bulkhead. There will be two fireballs on the drogue parachute shock cords to reduce the likelihood of zippering. The lengths of the recovery harnesses should be sufficient to prevent zippering but the addition of fireballs with further guarantee it. Figure 12 shows a diagram of the planned descent including positioning of the sections during freefall and the location of the two events.

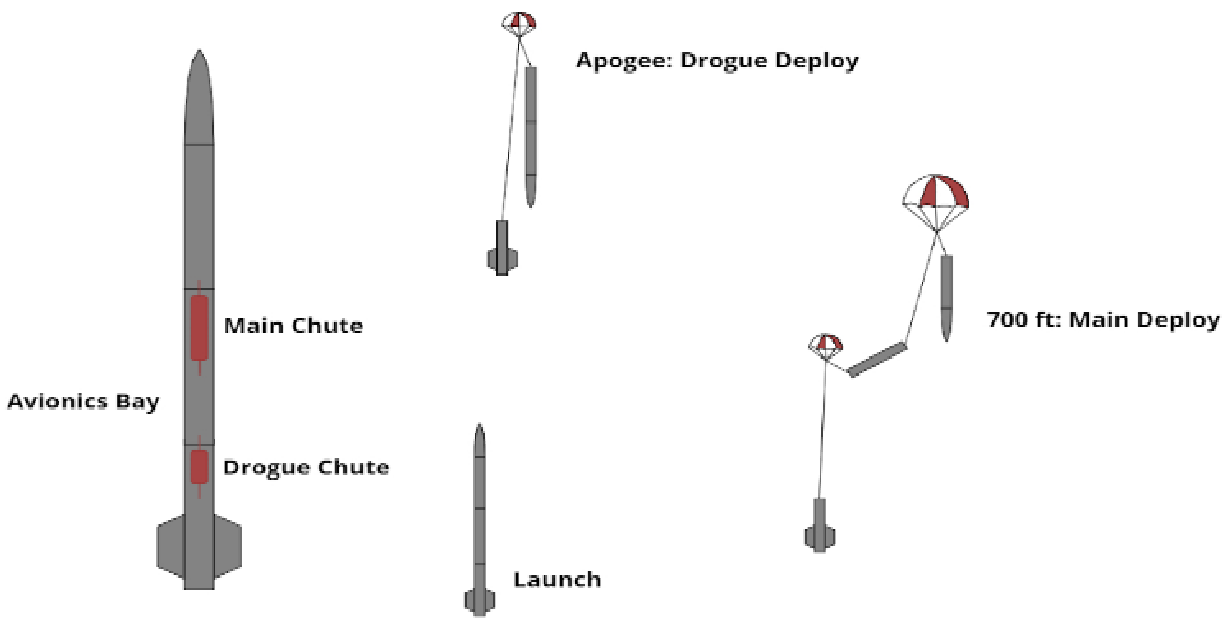


Figure 12. Parachute and Recovery Harness Diagram

Proof of Redundancy

The avionics system design includes multiple layers of redundancy. Primarily, there are two altimeters. Each altimeter is linked to its own separate main and drogue charge. Each altimeter is also powered by its own battery. Therefore, even with the failure of a battery, altimeter, initiator, or charge ignition in one of the systems, the other system is completely independent and should still operate correctly. The deployment charges are also staggered by one second so that they do not go of simultaneously, a precaution taken to avoid overpressure events. The redundancy allows LTRL to ensure that the parachutes will deploy and that the rocket will not have ballistic descent. The wiring diagram of this system is shown in Figure 13.

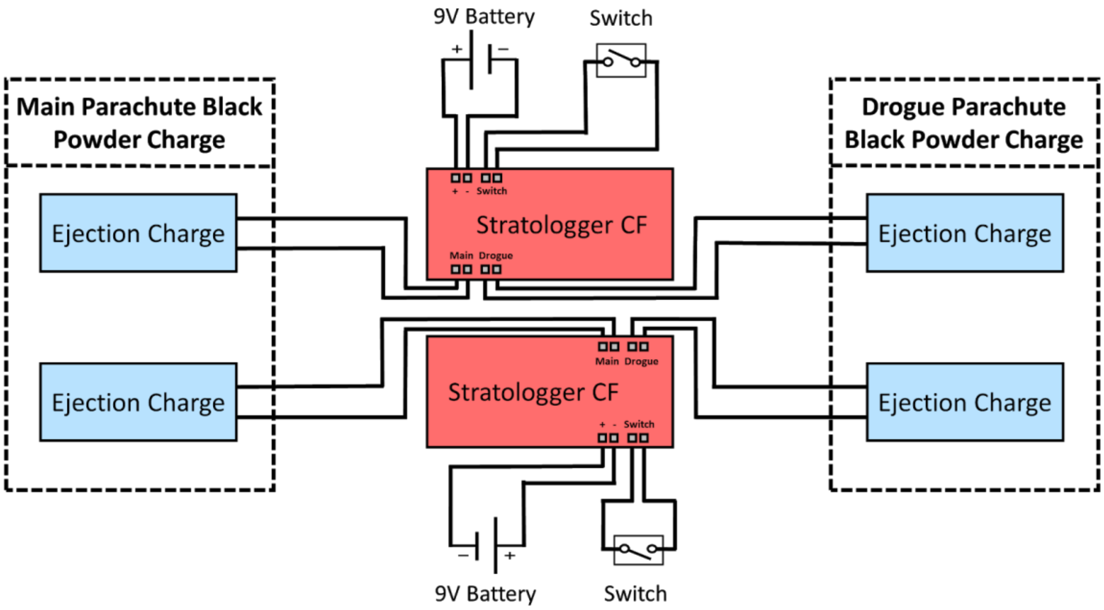


Figure 13. Wiring Diagram of Redundant Altimeters

Rocket-Locating Transmitters

The rocket will contain a Americaloc GL300W GPS transmitter. This transmitter uses an AT&T brand cell phone SIM card to relay its position and it operates at 850 MHz This GPS unit does not have any limitations on range since it uses cell phone service. Since this GPS unit actively sends out its position, all the electronics, especially the avionics electronics, will have a faraday cage. During the fullscale test flight, there were no problems with the GPS unit interfering with the rocket's electronics or any other surrounding rocket's electronics. The battery can last up to a week while turned on so LTRL is certain that the GPS unit will remain on all of launch day. The GPS contains an internal battery that can be recharged using a standard wall outlet. Hence, the GPS is not connected to any other electronic part in the rocket.

3.3 Mission Performance Predictions

Final Flight Vehicle

An OpenRocket model was created to simulate flight and vehicle characteristics. This model was used to calculate the static stability margin, the center of pressure (CP), and the center of gravity (CG). The CP is located 89.98 in. aft of the tip of the nose cone, and the CG is located 69.86 in. aft of the tip of the nose cone. The final flight vehicle has a diameter of 5.5 in., with a static stability margin of 3.6 calibers. The OpenRocket model is shown in Figure 14, with a breakdown of the component weights used within the model shown in Table 10. The target apogee of exactly 1 mile will be achieved through altering the rocket's mass very slightly via incorporated ballast, along with minor adjustments to the angle of the launch rail.

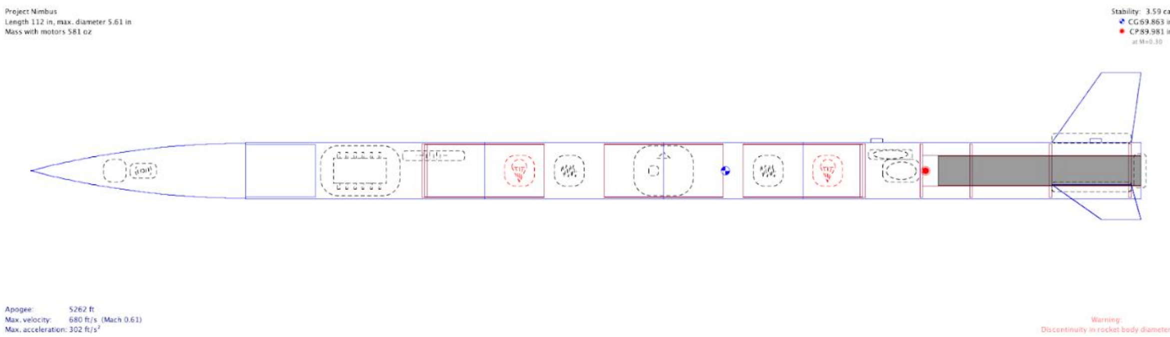


Figure 14. Fullscale OpenRocket Model

Table 10. Component weights

Component	Weight (oz)
Nose Cone	51.8
Payload Section	89.6
Payload-Main Coupler	17.4
Main Parachute Section	54.3
Main-Drogue Coupler	46.7
Drogue Parachute Section	37.6
Drogue-Booster Coupler	17.0
Booster Section	260.7

The simulated flight profile in average atmospheric conditions, detailing altitude, and vertical velocity versus time, are shown in Figure 15.

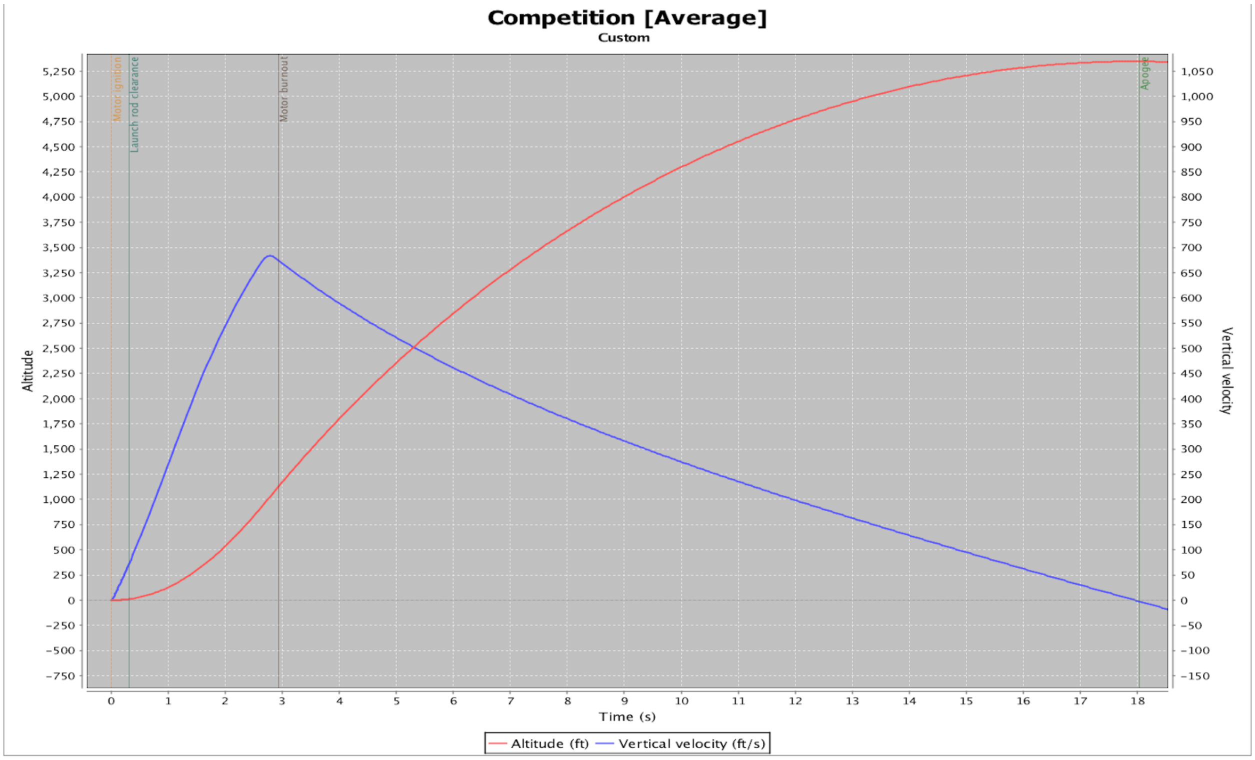


Figure 15. Flight characteristics with the L1390

It is shown in Figure 15 that a maximum velocity of 684 ft/s is reached just before motor burnout at 2.9 seconds and an altitude of approximately 3500 ft. This maximum velocity is well within the imposed limit of Mach 1 and occurs a safe distance from the launch pad. The rocket's velocity off a 10 ft rail is 71.5 ft/s, which is well above the imposed minimum of 55 ft/s and above the team's mission success criteria of 65 ft/s.

As in indicated in Figure 16, the stability off the launch rail is 2.6 calibers. This is above the team's mission success criteria and is indicative of a very stable flight, even in the low-velocity/low-altitude regime. As propellant mass decreases, the stability increases to approximately 4.5 calibers before leveling off around 4.35 calibers during the coast to apogee.

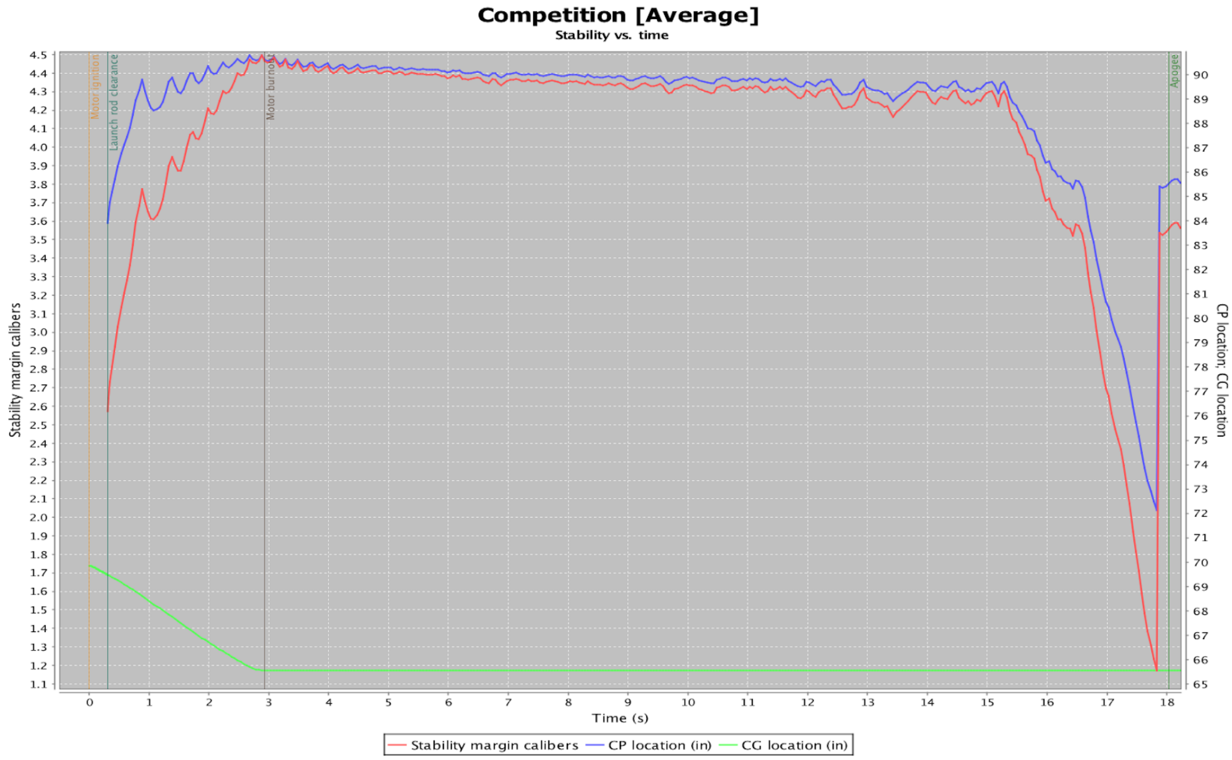


Figure 16. Stability Caliber for final flight vehicle

It is apparent that the thrust curve for the Aerotech L1390 motor has the necessary characteristics to achieve the minimum rail velocity for stable flight as the rocket leaves the pad. This was verified during the fullscale test flight through observational evidence and flight telemetry indicating that our minimum off-the-rail velocity was achieved.

Verification of OpenRocket

To verify the OpenRocket simulation results, the center of pressure, center of gravity, and flight apogee were calculated using MATLAB.

To calculate the center of pressure, the following calculations were conducted. First, the center of pressure of the nose cone, X_n, was calculated using Equation 1.

$$X_n = 0.466 * L_n \tag{1}$$

X_n is the location of the center of pressure for the fins as measured from the tip, and L_n is the length of the nose cone. The center of pressure of the fins was then calculated using Equation 2.

$$X_f = X_b + \frac{X_r * (C_r + 2 * C_t)}{3 * (C_r + C_t)} + \frac{1}{6} * \left(C_r + C_t - \frac{C_r * C_t}{C_r + C_t}\right) \tag{2}$$

X_f is the location of the center of pressure of the fins as measured from the tip, X_b is the length from the tip to the fin root chord, X_r is the length from the fin root leading edge to the fin tip leading edge, C_r is the fin root chord length, and C_t is the fin tip chord length. The coefficient for the center of pressure of the fins, C_{nf}, was calculated using Equation 3.

$$C_{nf} = 1 + \frac{R}{S+R} * \frac{4N\left(\frac{S}{D}\right)^2}{1 + \sqrt{1 + \left(\frac{2 * Lf}{C_r + C_t}\right)^2}} \tag{3}$$

Where R is the radius of the rocket body, S is the semi span of the fins, N is the number of fins, and L_f is the length of fin mid-chord line. The center of pressure as measured from the tip, X, was calculated using Equation 4.

$$X = \frac{C_{nn} * X_n + C_{nf} * X_f}{C_{nn} + C_{nf}} \tag{4}$$

Where C_{nn} is the coefficient for the center of pressure for the nose cone. The center of pressure was calculated to be 89.98 inches aft of the tip.

To calculate the center of gravity, cg, Equation 5 was used.

$$cg = \frac{d_n * m_n + d_p * m_{payload} + d_m * m_m + d_d * m_d + d_b * m_b}{M} \tag{5}$$

Where d_n is the distance from the center of mass of the nose cone to the tip, m_n is the mass of the nose cone, d_p is the distance of the center of mass of the payload section to the tip, $m_{payload}$ is the mass of the payload section, d_m is the distance of the center of mass of the main parachute section to the tip, m_m is the mass of the main parachute section, d_d is the distance of the center of mass of the drogue section to the tip, m_d is the mass of the drogue section, d_b is the distance of the center of mass of the booster section to the tip, m_b is the mass of the booster section, and M is the total mass of the rocket.

The center of gravity was calculated to be 68.99 in. aft of the tip.

To calculate the flight apogee, the altitude at which the motor burnout occurs must first be calculated. To calculate the burnout altitude, first the average mass, m_a, must be calculated. The average mass was calculated using Equation 6.

$$m_a = m_r + m_e - \frac{m_{prop}}{2} \tag{6}$$

Where m_r is the mass of the rocket without a motor, m_e is the mass of the motor, m_{prop} is the mass of the propellant. The aerodynamic drag coefficient, k, was calculated using Equation 7.

$$k = \frac{1}{2} * \rho * C_d * A \tag{7}$$

Where ρ is the density of air, C_d is the drag coefficient, and A is the cross-sectional area of the rocket. The burnout velocity, q_1, was calculated using Equation 8.

$$q_1 = \sqrt{\frac{T - (m_a * g)}{k}} \tag{8}$$

Where T is the average thrust of the motor, ma is the average mass of the rocket, and g is the gravitational constant. The burnout velocity decay coefficient, x_1, was calculated using Equation 9.

$$x_1 = \frac{2 * k * q_1}{m_a} \tag{9}$$

The burnout velocity, v_1, was calculated with Equation 10.

$$v_1 = q_1 * \frac{1 - \mathrm{e}^{-x_1 * t}}{1 + \mathrm{e}^{-x_1 * t}} \tag{10}$$

Where t is time at motor burnout. Finally, the altitude at which the motor burnout occurs, y_1 was calculated using Equation 11.

$$y_1 = -\frac{m_a}{2 * k} * \ln\left(\frac{T - (m_a * g) - (k * {v_1}^2)}{T - m_a * g}\right) \tag{11}$$

With the burnout altitude known the total altitude coasted can be calculated. To calculate the cost distance, the coast mass, m_c, must first be calculated. The coast mass was calculated using Equation 12.

$$m_c = m_r + m_e - m_{prop} \tag{12}$$

Where m_r is the mass of the rocket, m_e is the mass of the motor, and m_{prop} is the mass of the propellant. Next, the coast velocity coefficient, q_c, was calculated using Equation 13.

$$q_c = \sqrt{\frac{T - m_c * g}{k}} \tag{13}$$

Where T is the average thrust of the motor, g is the gravitational constant, and k is the aerodynamic drag coefficient. The coast velocity decay coefficient, x_c, was calculated using Equation 14.

$$x_c = \left(\frac{2 * k * q_c}{m_c}\right) \tag{14}$$

The coast velocity, v_c, was calculated using Equation 15.

$$v_c = q_c * \frac{1 - e^{-x_c * t}}{1 + e^{-x_c * t}} \tag{15}$$

The coast distance, y_c, was calculated using Equation 16.

$$y_c = \frac{m_c}{2 * k} * \ln\left(\frac{m_c * g + k * v_c^2}{T - m_c * g}\right) \tag{16}$$

Lastly, the flight apogee altitude, PA, was calculated using Equation 17.

$$PA = y_1 + y_c \tag{17}$$

The flight apogee altitude was calculated to be 5261 ft. The code used to calculate these values can be seen in Appendix C: Verification of OpenRocket Flight Calculations.

With the results of both simulation techniques, the team compared the two sets of results. A comparison to of the OpenRocket results and the MATLAB results can be seen in Table 11.

Table 11. Simulation Results Comparison

	OpenRocket	MATLAB
Center of Pressure (inches from tip)	89.98	89.49
Center of Gravity (inches from tip)	69.86	68.53
Static Stability (Calibers)	3.59	3.74
Altitude at Apogee (feet)	5256	5397

The results were very similar, yet not identical. This change is likely due to the estimated drag coefficient and initial launch angle being different. Our MATLAB model does not currently account for a launch angle greater than 0º, however the club is working on improving the model to include that capability. Despite this discrepancy, the two outcomes had a very low margin of error. To calculate the margin of error the following equation is used:

Margin of error = |(OpenRocket - MATLAB) / OpenRocket| * 100

The margins of errors can be seen in Table 12.

Table 12. Margin of Error

	Margin of Error
Center of Pressure	0.545%
Center of Gravity	1.90%
Static Stability	4.18%
Altitude at Apogee	2.68%

All the margins of error are less than 5%, this indicates that the simulations used in OpenRocket are highly accurate.

Kinetic Energy Calculations

LTRL's MATLAB rocket descent simulation program runs a recovery model in which the force balance between gravity and drag is integrated over time with separate phases for drogue and main. The model also assumes that the parachutes do not deploy instantaneously, but rather in a linear fashion, as the area increases linearly with respect to time until the deployment time is complete. The parameters of the parachute's coefficients of drag are based on both the manufacturer's specifications and the experimentally derived values. The experimental results are from previous USLI competition launches and they indicate that the manufacturer provided values for main parachutes are generous. This trend has lead LTRL to make conservative choices regarding the main parachute sizing as the coefficient of drag could lie anywhere between 2.0 and 2.2. This year's fullscale test flight was used to verify this concern through comparison of the actual flight data with the simulation. This comparison is shown in Figure 17 where the velocity during descent under both main and drogue parachute are seen to match very accurately that of the fullscale test flight. Therefore, the coefficient of drag used in the simulation, in this case a Cd of 2.2 was used, is accurate in predicting the behavior of the chosen 84" Iris Ultra Compact parachute.

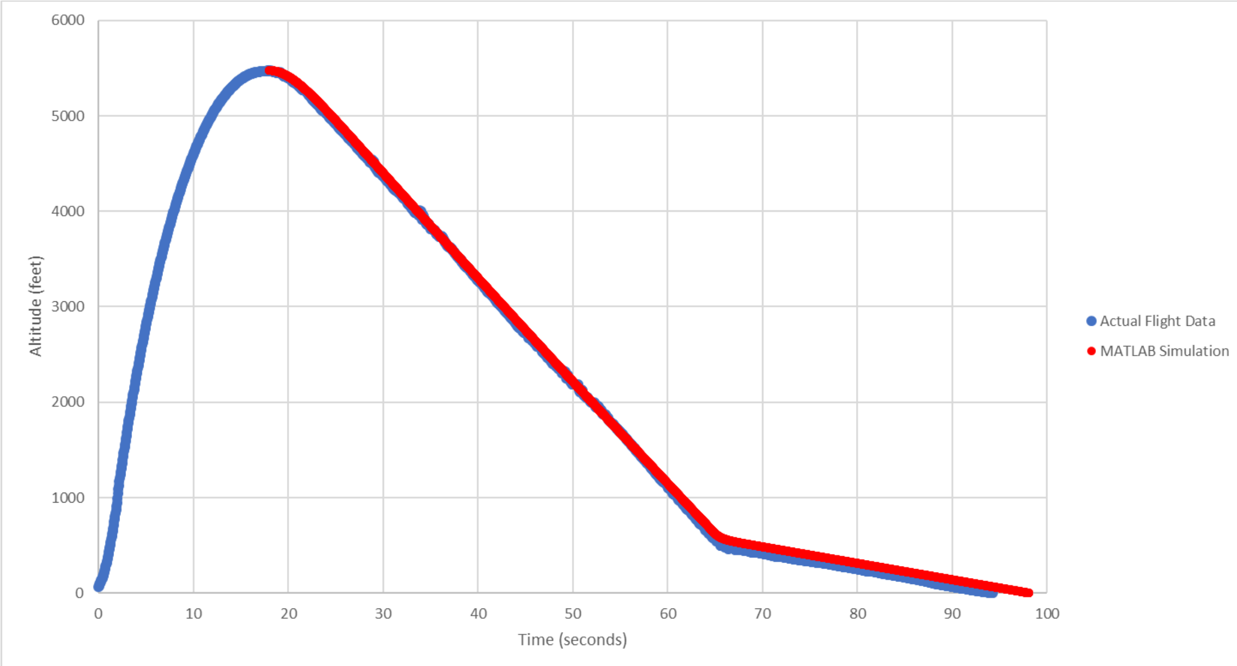


Figure 17. Descent slope comparison from Fullscale test flight results

To further verify that the chosen main parachute is adequate to meet kinetic energy requirements, the MATLAB simulation was used to generate a graph of expected kinetic energy at landing verses parachute size. Figure 18 shows this plot for main parachutes with a Cd of 2.2. Given the requirement to land at below 75 ft-lbs, an 84" main parachute is the best choice as it keeps us well below the kinetic energy limit as well as minimizes the rockets drift potential.

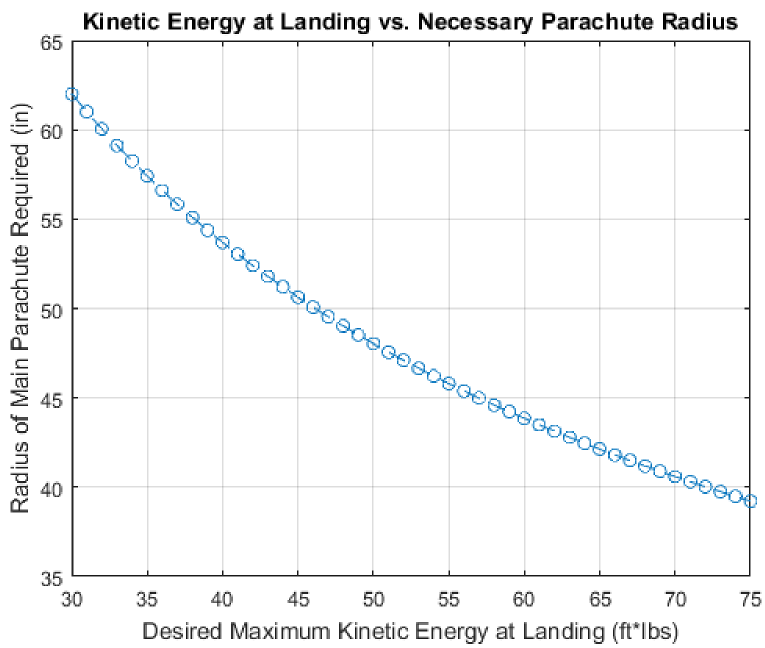


Figure 18. MATLAB Model of Kinetic Energy vs. Parachute Radius with CD = 2.2

The MATLAB simulation predicted a landing velocity of 17.32 ft/s with a coefficient of drag of 2.2. Calculations of kinetic energy can then be done by simply using the kinetic energy equation, which is a function of velocity and mass. Figure 19 and Table 13 show the kinetic energy of different sections of the rocket throughout descent using finalized flight vehicle masses. The booster section experiences the highest amount of kinetic energy due to its large mass. However, the predicted energy is only 60.91 ft-lbs, still significantly below the max energy allowed. The nose cone and avionics sections land with 47.57 and 26.4 ft-lbs respectively. These values are well below the max kinetic energy, providing he team with high confidence in our ability to land the rocket safely.

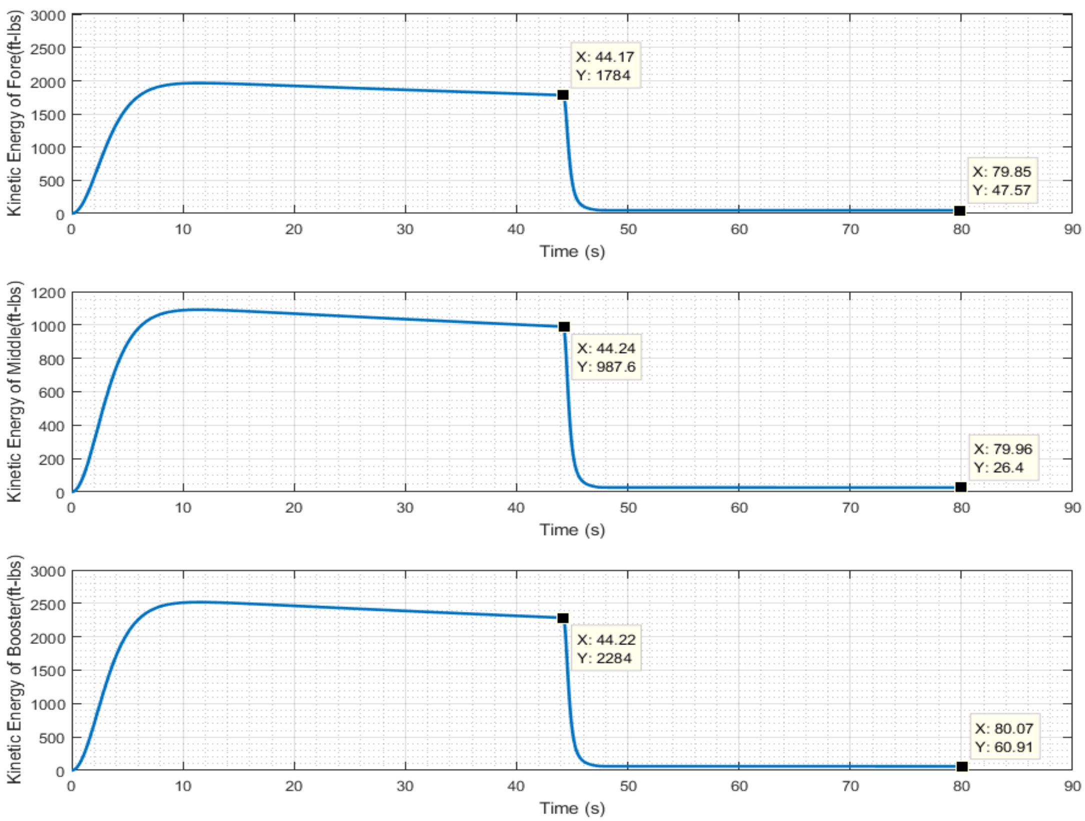


Figure 19. Kinetic Energy Plot during Descent

Table 13. Kinetic Energy of Parts During Descent Using a 2.2 Cd Main Parachute

Section	Mass (oz)	KE at Main Deployment (ft-lb)	KE Right Before Landing (ft-lb)
Nose cone	163.2	1784	47.57
Avionics bay	90.6	987.6	26.40
Booster	209	2284	60.91

This data can be further visualized in Figure 20. This figure shows the expected altitude and velocity vs time for a Cd value of 2.2. In addition, the accuracy of the model can be seen due to its ability to consider factors such as varying air density and parachute deployment speed. These can be seen by a drop in velocity during stable descent and a curved (non-instantaneous) change in velocity at main deployment.

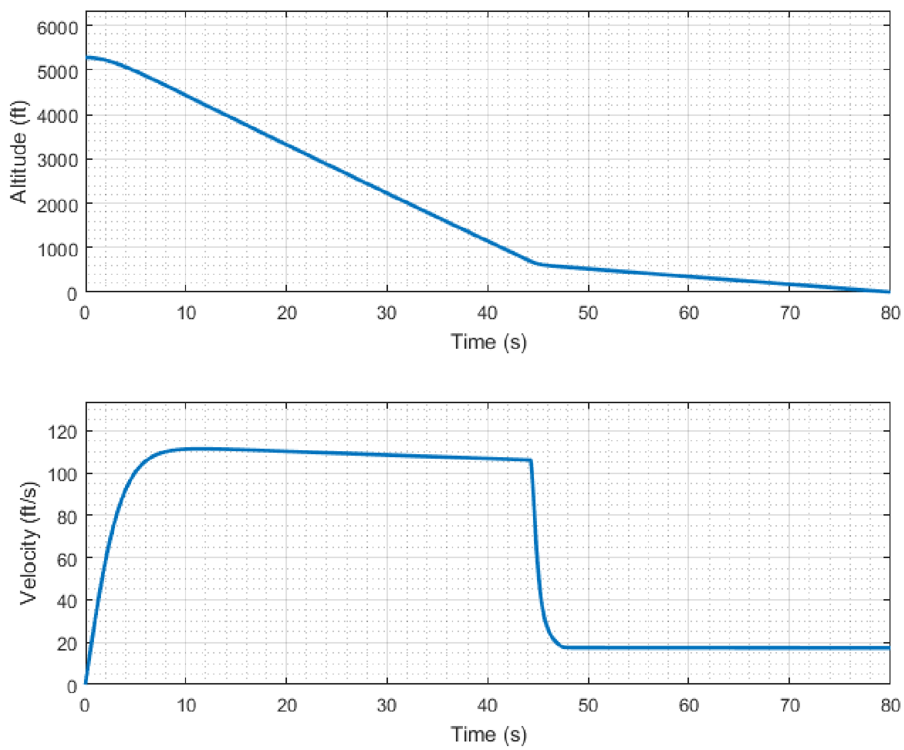


Figure 20. MATLAB Models of Descent and Altitude vs. Time with C_D = 2.2

A secondary method of determining kinetic energy is through OpenRocket's descent velocity predictions. This simulation used identical final flight masses, coefficient of drag values, and parachute sizes as the MATLAB simulation. A final landing velocity of 17.8 ft/s was calculated using this software and is very similar to the MATLAB simulation's 17.32 ft/s at landing. Calculations of kinetic energy can then be done by simply using the kinetic energy equation. The kinetic energy results for each section are shown following in Table 14 along with a comparison of the difference between the two simulations.

Table 14. Kinetic Energy upon Landing of Each Component

Section	Mass (oz)	Kinetic Energy (ft-lb) C_D = 2.2	Difference between MATLAB and OpenRocket (%)
Nose cone	163.2	50.25	5.333
Avionics bay	90.6	27.89	5.342
Booster	209	64.30	5.272

The conclusion has been reached that the predictions for descent speed and therefore kinetic energy differ because OpenRocket does not account for the drag of the rocket body while under drogue. This along with different integration techniques between the simulations accounts for the small difference of approximately 5 percent in landing velocity and kinetic energy. Using the most conservative estimates between these two simulations a maximum kinetic energy of 64.30 ft-lbs is seen. Using this value as our worst-case scenario, the rocket is still expected to land well below the required kinetic energy limit leading the club to have high confidence in the safety of our predictions.

Drift Calculations

The calculation for the drift of the rocket is straightforward in that it is just the product of the descent time and the wind velocity. The calibrated MATLAB simulation used the new predicted landing velocity, a drogue of 12”, and a main deployment height of 700 ft to calculate our maximum drift distance up to 20 mph winds. The drift distances at specific wind velocities are displayed in Figure 21. The coefficient of drag for this plot is 2.2, which results in the slowest descent time and therefore greatest possible drift distances.

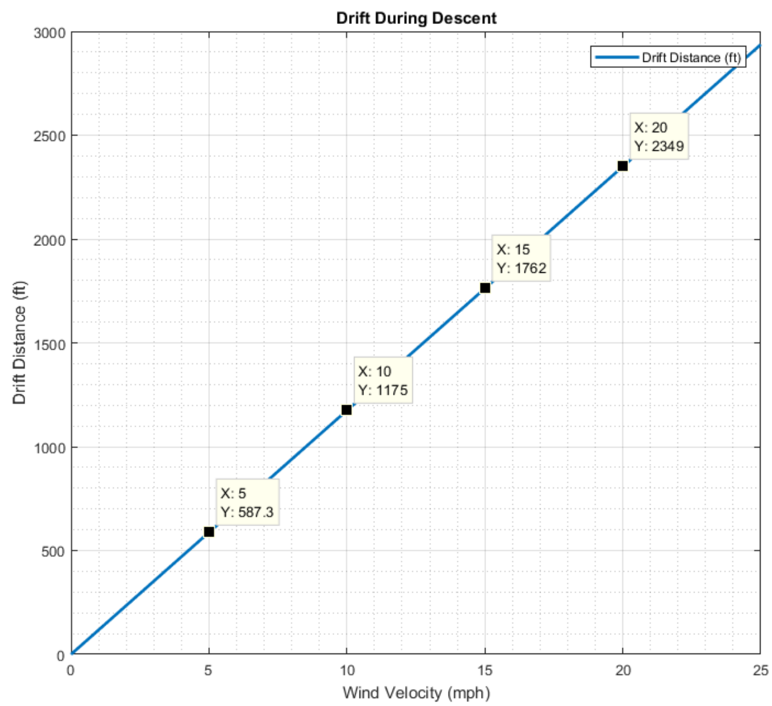


Figure 21. Drift Distance vs. Wind Speed for coefficient of drag of 2.2

Table 15 displays the information above in a table to quantify the expected drift distance at different wind speeds. The rocket is required to remain below a drift distance of 2500 ft and a wind speed of 20 mph. The MATLAB simulation, in which a Cd of 2.2 is used and the rocket body drag was corrected using fullscale flight data, results in a maximum drift of 2349 ft.

Table 15. Drift Speed of Rocket at Various Wind Speeds

Wind Speed (mph)	Drift Distance (ft) $C_D = 2.2$
0	0
5	587.3
10	1175
15	1762
20	2349

In conclusion, the club is highly confident in the rockets ability to remain below the drift limit. Only above 20 mph winds does the rocket approach the drift limit and for most launch day scenarios the rocket will not be launched near these conditions due to safety concerns.

3.4 Fullscale Test Flight Results

Launch Day Conditions

Weather conditions on the day of launch were very favorable. The air temperature was 47º F, the wind was averaging 7 mph primarily from the West, and there was little to no cloud cover. An OpenRocket simulation was run on the fullscale launch vehicle under these conditions, and the calculated apogee was 5419 feet. Figure 22 is a plot of simulated altitude and velocity versus time.

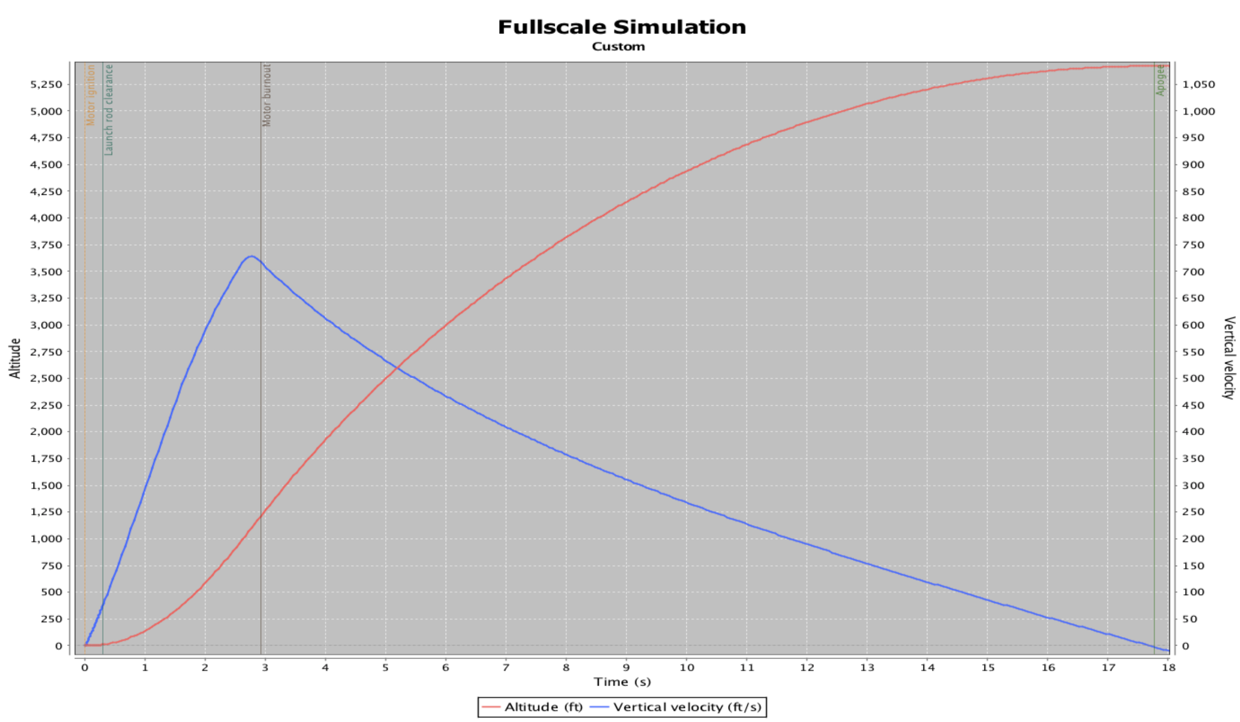


Figure 22. Simulated launch altitude and velocity versus time

This simulation matches our actual flight data very well, as our actual apogee was 5472 feet. Results this accurate validate that OpenRocket's simulation functions are very capable of reproducing atmospheric conditions and their effects on the launch vehicle. We will continue to use OpenRocket for atmospheric condition simulation.

Fullscale Flight Results

Fullscale launch went as projected with an apogee of 5472 feet, compared to the previously simulated 5419-foot apogee. This 1% error is well within the margins the team estimates for variations in upper-altitude winds and imprecise measurements of the launch rail angle. The smoothed flight data from the primary altimeter is shown in Figure 23.

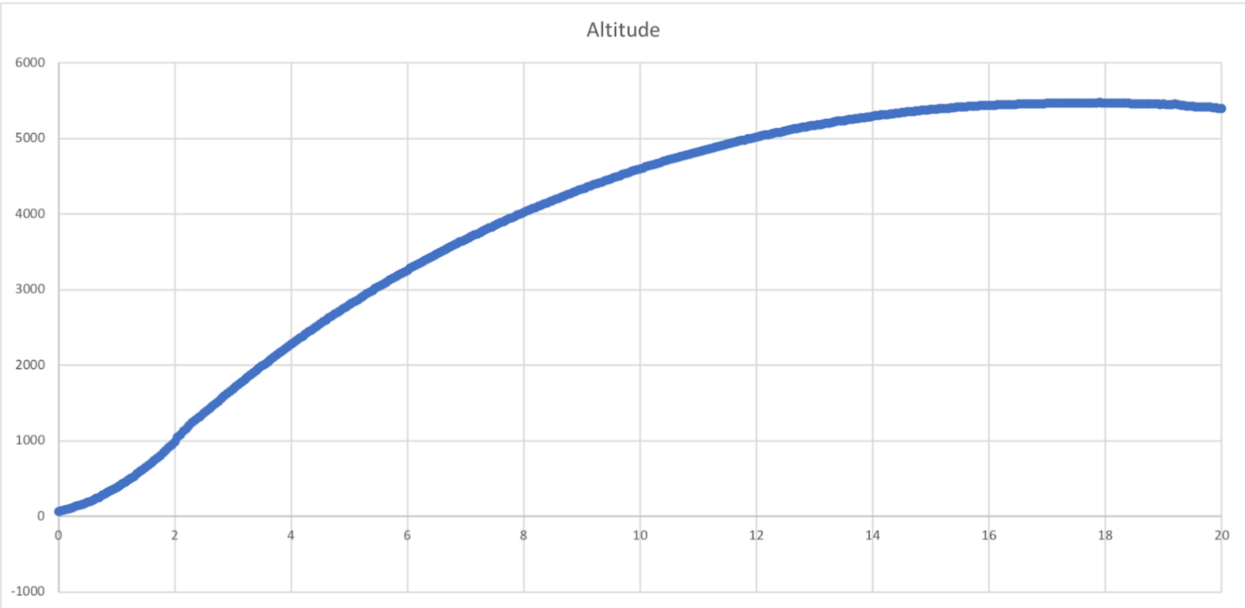


Figure 23. Smoothed Flight Data from Primary Altimeter

This data validates our OpenRocket and MATLAB simulations with respect to flight characteristics such as apogee and time to apogee. For second order flight characteristics such as velocity, the team relies on derivation from altitude data. This practice introduces a high level of noise into the data. This is demonstrated in the derived velocity results from this launch, which produced a maximum velocity of approximately 760 ft/s. This is 11% higher than the simulated maximum velocity of 684 ft/s. Considering the accuracy of the simulated apogee (1% lower than actual) and the simulated time to apogee (1.9% shorter than actual), the team believes that the derived maximum velocity is not a trustworthy enough value to validate our simulations.

Drag Coefficient Estimation and Post-Flight Simulation

To estimate the drag coefficient of our rocket, a MATLAB simulation was conducted. Using the component masses and apogee measured on the day of launch, the drag coefficient was adjusted until the simulated apogee matched the actual apogee to an accuracy of 0.2%. The drag coefficient that produced this result was 0.597. This drag coefficient very closely matches the drag coefficient of 0.600 that the OpenRocket program predicted.

Differences between Subscale and Fullscale

Both subscale and fullscale flights were successful in their aims to inform the team on the design choices made and validate those choices. Both flights were also accurately simulated before launch with OpenRocket and MATLAB.

One major difference between the flights was the launch operations procedures. During the subscale flight, assembly procedures were simplified drastically due to the lack of payload hardware present. But for fullscale, the structures team had to work closely with the payload team to ensure that all assembly procedures were carried out in the correct order.

Recovery Results

At apogee, the drogue parachute deployed with the primary ejection charge. The redundant charge also detonated but was not needed since the primary charge deployed. The rocket tumbled very little throughout descent and since there was little wind, it did not drift very much. The drogue parachute is small, so it is expected that there will be little drift and that the rocket will tumble some. The first part of descent went as expected.

At 700ft ABG, the main parachute deployed with the primary ejection charge. The redundant charge detonated as well but, again, was not the charge that ejected the parachute. The main parachute opened in about 2 seconds and did not tangle. The jerk of the main parachute opening caused parts of the rocket to swing around and minor zippering on the booster coupler. This will be prevented in future flights by adding two fireballs to the drogue parachute recovery harness.

LTRL was able to visually confirm that all ejection charges detonated during descent however, the rocket was still approached with caution. The A&R lead confirmed that the charges all detonated. The altimeters performed as expected and did not have any voltage issues or pressure issue. The porthole was sufficiently large for the altimeters to gather data. The rocket drifted less than 700ft from the launch pad which is reasonable given the launch conditions of a 5-degree launch angle and 7 mph winds.

Figure 24 demonstrates the predicted altitude versus time for the original model. This estimate was created using the drag of the body tube of last year's USLI rocket. This model has the body of the rocket as an 8" parachute with a Cd of 0.5. That rocket had slightly different dimensions, so it was not accurate. The model predicted a faster descent under drogue than actually happened during flight, but the total predicted flight time was close to the total actual flight time. The model inaccurately estimated the drag of the rocket due to tumbling throughout descent. The descent rate under the main parachute is comparable in the model as the actual fullscale test flight. Overall, the original model was moderately accurate but needed to be improved.

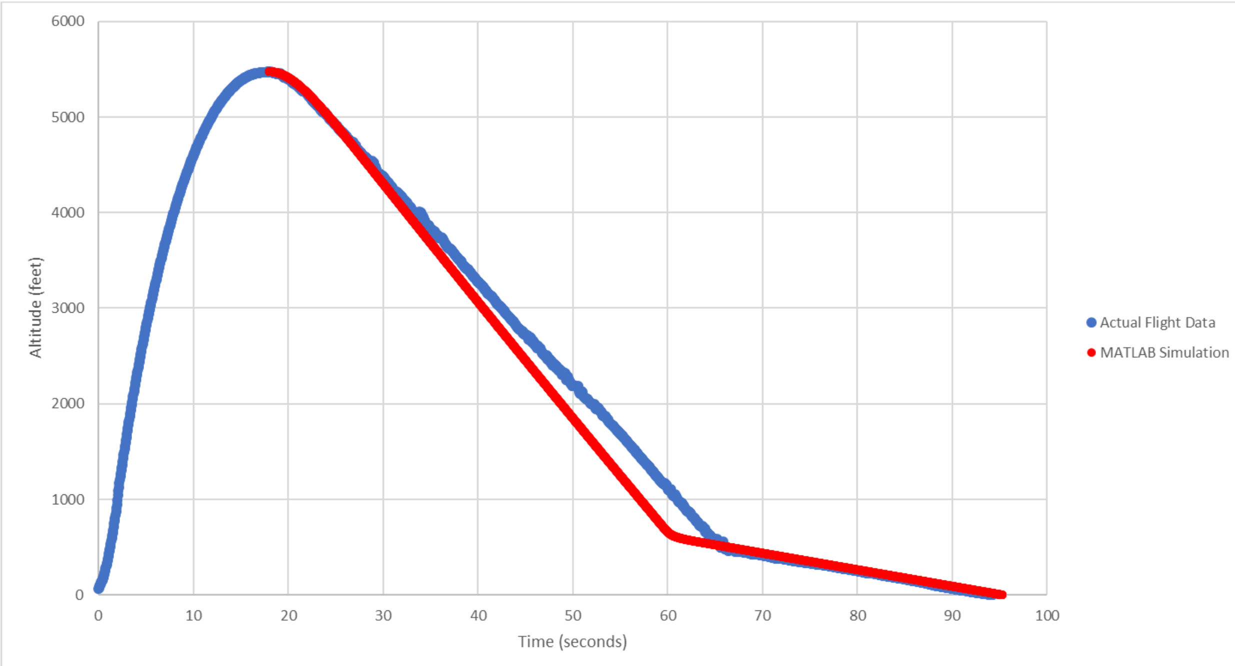


Figure 24. Pre-flight simulation compared to actual data

Figure 25 shows the corrected model that was created using the actual flight data. This model is much more precise and accurate to flight data. This model has the body of the rocket as a 10.5" parachute with a Cd of 0.5. The rate of descent under drogue and main parachutes are modeled accurately. The only part that has slight error is the total descent time. However, the error is very minimal, and the other parts of the model are accurate and precise.

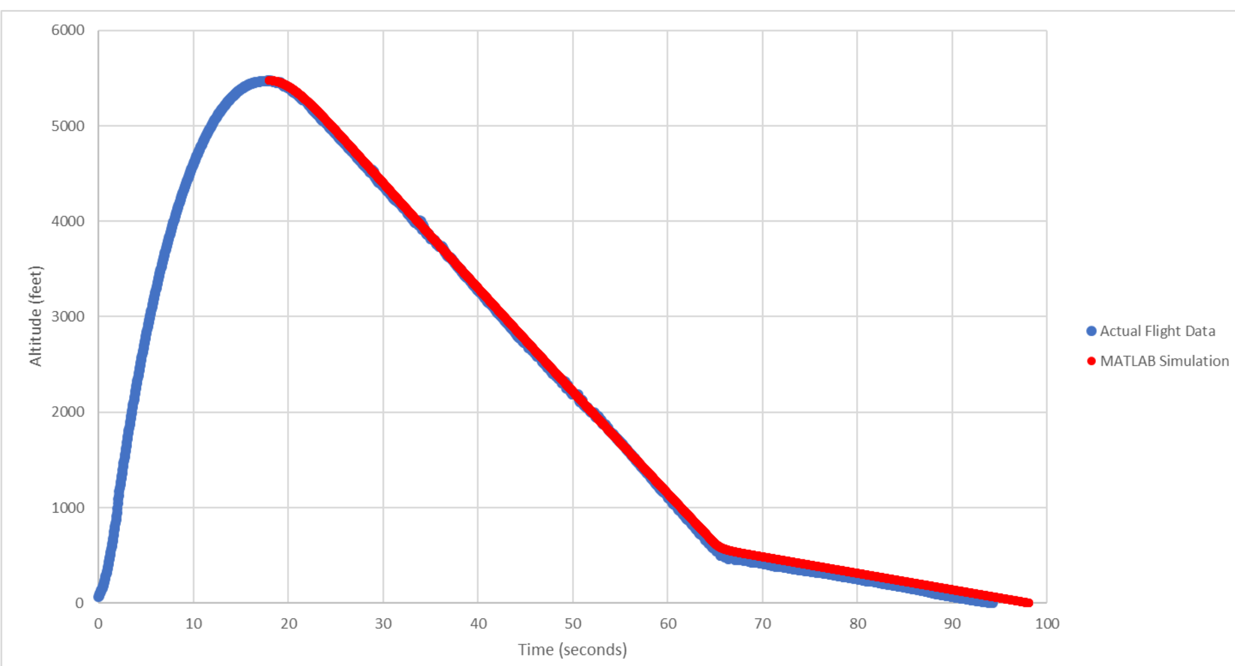


Figure 25. Post-flight simulation using corrected rocket body drag

Using the new, more accurate model, the kinetic energy of each section of the rocket was calculated as shown in Figure 26. The kinetic energy of each part of the rocket while only drogue is deployed is very large. However, once the main parachute is deployed, each section has a kinetic energy of less than 75 ft-lbs. The forwards section of the rocket lands with a kinetic energy of 46.83 ft-lbs. The middle section of the rocket has the lowest landing kinetic energy at 25.96 ft-lbs. The booster section has the highest landing kinetic energy at 59.95 ft-lbs. Every section is well below the 75 ft-lbs requirement.

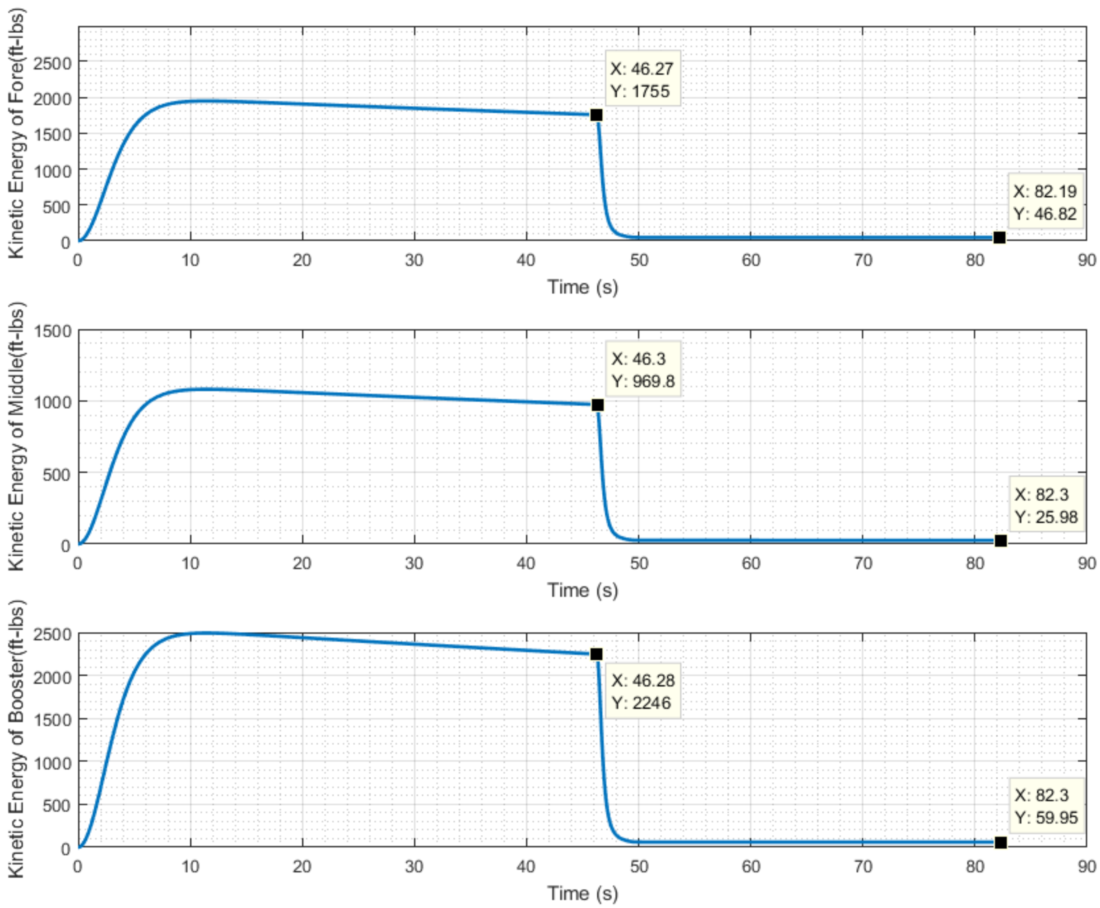


Figure 26. Post-flight simulation of KE seen during fullscale test flight

Rover Retainment Mechanism

The retainment mechanism was tested during fullscale flight to ensure that the rover will remain in place during competition launch. The rover was non-functional for flight; however, equivalent ballast was included inside of the rover body to simulate the expected final weight. The rover body was held in place through connection of an eyebolt to the shelves, keeping the rover from moving during flight. The shelves also performed as expected in holding the rover in place and were structurally strong enough to ensure the stresses apparent during flight.

4. Payload Criteria

4.1 Design Changes since CDR

The design of the rover body has been slightly modified since CDR. The design submitted in CDR did not consider the thickness of the ultrasonic sensor; the sensor would not have fit in the previous body. The new design adjusts the position of the wheel interfaces so that the ultrasonic sensor can fit comfortably inside the body.

Additional mounts were added inside the rover to support the electronics. Incorporating mounts organizes the electronics components and ensures that the limited space is maximized and that the electronics are secure during flight. Mounts for the motors were also modified to take up less space on the inside of the rover. Adding space was necessary to ensure all the components fit inside of the body.

The solar panel deployment mechanism was modified so that the panels can be retractable via servo motors. In CDR, the panels were designed using a spring-loaded mechanism that would not have allowed the solar panels to retract once deployed.

4.2 Unique Features of the Payload

Structural Elements

Unique structural elements include custom mounts for electronics, motors, and ultrasonic sensors. Custom wheels and chassis were also designed. The mounts, wheels, and chassis have all been constructed using additive manufacturing techniques. Specifically, these parts have been printed from PLA plastic, a material that the club has had a lot of experience and success with. Figure 27 below shows a rendering of one of the wheels.

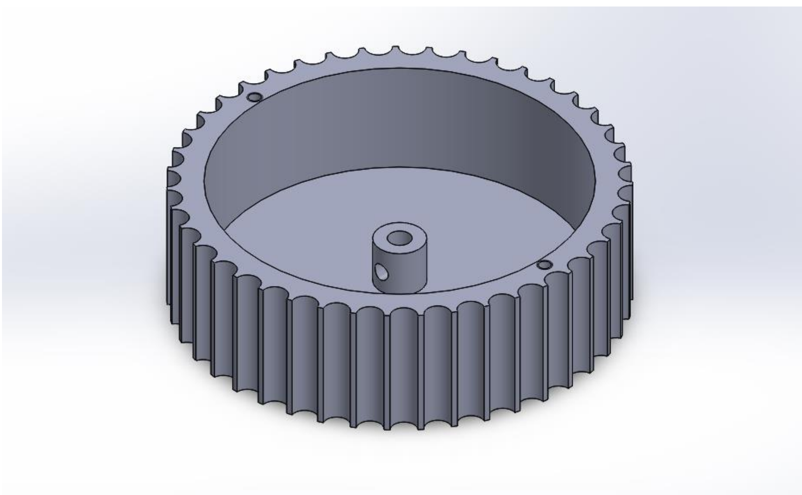


Figure 27. SolidWorks Rendering of Rover Wheel

The wheels are coated in a liquid rubber to create more friction between the wheels and the ground. Liquid rubber was chosen to increase friction because of the smooth nature of the PLA plastic. The ridges on the wheels allow for better grip and allow the rover to climb obstacles more easily. The holes shown on the edge of the wheel are for a detachable hubcap. The hubcap is mounted to the wheel so that it can rotate as the rover moves. A rotating hubcap allows for additional grip while driving and creates more points of contact with the ground when the rover is tilted. The center piece shown in Figure 27 acts as the connection point between the wheel and motor. This cylinder has a hole for a set screw so that the motor's axle can be firmly attach to the wheel. By extruding the center piece inside of the wheel, 0.5 inches is conserved on the width of the rover. The extra 0.5 inches allowed for space to add the hubcaps.

Figure 28 below shows the body of the rover. On either side of the rover are the slots for the solar panels to deploy from. The boxes on the outside of the rover are slots for the motors to sit. The hole at the front of the rover is for the mounting device to keep the rover in place during flight. An eyebolt will be placed in the front hole, facing the rear of the payload chamber. A servo-controlled hook will then lock the rover into place. The rover also has a removable cover that will be screwed into the holes shown at the top left and top right in Figure 28 below.

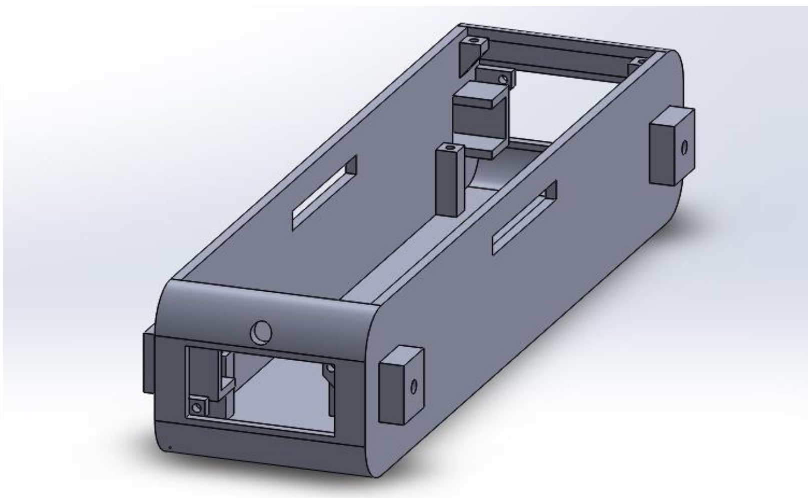


Figure 28. SolidWorks Rendering of final rover body

Figure 29 (left) shows the ultrasonic sensor as it will be mounted onto the outside face of the rover. There will be sensors on the front and back of the rover so that it is able to move in either direction and detect obstacles. The mounting surface was placed on the outside of the rover to allow for easy assembly. When the sensor was placed on the inside, it was difficult to get in and out of the body. Since there are various other components that must be inside of the rover, having the sensors on the outside allows the rover to be assembled quicker and easier. Figure 29 (right) shows how the motor fits into the body of the rover. The axle sticking out of the side is the attachment point for the wheel.

Figure 29. Ultrasonic sensor (Left), Installed motor (Right)

All mounts will be attached to the body of the rover using 0.1-inch screws. In Figure 29, the ultrasonic sensors can be seen attached to the rover at the bottom left and top right corners. Additionally, a board with custom mounts will be added to the center of the rover to hold all the electronics. Having an organized, custom, electronics board maximizes the space inside of the rover and makes the rover easier to assemble.

Figure 30 is a 3D rendering of the payload bay. The two notches shown at the top allow the rover to exit the launch vehicle without the wheels dragging on the top shelf. The notches were cut wide enough so that the body can rotate into the space below the shelf when exiting and so that the wheels can maintain contact with shelves. The system shown at the bottom of Figure 30 is the containment mechanism. A servo with a hook will be attached to the top of the shelf at the rear of the chamber. A breakaway wire will be connecting the Arduino and the servo so that the rover can communicate to the servo. Once the rocket has landed and the CO2 mechanism has separated the rocket, the servo mechanism will unlock the rover from the eye hook. When the rover is unlocked and begins exit from the launch vehicle, the servo wire will detach from the rover. The two vertical parts on the end of the payload bay are to keep the rover constrained.

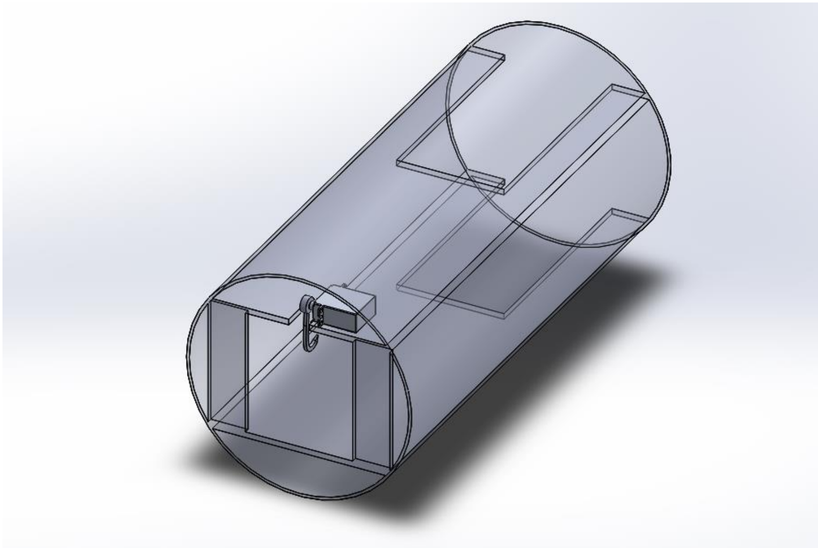


Figure 30. SolidWorks Rendering of built payload bay

The material being used for the shelves is 0.25-inch plywood and the 3D printed hook attachment is epoxied onto the servo arm.

Electrical Elements

The software flow diagram for the rover is shown in Figure 31 below.

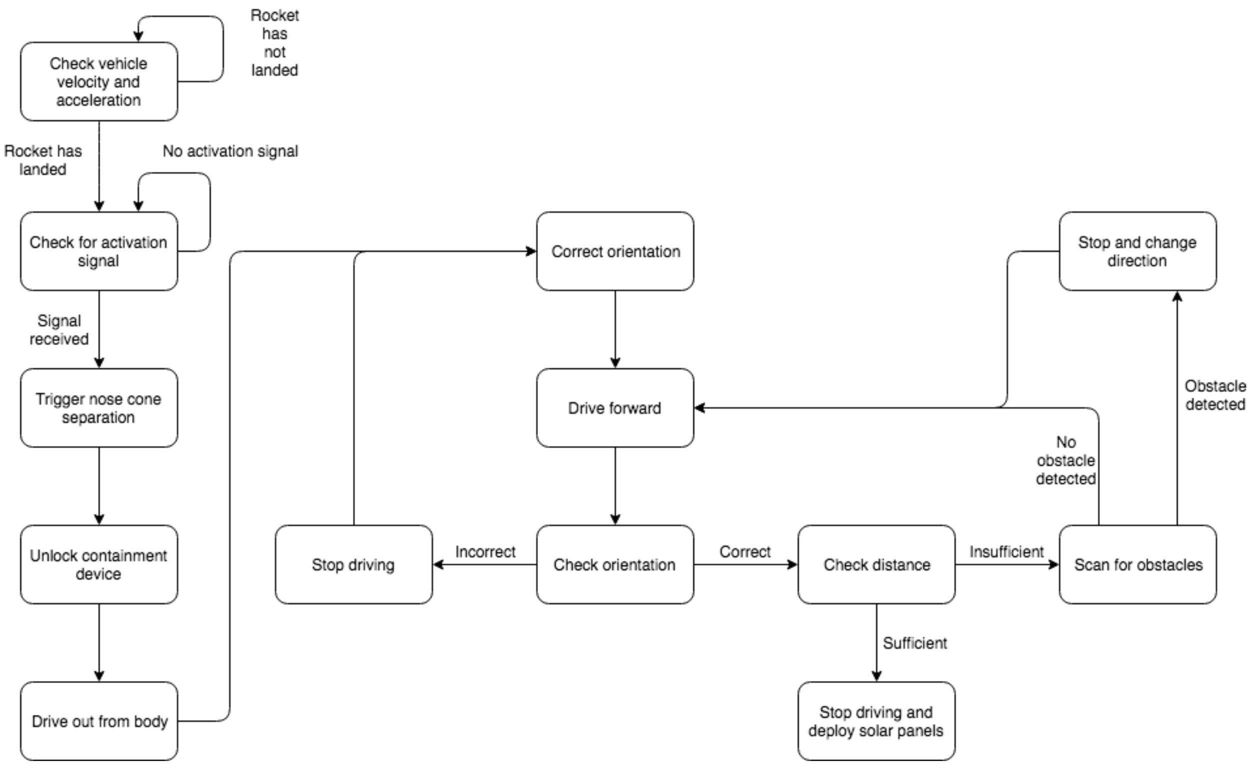


Figure 31. Software Flow Diagram for the Rover

When the rover is first powered on, it immediately begins monitoring its acceleration and velocity. When the rover detects that the rocket is in flight (marked by high acceleration and velocity), it will wait for the rocket to land (marked by near-zero velocity and acceleration), then begin listening for an activation signal to be sent from the ground station. Once the signal is received, the software activates the initiator to detonate the CO_2 charge and separate the nose cone from the rest of the rocket. After separating the nose cone, the software will then proceed to unlock the containment mechanism keeping the rover secured to the rocket and drive out from the interior of the body, correcting its orientation after exiting if needed. Since the rover only has passive corrective mechanisms (the hemispherical hubcaps), correcting orientation only involves waiting for the rover to settle on the ground due to gravity. After correcting its orientation, the software will continuously check its orientation, check the distance travelled from the rocket, and scan for obstacles. If the software detects that it has flipped, it will wait for the self-righting mechanisms to correct its orientation before resuming driving. If the software detects that it has travelled the appropriate distance, the rover will stop driving and deploy its solar panels. If the software detects an obstacle in the path of the rover using the ultrasonic sensors, the rover will change direction and resume driving again. The electrical schematic for the electronics on board the rover is shown in Figure 32.

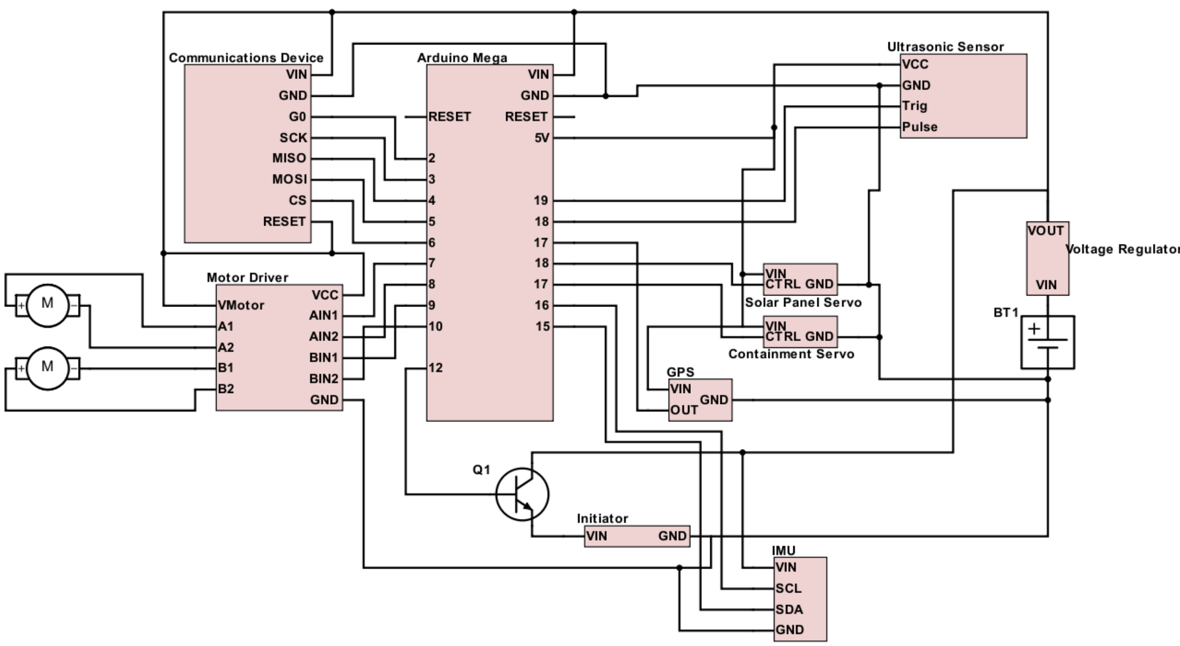


Figure 32. Electrical Schematic on board the Rover

Rechargeable batteries are providing power to all components. The four motors, used to power the wheels, are connected to the corresponding motor drivers, which is in turn wired to 4 pins on the Arduino microcontroller. The number of pins required was the primary factor in deciding to use the larger Arduino Mega instead of the smaller Arduino Nano. All power coming from the battery travels through a voltage regulator to ensure that sensitive electronic components are not subject to voltage spikes which may damage them. A digital LED display on the regulator allows the output voltage to be calibrated to the required value. To reduce the payload weight, a decision was made omit a switch from the circuit design and simply unplug the battery when the rover is not in use.

4.3 Flight Reliability Confidence

Testing has been conducted with the CO2 mechanism to ensure that the rocket separates once landing. This included multiple ground ejection tests using various sizes of CO2 cartridges. Results from these tests have concluded that a 25-gram CO2 cartridge is required to break the eight shear pins used to connect nose cone to the payload chamber.

The communications system has been range tested to ensure that the ground station can send the signal for the rover to detonate the CO_2 ejection charge. This system has been tested to a range of 0.75 miles**,** which is more than sufficient as our max drift distance is 2500 ft. Various forms of testing have been conducted in the lab to ensure that the communications system and moving parts of the rover are operational. These types of tests include verifying operation of the motors and servos, verifying that the code operates the electronics in the correct way, and verifying that the various components of the rover all operate well together.

The rover is designed to meet the given distance criteria with allotted room for error. To make sure that the rover meets the minimum distance requirement, the rover is programmed to reach a distance greater than the minimum distance. The GPS unit being used is accurate to approximately 5 feet and the minimum distance from the rocket is 5 feet. Therefore, the chosen distance for the rover to travel is 15 feet to allow for error.

To ensure that the solar panels will deploy, the rover is coded to deploy the solar panels once it has reached the chosen distance from the launch vehicle. In case the rover becomes immobile before reaching the designated 15 ft, the rover is programmed to deploy solar panels after multiple attempts to continue moving. This is important because if the rover gets stuck during movement, the solar panels must be deployed before the entire battery life is used. Testing has been conducted to make sure that all of these electrical components integrate together and perform as designed.

4.4 Payload Construction

The first part of the rover constructed was the code for the various maneuvers that the rover needs to make. This project was taken on first because it can be easily changed and was more abstract than the physical parts of the rover.

The first part of the rover that was manufactured was the wheels. The wheels were manufactured using PLA plastic with a 3D printer. The wheels were constructed first to begin testing with the motors to ensure correct sizing and integration between the wheels and the electronics. The hubcaps were also printed and mounted to the outside of the wheels with screws. Set screws are used on the inside of the wheel to attach the motor's axle.

Once the rover body was 3D printed, motors were placed into the motor mounts and the axles were screwed into the wheel's set screws. The electronics board was then screwed into the mounts on the inside of the rover. The electronics board shown in Figure 33 holds the Arduino, batteries (underneath), GPS unit, accelerometer, communications system, and servo. There is space on top and underneath the board for components to be placed for easier organization. This also helps to maximize the space being used on the inside of the rover. Once all the components of the rover are assembled, there is a cover that is screwed on top to protect the electrical components. Figure 33 below shows the current rover as constructed.

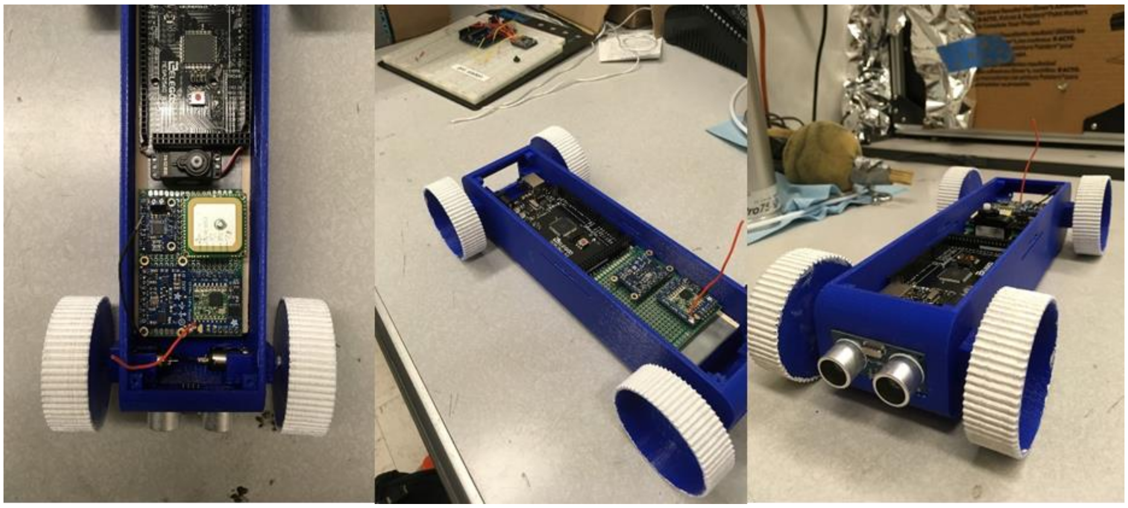


Figure 33. Images of as-built rover

Because most of the parts of the rover were printed on a 3D printer, the dimensions of the as built payload match the dimensions of the SolidWorks models. Figure 34 below shows a drawing of the rover body.

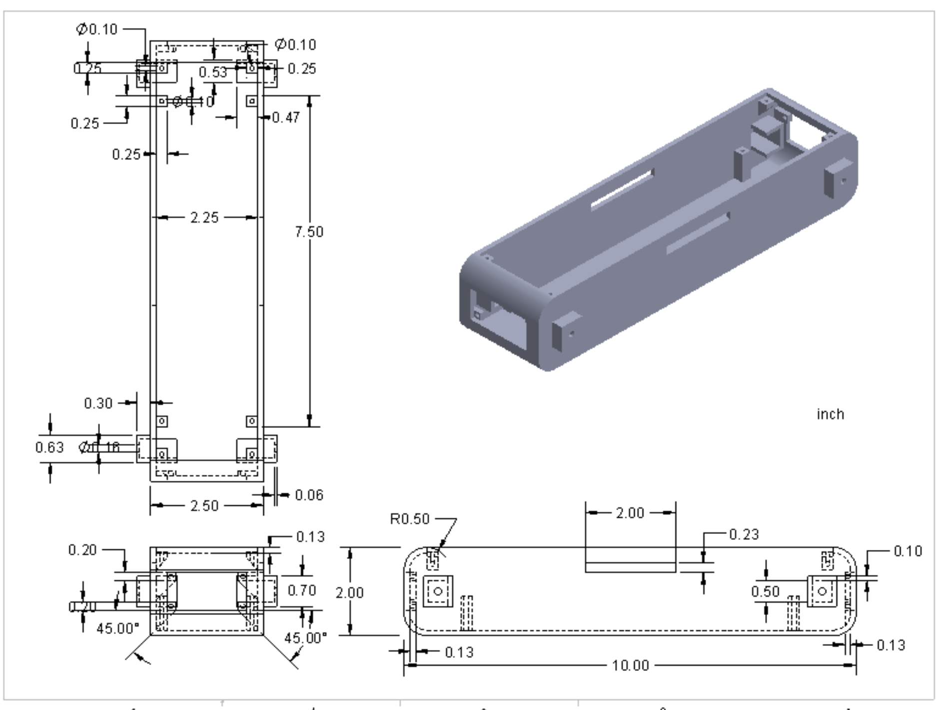


Figure 34. SolidWorks Drawing of Rover Body

Figure 34 shows that the rover's body is 10 inches long with a max width of 2.5 inches and a height of 2 inches. The rover's dimensions were designed to fit exactly between the shelves of the payload bay. Creating a tight fit for the rover minimizes the amount of movement inside the rocket during launch and descent. Figure 35 below shows a drawing of one of the wheels. The wheels are coated in liquid rubber to increases the coefficient of friction between the PLA plastic and the ground.

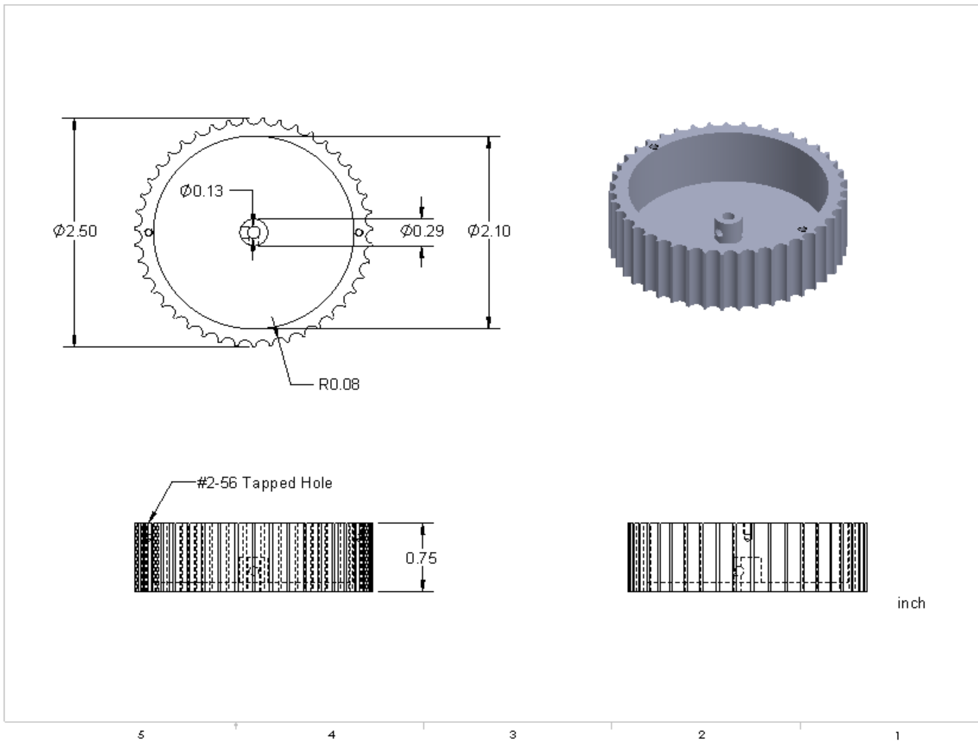


Figure 35. SolidWorks Drawing of 3D printed Wheels

The wheel was designed with grooves to increase the gripping ability of the rover when climbing obstacles. There is also a hollow cylinder for a set screw on the inside that matches the length of the motor axle. The cylinder and set screw allows for a firm attachment of the wheel to the motor axle.

Figure 36 below shows a drawing of the removable hubcap. The reason the hubcaps were made removable is because it allows for easy closing and access to the inside of the wheel where the set screw is. The cover protects dirt from getting into the wheel with the axle and allows the rover to have more rotating points of contact if it tips over.

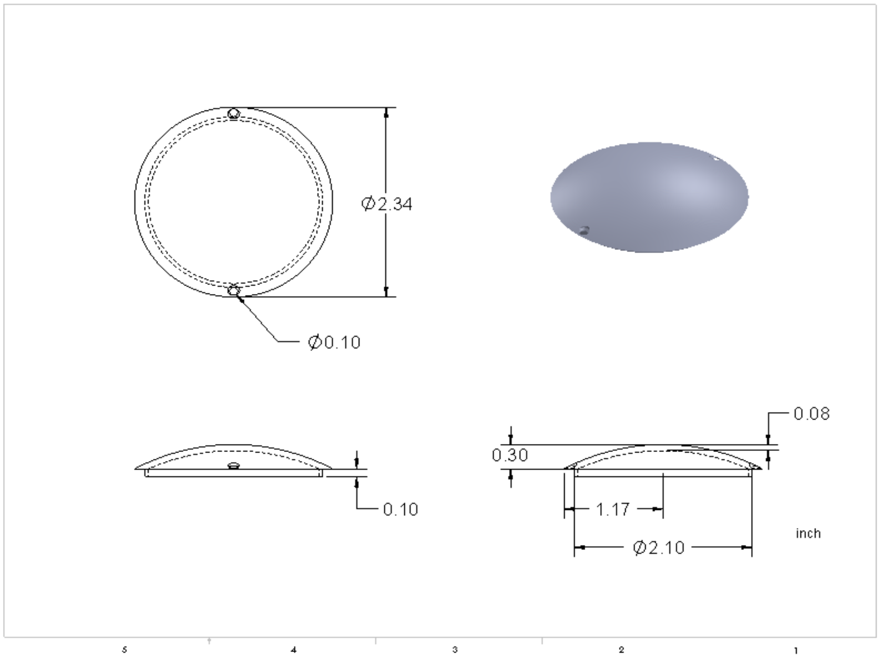


Figure 36. SolidWorks Drawing of 3D printed removable Hubcap

The lip seen on the bottom of the hubcap is to allow for a better fit of the hubcap onto the wheel. As all the parts shown above, the hubcaps are 3D printed using PLA plastic.

4.5 Differences in Constructed Payload

During the construction of the payload, various design changes needed to be made due to unforeseen problems. The earlier model included a solid exterior body with no extrusions for any of the components. Due to size constraints, the motors and ultrasonic sensors needed to be moved to the exterior of the body. Moving these pieces opened room inside of the rover and made it easier for construction.

The solar panel design was originally a spring-loaded system built on the outside of the rover. The spring-loaded design saved space because it had no parts internal to the rover, however it was not retractable, so a rotating arm design replaced the spring-loaded design. Additionally, the spring-loaded design was taking up more space and was more complex than anticipated. The rotating servo arm decreases the chance of failure and simplifies the design.

Modifications were also made to the shelves that hold the rover in place. The geometry of the rover stopped it from exiting smoothly, so notches were cut out of the shelves to prevent the rover from scraping against the top shelf in the bay while exiting the vehicle.

The wheels were modified multiple times throughout the design process to account for different size constraints. Having the axle go into the wheel was a modification to allow the body of the rover to be wider and maximize width. Maximizing width has its benefits in that it gives more space for more components and it also constrains the rover in another direction of motion. Reducing motion from side to side during flight decreases the chance that the rover gets damaged.

5. Safety

LTRL understands that there are inherent dangers in building and flying high powered model rockets. In the safety plan below, LTRL outlines the risks identified, and the preliminary steps taken to mitigate them.

5.1 Safety Officer Responsibilities

The person responsible for drafting and maintaining the LTRL safety plan is the Safety Officer. During the 2017-2018 project cycle, the Safety Officer is Laura Reese. The safety officer's responsibilities are as follows:

- Monitor team activities to ensure safety during design, assembly and ground testing of the rocket and payload.
- Monitor team activities to ensure safety during subscale and fullscale launches and recoveries.
- Monitor team activities during launch day to ensure safety.
- Manage and maintain current versions of the team's hazard analyses, failure modes analyses, and Safety Data Sheet (SDS) data.
- Manage and maintain a database of the Penn State safety certification status of all club members.
- Write and develop the team's hazard analyses.
- Assist in the writing and development of the team's failure modes analyses.

5.2 Safety Statement

LTRL will comply with all National Association of Rocketry (NAR), Federal Aviation Authority (FAA) and National Fire Protection Association (NFPA) regulations pertaining to high powered model rocketry. For convenience, and to help ensure the safety of LTRL members and the general public, LTRL will only launch at NAR or Tripoli Rocket Association certified club launches. LTRL and its members will comply with all instructions and guidance issued by the Range Safety Officer (RSO) of these launches. LTRL and its members will also comply with all instructions and guidance issued by the RSOs at the USLI launch in Huntsville.

5.3 Lab Safety

Design and construction of the rocket requires use of power tools, such as a Dremel and drill, as well as use of chemicals, primarily epoxies. These create hazards, which can be mitigated by wearing proper personal protective equipment (PPE), as well as exercising caution and proper shop safety. To foster a "safety-first" attitude, and to educate members about proper chemical safety, basic laboratory safety, and proper use of PPE, all members are required to take safety training that is offered through Penn State's Environmental Health and Safety (EHS). In addition, safety and emergency equipment is available to LTRL members in the lab and at launches.

Safety Training

All LTRL members are required to take a four-part Initial Lab Safety and Hazards Awareness training course offered online by Penn State's EHS. The course consists of four training videos: Introduction to Safety, Chemical Safety, Hazardous Waste Management and Disposal, and

Emergency Preparedness. Each training video concludes with a quiz. Members must score at least an 80% to pass that portion of the training. The website then generates a certificate, which is submitted to the Safety Officer. LTRL Members who have already completed the initial course can take a refresher course instead. The refresher course is also offered online, in a similar training video format. Members must score an 80% to pass the quiz at the end of the video, and are then issued a certificate, which is submitted to the Safety Officer. The Safety Officer keeps an electronic database recording which members have completed their safety training. The Safety Officer also keeps physical copies of all members' safety certificates in a binder that is stored in the lab. Subsystem leads are notified about which members are not compliant with the Safety Training requirement. Members who have not completed safety training are not allowed to work in the lab.

Safety and Emergency Equipment

Safety glasses, dust masks, and gloves are available in the LTRL lab. They are also brought to launches and used as necessary. In case of an emergency, a first aid kit is available in the lab. Fire extinguishers, both dry chemical and CO_2 types, are available in the hallway directly outside of the lab.

Launches and Motor Handling

For the LTRL subscale rocket, a J-class motor was used. The fullscale rocket will use an L-class motor. The rocket motors are purchase, handled, and transported by the club president, who has NAR Level 2 certification. They are stored in the High Pressure Combustion Lab (HPCL) when not in use. The HPCL has storage magazines for H/D 1.1 and H/D 1.3 energetic materials and propellants. These magazines are sited, licensed, and operated in compliance with all local, state, and federal regulations.

LTRL does not currently hold its own launches. Instead, the club attends launches organized by the Maryland and Delaware Rocket Association (MDRA) and the Pittsburgh Space Command (PSC). The PSC is an NAR registered club. Both launches require the presence of a member holding either Level 1 or Level 2 NAR certification, depending on the class of motor used.

Hazardous Materials

During the course of the project, construction and launching of the rocket will entail the handling and use of hazardous materials. Efforts to mitigate the risks posed by these hazards have been undertaken by the club.

Motor Storage

To reduce the risk of fires and explosions in the lab, all the motors LTRL uses are stored in the HPCL storage magazines.

Hazardous Materials Mitigations

LTRL maintains a chemical inventory, and SDS records for all hazardous chemicals used during the course of the project. The current list of chemicals and hazardous materials, the hazards that they pose, and the mitigations in place to lower the risk introduced by those hazards is given in Table 16. This list will be updated throughout the course of the project, if additional hazardous materials are used by LTRL during construction or launch operations. The hazards outlined in Table 16 are based on the hazards listed in SDS for each hazardous material. These safety data sheets are attached in Appendix A: MSDS Sheets.

Table 16. Material Hazards and Mitigations

Material	Hazards	Mitigations
JB Weld Professional	Causes skin and eye irritation	Wear protective gloves and eye protection. Wash hands thoroughly after working with epoxy.
JB Kwik	Causes skin and eye irritation	Wear protective gloves and eye protection. Wash hands thoroughly after working with epoxy.
Black powder	Explosions, fire, can also cause skin, eye, respiratory irritation	Protect black powder from flame, heat, and electrical discharge.
Fiberglass bulkheads	Skin and eye irritation, potentially severe respiratory tract irritation	Wear gloves, eye protection, and dust mask. Clear dust using a shop vacuum.
Carbon fiber wrapping	Airborne fibers can cause severe respiratory irritation. Electrically conductive airborne fibers can cause short circuits in electrical systems.	Limit airborne fiber production during machining operations. Wear a dust mask when machining carbon fiber wrapping.
Spray paint	Can explode or catch on fire. Causes serious eye irritation, skin irritation and serious respiratory tract irritation. Can be carcinogenic and is a narcotic when fumes are inhaled.	Paint only in a well ventilated area, preferably outside. Store cans away from any potential sources of heat or flame.
No. 2 Mystik high temp grease	No known hazards	Wear gloves while handling.
Talcum powder	May cause eye and skin irritation. Causes respiratory tract irritation which over long periods of time may lead to cancer.	Use only outside in well ventilated areas.

FibreGlast 2060 60 minute epoxy cure	Causes serious eye damage. Toxic if swallowed or inhaled. Can cause skin and respiratory tract irritation. Chronic exposure can result in harm to the liver, kidneys, eyes, skin or lungs.	Always wear gloves when applying the epoxy and epoxy cure.
FibreGlast 2000 epoxy resin	Skin and eye irritation	Wear gloves while handling.
Flexseal	Causes skin and eye irritation. Is a potential carcinogen	Wear gloves while handling.
Isopropyl alcohol	Can cause flash fire or explosion. Causes skin and respiratory irritation. Causes serious eye irritation.	Store away from potential sources of flame or heat.

5.4 Risk Assessment

To reduce the risks inherent in building and flying the rocket, the Safety Officer and Subsystem Leads have undertaken multiple risk assessments. These assessments outline personal risks to club members and environmental hazards. Failure modes of the rocket and its subsystems, their causes and effects and mitigations of these potential failures are also outlined. Lastly, risks to the overall project and club are outlined, along with mitigations of these risks.

In order to provide a scale of how hazardous each risk or failure is, the likelihood and severity of each risk were tabulated, and used to calculate a combined risk factor. This combined risk factor was then used to rank the risks or hazards within each table from most to least hazardous. The methodology used to assign numerical values to the likelihood and severity, and the methodology used to calculate and rate the combined risk factor is outlined below.

Personnel Hazard Analysis

The explanation below shows how the likelihood and severity values were assigned for risks to personnel.

Likelihood

1: The risk is highly unlikely. Over the historical legacy of the risk, it has never occurred. Mitigations have been put in place that would prevent the occurrence of the risk.

2: The risk is unlikely. Over the historical legacy of the risk, it has never occurred, but there may have been close calls, where the risk nearly did occur. Mitigations have been put in place that make the occurrence of the risk highly unlikely.

3: The risk is moderate. Over the historical legacy of the risk, it has occurred at least once. Mitigations have been put in place that make the occurrence of the risk unlikely.

4: The risk is likely. Over the historical legacy of the risk, it has occurred at least once during the course of last year’s project, or has recurred repeatedly in multiple years. Mitigations reduce the occurrence of the risk.

5: The risk is highly likely. Over the historical legacy of the hazard, it has occurred more than once over the course of a past project, or has recurred each year during the project's duration. Mitigations only nominally reduce the occurrence of the risk.

Historical legacy refers to the time period over which current active club members have been a part of the club. Some risks have long historical legacies, whereas others may have only begun to occur during this project cycle. If the design or procedure responsible for a risk has changed substantially, the likelihood for that risk also was changed to reflect the impact of the design or procedure on the risk's likelihood. The likelihood values also take into account the nature and efficacy of the mitigation designed to prevent the risk.

Severity

1: The risk is negligible. The occurrence of the risk would be barely noticeable to most club members or bystanders.

2: The risk is minimal. The occurrence of the risk could result in inconvenience to club members or bystanders.

3: The risk is moderate. The occurrence of the risk could result in minor injuries to a club member or bystander.

4: The risk is severe. The occurrence of the risk could result in moderate injuries to a club member or bystander.

5: The risk is very severe. The occurrence of the risk could result in severe injuries to a club member or bystander.

Severity and likelihood values were then added together to generate the combined risk factor. In Table 17 a combined risk factor matrix is given, which also ranks the combined risk factor as low, moderate, or high.

Table 17. Personnel Combined Risk Factor Matrix

	Likelihood					
		1	2	3	4	5
Severity	1	Low	Low	Low	Moderate	Moderate
	2	Low	Low	Moderate	Moderate	Moderate
	3	Low	Moderate	Moderate	Moderate	High
	4	Moderate	Moderate	Moderate	High	High
	5	Moderate	Moderate	High	High	High

The likelihood, severity and combined risk factor were then used to quantify the risks to personnel.

Risks to LTRL members were analyzed along with their causes, and effects, and the likelihood and severity and combined risk analysis were assigned to each of the risks. This work is shown in Table 18 below.

Table 18. Personnel Hazard Analysis Matrix

Hazard	Cause	Effect	Likelihood	Severity	Combined Risk Factor	Mitigation	Verification
Free falling debris generated during recovery system deployment hits personnel	Improper parachute deployment or linkages, structural failure of parachutes or parachute harnesses, no parachute deployment	Blunt force trauma, cuts or lacerations to the skin, eye damage	2	4	6. Moderate	All LTRL personnel will maintain a "heads-up" stance at all times while the LTRL rocket, or other rockets, are in the air. Planned trajectories are over the launch range.	The safety officer will ensure that LTRL personnel maintain a "heads-up" stance while rockets are in the air. The RSO and the safety officer will ensure that all launch angles are directed away from personnel.
Flying debris generated by explosives during launch operations hits personnel	Catastrophic explosions before or during liftoff	Cuts or lacerations to the skin, eye damage, blunt force trauma, burns	1	5	6, Moderate	All LTRL personnel will remain a safe distance from the pad, as determined by RSO. Only necessary personnel will go out to mount the rocket on the launch rail.	The RSO and the LTRL safety officer will ensure that no one approaches the pad too closely.
Free falling debris generated during rocket flight hits personnel	Structural failure during rocket flight, due to the forces experienced during launch and parachute deployment.	Cuts or lacerations to the skin, eye damage, blunt force trauma	2	4	6, Moderate	All LTRL personnel will maintain a "heads-up" stance at all times while the LTRL rocket, or other rockets, are in the air. Planned trajectories are over the launch range.	The safety officer will ensure that LTRL personnel maintain a "heads-up" stance while rockets are in the air. The RSO and the safety officer will ensure that all launch angles are directed away from personnel.

Electrical shock	Electrical shock from power tools or cords, electrical shock from extension cables	Deep skin damage from electrical burn, potential nerve damage, potential deeper tissue damage, can cause a heart attack	1	5	6, Moderate	Ensure all power tools and their cords and that all extension cords are well maintained and contain no exposed or frayed wires, or large nicks in the insulation	The safety officer will periodically check power tools and extension cords for exposed wires.
Trips and falls during launch and recovery operations	Uneven ground at the launch site	Cuts and lacerations, contusions, broken bones	2	4	6, Moderate	Exercise caution while retrieving the rocket	LTRL members will be advised to be cautious when retrieving the rocket.
Cuts and Lacerations from improper power tool usage	Improper use of power tools	Cuts and lacerations, potential serious injuries	1	4	5, Moderate	All instructions and best practices for the use of power tools will be followed. No one will work in the lab alone. Inexperienced members will always be guided by club members that are more experienced in machining protocols	Only subsystem leads and officers have access to the lab. Leads will remain in the lab at all times while general body members are working.
Eye irritation due to particulates	Eye exposure to irritating particulates	Discomfort, possible permanent eye damage	1	4	5, Moderate	Eye protection will be worn when members are cutting fiberglass or carbon fiber	LTRL personnel wear eye protection when cutting fiberglass or carbon fiber. Safety glasses are provided by the club.

Flying debris from cutting or drilling injures personnel	Flying debris is generated by machining operations such as drilling or cutting.	Cuts or lacerations to the skin, eye damage	1	4	5, Moderate	A safe distance between any member cutting or drilling material and everyone is maintained. Any member cutting or drilling material wears safety glasses.	LTRL personnel will notify anyone else in the lab before cutting or drilling material. LTRL personnel will wear safety glasses when cutting or drilling.
Fire in the lab injures personnel	Fire begins in the lab, or spreads from another portion of the building into the lab	LTRL members injured	1	4	5, Moderate	Maintain all electrical cables properly, greasy or solvent soaked rags will not be stored in the lab, e-matches will be stored away from flammable materials, only solvents needed for building the rocket will be stored in the lab, rocket motors will be stored in the HPCL. A fire extinguisher is located in the hallway directly across from the entrance to the lab.	The fire extinguisher is tested regularly by Penn State. The safety officer will ensure that no greasy or solvent soaked rags are stored in the lab. E-matches are stores in a separate box from all explosives, which are stored in an explosives rated box.
Trips and falls in the lab	LTRL member trips or falls because of obstacle in the lab	Cuts and lacerations, contusions, broken bones	1	4	5, Moderate	Keep extension cords and electrical cables coiled and placed under desks or tables, keep backpacks in the hallway when there are more than five people in the lab	The safety officer will ensure that all extension cords and electrical cables are properly stored and not stretched across the floor.
Respiratory irritation from particulates	Respiratory system exposure to irritating particulates	Discomfort, potential long term chronic illness	1	4	5, Moderate	Masks will be worn when members are machining hazardous materials. A shop vacuum will be used to limit the spread of the particulates.	Face masks are provided for LTRL personnel and will be worn by LTRL members while machining fiberglass or carbon fiber

Skin irritation from chemicals	Skin exposure to irritating chemicals	Discomfort, potential injuries, potential long term chronic illness	1	4	5, Moderate	Gloves will be worn when members are working with hazardous chemicals	Gloves are provided to LTRL personnel. Subsystem leads and the safety officer will ensure that LTRL members wear gloves when handling hazardous chemicals, such as epoxies.
Respiratory irritation from chemicals	Respiratory system exposure to volatile chemicals	Discomfort, potential long term chronic illness	1	4	5, Moderate	All operations utilizing volatile chemicals will be performed in areas with sufficient ventilation	All spray painting will be done outdoors. Subsystem leads and LTRL officers will ensure that the lab is well ventilated whenever solvents are being used in the construction of the rocket.
Black powder explosions during handling injure personnel	Black powder explodes or catches fire during measurement or transport operations	Burns and injuries from explosion	1	4	5, Moderate	No open flame, electrical spark or heat source will be used near the black powder operations	Black powder is stored in an explosives box. No smoking or open heat sources will be permitted at the launch sites.
Black powder explosions - while loaded in the rocket – injure personnel	Black powder charges explode prematurely, or explode after the rocket has landed	Burns, blunt force injuries from explosion and potential flying rocket debris	1	4	5, Moderate	Firing circuit will not be engaged until the rocket is on the pad, exercise "muzzle awareness" around both ends of the rocket after charges have been loaded, exercise "muzzle awareness" around both ends of the rocket until it has been determined by an A&R lead that all charges have deployed. Wait sixty seconds before approaching the rocket during ground testing of charges.	The safety officer will ensure that LTRL personnel maintain “muzzle awareness” around both ends of the rocket after charges have been loaded. An A&R lead will approach the rocket first to ensure that all charges have deployed properly.

Burns from motor retainers	Touching the motor retainer before it has cooled after launch	Skin damage, potentially severe	1	4	5, Moderate	Members will not approach the rocket for at least sixty seconds after the motor has been fired.	The safety officer will ensure that members do not approach the rocket for at least sixty seconds after the motor has been fired.
Skin irritation from particulates	Skin exposure to irritating particulates	Discomfort, potential injuries	2	3	5, Moderate	Gloves will be worn when members are machining hazardous material	Gloves are provided for LTRL personnel.

Environmental Hazards

One of the main environmental concerns includes the disposal of toxic substances, due to use of such substances in rocket construction. All toxic substances will be disposed in accordance with local laws and regulations by Penn State Environmental Health and Safety (EHS). During a launch, measures will be taken to minimize changes to the local environment due to the emission of hot, toxic gases from the rocket motor during launch.   A safe radius around the pad will be cleared of combustible materials. High winds during rocket flight could adversely impact the landing radius.

The explanation below shows how the likelihood and severity values were assigned for environmental hazards. In this analysis the environment includes both the biosphere (plants, animals, and microbes) and the physical environment (buildings, cars, etc.).

Likelihood

1: The hazard is highly unlikely. Over the historical legacy of the hazard, it has never occurred. Mitigations have been put in place that would prevent the occurrence of the hazard.

2: The hazard is unlikely. Over the historical legacy of the hazard, it has never occurred, but there may have been close calls, where the risk nearly did occur. Mitigations have been put in place that make the occurrence of the hazard highly unlikely.

3: The risk of the hazard occurring is moderate. Over the historical legacy of the hazard, it has occurred at least once. Mitigations have been put in place that make the occurrence of the hazard unlikely.

4: The hazard is likely. Over the historical legacy of the hazard, it has occurred at least once during the course of last year's project or has recurred repeatedly in multiple years. Mitigations reduce the occurrence of the hazard.

5: The hazard is highly likely. Over the historical legacy of the hazard, it has occurred more than once over the course of a past project or has recurred each year during the project's duration. Mitigations only nominally reduce the occurrence of the hazard.

Historical legacy refers to the time period over which current active club members have been a part of the club. Some risks have long historical legacies, whereas others may have only begun to occur during this project cycle. If the design or procedure responsible for a hazard has changed substantially, the likelihood for that risk also was changed to reflect the impact of the design or procedure on the hazard's likelihood. The likelihood values also consider the nature and efficacy of the mitigation designed to prevent the hazard.

Severity

1: The hazard is negligible. There is no noticeable effect on the environment or rocket.

2: The hazard is minimal. The occurrence of the hazard could result in a temporary effect on the environment or the rocket.

3: The hazard is moderate. The occurrence of the hazard could result in minor damage to the environment or to the rocket.

4: The hazard is severe. The occurrence of the hazard could result in moderate damage to the environment or to the rocket.

5: The risk is very severe. The occurrence of the hazard could result in severe damage to the environment or to the rocket.

Severity and likelihood values were then added together to generate the combined risk factor. In Table 19 a combined risk factor matrix is given, which also ranks the combined risk factor as low, moderate, or high.

Table 19. Environmental Combined Risk Factor Matrix

	Likelihood					
		1	2	3	4	5
Severity	1	Low	Low	Low	Moderate	Moderate
	2	Low	Low	Moderate	Moderate	Moderate
	3	Low	Moderate	Moderate	Moderate	High
	4	Moderate	Moderate	Moderate	High	High
	5	Moderate	Moderate	High	High	High

The likelihood, severity and combined risk factor were then used to quantify the environmental hazards – both of the rocket to the environment and of the environment to the rocket. Table 20 below summarizes these hazards.

Table 20. Environmental Hazard Analysis Matrix

Hazard	Cause	Effect	Likelihood	Severity	Combined Risk Factor	Mitigation	Verification
Flooding in the lab	The lab floods	Equipment, rocket parts, and supplies are ruined, risk of electrical shock from submerged electric cords and outlets.	2	4	6, Moderate	If a severe rainfall event is predicted, the club will move critical components, extension cords and equipment to higher places in the lab. Most components and equipment are stored in plastic boxes and are stored off the floor on shelving units.	Components and equipment are stored in plastic boxes in shelving units.
Brush fire	Hot motor gases	Hot motor gases ignite grass or brush	1	5	6, Moderate	LTRL will always use a blast deflector and ensure that dry grass and plant matter is cleared from the launch pad	The RSO and propulsion leads will ensure that the blast deflector is in place and that no dry grass or plant matter remains on the launch pad.
Brush fire	Ejection charges	Ejection charges ignite grass or brush causing a fire	1	5	6, Moderate	LTRL will not use more black powder than necessary for ejection charges. Ejection charges will be contained within the rocket, ejection charges will be deployed using an altimeter and so will explode in the air, not on the ground	The A&R leads have calculated the correct amount of black powder necessary. Redundant altimeters have been installed so that the ejection charges will be deployed properly.

Falling rocket injures animals	Rocket lands on animals	Animal is injured, rocket is trampled	2	4	6, Moderate	Launch in area free from livestock. Limit drift in order to land the rocket in the cleared landing area. Limit kinematic energy of rocket on landing so that potential injuries to livestock or wildlife are minimal.	The A&R leads have ensure that the rocket's kinetic energy remains at safe levels. LTRL will only launch at approved events under the supervision of the RSO.
Crop debris limits rover operation	Crop debris interferes with rover operations	Crop debris prevents the rover from exiting the rocket, or from moving forwards	3	3	6, Moderate	The rover is designed to have high ground clearance. The release mechanism for the rover allows the rover to freely exit the rocket, so that crop debris will not trap the rover in the rocket. Tests will be conducted in fields with soybean and/or corn crop debris to test the functionality of the rover.	The rover's ground clearance will be tested in fields with soybean or corn residue.
Water pollution caused by rocket parts	Unrecovered rockets in bodies of water	Residual motor components, ejection charges and electronic and structural components leach out of the submerged rocket and cause water pollution.	2	4	6, Moderate	LTRL will always make every attempt to retrieve the rocket from bodies of water. The team will always launch the rocket in a manner such that its flight path will not take it over large bodies of water.	The A&R leads have performed calculations to determine the drift rate of the rocket, and selected parachutes accordingly. The A&R leads have ensured that a working GPS is placed in the rocket.
Water pollution from chemicals used during rocket construction	Improper disposal of lab chemicals	Poisonous chemicals could cause fish kills and pollution of waterways.	1	4	5, Moderate	All chemicals will be picked up by Penn State EHS and safely treated and disposed.	The safety officer ensures that all hazardous chemicals are disposed of through Penn State EHS chemical pickup.

Ground pollution from litter	Littering	Trash such as plastic bags, wires, and cardboard is left behind at launch prep site.	2	3	5, Moderate	LTRL will always pick up all of the trash at the launch prep site.	The safety officer will check to see that all trash has been removed before the team leaves.
Ground Pollution from chemicals used during the construction of the rocket	Improper disposal of lab chemicals	Poisonous chemicals could cause soil contamination.	1	4	5, Moderate	All chemicals will be picked up by Penn State EHS and safely treated and disposed.	The safety officer will ensure that all hazardous chemicals are disposed of through Penn State EHS chemical pickup.
Ground pollution from unrecovered rockets	Unrecovered rockets on the ground	Residual motor components, ejection charges and electronic and structural components leach out of the submerged rocket and cause soil pollution.	2	3	5, Moderate	LTRL will always make every attempt to retrieve the rocket. A GPS transmitter will be placed in the rocket so that the team can locate the rocket.	The A&R leads have ensured that a working GPS is placed in the rocket.
Wind carries away trash from launch site	Gusts of wind at launch site	Loose objects blow away from launch prep site polluting the environment	2	2	4, Low	Keep all tools and components stored in storage boxes when not in use. Keep trash cleaned up while working.	The safety officer will keep tools and trash picked up during launch preparations.
Wind catches the parachute after the rocket has landed	Gusts of wind after rocket lands	Parachute drags rocket across the ground, causing potential damage to the rocket body	2	2	4, Low	Use a parachute no larger than necessary to land the rocket safely. Launch in winds under 20 mph.	The A&R leads have selected the smallest parachute necessary to bring the rocket down safely. The rocket will not be launched in winds over 20 mph.

Rain damages rocket components	Rain at launch site	Explosives get wet and do not ignite properly, electronics are damaged	1	3	4, Low	Protect explosives from rain until their placement in the rocket. Rocket is designed to protect explosives and electronics from the elements	The A&R leads will ensure that explosives are prepared in a place sheltered from the rain.
Direct midday sunlight harms electronics	Heating of rocket body	Electronics could malfunction due to overheating	1	3	4, Low	Use electronic components designed to withstand a range temperatures. Keep the rocket in the shade until it is moved to the launch pad.	High quality electronics have been used in the rover.
Excessive humidity causes electronics to malfunction	Humidity is high enough to interfere with electronics operation	Malfunctioning electronics cause the rover to malfunction	1	3	4, Low	Use quality electronic components less likely to be affected by humidity. If problems are experienced, use desiccants to lower the humidity near the problematic electronic components.	High quality electronics will be used in the rover.
The rocket drifts out of the landing zone	High winds during parachute deployment	The rocket drifts out of the landing zone, and/or into hazards such as buildings, trees or power lines.	1	3	4, Low	The main parachute will be deployed at 700ft to limit drift, drift has been calculated to fall within the proper range for up to 20 mph wind speeds. The rocket will be not be launched in winds over 20 mph.	The A&R leads have performed calculations to determine the drift rate of the rocket, and have selected parachutes accordingly.
Cold temperatures cause electronics to malfunction	The temperature is below the range which the electronic components are designed to handle	Malfunctioning electronics cause the rover to malfunction, or be unable to complete its mission	1	3	4, Low	Use electronic components designed to withstand a range of temperatures. Keep the payload and avionics bays in a warm environment as long as possible.	High quality electronics will be used in the rover.

Rain causing launch cancellation	Rain during launch window	Launch is cancelled, causing LTRL to waste time and money travelling to the cancelled launch	2	1	3, Low	Check weather reports before leaving for the launch.	The president, or designated launch leader will check the weather in the launch area, and call the launch organizers if the weather appears to be inclement.
Low level clouds or fog cause launch cancellation or delay	Low level clouds or fog at launch site	Launch is cancelled or delayed, causing LTRL to waste time and money	2	1	3, Low	Check weather reports before leaving for the launch.	The president, or designated launch leader will check the weather in the launch area, and call the launch organizers if the weather appears to be inclement.

Failure Modes and Analysis

To ensure a safe and effective launch, an assessment of possible failures has been made. After analyzing the cause of the potential failure, mitigations have also been implemented.

The explanation below shows how the likelihood and severity values were assigned for the Failure Modes and Effects Analysis.

Likelihood

1: The failure mode is highly unlikely. Over the historical legacy of the risk, the failure has never occurred. Mitigations have been put in place that would prevent the occurrence of the risk.
2: The failure mode is unlikely. Over the historical legacy of the risk, the failure has never occurred, but there may have been close calls, where the risk nearly did occur. Mitigations have been put in place that make the occurrence of the risk highly unlikely.
3: The failure mode is moderate. Over the historical legacy of the risk, the failure has occurred at least once. Mitigations have been put in place that make the occurrence of the risk unlikely.
4: The failure mode is likely. Over the historical legacy of the risk, the failure has occurred at least once during the course of last year's project or has recurred repeatedly in multiple years. Mitigations reduce the occurrence of the risk.
5: The failure mode is highly likely. Over the historical legacy of the risk, the failure has occurred more than once over the course of a past project or has recurred each year during the project's duration. Mitigations only nominally reduce the occurrence of the risk.

Historical legacy refers to the time period over which current active club members have been a part of the club. Some risks have long historical legacies, whereas others may have only begun to occur during this project cycle. If the design responsible for a risk has changed substantially, the likelihood for that risk also was changed to reflect the impact of the design on the risk's likelihood. The likelihood values also consider the nature and efficacy of the mitigation designed to prevent the failure from occurring.

Severity

1: The effects of the failure are negligible. The occurrence of the failure could result in: the rocket performing more poorly than expected, or not operating within the expected parameters, and/or the payload might not operate within the expected parameters.
2: The effects of the failure are minimal. The occurrence of the failure could result in: minimal damage to the rocket necessitating repairs on the field, and/or portions of the payload not operating as expected.
3: The effects of the failure are moderate. The occurrence of the risk could result in: moderate damage to the rocket necessitating repairs of portions of the rocket, and/or the payload fails completely in its mission.
4: The effects of the failure are severe. The occurrence of the risk could result in: severe damage to the rocket or payload.
5: The effects of the failure are very severe. The occurrence of the risk could result in catastrophic damage to the rocket or payload necessitating a complete re-build of the rocket.

Severity and likelihood values were then added together to generate the combined risk factor. In Table 21 a combined risk factor matrix is given, which also ranks the combined risk factor as low, moderate, or high.

Table 21. Combined Risk Factor Matrix for Failure Modes

	Likelihood					
		1	2	3	4	5
Severity	1	Low	Low	Low	Moderate	Moderate
	2	Low	Low	Moderate	Moderate	Moderate
	3	Low	Moderate	Moderate	Moderate	High
	4	Moderate	Moderate	Moderate	High	High
	5	Moderate	Moderate	High	High	High

The likelihood, severity and combined risk factor were then used to quantify the severity of the failure modes. Table 22 shows the set of failure modes.

Table 22. Failure Modes and Analysis Matrix

PAYLOAD							
Failure	**Mechanism**	**Effect**	**Likelihood**	**Severity**	**Combined Risk Factor**	**Mitigation**	**Verification**
Rover tips over and is unable to right itself	Uneven terrain	Rover will be unable to move and complete the mission	4	3	7, Moderate	Rigorously test the self-righting mechanism with various terrain	Rover design has been tested
Premature activation of CO2 canisters	Control software malfunction	Nose cone of the rocket separates prematurely during flight - can cause massive instability during launch, and free-falling body sections pose a serious danger to bystanders on the ground	2	5	7, Moderate	Perform thorough rigorous testing on the control software to prevent premature triggering	Unit tests have been written for the control software
Premature activation of CO2 canisters	Accidental activation of detonation switch on the ground station	Nose cone of the rocket separates prematurely during flight - can cause massive instability during launch, and free-falling body sections pose a serious danger to bystanders on the ground	2	5	7, Moderate	Build physical guard for the detonation switch to prevent accidental activation, establish launch procedure so that only select personnel have physical access to the ground station, design control software to only detonate under certain conditions even if the detonation signal is sent.	Physical cover has been installed on the switch and procedures have been written (Assembly, Step 7)

Premature activation of CO2 canisters	Physical damage to canister/trigger	Nose cone of the rocket separates prematurely during flight - can cause massive instability during launch, and free-falling body sections pose a serious danger to bystanders on the ground	1	5	6, Moderate	Build guards for the separation trigger to prevent accidental activation	Initiator wires are physically isolated to prevent accidental detonation, and CO2 penetration mechanism is covered to prevent accidental movement of the piston.
Rover containment latch fails during flight	Acceleration experienced during launch or landing	Rover becomes unsecured during launch - an unsecured mass can cause instability during flight	2	4	6, Moderate	Verify structural integrity of rover housing before launch, ensure that materials used to construct rover containment mechanism can withstand launch acceleration	Test that the rover and payload bay can withstand forces similar to those experienced during flight
CO2 canister fails to activate	Faulty initiator	Rover will be unable to deploy from the rocket	1	3	6, Moderate	Use a multimeter to test the initiator before wiring it into the circuit	Initiator testing has been written into launch procedure (Assembly, Step 8)
Ultra-sonic sensor failure	Control software malfunction	Rover will be unable to detect and avoid obstacles in its path	3	2	5, Moderate	Thoroughly test control software to ensure that obstacles are able to be detected and avoided	Unit tests have been written for the control software
Structural damage to payload bay	Acceleration experienced during launch or landing	A breach in the wall of the body tube would prevent the CO2 canister from creating enough pressure to separate the nose cone from the rocket body	2	3	5, Moderate	Check parachute deployment mechanism with A&R subsystem to ensure that the rocket does not land a high rate of speed	Verified with A&R subsystem that expected landing speed of the rocket does not damage rover

CO_2 canister fails to activate	Control software malfunction	Rover will be unable to deploy from the rocket	2	3	5, Moderate	Perform rigorous testing on the control software to ensure that canister is triggered, test physical trigger method to ensure it works consistently	Unit tests have been written for the control software
Discharged battery pack due to improper charging/pre-flight procedures	Faulty battery	Loss of power to rover and associated electronics - payload section of the rocket will be unable to separate, leaving the rover unable to execute its mission	1	3	4, Low	Thoroughly test all batteries (primary and any backups) before launch to ensure that they can hold sufficient charge	Battery testing has been written into launch procedure (Assembly, Step 11)
Physical damage to the rover	Acceleration experienced during launch or landing	Rover is damaged during launch or deployment - if damage sustained is severe enough, rover may be unable to operate correctly	2	2	4, Low	Construct the rover out of materials durable enough to withstand launch forces, minimize rover weight to minimize force transferred to rover components	Test that the rover can withstand forces similar to those experienced during flight
CO_2 canister fails to activate	Trigger mechanism becomes physically disconnected/damaged due to acceleration experienced during launch or landing	Rover will be unable to deploy from the rocket	1	3	4, Low	Double check integrity of physical mount points for the activation trigger and soldered wires between the control board and trigger	Test durability of trigger mechanism
Ultra-sonic sensor damaged	Acceleration experienced during launch or landing	Rover will be unable to detect and avoid obstacles in its path	2	2	4, Low	Perform ground testing to ensure that ultra-sonic sensor can withstand forces sustained during launch and landing	Test that the sensor can withstand forces similar to those experience during flight

STRUCTURES							
Failure	**Mechanism**	**Effect**	**Likelihood**	**Severity**	**Combined Risk Factor**	**Mitigation**	**Verification**
Bulkhead Separation from body tube	Insufficient Epoxy strength	Unwanted separation of rocket, potential free falling sky debris	1	5	6, Moderate	The bulkheads were firmly epoxied into the rocket. They were force tested in order to ensure that they were firmly attached. Prior to and following each launch the bulkheads were inspected for signs of separation from the rocket.	The bulkheads were inspected prior to and following each launch and no signs of separation were observed.
Eyebolts Separation from bulkheads	Extreme stress from shock cord or insufficient thread strength on bulkhead. Loosening of eyebolt due to excess vibrations during launch, flight, parachute deployment, decent, and landing.	Unwanted separation of rocket, potential free falling sky debris	1	5	6, Moderate	The eyebolts will be inspected prior to and following each launch.	The eyebolt attachments were inspected prior to and following fullscale launch. No evidence of eyebolt loosening was observed.
Fin Separation from fin brackets	Loosening of bolts due to excess vibrations experienced during launch, flight, parachute deployment, decent, and landing.	Potential free falling sky debris	1	5	6, Moderate	The fin brackets will be inspected prior to and following each flight.	The fin brackets were well secured prior to and following the fullscale flight.

Fin bracket fracture	Extreme or repeated impact, bending moment	Aerodynamic instability, Structural failure, potential free falling sky debris	1	4	5, Moderate	The fin brackets have been designed for structural strength. They fit into slits in the body tube, utilizing the added strength of the carbon fiber to form a secure and structurally sound attachment. The fin brackets will be inspected prior to and following each launch for any sign of structural instability.	The fin brackets were in structurally sound condition prior to and following the fullscale launch.
Cascading Fracture, body tube	Extreme stress due to sudden change in acceleration due to takeoff, parachute deployment, and landing localized around bolt hole.	Functional/Structural inadequacy	1	4	5, Moderate	Due to the heterogeneous nature of the frame material, FEA simulations did not provide accurate results. To mitigate this issue, components were verified before and after fullscale test launch to verify any surface defects, cracks, or other abnormalities that may appear.	Components were examined after recovery of the launch vehicle. No defects or abnormalities were detected upon visual inspection
Crack along inner/outer seam, body tube	Extreme torsional stress or bending moment due to extreme rotational acceleration.	Functional/Structural inadequacy	2	3	5, Moderate	Due to the heterogeneous nature of the frame material, FEA simulations did not provide accurate results. To mitigate this issue, components were verified before and after fullscale test launch to verify any surface defects, cracks, or other abnormalities that may appear.	Components were examined after recovery of the launch vehicle. No defects or abnormalities were detected upon visual inspection

Unwanted coupler separation from body tube	Premature shear pin fracture due to extreme axial or torsional stress caused by extreme jerk or excess rotational acceleration.	Undeployed parachutes, incorrectly timed parachute deployment, incorrect descent	3	2	5, Moderate	Simulations of the most extreme cases expected will be conducted. Shear pin locations will be optimized using stress analysis so that a minimum value of shear pins can be employed. Total shear pin stress resistance will be rated at a minimum of 1.2 times the maximum stresses simulated.	No unexpected separation has occurred during fullscale test flight.
Coupler Fracture crack	Extreme torsional stress or bending moment due to extreme rotational acceleration.	Aerodynamic inconsistency/Structural Failure	3	2	5, Moderate	The couplers will be inspected before and after each launch in order to verify that the couplers are in good working condition. Fireballs and proper shockcord length assignments will be used to reduce the occurrence of extreme torsional stress on the coupler.	The couplers were inspected before fullscale flight and showed no signs of structural failure.
Premature nose cone separation	Premature shear pin fracture due to extreme axial or torsional stress caused by extreme jerk or excess rotational acceleration.	Aerodynamic inconsistency/ Instability, sky debris	1	4	5, Moderate	Verify that nose cone separation will not occur during ground testing and test flight.	There was no unexpected nose cone separation during either ground testing or test flight.
Coupler/Body Tube Zippering	Extreme sudden stress from shock chord when parachute deploys.	Structural Failure, potential sky debris	3	1	4, Low	Implementation of proper fireball use. Reinforcing location(s) of the rocket where highest probability of zippering is expected to occur.	Although zippering did occur, fireballs were not utilized which led to the zippering. They will be implemented during competition flight.

Fin fracture crack	Extreme or repeated impact, bending moment	Aerodynamic instability, Structural failure	2	2	4, Low	Simulations of the most extreme cases expected will be conducted. Material testing will be performed to determine the material properties. Design iterations will be conducted until a design is able to withstand all forces and stresses that may be present on launch day, with a factor of safety of at least 1.2. Visual inspection will be conducted before and after every launch/landing cycle. New parts will be fabricated if necessary.	No defects or abnormalities were observed after fullscale test flight.
Body tube Fracture crack	Material Defect, Repeated impact	Aerodynamic inconsistency/Structural Failure	1	2	3, Low	A visual inspection will be conducted for each piece of the body tube before and after each launch/landing cycle. If any parts are damaged beyond repair, a new replacement part will be fabricated.	No failure that has required component replacement has occurred during fullscale test flight
Bulkhead Fracture crack	Material Defect, stress on eyebolt threads	Structural Failure, pressure leakage	1	2	3, Low	Plywood bulkheads were used in order to take advantage of the structural strength of the plywood. Holes were carefully drilled so as to reduce the incidence of splitting. The bulkheads will be examined prior to and following each launch for any signs of splitting or other structural instability.	No signs of splitting or other structural instability were observed prior to or following the fullscale launch.

PROPULSION							
Failure	**Mechanism**	**Effect**	**Likelihood**	**Severity**	**Combined Risk Factor**	**Mitigation**	**Verification**
Motor CATOs	Motor casing or components rupture	Catastrophic damage to rocket	2	5	7, Moderate	Inspect motor grains prior to installation. The Propulsion lead will assemble the motor according to the assembly instructions with the mentor observing. An internal checklist has been developed.	Motor grains will be inspected prior to installation on launch day. The propulsion lead, will assemble the motor according to the assembly instructions with the mentor and/or president, who are Level 2 certified, observing.
Motor does not stay retained	Motor thrust pushes the motor into the rocket	Catastrophic damage to rocket	1	5	6, Moderate	Verify that the motor retention system can handle the motor thrust, with a safety margin	The motor retention system was tested during fullscale launch and fully retained the motor during the launch phase of the flight.
Motor does not stay retained	Ejection charges push motor out of rear of rocket	Motor does not remain in rocket	1	5	6, Moderate	Use of active motor retention, Use of lower impulse motor. A bulkhead forms a barrier between the motor and the portion of the rocket pressurized by the ejection charges.	The motor retention system was tested during fullscale launch and fully retained the motor during recovery phase.
Motor does not ignite	Motor does not ignite on launch day	Rocket does not lift off pad	2	2	4, Low	Use recommended igniters. Store motors properly to avoid oxidation. Verify that the initiator is inserted all the way to the top of the motor grains.	Motors are stored in a cool, dry place in the HPCL. Recommended motor igniters will be used on launch day. The initiator will be inserted to the top of the motor grains.

Avionics and Recovery							
Failure	**Mechanism**	**Effect**	**Likelihood**	**Severity**	**Combined Risk Factor**	**Mitigation**	**Verification**
Altimeter has complete or partial power loss in flight due to faulty wiring of battery or switch	Wiring of switch and/or battery is not secure	Parachutes may not deploy, rocket descends at terminal velocity, rocket body and/or payload components are damaged	2	5	7, Moderate	Perform sharp, forceful 'tug' test on wires, make connections with snapping and/or pinching mechanisms, not twisting	The Avionics Assembly procedure will be followed, ensuring that the 'tug' test will be performed on each wire.
Altimeter fails to detect outside pressure accurately	Pressure port into avionics bay is not sufficiently large to allow outside pressure to be measured	Late or no deployment of parachutes, rocket descends at terminal velocity, rocket body and/or payload components are damaged	1	5	7, Moderate	Ensure pressure port is at least the size of a grape	The pressure port is the size of a large grape. Fullscale parachute deployment was successful.
Main and drogue charges fail to separate the rocket	Use of too many shear pins, too little black powder	Parachutes do not deploy; the rocket descends at terminal velocity	1	5	6, Moderate	Perform ground testing to determine the number of shear pins and proper amount of black powder.	Ground testing was successfully performed before the fullscale launch.
Drift distance from launch pad is greater than required safety range	Main parachute is too large and/or deployment height is high	Rocket falls outside of launch boundaries, may cause damage to property, vehicles, or people	2	4	6, Moderate	Select parachute sizes based on models of minimum descent speed, given various wind conditions	Drift distance has been calculated for various wind conditions.

Altimeter loses continuity	Wiring of leads from altimeter and/or connection to initiators is not secure	Altimeter cannot ignite initiator, rocket descends too quickly	2	4	6, Moderate	Perform sharp, forceful ‘tug’ test on wires, make connections with snapping and/or pinching mechanisms, not twisting	The Avionics Assembly procedure will be followed, ensuring that the 'tug' test will be performed on each wire.
Drogue parachute undergoes fire damage due to ejection charge detonation	Parachute is damaged and may fail upon deployment	Rocket descends too quickly, main parachute may be damaged or cause damage to body tube upon deployment	2	3	5, Moderate	Standard operating procedure for parachute packing, included wrapping with fire retardant blanket	The Recovery Assembly procedure will be followed, ensuring that the parachutes are assembled in the correct manner.
Main parachute undergoes fire damage due to ejection charge detonation	Parachute is damaged and may fail upon deployment	Rocket descends and lands too quickly, damage may be inflicted onto rocket body	2	3	5, Moderate	Standard operating procedure for parachute packing, included wrapping with fire retardant blanket	The Recovery Assembly procedure will be followed, ensuring that the parachutes are assembled in the correct manner.
Fire retardant blanket slides up shroud lines of parachute and prevents it from opening fully	Fire retardant blanket is attached by running shroud lines through the hole in blanket as opposed to directly to the quicklink	Parachute’s effectiveness is diminished, rocket descends and/or lands too quickly, damage may be inflicted on rocket body	2	3	5, Moderate	Secure fire retardant blanket to quicklink	The Recovery Assembly procedure will be followed, ensuring that the parachutes are assembled in the correct manner.
Main side charges fail to separate rocket	Ejection charge strength is not matched to shear pin strength	Rocket descends and lands too quickly, damage may be inflicted onto rocket body	1	4	5, Moderate	Ground testing to determine ratio of shear pins to black powder	Ground testing was successfully performed before the fullscale launch.

Main parachute deploys below drogue parachute and tangles	Shock cord lengths are incorrectly proportioned	Rocket descends and lands too quickly, damage may be sustained by rocket body	2	3	5, Moderate	Designating specific lengths based on rocket section lengths, weights, and parachute locations	The rocket has been designed so that the main and drogue parachutes will be appropriately placed following deployment. Successful parachute deployment was achieved during subscale launch.
Main parachute either does not leave body tube or does not unfurl	Parachute, fire retardant blanket, and/or shock cord are not packed correctly	Rocket descends too quickly, damage may be inflicted on the rocket body	1	4	5, Moderate	Standard operating procedure for parachute packing	The Recovery Assembly procedure will be followed, ensuring that the parachutes are assembled in the correct manner.
Body tube of the rocket is zippered by shock cord during parachute deployment	Rocket is falling too quickly when parachute is deployed	Permanent damage to body tube, which may need to be replaced.	3	2	5, Moderate	Select parachute sizes based on models of maximum descent speed. During fullscale flight zippering did occur. Therefore further mitigations will be implemented including using a cushioned ball around shock cord to prevent damage and switching lengths of shock cord so that the booster section will be slowed by the drogue parachute before main fully deploys.	Parachute sizes have been selected based on models of maximum descent speed as detailed in the avionics and recovery section of this report. Zippering did occur during fullscale flight. Thus, a fireball will be attached to the drogue shock cord to prevent zippering and the shock length between the booster section and the drogue parachute is now 10', in order to slow the booster section prior to the full deployment of main.

Electromagnetic field trigger altimeter to detonate early	Faraday cage is not constructed to effectively shield altimeter	Rocket experiences explosive separation while on the ground and/or while being handles	1	3	4, Low	Construct faraday cage so that it is sufficiently thick and has complete coverage.	A Faraday cage has been constructed from several sheets of aluminum foil. It completely covers the inside of the avionics bay.
Jostling of rocket vertically triggers altimeter to detonate early	Altimeter detects changes in pressure that resemble apogee and detonates drogue charges	Rocket experiences explosive separation while on the ground and/or while being handles	1	3	4, Low	Setting minimum detonation height of altimeter to at least 100 ft. above ground level, only enabling altimeters with charges on the launch pad	The detonation height of the main charges is set to 700ft, the detonation height of the drogue charges is set to apogee. Structures Launch Pad procedures will be followed so that the altimeters are only enabled on the launch pad.
Kinetic energy at landing is above required safety threshold	Main parachute is not sufficient large to slow descent	Rocket lands with too much force, rocket body and/or payload components are damaged	1	3	4, Low	Select parachute sizes based on models of maximum descent speed, ensure masses of rocket section are accurate and up to date	Parachute sizes have been selected based on models of maximum descent speed as detailed in the avionics and recovery section of this report.
Main parachute deploys at apogee with the drogue parachute	Main side shear pin strength is not matched to exceed drogue side ejection charge strength; main and drogue parachutes are mistakenly swapped	Rocket descends too slowly, drift distance exceeds maximum	2	2	4, Low	Ground testing to determine ratio of shear pin to black powder; standard operating procedures for assembling recovery harnesses and parachutes	Ground testing was successfully performed before the fullscale launch. The Recovery Assembly procedure will be followed, ensuring that the parachutes are assembled in the correct manner.

Drogue parachute either does not leave body tube or does not unfurl	Parachute, fire retardant blanket, and/or shock cord are not packed correctly	Rocket descends too quickly, main parachute may be damaged or cause damage to the body tube upon deployment	1	3	4, Low	Standard operating procedure for parachute packing	The Recovery Assembly procedure will be followed, ensuring that the parachutes are assembled in the correct manner.
Drogue side charges fail to separate the rocket	Ejection charge strength is not matched to exceed shear pin strength	Rocket descends too quickly, main parachute may be damaged or cause damage to body tube upon deployment	1	3	4, Low	Ground testing determine ratio of shear pins to black powder	Successful round testing was performed before the fullscale launch.

Explanation of Project Risk Assessment

The risks to the overall project were assessed, not with numerical values, but with descriptors such as "low", "moderate", and "high" for Likelihood and Impact. These were assigned based on list given below.

LIKELIHOOD

Low: The risk is unlikely. Over the historical legacy of the risk, it has never occurred.
Moderate: The risk is likely. Over the historical legacy of the risk, it has occurred at least once.
High: The risk is very likely. Over the historical legacy of the risk, is has occurred several times.

IMPACT

Low: The risk will cause disruption within the club and could delay the progress of the project.
Moderate: The risk could cause the project to be severely delayed and/or reduce the quality of the finished product.
High: The risk could cause the project to fail, cause the team to be unable to make it to Alabama, or cause the club to be disbanded by Penn State.

Project Risk Assessment

There are several concerns with the overall project, mostly related to budget and personnel management. These are presented in Table 23 below.

Table 23. Project Risk Assessment Matrix

Risk	Cause	Effect	Likelihood	Impact	Mitigation
Club loses funding	One or more sources can no longer provide funding	There is not enough money to pay for transportation or necessary parts and equipment	Moderate	High	Dedicated member to track expenses and make funding contracts possible.
Project over budget	Testing/fabrication/ travel costs exceed expectations	Project cost exceeds amount of money projected	Moderate	High	Compare prices from different vendors, avoid excess shipping costs
Parts are unavailable	Parts needed for the rocket are not available commercially	Rocket cannot be completed using the planned parts	Moderate	High	Use non-exotic materials and check for availability. Order parts far in advance

Damage during testing	Accident/malfunction during testing	Catastrophic damage to the rocket	High	Moderate	Ground testing, maintain a stock of spare parts
Project falls behind schedule	Team fails to build critical components in a timely manner	Major milestones are not met in time	Moderate	Moderate	Weekly status meetings, follow project plan
Failure to acquire transportation	Transportation to Alabama not acquired	Team is unable to travel to the competition	Low	High	Carpool to Alabama if necessary
Injury of team personnel	Hazards outlined in Table (4.3)	Team member is injured	Low	High	Inform and enforce team safety
Club loses facilities	University revokes club access to the lab	Club loses access to 46 Hammond	Low	High	Maintain clean and safe environment in the lab and store hazardous materials safely
Labor leaves/graduates	Seniors graduate or students stop attending meetings	There are no longer enough students available to perform the necessary work	Low	Moderate	Recruitment at the beginning of each semester. Team building activities.
Theft of equipment	Parts or testing equipment get stolen	Rocket construction becomes more difficult, excess cost to the club	Low	Moderate	Only subsystem leaders and officers will have card access to the LTRL lab

6. Launch Procedures

6.1 Recovery Preparation

Avionics Assembly

Note: Assembling the avionics bay begins the day before arriving to the launch site. The avionics sled is mostly assembled in advance to reduce the amount of time necessary to assemble the overall rocket.

1. Attach the battery connectors to two 9V batteries.
   Caution: Make sure these batteries are new to ensure that the altimeters will have power.

2. Place the batteries in the battery slots on the avionics sled.

3. Screw in two Stratologger CF altimeters into the altimeter ports on the avionics sled.

4. Screw in the battery connector wires into the altimeter power supply ports. Note that the black wire is negative and should be screwed into the proper port. Tug on each wire to ensure that the connection is secure.
   Caution: The altimeters will not turn on if the batteries are installed incorrectly.

5. Install the secure clip wire connectors into the switch ports. Each altimeter should have a female connector and a male connector. The switches come as sets. One set is unlabeled, the other is labeled with an X. Tug on each connector to ensure that the connection is secure.
   Caution: It is important to note that the switches must not be connected or in the on position.

6. At this point, the avionics sled should have the two altimeters and two batteries installed. Additionally, the altimeter should have the battery connector wires and switch wires installed. The inner bulkheads can now be installed.

7. Place one bulkhead against the avionics bay inner coupler so that the holes for the all-thread rods are on either side of the avionics sled.

8. Place the insulated all-thread rods through the all-thread rods hole in the bulkhead.

9. Place the second bulkhead on the opposite side of the avionics bay such that the all-thread rod going through the orange hole in the first bulkhead, goes through the orange hole in the second bulkhead.

10. Repeat this process for the blue hole and its corresponding all-thread rod. Screw in the all-treads and ensure that they are secure.

Ejection Charge Assembly

Warning! Only leads should handle the black powder and the initiators.

1. The avionics sled should be outside of the coupler. Take orange plastic off four initiators and thread two initiators through each bulkhead for a total of four initiator wires. Strip the plastic from the ends of the wires.
   Caution: Before continuing to the next step, make sure the altimeters are turned off!

2. Install one of the initiators from the booster side bulkhead into the drogue port of the primary altimeter.

3. Repeat this for the other initiator and the redundant altimeter, which is marked with yellow lettering. Label the end of this initiator with electrical tape in order to mark it as redundant.

4. Install one of the initiators from the forward bulkhead into the main port of the primary altimeter.

5. Repeat this procedure for the other initiator, making sure to mark the end of the initiator with electrical tape to mark it as redundant.

6. Place the initiator heads into the blast caps and secure them with electrical tape.
   Caution: The initiators must be secure to ensure proper detonation.

7. Ensure that the redundant altimeters remain labeled.

8. Slide the avionics sled into the coupler but do not attach the door yet.

9. Place 1.5 grams of black powder into the blast cap of the primary drogue initiator. Pack the blast cap with shredded newspaper and cover it with electrical tape.
   Caution: The black powder must be secured so that it does not leak and burn incorrectly.

10. Place 2.5 grams of black powder into the blast cap of the redundant drogue initiator. Again, pack the blast cap with shredded newspaper and cover it with electrical tape.

11. Place 2 grams of black powder into the blast cap of the primary main initiator. Secure the charge the same way that the drogue charges were secured.

12. Place 3 grams of black powder into the blast cap of the redundant drogue initiator and secure the charge.

Warning! Handle the coupler carefully so as to not displace any of the tape of black powder.

DANGER! THE COUPLER NOW CONTAINS BLACK POWDER CHARGES AND NO MEMBERS SHOULD STAND IN THE LINE OF FIRE OF EACH END OF THE COUPLER.

6.2 Motor Preparation

Hardware List

Quantity is one of each item unless otherwise specified ([N] Item)

- 75mm Cesaroni 3-Grain Motor Case
- 75mm Aft Closure
- 75mm Forward Seal Disk (FSD)
- 75mm Smoke Charge Enclosure
- 75mm Cesaroni Spacer Ring
- 75mm Forward Closure
- Liner
- Nozzle
- Nozzle Cap
- [3] Propellant Grains
- Smoke Charge
- [2] Forward and Aft O-rings (⅛" thick x 2 ¾" O.D.)
- FSD O-ring (3/32" thick x 2 9/16" O.D.)
- [2] Grain Spacer O-rings (1/16" thick x 2 ½" O.D.)
- Lubricating grease and popsicle stick
- Sharp blade (exacto knife or Leatherman blade)

Pre-Assembly

1. **Required PPE: Latex gloves.** Apply a light coat of grease to all threads and O-rings (except the grain spacer O-rings).
   Caution: When working with the grease, the team member applying it needs to be wearing latex gloves. The grease can be an irritant if it comes into contact with skin. This caution applies to any and all later steps that involve working with grease.

Case Assembly

2. Use a sharp blade to deburr the forward and aft inside edges of the liner tube to provide more friction for the fit of the nozzle and forward closure assembly.
   Warning! Using a sharp blade carelessly can result in serious injury. When using the blade, always concentrate completely on the task at hand.

3. Insert the larger diameter portion of the nozzle into the aft end of the liner and slide the nozzle all the way in to the point that the flange is in contact with the aft edge of the liner.

4. Ensure that all following procedures are carried out with the assembly in the horizontal position.

5. **Required PPE: Latex gloves** Install the propellant grains into the liner, sliding them in from the forward end. Place a Grain Spacer O-ring between each propellant grain, and again ensure that they are not lubricated with grease.

Warning! Before handling the propellant grains, the handler needs to put on well-fitting latex gloves. The propellant grains are classified as a dangerous explosive and can result in serious harm if not handled properly.

6. Once the propellant grains are installed in the liner, avoid letting any personnel stand directly in line with either end of the case assembly.

7. Place the lubricated FSD O-ring into the groove in the FSD.

8. Insert the end of the disk with a smaller cross-sectional area into the forward end of the liner so that the FSD O-ring is no longer visible and the flange on the FSD is in contact with the forward edge of the liner.

9. Apply a light coat of lubricating grease to the outside of the liner to facilitate liner assembly removal from the case after launch.

10. Insert the liner assembly into the aft end of the motor case until the nozzle protrudes from the aft end of the case by 1 ¾”.

11. Place the lubricated Forward O-ring into the groove in the Smoke Charge Enclosure.

12. Insert the Smoke Charge into the aft end of the Smoke Charge Enclosure.

13. Insert the fully assembled Smoke Charge Enclosure into the forward end of the motor case until it is firmly in contact with the forwardmost propellant grain.

14. Insert the 75mm Cesaroni Spacer Ring into the forward end of the motor casing until it touches the forward end of the Smoke Charge Enclosure.

15. Thread the Forward Closure into the forward end of the motor casing until it is firmly in contact with the forward end of the Spacer Ring, completing the Forward Closure Assembly.

16. Place the lubricated Aft O-ring into the groove on the aft end of the nozzle.

17. Thread the Aft Closure into the aft end of the motor case until the flange is firmly in contact with the aft face of nozzle flange.

6.3 Vehicle Assembly

Hardware List

Quantity is one of each item unless otherwise specified

- 4:1 Ogive Fiberglass 5.5" Filament Wound with Metal Tip
- 24" Carbon Fiber Wrapped Blue Tube Body Tube
- 18" Carbon Fiber Wrapped Blue Tube Body Tube
- 14" Carbon Fiber Wrapped Blue Tube Body Tube
- 34" Carbon Fiber Wrapped Blue Tube Body Tube
- 12" Payload-Main Blue Tube Coupler
- 12" Avionics Bay Blue Tube Coupler
- 12" Drogue-Booster Blue Tube Coupler
- Avionics Bay Door
- Phillips Screwdriver
- Seventeen (17) M-2 Shear Pins
- Thirty-Four (34) ½" #6 Screws
- Camera Recording Device
- Mini-USB to USB Connector
- Down Body Camera

Warning! Safety glasses must be worn by every team member in the vicinity when a power drill is in operation.

Nose cone

1. Insert the shoulder coupler into the open end of the nose cone.

2. Align the depth markings and the registration marks on the shoulder with the matching markings on the nose cone.

3. Screw in a half-inch #6 screw into each of the six (6) holes near the aft edge of the nose cone.

4. Prepare the GPS by turning it on and verifying that it is transmitting.

5. Insert the GPS into the 3D printed GPS holder and thread the GPS holder onto the all-thread inside the nose cone.

6. Thread a washer and nut onto the all-thread to secure the GPS holder.

Payload Section

1. Once the GPS is installed in the nose cone, insert the payload body tube over the aft end of the nose cone shoulder so that the eight (8) shear pin hole side of the payload body tube is over the nose cone shoulder.

2. Align the depth markings and the registration marks on the nose cone with the matching markings on the payload body tube.

3. Insert eight (8) M-2 shear pins into the shear pin holes to connect the nose cone shoulder and payload separation point.

4. Follow procedure 5. Payload Assembly in order to load the rover into the rocket.

5. After the rover and nose cone deployment are ready for launch, insert the payload-main coupler into the payload section.

6. Align the depth markings and the registration marks on the payload body tube with the matching markings on the payload-main coupler.

7. Screw in six (6) half-inch #6 screws into the six (6) holes near the forward edge of the payload-main coupler to attach the payload body tube and the payload-main coupler.

Main Section

This rocket has an 84" Fruity Chutes Iris Ultra Compact as the main parachute.

1. Assemble the main parachute recovery harness by attaching the 27' shock cord marked "av-bay to main" to the avionics bay bulkhead u-bolt using a ⅜" quicklink.

2. Attach the other end of the 27' shock cord to the main parachute using a ⅜" quicklink.

3. Using the same quicklink attach the 7' shock cord marked "payload to main" to the main parachute. Attach the other end of the 7' shock cord to the forwards section (payload) bulkhead u-bolt using a ⅜" quicklink.

4. Attach a Nomex blanket to the quicklink connected to the main parachute.

5. Fold the main parachute and cover it with the Nomex blanket.
Warning! The Nomex blanket must completely cover the side of the parachute facing the charges, or the parachute could be burned and damaged.

6. Insert the shock cord into the rocket, followed by the main parachute.
Note: If the parachute sticks, talcum powder will help it to slide in easily.
Caution: A sticky parachute will not deploy easily and might cause a recovery failure.

7. After A&R has packed the main parachute, slide the main body tube section over the payload-main coupler so that the shear pin holes on the main body tube section are over the payload-main coupler.

8. Align the depth markings and the registration marks on the aft side of the payload body tube with the matching markings on the forward side of the main body tube.

9. Insert five (5) M-2 shear pins into the shear pin holes to connect the main body tube and the payload-main coupler attachment point.

10. Once the avionics bay is fully assembled, insert the avionics bay coupler into the aft end of the main body tube.

11. Align the depth markings and the registration marks on the main body tube with the matching markings on the avionics bay coupler.

12. Screw in six (6) half inch #6 screws into the six (6) screw holes.

Drogue Section

This rocket has a 12" Fruity Chutes Classic Elliptical drogue parachute.

1. Insert the forward section of the drogue body tube over the avionics bay coupler.

2. Align the depth markings and the registration marks on the aft side of the main body tube with the matching markings on the forward side of the drogue body tube.

3. Screw in six (6) half inch #6 screws into the six (6) screw holes to attach the avionics bay to the drogue body tube.

4. Connect the 10' shock cord marked "booster to drogue" to the drogue parachute and to the booster coupler u-bolt, using two ⅜" quicklinks.

5. Attach one end of the 24' shock cord marked "drogue to AV bay" to the ⅜" quicklink attached to the parachute. Attach the other end to the booster-side avionics bay bulkhead using another ⅜" quicklink.

6. Attach a Nomex blanket to the quicklink connected to the drogue parachute.

7. Fold the drogue parachute and cover it with the Nomex blanket.
   Warning! The Nomex blanket must completely cover the side of the parachute facing the charges, or the parachute could be burned and damaged.

8. Insert the shock cord into the rocket, followed by the main parachute.
   Note: If the parachute sticks, talcum powder will help it to slide in easily.
   Caution: A sticky parachute will not deploy easily and might cause a recovery failure.

9. Once the drogue parachute is attached and packed, insert the drogue-booster coupler into the aft end of the drogue body tube.

10. Align the depth markings and the registration marks on the drogue body tube with the matching markings on the drogue-booster coupler.

11. Insert four (4) M-2 shear pins into the shear pin holes to connect the drogue body tube and the drogue-booster coupler attachment point.

Booster Section

1. Ensure that the camera cover is properly secured to the booster body tube by checking all screws between the booster body tube and the camera cover.

2. Attach the downbody recording device to the motor stop in the booster section.

3. Attach the camera mini-usb to usb connector to the camera recording device and snake the cable through the hole in the booster body section and through the camera cover that is attached to the outside of the booster body tube.

4. Connect the other end of the mini-usb to usb connector to the down body camera and firmly secure the down body camera into the designed camera cover so that the down body camera snaps snuggly into the camera cover.

5. Insert the forward section of the booster body tube over the drogue-booster coupler.

6. Align the depth markings and the registration marks on the aft end of the drogue body tube with the matching markings on the forward end of the booster body tube.

7. Screw in six (6) half inch #6 screws into the six (6) screw holes to attach the booster body tube to the drogue-booster coupler.

8. Ensure that the fin brackets are properly secure by checking all screws between the body tube and fin bracket as well as the screws between the fins and the fin brackets.

6.4 Payload Assembly

Note: While following assembling instructions, reference the Payload Assembly Sign-off sheet. Receive signatures by payload leads or safety officer for all required tasks. The sheet can be found in Appendix F: Payload Launch Procedures Sign-Off.

Arduino Preparation

1. Connect the ground station Arduino to a laptop with the Arduino IDE installed.

2. Open the serial monitor in the Arduino IDE (CTRL + SHIFT + M) and set the baud rate of the monitor (in the lower right-hand corner) to 9600.

3. Ensure that the message “LoRa radio init OK!” is printed.

4. On the rover, attach a 9-volt battery to the terminal connected to the Arduino. SAFETY NOTE: Do NOT attach a battery to the terminal connected to the initiator circuit (marked with red electrical tape).

5. Confirm that the LED on the Arduino (labelled "L" and located near pin 13) blinks once repeatedly. If the LED blinks twice, toggle the switch on the ground station.

6. Confirm that the serial monitor connected to the ground station prints "Got: Hello World" followed by "Sent: okay" repeatedly. If "Sent: detonate" is printed instead, toggle the switch on the ground station. Toggle the ground station switch to confirm that the message being sent is changing with every toggle. After testing, toggle the switch so that "Sent: okay" is being printed to the serial monitor.

7. Have a payload lead sign-off on the successful completion of this step on the sign-off sheet.
   Note: After this point, only payload leads should be handling the rover and the ground station.

CO2 Ejector Preparation

1. Test the resistance of the initiator with a multimeter. The reading should be 2-4 ohms.
   Warning! The following steps should ONLY be performed by a payload lead.

2. Thread the wires from the initiator through one of the holes in the CO2 penetration mechanism so that the explosive tip of the initiator is completely concealed within the cylindrical chamber.

3. Tape the wires on the outside to prevent the initiator from sliding.

4. Place wadding in the other chamber to block off one end of the hole.

5. Place the manufacturer determined black powder charge size in the same chamber.

6. Retract the plunger completely.

7. Screw on the knurled cap over the initiator wires.

8. Screw the entire assembly onto the flange attached to the bulkhead.

9. Screw on the CO2 canister to the other side of the flange.

10. Have a payload lead sign-off on the successful completion of this step on the sign-off sheet

Final Payload Preparation

1. Immediately before final assembly of the rocket and launch, confirm that the LED on the rover Arduino is blinking once repeatedly. If it is blinking twice, toggle the switch on the ground station and confirm that the LED is now blinking once.

DANGER! DO NOT PROCEED UNTIL THE LED IS BLINKING ONCE. FAILURE TO DO SO MAY RESULT IN PREMATURE DETONATION OF THE INITIATOR.

2. Have a payload lead sign-off on the successful verification of this step on the sign-off sheet.

3. Using a multimeter, test a 9-volt battery and ensure that the voltage reading is at least 8 volts (use a new battery if possible).
   Caution: Failure to test the battery may result in the initiator not detonating.

4. Have a payload lead sign-off once the battery is shown to have sufficient voltage.

5. From this point forward, the ground station should be watched carefully to ensure that the switch is not toggled until the appropriate time after the rocket has landed. Only payload leads and the payload systems engineer should have access to the ground station after this point.
   DANGER! ACCIDENTAL TOGGLING OF THE SWITCH MAY LEAD TO PREMATURE DETONATION OF THE INTIATOR.

6. **This step to be performed by a payload lead or payload systems engineer only:** attach the tested 9-volt battery to the terminal connected to the initiator circuit.
   DANGER! THE INITIATOR CIRCUIT IS NOW LIVE AND SHOULD BE TREATED AS AN ARMED EXPLOSIVE. CARE SHOULD BE TAKEN WHEN HANDLING BOTH THE ROVER AND THE GROUND SATION TO PREVENT ACCIDENTAL DETONATION.

7. Connect the wires from the initiator to the wire fastener in the rover's initiator circuit.

8. Load the rover into the rocket and connect the eye hook protruding from the rover to the hook inside the payload bay.
   Note: To reduce the risk of accidental detonation, only payload leads should be handling the ground station.

9. Once the rover is assembled and inside the rocket, keep the switch on the ground station physically covered so that it is not accidentally toggled.

6.5 Launch Procedures

Transportation to Launcher

1. Assemble the launch team, which consists of the Flight Systems Engineer, A&R Lead Engineer(s), Propulsion Lead Engineer, and the Safety Officer to carry the rocket to the launcher and set it up.
   Warning! All team members *must* leave their cell phones in the launch preparation area after this step. Electromagnetic signals from the devices may cause the avionics

to prematurely detonate the parachutes' black powder charges, causing serious harm to team members or even bystanders.

2. 6.1.2 Make sure all members of the team have a firm grasp on the rocket, and lift the rocket to a comfortable carrying height. Make sure the rocket stays as close to horizontal as possible at all points during transportation.

3. Walk the rocket out to the launcher, ensuring that no people are too near or directly in line with either end of the rocket.
Caution: Standing in-line with the either end of the rocket increases the likelihood a team member or bystander will sustain an injury in the event of an explosive failure.

Setup on Launcher

1. Have a member or two of the launch team bring the launch rail from vertical to horizontal and hold it in that position.

2. Align the rocket's rail buttons so that they are pointed directly down towards the ground.

3. Slide the aft rail button into the launch rail so that the weight of the rocket is resting on the rail buttons. Make sure the rocket is not "hanging" off the rail only attached at the rail buttons.

4. Slide the aft rail button towards the flame deflector at the base of the launch rail, minimizing twisting of the rocket relative to the launch rail and scraping of the rocket airframe against the leading edge of the launch rail.

5. Once the forward rail button is securely inserted into the launch rail, slide the rocket towards the flame deflector until it makes contact.

6. Several members of the team should then push the launch rail into a vertical position while the rest of the team stabilizes the rocket on the rail to prevent twisting relative to the rail.

7. Once the launch rail is in a vertical position, lock the rail into this position with a bolt or screw.

8. Verify that:
    a. The rocket is secured to the launch rail.
    b. The launch rail is secured in the upright position.

9. Connect the primary altimeter secure wire switch.

10. Audibly verify that the primary altimeter has continuity through the initiators in both the main and drogue charges by listening for three consecutive beeps.

11. Connect the secondary altimeter secure wire switch.

12. Audibly verify that the secondary altimeter has continuity through the initiators in both the main and drogue charges by listening for three consecutive beeps.

13. Tuck both sets of connected wires back into the AV Bay, ensuring not to disconnect, short circuit, or otherwise adversely affect the avionics system.

14. Take the AV Bay Panel and have another team member hold it over the AV Bay access port.

15. Screw all four #6 screws into the four corners of the Panel, securing it in place for flight.

6.6 Initiator Installation

Warning! The initiators are harmful explosives if not handled properly. After initially separating the initiator leads, do not allow them to come into contact with each other at any point.

1. Verify with the A&R lead that the altimeter is correctly and completely initialized.

2. If the rocket's nozzle is resting on the flame deflector, proceed to **Step 3.** Otherwise, proceed to **Step 4.**

3. Have several team members raise the rocket a few inches vertically so that it no longer rests on the flame deflector and ensure that the team members can hold the rocket in this position for as long as it takes to install the initiator.

4. Thread the initiator through the pre-cut hole in the wall of the nozzle cap. For now, ignore the nozzle cap but make sure it does not slide off the initiator wire.

5. Insert the end of initiator that contains the charge into the nozzle of the rocket and continue to slide the initiator upwards through the propellant grains.

6. When you feel the initiator contact the aft end of the smoke charge, stop feeding the initiator into the motor.

7. Secure the initiator wire to the nozzle with tape, making sure the initiator stays in contact with the aft end of the FSD.

8. Secure the nozzle cap over the end of the nozzle, again making sure not to pull the initiator wire any further out of the motor.

9. Separate the initiator wire leads as far apart as possible without damaging the wire.

10. Take one alligator clip from the power supply extension and connect it to one lead on the initiator wire.

11. Secure this connected wire to the launcher a safe distance from the second lead.

12. Take the second alligator clip from the power supply extension and connect it to the remaining lead on the initiator wire.

13. Secure this second wire to the launcher a safe distance from the first wire.

6.7 Post Flight Procedures

Rover Deployment

1. Once the rocket lands:

1.1 If it is deemed unsafe to continue with the rover deployment, disconnect the ground station from power. Wait at least 30 seconds before approaching the rocket. Once the rocket has been opened, immediately disconnect the initiator from the rover circuitry, then disconnect the batteries powering the initiator circuit and the rover. Proceed to post-flight inspection.
Note: Only a payload lead should accompany the rocket recovery team to safely dismantle the rover and initiator.

1.2 If it is deemed safe to continue with the rover deployment, toggle the switch on the ground station.

2. The nose cone should eject from the body of the rocket and the rover will begin operating autonomously. No further input is required.

Rocket Retrieval and Recovery Harness Inspection

Warning! Approach the rocket with caution because parts might be hot from the ejection charges, or ejection charges might still be live.

1. Check to see that all charges have properly deployed. If not, notify the RSO, and maintain muzzle awareness on both ends of the rocket while an A&R lead disconnects the altimeters.

2. Disconnect any shock cords necessary in order to safely remove the rocket from the range or field to the launch preparation area.

3. Disassemble the recovery harness by detaching all of the quicklinks from the bulkhead eyebolts, parachutes and shock cords.

4. Wrap the shock cords to be stored.

5. Lay out parachutes and inspect them for any damage.
Warning! Damaged parachutes must be replaced.

6. After inspection, fold and wrap the parachutes for storage, separating out and labeling any damaged parachutes.

7. Place all quicklinks, shock cords, fireballs and parachutes in their respective places to be transferred to the lab and stored.

Post Flight Avionics Inspection

1. Unscrew the avionics bay door.

2. Disconnect the secure wire connectors to turn the altimeters off.

3. Remove the avionics sled from the avionics coupler.

4. Unscrew all of the wire terminals of the two altimeters and remove the wires.
   Caution: Properly dispose of burnt initiators.

5. Unscrew the altimeters and place them into the A&R box.

6. Remove the batteries and place them into the A&R box.

7. Place the avionics sled back into the rocket for ease of transportation.

8. Screw the door back onto the rocket.

9. At a computer, plug the altimeters in and extract the data. Compare the actual flight data to the estimated data from computer simulations. IF there are any discrepancies, the flight model must be adjusted. The flight data should be stored on the computer for future reference.

6.8 Troubleshooting

1. During Arduino Preperation - Step 3, "LoRa radio init OK!" is not printed to the serial monitor by the ground station or an error message is printed.

   1.1 Confirm that the baud rate of the serial monitor is set to 9600.

   1.2 If the message is still not printed, find a payload lead or payload systems engineer with a master copy of the rover control software on a flash drive.

   1.3 Connect the flash drive to the laptop. Use the Arduino IDE to open the file containing the control code for the ground station.

   1.4 In the tools menu, under the "Board" option, select "Arduino/Genuino Uno"

1.5 In the tools menu, under the “Port” option, select the USB port that the Arduino is connect to. (Disconnect all other USB devices to make finding the appropriate port easier.)

1.6 Upload the code to the Arduino (CTRL + U).

1.7 Reperform Arduino Preparation procedures.

2. During Arduino Preparation – Step 5, the LED on the Arduino does not illuminate

2.1 Replace the 9-volt battery powering the Arduino

2.2 If the LED still does not illuminate, follow the procedure for uploading code to the Arduino as outline in Troubleshooting, Section 1 using the file containing the rover control code.

2.3 Return to Arduino Preparation – Step 5.

3. (Arduino Preparation – Step 6) The appropriate messages are not printed to the serial monitor.

3.1 Confirm that the baud rate of the serial monitor is set to 9600

3.2 If the messages are still not printed, follow the procedures described in Troubleshooting, Sections 1 and 2 to confirm proper operation of the rover and ground station.

3.3 Return to Arduino Preparation – Step 6.

4. (Post Flight Procedures, Rover Deployment - Step 2) The nose cone does not eject from the body.

4.1 Confirm that the ground station serial monitor is printing “Sent: detonate” instead of “Sent: okay.” If it is not, toggle the switch once. If the message still does not read “Sent: detonate” follow Troubleshooting, Section 1 to reupload control code to the ground station.

4.2 If the serial monitor is printing “Sent: detonate” and the nose cone still does not eject, abort the mission. Disconnect the ground station from power and follow the procedure from Post Flight Procedures, Rover Deployment - Step 1.1.

7. Project Plan

7.1 Testing

Communication Systems

To test that the rover and ground station can communicate with each other.

The ground station and the rover were powered on and a communications link was established between them. Then, club members holding each component walked away from each other along a sidewalk to increase the distance between the rover and the ground station.

The rover and ground station were able to maintain a communication link up to a distance of .75 miles with minimal packet loss. Communication at a larger distance was unable to be tested due to lack of a road longer than .75 miles. However, due to minimal interference occurring at .75 miles it is expected that the rover and ground station will be able to maintain communications with each other at distance up to a mile. Testing without line of sight between the rover and the ground station was undesirable as it is expected that the ground station and rover will always be within line of each other.

The test was successful because it demonstrated that the rover and ground station could communicate with each other at large distances, a result which corroborates the expected test result.

CO2 Ejection

To test that the rover can interpret a detonation signal from the ground station successfully, that the ejection system fires properly when triggered, and that the CO2 ejection system is able to separate the nose cone from the rocket body.

Methodology: The CO2 ejection system was assembled inside of the rocket and a communications link was established with the ground station. The detonation switch on the ground station was toggled, signaling the CO2 ejection system to trigger.

Results: While the communications portion of the test was successful, and the CO2 ejection system did fire, the pressure created by the system was not high enough to separate the nose cone from the rest of the rocket body.

The test was unsuccessful because the nose cone ultimately failed to separate from the rest of the rocket. Because of this test, the payload, structures, and A&R subsystems have decided to add an additional bulkhead in the payload bay and increase the size of the CO2 cartridge. This will reduce the volume of the bay, increasing the pressure generated by the CO2 system. Further testing will show that the new configuration results in a successful nose cone separation.

7.2 Requirements Compliance

General Requirements

Requirement	Method of Verification	Verification
1.1	Inspection	The club is 100% student run, and only turns to mentors for advice and motor assembly, handling all ejection charges, and preparation and installation of electric matches.
1.2	N/A	The team has established Gantt Charts to maintain a project plan that includes but is not limited to project milestones, budget and community support, checklists, personnel assigned, educational engagement events, and risks and mitigations.
1.3	N/A	Foreign National members will be identified to NASA by PDR via email.
1.4	N/A	The team will identify all members attending launch week activities in the launch week member list to be submitted with CDR.
1.4.1	Inspection	LTRL leadership will keep track of the students who are actively engaged in the project, and only send them to launch week activities.
1.4.2	N/A	The team will bring Alex Balcher as its mentor. (NAR Level 2 Certified)
1.4.3	N/A	The team will bring no more than two adult educators.
1.5	Inspection	The team will engage at least 200 participants in hands-on, educational STEM activities by participating in STEM events at middle and high schools in Centre County and going to visit team members' former middle and high schools to give STEM talks.
1.6	Inspection	The team has created a website on Penn State's sites server which it will continually update during the project year.
1.7	Inspection	The team will post the required deliverables to the LTRL website before the due dates specified in the NASA USLI Handbook.
1.8	Inspection	The files will be posted to the website in PDF format.
1.9	Inspection	LTRL will include a table of contents in all reports that includes major sections and subsections.
1.10	Inspection	The team will always include page numbers at the bottom of each page of each report.
1.11	Inspection	The team will ensure they have all equipment necessary for a video teleconference at the time of each review conference. LTRL will make sure they have a speakerphone that is not a cellular phone.
1.12	Inspection	The team will make sure their rocket does not require a custom launch rail, and that their rocket can be launched on

		the launch pads provided by the USLI launch service provider.
1.13	Inspection	LTRL will implement the Architectural and Transportation Barriers Compliance Board EIT Accessibility Standards (36 CFR Part 1194)
1.14	Demonstration	Alex Balcher is LTRL's mentor for this academic year. He maintains a level 2 certification and is in good standing through NAR. He is the designated owner of the rocket and will travel with the team during launch week.

Structures Requirements

Requirement	Method of Verification	Verification
2.1	Analysis	Accurate simulations using OpenRocket have been performed to ensure that the rocket design is capable of reaching an apogee altitude of 5,280 feet above ground level. A test launch was conducted to test prove the accuracy of the simulations. Up to 10% of ballast was added to the rocket to get the specific weight needed to get to a mile high.
2.2	Inspection	A visual inspection of the official barometric altimeter will be conducted to ensure that it is installed properly and a continuity test will be conducted prior to flight to ensure that the altimeter is functional.
2.3	Demonstration	The rocket was designed and built with one designated arming switch for each altimeter. A visual inspection prior to flight on competition launch day can confirm this.
2.4	Inspection	A visual inspection will be conducted prior to launch to ensure that each altimeter is powered by a dedicated 9V battery.
2.5	Demonstration	Key switches that lock in the ON position will be used. A visual inspection and functionality test will be conducted prior to launch to ensure that the key switches are functioning properly.
2.6	Demonstration / Testing	Carbon fiber wrapped blue tube was used for the air frame. This composite material has proven to withstand any and all stresses experienced from launch to landing. Fiberglass was used for the fins and nose cone to ensure that they would be able to withstand any stresses experienced from launch to landing.
2.7	Demonstration	The rocket was designed and built to only have three (3) independent sections A visual inspection prior to flight on competition launch day can confirm this.

2.8	Analysis	The rocket was designed and built to use a single Aerotech L1390.
2.9	Demonstration	The rocket was designed so that minimal assembly was be needed on launch day. Three sections of the rocket will be independent of each other and each subsystem will be able to work on their specific section independent of the other subsystems to allow a quicker assembly time. The rocket was launched prior to competition launch day, and the time needed to assemble the rocket met this requirement.
2.10	Analysis	Energy consumption calculations will be performed for all on-board components. Power supplies that meet this requirement will be selected.
2.11	Testing	Tests will be performed on a fullscale primary motor prior to the fullscale test launch to demonstrate that the motor can be ignited with a 12-volt direct current firing system. These tests will be part of the larger test goal to gather operational and performance characteristics of the primary fullscale motor before the fullscale test launch.
2.12	Demonstration	The rocket was designed and built so that launch can be initiated with standard initiators.
2.13	Demonstration	The rocket was designed and built to use an Aerotech L1390. This type of motor complies with all of the motor requirements. A visual inspection prior to flight on competition launch day can confirm this.
2.13.1	Analysis	The motor was chosen by CDR.
2.13.2	N/A	No changes are needed at this time.
2.14.1 - 3	N/A	The final flight vehicle will not contain any custom pressure devices except for possible CO_2 cartridges which will be commercially bought.
2.15	Analysis	Analysis will be conducted via OpenRocket and MATLAB models to simulate the flight profile of the vehicle, and the associated motor selection process will be limited to motors approved by the aforementioned bodies.
2.16	Analysis	Accurate simulations were conducted to ensure that the rocket meets this requirement. The rocket is designed with the rover payload towards the front of the rocket to bring the center of gravity closer to the front of the rocket and bring the stability of the rocket up as a result. The fins are large and bring the center of pressure back far enough so that the stability is further increased.
2.17	Analysis	Accurate simulations and a test launch were conducted to ensure that the rocket meets this requirement.
2.18	Demonstration	The team has launched and recovered a subscale model of the rocket prior to CDR.

2.18.1	Demonstration	The subscale rocket was designed to accurately imitate the fullscale geometry as closely as possible. All materials that were used for subscale were also used for fullscale. The same methods used to build the subscale rocket were also used for the fullscale rocket.
2.18.2	Demonstration	The avionics bay will be designed to include an altimeter that will record the altitude the launch rocket reaches.
2.19	Demonstration	The rocket was launched and recovered in its final flight configuration prior to FRR. This flight took place on February 18, 2018. The stability was within the desired range. Upon post flight inspection, there were no damages to the rocket. The recovery system deployed as designed. The team prepared the launch vehicle within three hours. Overall, this demonstration flight was a success.
2.19.1	Inspection / Analysis	After the rocket is launched, the team will inspect each system to confirm that it functioned properly. The structural integrity of the vehicle will be inspected to ensure that no part of the rocket suffered severe damages during flight, and flight data will be analyzed to ensure that recovery systems were deployed at their correct altitudes, and to determine if drift calculations were correct.
2.19.2	Demonstration	If the payload is not ready for a fullscale test launch, it will not be flown, but it should be thoroughly tested regardless.
2.19.2.1	Demonstration	A custom mass simulator will be made if the payload is not ready to be installed into the rocket for the test launch. The mass simulator will be made to be identical in mass as the final design of the payload.
2.19.2.2	Inspection	A visual inspection will be conducted prior to the test flight to ensure that either the final design of the payload or the mass simulator are installed properly.
2.19.3	Inspection	A visual inspection will be conducted prior to the test flight to ensure that all parts that affect the external surfaces of the rocket are present and installed properly.
2.19.4	Analysis	The fullscale motor was used during the fullscale test flight. The motor performed as expected.
2.19.5	Inspection	The rocket was weighed and recorded prior to test flight. The ballast configuration that will be used on launch day flight will be identical to the ballast configuration that was used during the test flight.
2.19.6	Inspection	Proper documentation was collected and recorded at the test launch. This documentation will be used to ensure that the launch vehicle or any of its components have not been modified. If modification is required, the concurrence of the NASA Range Safety Officer (RSO) will be acquired.

2.19.7	Demonstration	The rocket was launched and recovered in its final flight configuration prior to FRR. This flight took place on February 18, 2018.
2.20	Demonstration	The fins and camera cover are located aft of the burnout center of gravity. Center of gravity was recorded through multiple procedures to validate its location. The center of gravity will be moved to the front of the rocket as much as possible by having the rover payload at the front of the rocket. A visual inspection will be conducted prior to launch to ensure that the rocket complies with this requirement.
2.21.1	Inspection	The rocket does not any forward canards. . A visual inspection prior to flight on competition launch day can confirm this.
2.21.2	Inspection	The rocket does not have any forward firing motors. A visual inspection prior to flight on competition launch day can confirm this.
2.21.3	Inspection	The motor used is an Aerotech L1390. This motor complies with this requirement. A visual inspection prior to flight on competition launch day can confirm this.
2.21.4	Inspection	The motor used is an Aerotech L1390. This motor complies with this requirement. A visual inspection prior to flight on competition launch day can confirm this.
2.21.5	Inspection	The motor used is an Aerotech L1390. This motor complies with this requirement. A visual inspection prior to flight on competition launch day can confirm this.
2.21.6	Inspection	The rocket is designed to have active motor retainment via the use of centering rings and a motor retainer A visual inspection prior to flight on competition launch day can confirm this.
2.21.7	Analysis	Accurate calculations and simulations have been conducted as well as the collection of test flight data. All of these methods confirm that the rocket does not exceed Mach 1 at any point during flight.
2.21.8	Demonstration	A full inventory of the rocket components have been recorded. All components have part name, mass, and function recorded. Ballast does not exceed 10% of the total weight of the rocket. A visual inspection of the rocket will be conducted prior to flight to ensure that all components recorded on the inventory list are present. There will be no components missing or in excess of what is documented in the inventory list.

Avionics Requirements

Requirement	Method of Verification	Verification
3.1	Demonstration	Altimeter has been programmed so that drogue deploys at apogee and main will deploy at 700ft.
3.2	Test	LTRL has tested ejection charges prior to fullscale test flight and confirmed functionality.
3.3	Analysis	The parachute sizes have been determined from the kinetic energy requirements. The predicted kinetic energy from the largest section was determined to be only 60.91 ft-lbs, which is well under the 75 ft-lbs requirement.
3.4	Inspection	The recovery system wiring is completely independent of any payload components.
3.5	Inspection	Each altimeter has an independent, commercially available battery.
3.6	Inspection	There are two independent, commercially available altimeters per avionics bay. Each altimeter has independent power, ejection charges, and switches for redundancy.
3.7	Inspection	Motor ejection is not used to separate the rocket at any point.
3.8	Inspection	Removable shear pins are used to secure all parachute compartments until altimeters initiate separation.
3.9	Analysis	The parachutes were determined to be sufficient size such that drift does not exceed 2500 ft.
3.10	Inspection	A GPS tracking device is placed inside the launch vehicle and will transmit the position of any independent section to a ground receiver.
3.10.1	Inspection	The launch vehicle will descend entirely connected and employs 1 GPS device.
3.10.2	Test	The electronic tracking device performance has been tested during the test flight and has been verified functional.
3.11	Demonstration	The recovery system electronics is not adversely affected by any other on-board electronic devices during flight due to implementation of a faraday cage.
3.11.1	Inspection	The recovery system altimeters are located in a separate compartment within the vehicle without any other payloads or electronic components.
3.11.2	Test	A faraday cage was tested for ability to shield the recovery system electronics from all onboard transmitting devices during the fullscale test flight.
3.11.3	Test	A faraday cage was tested for ability to shield the recovery system electronics from all onboard transmitting devices during the fullscale test flight.
3.11.4	Test	A faraday cage was tested for ability to shield the recovery system electronics from all onboard transmitting devices during the fullscale test flight.

Payload Requirements

Requirement	Method of Verification	Verification
4.1	N/A	The team will construct a rover which will deploy from the rocket upon landing and operate autonomously
4.2	N/A	No additional experiments
4.3	N/A	No additional experiments
4.4	N/A	N/A
4.5	N/A	Deployable Rover
4.5.1	Inspection	The rover and its containment mechanism will autonomously deploy the rover from the inside of the rocket upon landing. The team will design, manufacture, and test the rover and containment system following the engineering design process.
4.5.2	Test	The communication protocols between the rover and the ground station will be tested in a variety of scenarios to ensure communication. Hardware communication components (XBee radios) will be procured and manufactured and control software will be written to establish a communications link between the rover and the ground station.
4.5.3	Test	The rover will be tested thoroughly on different terrains and in different weather conditions to prove its ability to travel the minimum required distance. The team will scout test sites on and around campus to determine potential proving grounds for the rover's travel abilities.
4.5.4	Test	The solar cell deployment mechanism will be tested thoroughly to ensure deployment after the rover has travelled to its final position. The solar panel deployment mechanism will be iteratively prototyped and tested to ensure that it can meet and exceed the given requirements.
4.6	N/A	N/A

Safety Requirements

Requirement	Method of Verification	Verification
5.1	Demonstration	The team will use launch and safety checklists during all fullscale launches.
5.2	Demonstration	Laura Reese is identified as the club safety officer in each report.
5.3.1	Demonstration	Laura Reese will perform all of the duties of the safety officer.

5.3.2	Demonstration	The safety officer will implement the safety procedures developed by the team for construction, assembly, launch and recovery activities.
5.3.3	Demonstration	The safety officer will manage and maintain current revisions of the team's hazard analyses, failure modes analyses, and SDS data.
5.3.4	Demonstration	The safety officer will assist in the writing and development of the team's hazard analyses and failure modes analyses
5.4	Demonstration	LTRL will abide by the rules and guidance of the RSOs of the Pittsburgh Space Command, Maryland Delaware Rocketry Association, and any other launch which the club chooses to attend.
5.5	Demonstration	LTRL will only launch at locations which have been given FAA clearance for the altitude to which the rocket is projected to attain.

Team derived requirements

Requirement	Method of Verification	Verification
Flight Vehicle		
Launch vehicle fins will be removable	Demonstration	Fins on the launch vehicle are able to be removed without disassembly of the launch vehicle. This has been accomplished by securing the fins into 3D printed fin brackets using machine screws. These fins can be unbolted from the fin brackets and safely removed.
Launch fin brackets will be removable	Demonstration	Fins brackets on the launch vehicle are able to be removed without disassembly of the launch vehicle. This is accomplished by 3D printing the fin brackets and sliding the brackets into pre-cut slots in the airframe. The fin brackets are then secured to the airframe using machine screws, which can be removed at any time.
Camera will be housed in the launch vehicle with aerodynamics in mind	Demonstrations / Testing	A 3D-printed camera cover has been screwed into the rocket so that the camera can record video data with minimal disturbance to aerodynamics.
Maintain a circular profile after wrapping the body tube in carbon fiber	Demonstration / Testing	Bulkheads were placed inside the blue tube during the wrapping process. This was done to support the blue tube so as to prevent it from warping during the wrapping process.

		This method worked well and ensured that the airframe remained cylindrical.
Flush cuts between separation points to ensure structural integrity	Demonstration / Testing	The team tried several methods to ensure that the cuts between separation points were flush. In the end, the method that produced the best result was to simply cut carefully with a hacksaw. All cuts were done in this manner.
Cut screws so that they will not interfere with parachute deployment	Demonstration	Screws were measured and cut to a length that remains long enough to maintain structural integrity but short enough so that they do not interfere with parachute deployment.
Coupler length is twice the diameter of the rocket to ensure structural integrity	Demonstration	The team has purchased and utilized couplers that are twice the length of the diameter and have measured the couplers to verify length.
Rocket is designed so that assembly is optimized on launch day	Analysis / Demonstration	When finalizing the design of the rocket, separation points were picked so that each subsystem can work on the respective section of the rocket independently.
Camera can start recording after it is fastened into the rocket.	Demonstration	The 3D-printed camera cover design has been modified so that an external recording button can be threaded through the rocket and accessed from the outside of the rocket after full assembly. This access is through a pinhole in the camera cover. This allows for external access while minimally affecting aerodynamics.
Avionics and Recovery		
The avionics bay will be able to be assembled into a transportable state within 2 hours.	Demonstration	The avionics bay is able to be assembled within two hours and be able to be transported.
Avionics bay will be able to be transformed from a transportable state to a launch ready state in 30 minutes.	Demonstration	The avionics bay is able to be assembled within 30 minutes on launch day.
The detonation of charges shall not cause the pressure within the avionics bay to exceed the rated pressure for the body tube	Analysis	The charges do not overwhelm the body tube and the redundant charges will be at a two-second delay.
The pressure produced during detonation shall exceed the rating of the	Test	The black powder has been measured such that it is sufficient to separate the rocket and also not so much that over-pressurization occurs.

shear pins by a factor of at least 2.5		
The avionics bay shall contain fully redundant parachute deployment systems	Inspection	The avionics bay has two independent altimeters with corresponding independent charges, power supplies, and switches.
Each altimeter arming switch shall be no more than five feet up the rocket	Inspection	The avionics bay is not located more than five feet up the rocket.
The avionics bay shall utilize a simple design that allows for clear and unambiguous instructions and assembly	Demonstration	The avionics bay can be easily assembled and bulkheads have been cut to ensure perfect symmetry.
The faraday cage shall protect the avionics bay from both internal and external interference	Test	The avionics bay is enclosed in a faraday cage that will protect it from interference from other electronic components.
Any load-bearing hardware in the recovery system shall have a factor of safety of at least 3	Analysis	All load-bearing hardware is ensured to have at least a safety factor of at least 3.
Avionics bay shall have a system to easily incorporate ballast securely	Demonstration	The avionics bay and avionics bay coupler allows ballast to be incorporated in the coupler.
Payload		
Maintain constant communication between the ground station and the rover throughout the mission	Test	Test the maximum range of the communications system to show that it is greater than the maximum drift range of the rocket. Find a test location where launch conditions can be most accurately replicated (including distance, duration of operation, and line of sight to the vehicle).
Design the rover to be self-righting in case it is overturned while maneuvering	Test	Places the rover in different orientations on different terrains and ensure that it can return to a drivable orientation without human intervention. Find various terrain and determine if the rover's self-righting capability can adequately perform on all terrains for any given orientation.
Avoid obstacles on the ground and navigate around terrain during operation	Test	Test the rover's navigational abilities by placing various sized obstacles in its path and driving it over various types of terrain. Find various terrain and determine if the rover's obstacle detection and avoidance system can

		accurately detect and avoid various sized and shaped obstacles
Deploy solar panels so that they are able to collect sunlight	Inspection	Confirm that the solar panels are exposed to sunlight when deployed. Design the solar panel deployment mechanism so that the solar panels will be exposed to sunlight (parallel to the ground) regardless of the rover's orientation.
Safely deploy the rover from the rocket body	Demonstration	Show that the CO2-powered ejection of the nose cone does not harm the rover or hinder its operation. Conduct ground testing of the nose cone ejection to determine the maximum force able to be sustained by the rover

7.3 Budgeting and Timeline

Table 24 displays the expected costs of the 2017-2018 with the most recent design changes accounted for. This table includes every individual item that has been purchased so far and any remaining projected costs.

Table 24. Expected Line Item Outflow 2017-2018

Fullscale			
Payload			
Arduino Nano	5	$15.99	$79.95
Arduino Mega	2	$13.99	$27.98
Wheel and Treads Kit	1	$14.95	$14.95
Solar Panels	2	$5.69	$11.38
Motor Driver	2	$4.95	$9.90
Double Sided PCB Board Variety Pack	1	$10.99	$10.99
Radio Transceiver	3	$19.95	$59.85
Antenna Connector	3	$0.75	$2.25
MOSFET Transistor	3	$1.75	$5.25
Ultrasonic Sensor	3	$3.95	$11.95
Micro Metal Gearmotor	4	$18.95	$75.80

Jumper Wire Kit	1	$14.60	$14.60
Soldering Station	1	$49.80	$49.80
4-Pack of 9V Batteries	1	$10.81	$10.81
Freight Charges	1	$32.00	$32.00
Structures			
5.5" Fiberglass Ogive Nose cone	1	$84.95	$84.95
5.5" Blue Tube (48" Length)	3	$56.95	$170.85
5.5" Blue Tube Couplers	5	$18.95	$94.75
Carbon Fiber Fabric	1	$329.95	$329.95
Epoxy Resin for Carbon Fiber	1	$44.95	$44.95
Epoxy Hardener for Carbon Fiber	1	$21.95	$21.95
1.25" Shrink Tape	2	$39.95	$79.90
Fiberglass Sheet ⅛" x 1 square feet	4	$27.00	$108.00
Large Rail Buttons for 1515 Rail	1	$4.65	$4.65
Center Rings 75mm to 5.36"	2	$13.55	$27.10
5.36" Tube Bulkheads	6	$7.61	$45.66
5.26" Coupler Bulkheads	5	$7.61	$38.05
Freight Charges	1	$134.21	$134.21
Avionics and Recovery			
Blast Caps	4	$15.00	$60.00
GPS	1	$106.00	$106.00
GPS Monthly Fee	4	$25.00	$100.00
Initiators	2	$27.20	$54.40
Shear Pins	1	$11.35	$11.35
Key Switches	3	$13.00	$39.00
Spare Key	1	$2.12	$2.12

Wire Connector	1	$6.55	$6.55
Freight Charges	1	$18.91	$18.91
Propulsion			
Aerotech L1390 Motor Reload	2	$199.99	$399.98
Aerotech 75mm Forward Seal Disk	2	$35.00	$70.00
Fiberglass Motor Tube	1	$41.02	$41.02
AeroPack 75mm Retainer	1	$47.08	$47.08
Freight Charges	1	$103.96	$103.96
Fullscale Total			**$2,662.80**
Subscale			
Structures			
75 mm Blue Tube	2	$29.95	$59.90
75 mm Blue Tube Coupler	3	$9.95	$29.85
Fiberglass Sheet ⅛" x 1 square feet	2	$27.00	$54.00
Centering Rings 54mm to 75mm	2	$7.30	$14.60
Tube Bulkhead Disk 75mm	5	$3.83	$19.15
Large Rail Button for 1515 Rail	1	$4.65	$4.65
1.25" Shrink Tape	2	$39.95	$79.90
Satin Weave Carbon Fiber Fabric	1	$79.95	$79.95
Epoxy Hardener for Carbon Fiber	1	$21.95	$21.95
Epoxy Resin for Carbon Fiber	1	$104.95	$104.95
Freight Charges	1	$56.27	$56.27
Propulsion			
JS80SS 54-2 Grain Motor	1	$79.20	$79.20
Subscale Total			**$604.37**

Travel			
Hotel Costs - 1 King, 1 Sofa Bed - SpringHill Suites	7	$636.75	$4,457.25
Minivan Car Rentals	4	$508.79	$2,035.16
Fuel Costs - Alabama Trip	4	$140.00	$560.00
Fuel Costs - Fullscale	1	$400.00	$400.00
Fuel Costs - Subscale Launch	1	$160.15	$160.15
Travel Total			**$7,612.56**
Outreach			
Miscellaneous Supplies	1	$150.00	$150.00
Outreach Total			**$150.00**
Miscellaneous Supplies and Equipment			
Shop Towels	6	$4.90	$29.40
Electrical Tape	1	$6.73	$6.73
3D Printing Filament	2	$25.50	$51.00
Birch Plywood	1	$12.42	$12.42
Douglas Fir Lumber	1	$14.10	$14.10
Sheet Metal Screw Pan	2	$3.87	$7.74
Hex Nuts	1	$10.67	$10.67
U-bolts	4	$1.14	$4.56

Eye Bolt	4	$1.18	$4.72
Threaded Rod	4	$1.47	$5.88
Lowe's Bucket	1	$3.68	$3.68
Yard Stick	1	$0.98	$0.98
Flex Seal	1	$31.98	$31.98
Multimeter	2	$17.99	$35.98
J-B Weld Original	3	$12.95	$38.85
J-B Weld KwikWeld	1	$15.81	$15.81
Switch Power Supply Driver	1	$25.99	$25.99
Other Unexpected Miscellaneous Costs	1	$200.00	$200.00
Miscellaneous Supplies and Equipment Total			**$500.49**
Overall Total			**$11,530.22**

The expenditures for the 2017-2018 school year are broken up by fullscale, subscale, travel, outreach, and miscellaneous supplies and equipment. The costs of fullscale and subscale are broken up by subsystem. Subscale contains finalized expenditures only since the rocket has been completed successful. Structures and propulsion are the only subsystems listed since avionics and recover and payload used equipment the club already had access to in the lab. Fullscale consists of items that have already been purchased. There are currently no other projected costs as the rocket is finalized. Travel is still the most expensive sector of this competition. The hotel cost is definitive as the rooms have been booked. The budget for outreach is used for any supplies for the different outreach projects the club completes throughout the year. Miscellaneous supplies and equipment shows expenses of items that are shared between subsystems. There is an additional $200.00 in miscellaneous supplies and equipment set aside in case other costs do come up for the rocket. Table 25 gives a summary of the outflow for the academic year. Figure 37 shows a pictorial representation of the cost breakdown.

Table 25. Expected Outflow Overview 2017-2018

Budget	Total Cost
Fullscale	$2,662.80
Subscale	$604.37
Travel	$7,612.56
Outreach	$150.00
Miscellaneous Supplies and Equipment	$500.49
Total	**$11,530.22**

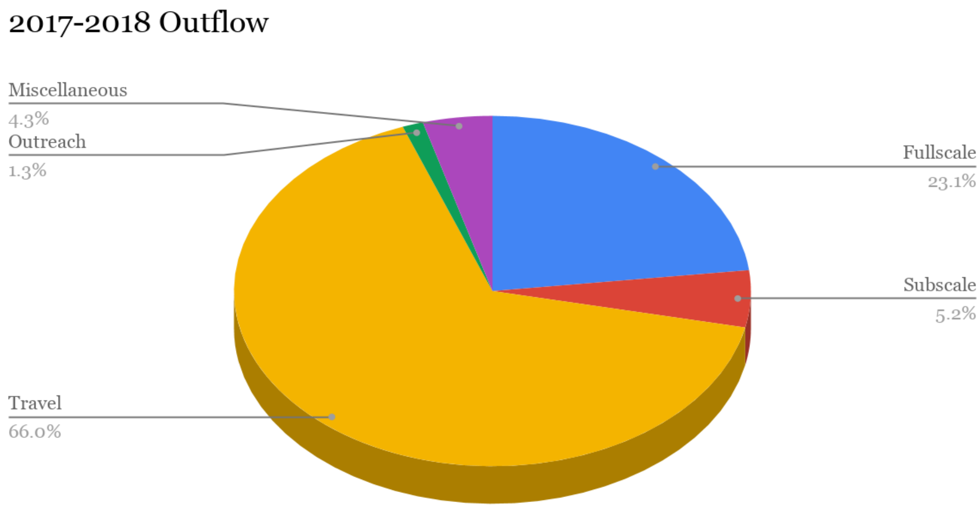


Figure 37. Budget Outflow Overview

Travel and fullscale continue to be the most expensive pieces of the budget. The club takes as many students as possible to Huntsville, Alabama in the spring every year, which is what causes the expenses to be the highest. Fullscale ends up being costly due to needing large equipment and supplies to ensure a safe and secure rocket. Table 26 shows the planned inflow for the 2017-2018 academic year and Figure 38 gives a visual display of the breakdown of LTRL's planned income for the school year.

Table 26. Expected Inflow 2017-2018

Donor	Requested Amount
Penn State College of Engineering	$1,000.00
Penn State Aerospace Engineering Department	$2,000.00
Penn State Mechanical Engineering Department	$1,000.00
University Park Allocations Committee (UPAC)	$6,000.00
Pennsylvania Space Grant	$3,965.62
The Boeing Company	$500.00
Club Fundraising	$1,105.00
Prior Club Funds	$1,502.59
Total	**$17,073.21**

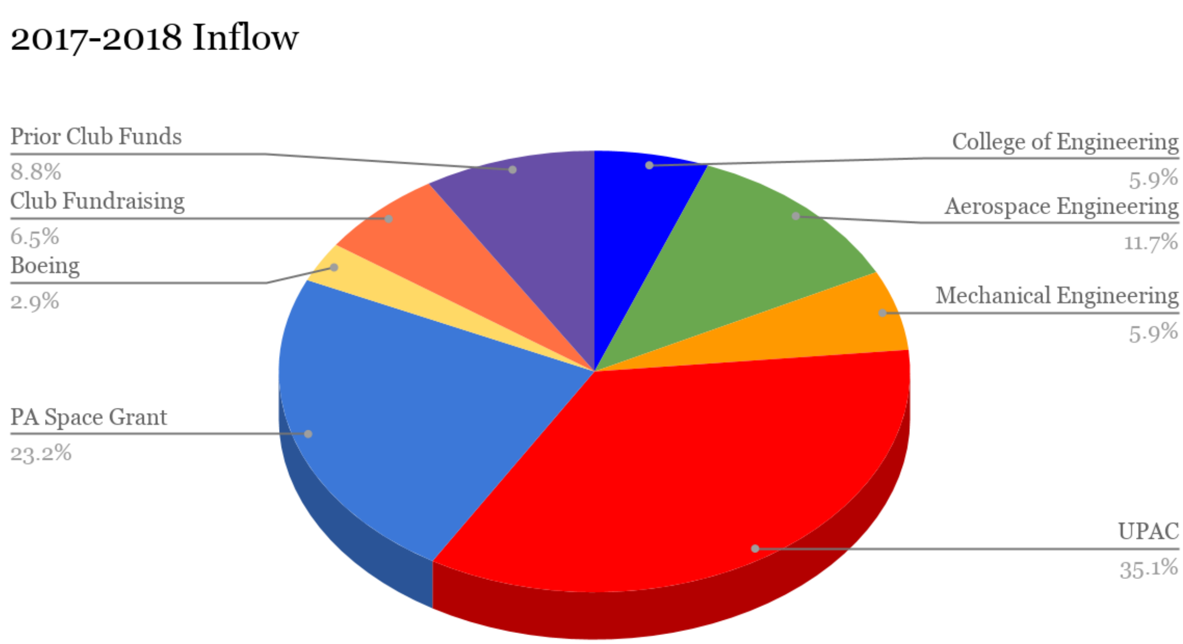
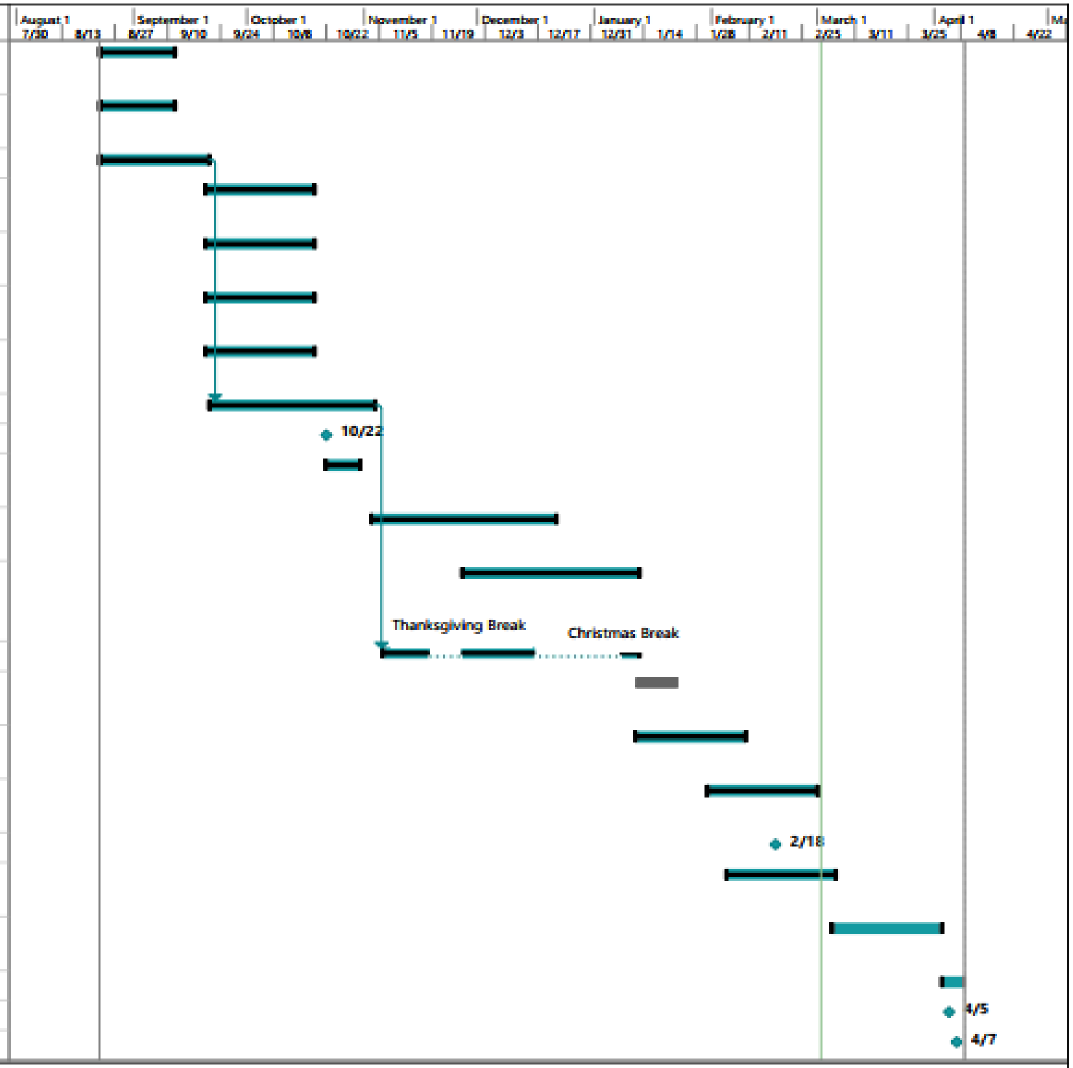


Figure 38. Budget Inflow Overview

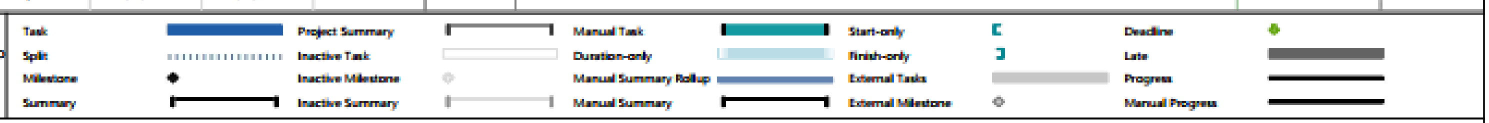
The Penn State College of Engineering has donated $1,000.00 to the club. The Penn State Aerospace Engineering Department has agreed to give $2,000.00 to support LTRL. Also, the Aerospace Engineering Department has provided the club with lab space. The Penn State Mechanical and Nuclear Engineering has given LionTech Rocket Labs $1,000.00. The club has been guaranteed $5,000.00 from the University Park Allocations Committee (UPAC) for travel and is expecting another $1,000.00 to go towards equipment. The club received financial support from the Pennsylvania Space Grant, in which $3,965.62 was given. This money must be used by the end of April, so LTRL will focus on spending this money on travel. The Boeing Company has continued its financial support and granted the club $500.00. Through club dues and other club fundraising LTRL has raised $1,105.00. Lastly, the club has funds from the previous academic year that was used to start the club off. LTRL has plenty of funding to cover this year's costs and hopes to leave money in the account for next year to help the future of the club.

Structures/Propulsion Gantt Chart

ID	Task Name	Duration	Start	Finish	% Complete
1	Preliminary Desgin	14 days	Wed 8/23/17	Mon 9/11/17	100%
2	Material Testing	14 days	Wed 8/23/17	Mon 9/11/17	100%
3	Proposal	21 days	Wed 8/23/17	Wed 9/20/17	100%
4	Subscale Design	21 days	Wed 9/20/17	Wed 10/18/17	100%
5	Subscale Motor Testing	21 days	Wed 9/20/17	Wed 10/18/17	100%
6	Subscale Modeling & Simulations	21 days	Wed 9/20/17	Wed 10/18/17	100%
7	Subscale Construction	21 days	Wed 9/20/17	Wed 10/18/17	100%
8	PDR	32 days	Thu 9/21/17	Fri 11/3/17	100%
9	Subscale Test Flight	0 days	Sun 10/22/17	Sun 10/22/17	100%
10	Subscale Evaluation	7 days	Sun 10/22/17	Mon 10/30/17	100%
11	Finalize Fullscale Design	35 days	Fri 11/3/17	Thu 12/21/17	100%
12	Fullscale Rocket Modeling & Simulations	35 days	Mon 11/27/17	Fri 1/12/18	100%
13	CDR	30 days	Mon 11/6/17	Fri 1/12/18	100%
14	Fullscale Motor Testing	7 days	Fri 1/12/18	Mon 1/22/18	0%
15	Fullscale Construction	21 days	Fri 1/12/18	Fri 2/9/18	100%
16	Fullscale Evaluation	21 days	Wed 1/31/18	Wed 2/28/18	100%
17	Fullscale Test Flight	0 days	Sun 2/18/18	Sun 2/18/18	100%
18	FRR	21 days	Mon 2/5/18	Mon 3/5/18	100%
19	USLI Preparation and Launch	21 days	Mon 3/5/18	Mon 4/2/18	0%
20	USLI Competition	5 days	Tue 4/3/18	Sun 4/8/18	0%
21	LRR	0 days	Thu 4/5/18	Thu 4/5/18	0%
22	Launch Day	0 days	Sat 4/7/18	Sat 4/7/18	0%



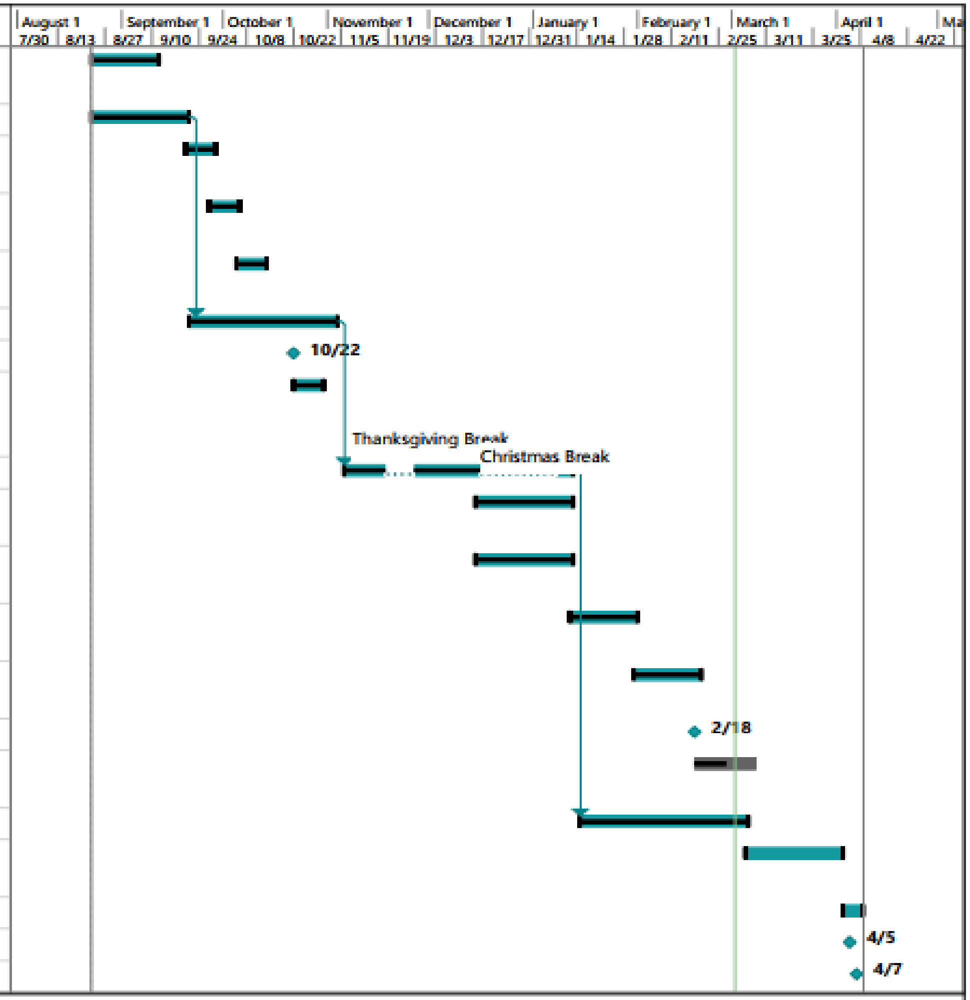
Project: LTRL Structures and Pro
Date: Fri 3/2/18



Page 1

A&R Gantt Chart

ID	Task Name	Duration	Start	Finish	% Complete
1	Preliminary Recovery System Concept	14 days	Wed 8/23/17	Mon 9/11/17	100%
2	Proposal	21 days	Wed 8/23/17	Wed 9/20/17	100%
3	Subscale Recovery System Design	7 days	Wed 9/20/17	Thu 9/28/17	100%
4	Subscale Recovery System Construction	7 days	Wed 9/27/17	Thu 10/5/17	100%
5	Subscale Recovery System Testing	7 days	Thu 10/5/17	Fri 10/13/17	100%
6	PDR	32 days	Thu 9/21/17	Fri 11/3/17	100%
7	Subscale Test Flight	0 days	Sun 10/22/17	Sun 10/22/17	100%
8	Final Subscale Recovery System Verification	7 days	Sun 10/22/17	Mon 10/30/17	100%
9	CDR	30 days	Mon 11/6/17	Fri 1/12/18	100%
10	Fullscale Recovery System Modeling	21 days	Fri 12/15/17	Fri 1/12/18	100%
11	Fullscale Recovery System Design	21 days	Fri 12/15/17	Fri 1/12/18	100%
12	Fullscale Recovery System Construction	14 days	Fri 1/12/18	Wed 1/31/18	100%
13	Fullscale Recovery System Testing	14 days	Wed 1/31/18	Mon 2/19/18	100%
14	Fullscale Test Flight	0 days	Sun 2/18/18	Sun 2/18/18	100%
15	Fullscale Recovery System Verification	14 days	Sun 2/18/18	Wed 3/7/18	50%
16	FRR	36 days	Mon 1/15/18	Mon 3/5/18	100%
17	USLI Preparation and Launch	21 days	Mon 3/5/18	Mon 4/2/18	0%
18	USLI Competition	5 days	Tue 4/3/18	Sun 4/8/18	0%
19	LRR	0 days	Thu 4/5/18	Thu 4/5/18	0%
20	Launch Day	0 days	Sat 4/7/18	Sat 4/7/18	0%



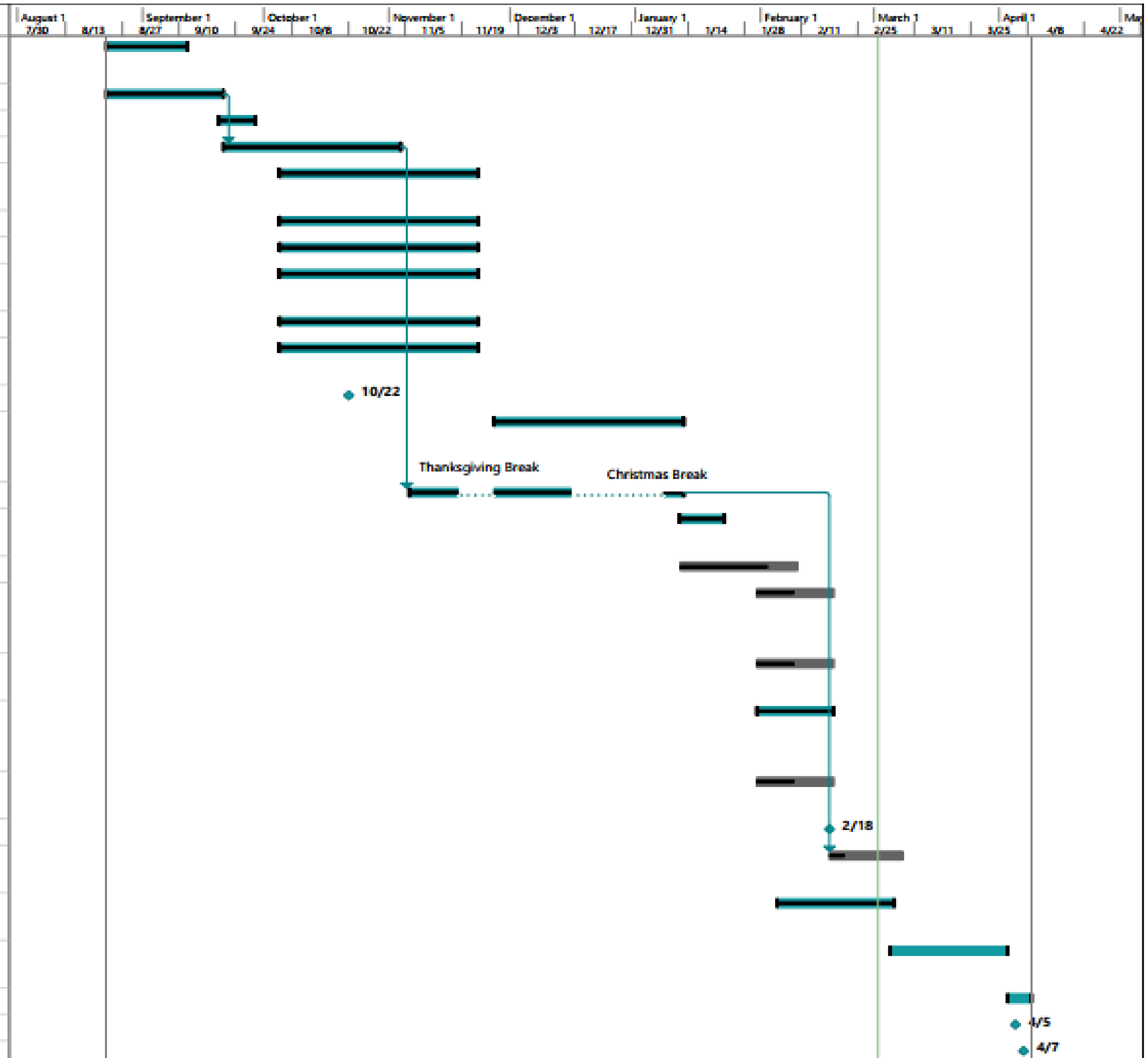
Project: LTRL A&R
Date: Fri 3/2/18

Task		Inactive Task		Manual Summary Rollup		External Milestone	
Split		Inactive Milestone		Manual Summary		Deadline	
Milestone		Inactive Summary		Start-only		Late	
Summary		Manual Task		Finish-only		Progress	
Project Summary		Duration-only		External Tasks		Manual Progress	

Page 1

Payload Gantt Chart

ID	Task Name	Duration	Start	Finish	% Complete
1	Preliminary Conceptualization	14 days	Wed 8/23/17	Mon 9/11/17	100%
2	**Proposal**	21 days	Wed 8/23/17	Wed 9/20/17	100%
3	Material Selection	7 days	Wed 9/20/17	Thu 9/28/17	100%
4	**PDR**	32 days	Thu 9/21/17	Fri 11/3/17	100%
5	Electronics Container Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
6	Motor Selection	35 days	Thu 10/5/17	Wed 11/22/17	100%
7	Drive Train Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
8	Frame/Suspension Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
9	Wheel Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
10	Solar Panel Deployment Design	35 days	Thu 10/5/17	Wed 11/22/17	100%
11	**Subscale Test Flight**	0 days	Sun 10/22/17	Sun 10/22/17	100%
12	Create Software Flowchart/Identify Modules	35 days	Mon 11/27/17	Fri 1/12/18	100%
13	**CDR**	30 days	Mon 11/6/17	Fri 1/12/18	100%
14	Complete Software Modules	7 days	Fri 1/12/18	Mon 1/22/18	100%
15	Assembly of Rover	21 days	Fri 1/12/18	Fri 2/9/18	75%
16	Test/Review Modules Independently	14 days	Wed 1/31/18	Sun 2/18/18	50%
17	Test Subsystems of Rover	14 days	Wed 1/31/18	Sun 2/18/18	50%
18	Design/Build Containment Chamber	14 days	Wed 1/31/18	Sun 2/18/18	100%
19	Consolodate Modules	14 days	Wed 1/31/18	Sun 2/18/18	50%
20	**Fullscale Test Flight**	0 days	Sun 2/18/18	Sun 2/18/18	100%
21	Test Full Assembly of Rover	14 days	Sun 2/18/18	Wed 3/7/18	25%
22	**FRR**	21 days	Mon 2/5/18	Mon 3/5/18	100%
23	USLI Preparation and Launch	21 days	Mon 3/5/18	Mon 4/2/18	0%
24	**USLI Competition**	5 days	Tue 4/3/18	Sun 4/8/18	0%
25	**LRR**	0 days	Thu 4/5/18	Thu 4/5/18	0%
26	**Launch Day**	0 days	Sat 4/7/18	Sat 4/7/18	0%



Project: LTRL Payload
Date: Fri 3/2/18

Task, Split, Milestone, Summary, Project Summary, Inactive Task, Inactive Milestone, Inactive Summary, Manual Task, Duration-only, Manual Summary Rollup, Manual Summary, Start-only, Finish-only, External Tasks, External Milestone, Deadline, Late, Progress, Manual Progress

Page 1

Appendix A: MSDS Sheets

Epoxy Resin SDS

Fibre Glast
Developments Corporation

GHS SAFETY DATA SHEET (SDS)

SECTION 1 - PRODUCT AND COMPANY IDENTIFICATION

PRODUCT: Part #2000 System 2000 Epoxy Resin

FIBRE GLAST DEVELOPMENTS CORP.
385 CARR DRIVE
BROOKVILLE, OH 45309

TELEPHONE: (937) 833-5200
FAX: (937) 833-6555
FOR CHEMICAL EMERGENCY
CALL (800) 424-9300 24 HRS.

RECOMMENDED USE: Industrial Epoxy Resin supplied exclusively for workplace use.

SECTION 2 – HAZARDS IDENTIFICATION

GHS CLASSIFICATION

Eye Irritation	:	Category 2B
Acute Toxicity (Oral)	:	Category 5
Skin Irritation	:	Category 2
Skin Sensitizer	:	Category 1
Respiratory Irritation	:	STOT SE3

GHS Label Element
Hazard pictogram :

Signal Word : Warning

Hazard statements : H320 Causes eye irritation.
H303 May be harmful if swallowed.
H315 Causes skin irritation.
H317 May cause an allergic skin reaction.

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PDCT-MSDS-00130-04/15-CM

Epoxy Hardener SDS

Fibre Glast Developments Corporation

GHS SAFETY DATA SHEET (SDS)

SECTION 1 - PRODUCT AND COMPANY IDENTIFICATION

PRODUCT: Part #2060 Epoxy Hardener

FIBRE GLAST DEVELOPMENTS CORP.
385 CARR DRIVE
BROOKVILLE, OH 45309

TELEPHONE: (937) 833-5200
FAX: (937) 833-6555
FOR CHEMICAL EMERGENCY CALL (800) 424-9300 24 HRS.

RECOMMENDED USE: Industrial Curing Agent supplied exclusively for workplace use.

SECTION 2 – HAZARDS IDENTIFICATION

GHS CLASSIFICATION

Eye Damage	: Category 1
Acute Toxicity (Oral and Inhalation)	: Category 4
Skin Sensitizer	: Category 1

GHS Label Element

Hazard pictograms :

Signal Word	: Danger
Hazard statements	: H318 Causes serious eye damage. H302+332 Harmful if swallowed, or if inhaled. H317 May cause an allergic skin reaction.
Precautionary statements	: P202 Do not handle until all safety precautions have been read/understood. P261 Avoid breathing dust/fume/gas/mist/vapours/spray. P270 Do not eat, drink or smoke when using this product. P281 Use personal protective equipment as required. P285 In case of inadequate ventilation wear respiratory protection. P273 Avoid release to the environment.

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PDCT-MSDS-00132-04/15-CM

Black Powder SDS

1 **SAFETY DATA SHEET-BLACK POWDER**

Section 1: Identification

Product Identifier: Black Powder (includes all grades)

Manufacturer's Name: GOEX Powder, Inc. **Informational Telephone Number:** 1-(318) 382-9300

Address: P.O. Box 659, Doyline, LA 71023-0659 **Emerg. Phone Number:** 1-(800) 255-3924 (Chem Tel)

Recommended Use: for use in competitive and recreational shooting, muzzleloading hunting and the U.S. Military .

Section 2: Hazard(s) Identification

Hazard category:	Signal Word	Hazard statement	Pictogram
Division 1.1	Danger	Explosive; mass explosion hazard	

Target Organ Warning: Above OSHA levels, chronic exposure may cause skin irritation and damage to the respiratory system, and acute exposure can cause skin, eye, and respiratory irritation.

Section 3: Composition/information on ingredients

Component	CAS-Number	Weight %
Charcoal	16291-96-6	8-18%
Sulfur	7704-34-9	9-20%
Potassium Nitrate	7757-79-1	70-76%
Graphite (note: not contained in all grades of black powder)	7782-42-5	<1%

Section 4: First-aid measures

Ingestion: * Not a likely route of exposure. If ingested, dilute by giving two glasses of water and induce vomiting. Avoid, when possible and contact a Poison control center for advice on treatment, if unsure.

Eye Contact: * Not a likely route of exposure. Flush eyes with water.

Inhalation: * Remove patient from area to fresh air. If not breathing, give artificial respiration, preferably by mouth to mouth. If breathing is difficult, give oxygen. Seek prompt medical attention. Avoid when possible.

Skin Contact: * wash the affected area with copious amounts of water. Some persons may be sensitive to product.

Injury from detonation: * Seek prompt medical attention immediately.

Note to Physician: * Treat symptomatically.

Section 5: Fire-fighting measures

Extinguishing media: * Water may be used as the extinguishing method. DO NOT FIGHT EXPLOSIVES FIRES. Evacuate the area according to Emergency Response Guide 112 guidelines. Isolate the area and guard against any intruders.

Special Procedures: * Black Powder is extremely flammable and may deflagrate. Get away and evacuate the area.

Unusual Hazards: * As with any pyrotechnic, if under confinement or piled in slight confinement, Black Powder can explode. No known toxic fumes are emitted, but good ventilation should still be present.

Flash Point: not applicable.

Auto ignition Temp: Approximate range: 392°-867°F /(200°-464°C)

NFPA Ratings: **Health=1** **Flammability=3** **Reactivity=1**

Advice and PPE for Firefighters: * Fires involving Black Powder should not be fought unless extinguishing media can be applied from a well protected and distant location from the point of fire. Self-contained breathing apparatus (SCBA) and protective clothing must be worn. Follow Emergency Response Guide 112. Wash all clothes prior to reuse.

Carbon Fiber Fabric Wrap SDS

SAFETY DATA SHEET

structural TECHNOLOGIES

SDS IDENTIFICATION NAME: V-Wrap Carbon Fiber Fabric	**PAGE:** 1 OF 4
Product Group: V-Wrap C200H & V-Wrap C400H	**DATE:** 10/08/2015

SECTION I: MATERIAL AND MANUFACTURER IDENTIFICATION

MANUFACTURER:
STRUCTURAL TECHNOLOGIES, LLC
10150 Old Columbia Road
Columbia, MD 21046

EMERGENCY TELEPHONE NUMBER:
800-424-9300
INFORMATION TELEPHONE NUMBER:
410-859-6539

CHEMICAL FAMILY: Carbon Fiber

SECTION II: HAZARD(S) IDENTIFICATION

EMERGENCY OVERVIEW: No unusual conditions are expected from this product.

APPEARANCE AND ODOR: Resin-coated black carbon fibers woven into fabric of varying weight and thickness, depending on the style, with no distinctive odor.

STATEMENTS OF HAZARD:
CARBON MATERIAL IS ELECTRICALLY CONDUCTIVE. ELECTRICAL SYSTEMS SHOULD BE PROTECTED FROM EXPOSURE TO AIRBORNE FIBER.
DUST PARTICLES ASSOCIATED WITH THIS PRODUCT MAY CAUSE IRRITATION OF THE SKIN, EYES, OR UPPER RESPIRATORY TRACT.

PRIMARY ROUTES OF EXPOSURE:
EYES--YES SKIN CONTACT--YES INHALATION--NO INGESTION--NO

HMIS RATING:

CARBON:	HEALTH--1	FLAMMABILITY--0	REACTIVITY--0	SPECIAL—NONE
GLASS:	HEALTH--2	FLAMMABILITY--1	REACTIVITY--0	SPECIAL—NONE
SIZING:	HEALTH--1	FLAMMABILITY--1	REACTIVITY--0	SPECIAL—NONE

POTENTIAL HEALTH EFFECTS:
EYES: Low hazard. May cause temporary irritation.
SKIN: Low hazard for usual industrial or commercial production. No effects expected under normal use.
INHALATION: In some cases – see Section VII. No effects expected under normal use.
INGESTION: Ingestion unlikely under normal use. May cause gastrointestinal irritation.

SIGNS AND SYMPTOMS OF EXPOSURE: Possible Rash.

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE: None known

SECTION III: COMPOSITION/INFORMATION ON INGREDIENTS

This document is prepared pursuant to the OSHA Hazard Communication Standard (29 CFR 1910.1200).

MATERIAL OR COMPONENT	CAS NUMBER	% BY WEIGHT	OSHA(PEL)	ACGIH(TLV)
CARBON FIBER	7440-44-0	92-96	15 mg/m^3 (Total) 5 mg/m^3 (Respirable)	15 mg/m^3 (Total) 3 mg/m^3 (Respirable)
EPOXY SIZING	25068-38-6	2-4	Not Determined	Not Determined

Fiberglass SDS

Fiberglass Safety Data Sheet

SECTION 1: Identification of the substance/mixture and of the company/undertaking

1.1 Product identifier

- Fiberglass

1.2 Relevant identified uses of the substance or mixture and uses advised against

- Structural reinforcement for thermoset resin products.

1.3 Details of the supplier of the safety data sheet

- NOV Fiber Glass Systems
17115 San Pedro Avenue, Suite 200
San Antonio, Texas 78232 USA
Tel: 1-210-477-7500
Fax: 1-210-231-5915
E-mail: Mike.Thayer@nov.com

1.4 Emergency telephone number(s)

- 3E Company, 24-Hour Support (Access Code/Contract Number: 333386)
  - USA, Canada 1-888-298-2344
  - Asia, Pacific 1-760-476-3960
  - Europe, Middle East, Africa 1-760-476-3961
  - Americas 1-760-476-3962

SECTION 2: Hazards identification

2.1 Classification of the substance or mixture

Physical

- Not classified

Health

- Skin irritation, Category 2
- Eye irritation – Category 2
- Specific target organ systemic toxicity – single exposure, Category 3 (respiratory tract irritation)

Environmental

- Not classified

Isopropyl Alcohol SDS

SAFETY DATA SHEET

1. Identification

Product identifier: Isopropyl Alcohol

Other means of identification
Product No.: 9088, 5892, 9095, 9084, 9083, 9082, 9079, 9078, 9059, 9055, 9045, 5986, 5978, 5977, 5967, 5873, 5863, 9827, 5373, 9334

Recommended use and restriction on use
Recommended use: For use in the PortaCount® Respirator Fit Tester
Restrictions on use: Not known.

Manufacturer/Importer/Supplier/Distributor information
Manufacturer

Company Name:	TSI Incorporated
Address:	500 Cardigan Road Shoreview, MN 55126
Telephone:	Customer Service: 800-874-2811
Fax:	
Contact Person:	
e-mail:	answers@tsi.com

Emergency telephone number:
24 Hour Emergency: 908-859-2151

Chemtrec: 800-424-9300

2. Hazard(s) identification

Hazard classification

Physical hazards

Flammable liquids	Category 2

Health hazards

Serious eye damage/eye irritation	Category 2A
Specific target organ toxicity - single exposure	Category 3

Label elements
Hazard symbol:

Signal word: Danger

Hazard statement: Highly flammable liquid and vapor.
Causes serious eye irritation. May cause respiratory irritation.
May cause drowsiness or dizziness.

JB Kwik SDS

MATERIAL SAFETY DATA SHEET

1. Product and Company Identification

Product Name	J-B Kwik
Synonym(s)	Resin and Hardener
CAS #	Mixture
Product use	Bonds and repairs
Manufacturer	J-B Weld Company P.O. Box 483 Sulphur Springs, TX 75482 US Phone: 903-885-7696

2. Hazards Identification

Emergency overview
CAUTION
MAY CAUSE EYE IRRITATION. MAY CAUSE SKIN IRRITATION.
MAY CAUSE ALLERGIC SKIN REACTION.

Potential short term health effects

Routes of exposure Eye, Skin contact, Ingestion.

Eyes May cause irritation.

Skin Contact with skin can cause irritation and allergic reaction (sensitization) in some individuals.

Inhalation Not a normal route of exposure.

Ingestion May cause stomach distress, nausea or vomiting.

Target organs Eyes. Skin.

Chronic effects Prolonged or repeated exposure can cause drying, defatting and dermatitis.

Signs and symptoms Symptoms may include redness, edema, drying, defatting and cracking of the skin. Symptoms of overexposure may be headache, dizziness, tiredness, nausea and vomiting.

OSHA Regulatory Status This product is a "Hazardous Chemical" as defined by the OSHA Hazard Communication Standard, 29 CFR 1910.1200.

Potential environmental effects See section 12.

3. Composition / Information on Ingredients

Ingredient(s)	CAS #	Percent
Iron	7439-89-6	5 - 10
Limestone	1317-65-3	10 - 30
Oxirane, 2,2-[(1-methylethylidene)bis(4,1-phenyleneoxymethylene)]bis, homopolymer	25085-99-8	10 - 30
Phenol, 2,4,6-tris[(dimethylamino)methyl]-	90-72-2	1 - 5
Phenol, polymer with formaldehyde, glycidyl ether	28064-14-4	1 - 5
Carbon black	1333-86-4	0.1 - 1
Titanium oxide	13463-67-7	0.1 - 1

4. First Aid Measures

First aid procedures

Eye contact Flush with cool water. Remove contact lenses, if applicable, and continue flushing. Obtain medical attention if irritation persists.

Skin contact Flush with cool water. Wash with soap and water. Obtain medical attention if irritation persists.

Inhalation Not a normal route of exposure.

Ingestion Do not induce vomiting. Never give anything by mouth if victim is unconscious, or is convulsing. Obtain medical attention.

JB Weld SDS

SAFETY DATA SHEET

Issuing Date 11-Nov- 2014 **Revision Date** 11-Nov-2014 **Revision Number** 1

1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

Product identifier

Product SDS Name **Steel Reinforced Epoxy Resin – Twin Tubes - Part A**

J-B Weld FG SKU Part Numbers Covered

8265, 8265F, 8276, 8276F, 8265S, 8265A, 8265H, 8272, 8272F, 8280, 8280F, 8281, 80165, 7265S, 7280, 8276A, 8273H, 8270, 8270F, 8271, 80176, 7276, 7270

J-B Weld Product Names Covered

J-B Weld™ (all Twin Tubes), KwikWeld™ (all Twin Tubes), MarineWeld™ (Twin Tubes Only)

J-B Weld Product Type

Steel Reinforced Epoxy

Recommended use of the chemical and restrictions on use

Recommended Use General Purpose Adhesive

Uses advised against No information available

Details of the supplier of the safety data sheet

Supplier Name J-B WELD COMPANY,LLC

Supplier Address 1130 COMO ST
SULPHUR SPRINGS, TX 75482
USA

Emergency Telephone Numbers Transportation Emergencies: Chemtrec (24 hour transportation emergency response info): 800-424-9300 or 703-527-3887

Poison/Medical Emergencies: Poison Control Centers (24 hour emergency poison / medical response info): 800-222-1222

Supplier Email info@jbweld.com

Supplier Phone Number 903-885-7696

2. HAZARDS IDENTIFICATION

OSHA/HCS status This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture
SKIN CORROSION/IRRITATION - Category 2
SERIOUS EYE DAMAGE/ EYE IRRITATION - Category 2B
SKIN SENSITIZATION - Category 1

GHS label elements

Hazard pictograms

Signal word Warning!

Hazard statements Causes skin and eye irritation.
May cause an allergic skin reaction.

Mystik Hi-Temp Grease SDS

SAFETY DATA SHEET

Mystik® JT-6® Synthetic Hi-Temp Grease, No. 2, ISO 220

Section 1. Identification

GHS product identifier	: Mystik® JT-6® Synthetic Hi-Temp Grease, No. 2, ISO 220
Synonyms	: Lubricating grease; CITGO® Material Code: 665077002
Code	: 665077002
MSDS #	: 665077002
Supplier's details	: CITGO Petroleum Corporation P.O. Box 4689 Houston, TX 77210 sdsvend@citgo.com
Emergency telephone number	: Technical Contact: (800) 248-4684 Medical Emergency: (832) 486-4700 CHEMTREC Emergency: (800) 424-9300 (United States Only)

Section 2. Hazards identification

OSHA/HCS status	: While this material is not considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200), this SDS contains valuable information critical to the safe handling and proper use of the product. This SDS should be retained and available for employees and other users of this product.
Classification of the substance or mixture	: Not classified.

GHS label elements

Signal word	: Warning
Hazard statements	: Injection under the skin can cause severe injury. Most damage occurs in the first few hours. Initial symptoms may be minimal.

Precautionary statements

General	: Avoid contact with eyes, skin and clothing.. IF IN EYES: Rinse cautiously with water for several minutes. IF SWALLOWED: Do NOT induce vomiting. After handling, always wash hands thoroughly with soap and water. If you feel unwell, seek medical attention and show the label when possible. Keep out of reach of children.
Prevention	: Not applicable.
Response	: Not applicable.
Storage	: Store in a dry place and/or in closed container. Store in accordance with all local, regional, national and international regulations.
Disposal	: Dispose of contents and container in accordance with all local, regional, national and international regulations.
Hazards not otherwise classified	: Injection of petroleum hydrocarbons requires immediate medical attention

Section 3. Composition/information on ingredients

Substance/mixture	: Mixture
Other means of identification	: Lubricating grease; CITGO® Material Code: 665077002

CAS number/other identifiers

CAS number	: Not applicable.

Date of issue/Date of revision : 1/21/2016 1/9

Spray Paint SDS

SAFETY DATA SHEET

51601

Section 1. Identification

Product name : KRYLON® ColorMaster™ with Covermax™ Technology Paint + Primer Gloss Black

Product code : 51601

Other means of identification : Not available.

Product type : Aerosol.

Relevant identified uses of the substance or mixture and uses advised against

Not applicable.

Manufacturer : Krylon Products Group
101 W. Prospect Avenue
Cleveland, OH 44115

Emergency telephone number of the company : US / Canada: (216) 566-2917
Mexico: SETIQ 01-800-00-214-00 / (52) 55-5559-1588 24 hours / 365 days a year

Product Information Telephone Number : US / Canada: (800) 457-9566
Mexico: Not Available

Regulatory Information Telephone Number : US / Canada: (216) 566-2902
Mexico: Not Available

Transportation Emergency Telephone Number : US / Canada: (216) 566-2917
Mexico: SETIQ 01-800-00-214-00 / (52) 55-5559-1588 24 hours / 365 days a year

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : FLAMMABLE AEROSOLS - Category 1
GASES UNDER PRESSURE - Compressed gas
SKIN CORROSION/IRRITATION - Category 2
SERIOUS EYE DAMAGE/ EYE IRRITATION - Category 2A
CARCINOGENICITY - Category 2
TOXIC TO REPRODUCTION (Fertility) - Category 2
TOXIC TO REPRODUCTION (Unborn child) - Category 2
SPECIFIC TARGET ORGAN TOXICITY (SINGLE EXPOSURE) (Respiratory tract irritation) - Category 3
SPECIFIC TARGET ORGAN TOXICITY (SINGLE EXPOSURE) (Narcotic effects) - Category 3
SPECIFIC TARGET ORGAN TOXICITY (REPEATED EXPOSURE) - Category 2
ASPIRATION HAZARD - Category 1

Percentage of the mixture consisting of ingredient(s) of unknown oral toxicity: 39.3%
Percentage of the mixture consisting of ingredient(s) of unknown dermal toxicity: 70.8%
Percentage of the mixture consisting of ingredient(s) of unknown inhalation toxicity: 72.2%

GHS label elements

Date of issue/Date of revision	: 10/3/2017	Date of previous issue	: 8/25/2017	Version	: 9	1/17

Talcum Powder SDS

TALC

Safety Data Sheet

according to Federal Register / Vol. 77, No. 58 / Monday, March 26, 2012 / Rules and Regulations

Date of issue: 09/11/2012 Revision date: 05/09/2016 Supersedes: 02/06/2015 Version: 2.1

SECTION 1: Identification

1.1. Identification

Product form	:	Mixture
Product name	:	TALC
Product code	:	C-MS-AT-2042STDTALC
Other means of identification	:	A-0005 FILLER, ABT® 1000, ABT® 2500, ABT® 2501, CERCRON® MB 2900, CERCRON® MB 3900, CERCRON® MB 50-60, CERCRON® MB 93-37, CERCRON® MB 96-67, CERCRON® MB 96-68, CERCRON® MB 99-01, CERCRON® MP 97-30, CERCRON® MP 98-25, CERCRON® MP 99-48, MICROTALC® BP-210, MICROTALC® DM 12-50, MICROTALC® MP 10-52, MICROTALC® MP 11-51, MICROTALC ®MP 12-50, 399 TALC, MICROTALC® MPD 12-50, MICROTALC® MP 12-52, MICROTALC® MP 15-38, MICROTALC® MP 20-40, MICROTALC® MP 25-38, MICROTALC® MP 30-36, MICROTALC® MP 50-26, MICROTALC® MP 70-22, MICROTALC® MP 98-28BC, MICROTALC® MP 45-26 BC, MICROTALC® MPD 2500, MICROTALC® MPD 2501, MICROTALC MPD1250UC, MICROTALC MP210, MICROTUFF® 111, MICROTUFF® 191, PC 2000, TALCRON® MP 10-52, TALCRON® MP 12-50, TALCRON® MP 15-38, TALCRON® MP 25-38, TALCRON® MP 30-36, TALCRON® MP 40-27, TALCRON® MP 44-26, TALCRON® 45-26, ULTRATALC® 609, ULTRATALC® 609D, 9910 Talc, TALCRON 25 LOA, TALCRON 35 LOA, TALCRON 40 LOA, TALCRON 45 LOA, TALCRON 30 LOA, FLEXTALC 405D, FORTI-TALC™ 609LC TALC, FORTI-TALC™ 609HC TALC, FORTI-TALC™ MP1250LC TALC, FORTI-TALC™ MP1250HC TALC, FORTI-TALC™ MP1250UC TALC, FORTI-TALC™ MP1538LC TALC, FORTI-TALC™ MP1538HC TALC, TALCRON MP2040, PC 2000, ICMP 4426, FORTI-TALC™ AG111 LC TALC, FORTI-TALC™ AG111 HC TALC

1.2. Relevant identified uses of the substance or mixture and uses advised against

Use of the substance/mixture	:	Mineral Additive

1.3. Details of the supplier of the safety data sheet

Barretts Minerals Inc.
8625 Highway 91 South
Dillon,. MT 59725
USA

Tel. 406-683-3323

1.4. Emergency telephone number

Emergency number	:	+1 760 476 3962 3E Global Emergency Response Services. Access code: 333336 (if you mention SDS name and company name-you don't need the access code)

SECTION 2: Hazard(s) identification

2.1. Classification of the substance or mixture

GHS-US classification

Carcinogenicity Category 1A H350

Full text of H statements : see section 16

2.2. Label elements

GHS-US labeling

Hazard pictograms (GHS-US) :

GHS08

Signal word (GHS-US)	:	Danger
Hazard statements (GHS-US)	:	H350 - May cause cancer (Inhalation)
Precautionary statements (GHS-US)	:	P201 - Obtain special instructions before use P202 - Do not handle until all safety precautions have been read and understood P260 - Do not breathe dust P280 - Wear protective gloves, protective clothing, eye protection, face protection

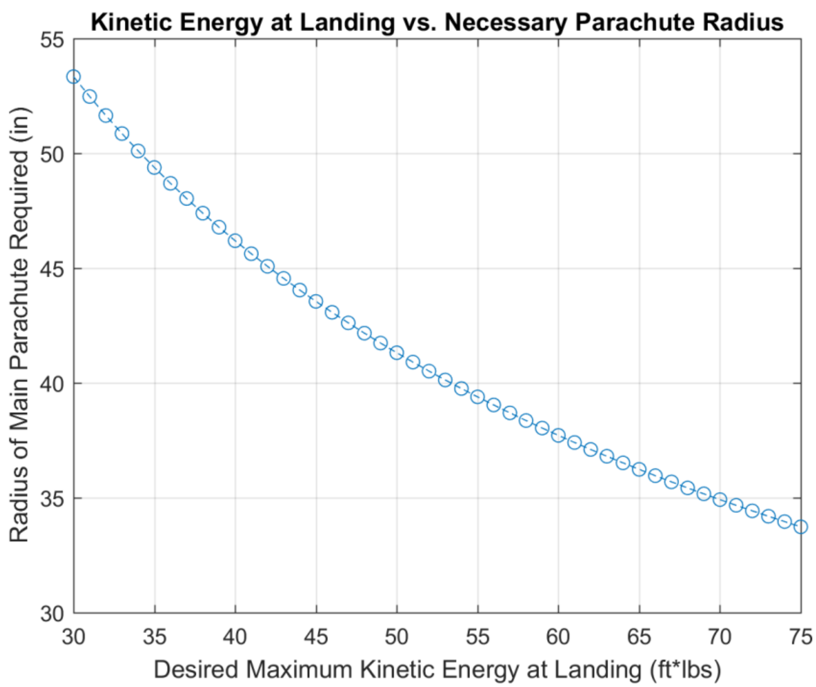
Appendix B: Recovery Decent Profile Calculator

```
% RECOVERY DESCENT PROFILE CALCULATOR (RDPC)
% WRITTEN BY EVAN KERR
% PENN STATE LION TECH ROCKET LABS
% AVIONICS AND RECOVERY LEAD
% LATEST UPDATE: 4/20/2017
```

Calculate necessary area of Parachute to meet certain KE on landing

```
clc, clear, close all
%Gravitational acceleration, units: m/s^2
g = 9.81;
%Density in kg/m^3
rho = 1.225;
%Kinetic Energy Limit in ft-lbs
keMax = 75;

%%%%%%%%%%%%%%%%%%%%%%%% Input Begin %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Coefficient of drag of drogue, main, and tumbling rocket respectively
Cdd = 1.5;
Cdm = 2.2;
Cdr = 1.0;

%These should be in kg
mass(1) = 4.030; %For the fore
mass(2) = 3.478; %For the avionics bay (model minus chord, chutes, and copter)
mass(3) = 4.660; %For the booster
mass(4) = 0.953; %Main parachute
mass(5) = 0.502; %Drogue parachute
%%%%%%%%%%%%%%%%%%%%%%%%%% Input End %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

maxMass = max(mass);
totMass = sum(mass);

radiusMainM = ones(1,10);
keMatFtLbs = (30:1:75);
keMatJoule = keMatFtLbs*1.3358;

for i = 1:length(keMatJoule)
    radiusMainM(i) = sqrt((maxMass*totMass*g)/(Cdm*keMatJoule(i)*rho*pi));
end

radiusMainFt = 3.281*radiusMainM;
radiusMainIn = radiusMainFt * 12;
```

```
figure(1);
plot(keMatFtLbs,radiusMainIn,'--o')
title('Kinetic Energy at Landing vs. Necessary Parachute Radius');
xlabel('Desired Maximum Kinetic Energy at Landing (ft*lbs)');
ylabel('Radius of Main Parachute Required (in)');
grid on;
```



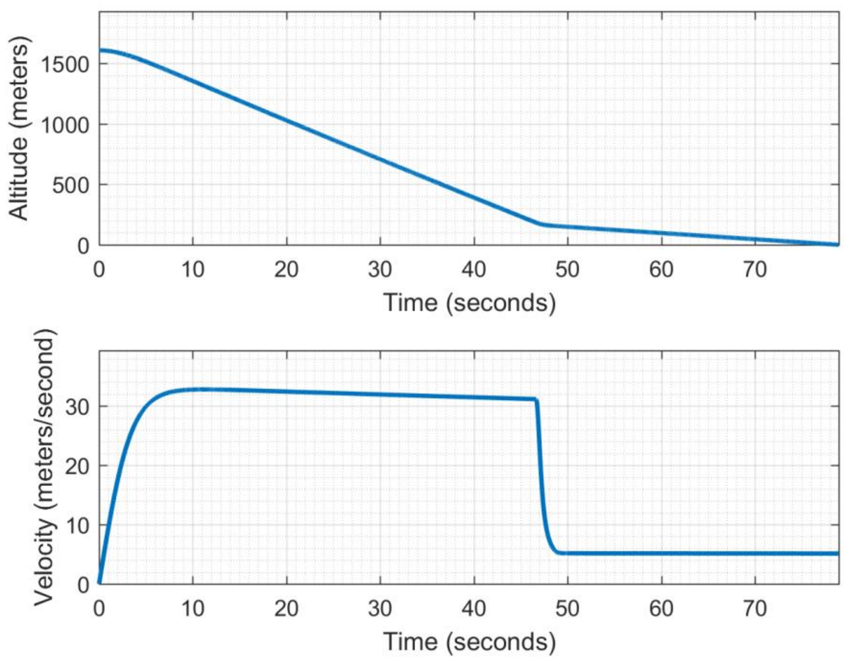
Calculating Force based results

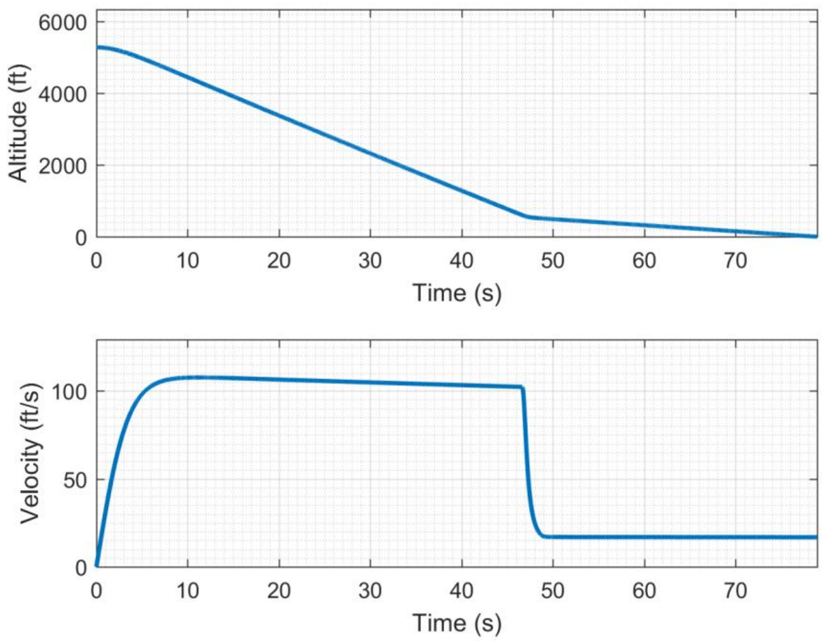
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Input Begin %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Rd_in = 6; %radius of drogue[in]
Rm_in = 42; %radius of main[in]
Rr_in = 7.5; %simulated radius of "tumbling" rocket parachute[in]

apogeeft = 5280; %apogee altitude above ground level [ft]
altDrogueft = apogeeft-1; %altitude above ground level of drogue deployment[ft]
altMainft = 600; %altitude above ground level of main parachute deployment[ft]

altLaunchSite = 183; % Altitiude above sea level of the launch site in meters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Input End %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Rd = 0.0254*Rd_in; %radius of drogue[m]
Rm = 0.0254*Rm_in; %radius of main[m]
Rr = 0.0254*Rr_in; %simulated radius of "tumbling" rocket parachute[m]

apogee = 0.3048*apogeeft;
```

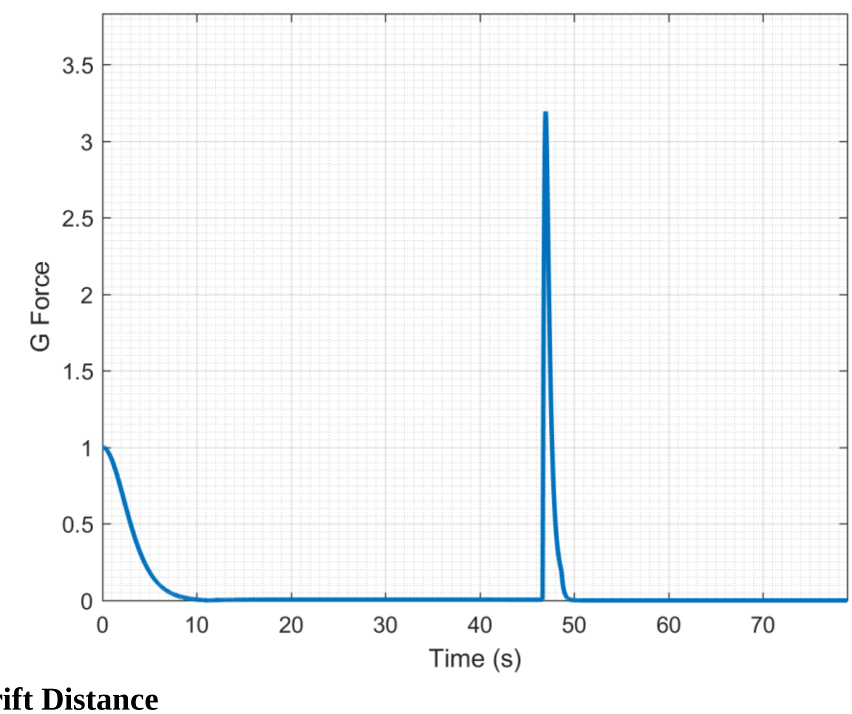
```
altDrogue = 0.3048*altDrogueft;
altMain = 0.3048*altMainft;

% Declare Constants
h = apogee+altLaunchSite; % Initial altitude of the rocket above sea level
h_matrix(1) = h;
time(1) = 0;
dt = 0.01;
v(1) = 0;
a(1) = g;
i = 1; % Counter variable
Temp = 2; % Temperature in Celcius at ground level.
Weight = totMass*g;

% Deployment time and counter initialization for the main and drogue
% parachutes
Kd_dep = 0; % Drogue deployment factor, or how many iterations have run since the drogue was deployed.
Td_dep = 0.25; % Drogue deployment time (how long it takes) in seconds
Td_dep_elapsed = 0;  % Time elapsed since drogue deployment
Km_dep = 0; % Main deployment factor, or how many iterations have run since the main was deployed
Tm_dep = 2;
Tm_dep_elapsed = 0;

%Drag Calculation
while(h >= altLaunchSite) % Although we are integrating over time, the check is whether the height is still above ground level.
  rho_new = rhocalcestSI(h,Temp); % Calculate the density at the given altitude and temperature
  Dragr(i) = .5*Cdr*rho_new*v(i)^2*pi*Rr^2; % Drag of the rocket body
  Dragd(i) = .5*Cdd*rho_new*v(i)^2*pi*Rd^2; % Drag of the drogue parachute
  Dragm(i) = .5*Cdm*rho_new*v(i)^2*pi*Rm^2; % Drag of the main parachute

    if h > (altDrogue + altLaunchSite)% Determines which state of descent the rocket is in and adjusts accordingly by adding the drags
      Drag = Dragr(i); % If the drogue has yet to deploy, the drag of the rocket is the only factor
    elseif h > (altMain + altLaunchSite)
      Kd_dep = Kd_dep + 1; % Increment drogue deployment factor
      Td_dep_elapsed = Kd_dep*dt; % Use the drogue deployment factor to calculate time since drogue deployed
      Drag = Dragr(i) + Dragd(i); % Calculate drage when drogue fully deployed

      % This loop only runs right after chute deployment and models
      % the chute as opening in a linear matter
      if Td_dep_elapsed < Td_dep
        Drag = Dragr(i) + (Td_dep_elapsed/Td_dep)*Dragd(i);
      end
    else
      Km_dep = Km_dep + 1;
      Tm_dep_elapsed = Km_dep*dt;
      Drag = Dragr(i) + Dragd(i) + Dragm(i);
```

```
            if Tm_dep_elapsed < Tm_dep
                Drag = Dragr(i) + Dragd(i) + (Tm_dep_elapsed/Tm_dep)*Dragm(i);
            end
        end
    i = i + 1; % Increment i, the current index value
    a(i) = (-Drag+Weight)/totMass;
    v(i) = v(i-1)+a(i)*dt;
    delh(i) = v(i)*dt;
    h = h-delh(i);
    h_matrix(i) = h;

    time(i) = time(i-1) + dt;
end

figure(2);
ax11 = subplot(2,1,1);
title('Descent Profile In SI Units');

plot(time,h_matrix-altLaunchSite,'LineWidth',2)
ylabel('Altitude (meters)');
xlabel('Time (seconds)');
grid on;
grid minor;
axis([0 max(time) 0 max(h_matrix-altLaunchSite)*1.2]);

ax21 = subplot(2,1,2);
plot(time,v,'LineWidth',2);
ylabel('Velocity (meters/second)');
xlabel('Time (seconds)');
grid on;
grid minor;
axis([0 max(time) 0 max(v)*1.2]);
linkaxes([ax11 ax21],'x');

figure(3)
ax12 = subplot(2,1,1);
title('Descent Profile in English Units');

plot(time,(h_matrix-altLaunchSite)*3.281,'LineWidth',2);
ylabel('Altitude (ft)');
xlabel('Time (s)');
grid on;
grid minor;
axis([0 max(time) 0 max(h_matrix-altLaunchSite)*3.281*1.2]);
```

```
ax22 = subplot(2,1,2);
plot(time,v*3.281,'LineWidth',2);
ylabel('Velocity (ft/s)');
xlabel('Time (s)');
grid on;
grid minor;
axis([0 max(time) 0 max(v)*3.281*1.2]);
linkaxes([ax12 ax22],'x');

figure(4)
title('G Forces vs Time');
plot(time,abs(a/g),'LineWidth',2);
ylabel('G Force');
xlabel('Time (s)');
grid on;
grid minor;
axis([0 max(time) 0 max(abs(a/g))*1.2]);
```





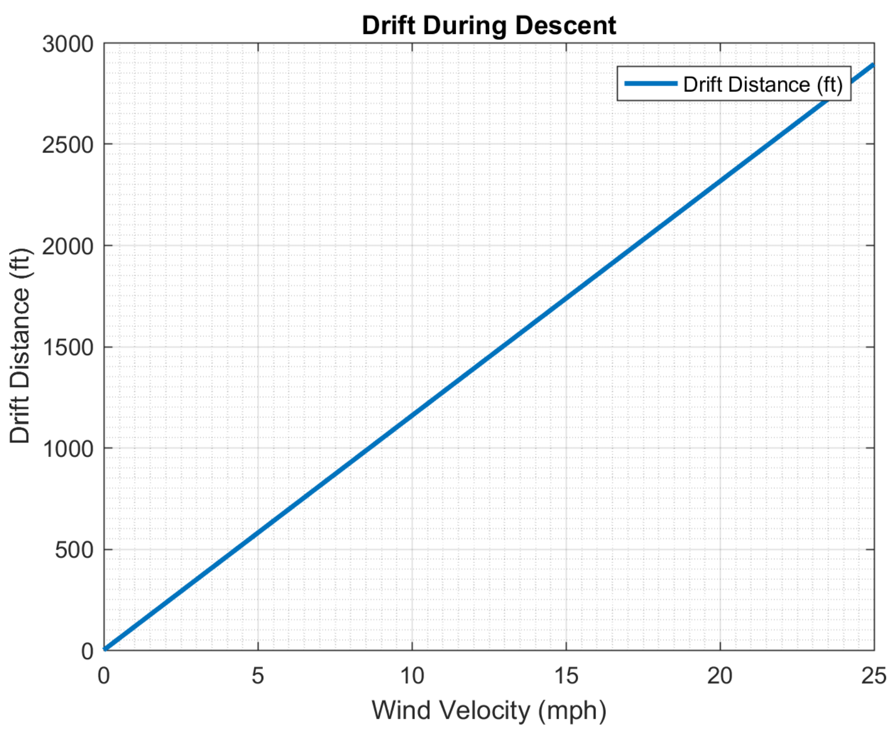


Calculate Drift Distance

```
Windmph = 0:1:25; % Velocity of wind[mph]
Windfps = 1.467*Windmph;
Windmps = Windfps*0.3048;

% Calculate drift distance in metric and standard
descentTime = max(time);
```

```
driftDistM = Windmps*descentTime;
driftDistFt = Windfps*descentTime;

% Plot drift distance
figure(5)
plot(Windmph,driftDistFt,'LineWidth', 2);
ylabel('Drift Distance (ft)');
xlabel('Wind Velocity (mph)');
grid on;
grid minor;
title('Drift During Descent');
legend('Drift Distance (ft)');

% Output max drift distance
fprintf('The drift distance at a wind velocity of 25 mph is %6.1f ft\n\n', max(driftDistFt));
```

The drift distance at a wind velocity of 25 mph is 2894.0 ft



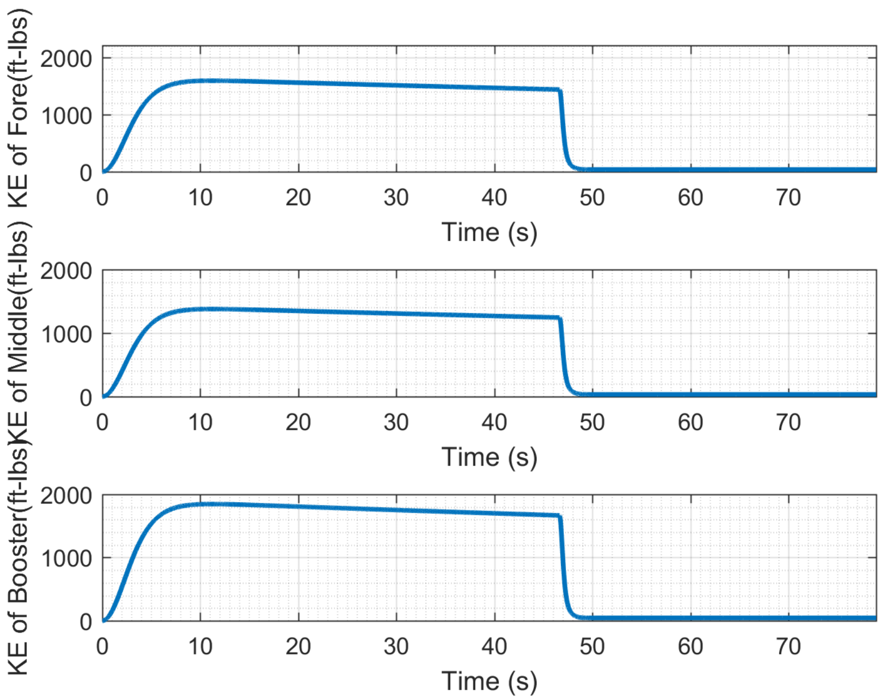
Calculate KE History of each component

```
KEforeSI_mat = (1/2)*v.^2*mass(1);
KEavSI_mat = (1/2)*v.^2*mass(2);
KEboostSI_mat = (1/2)*v.^2*mass(3);

maxKE_SI = max([max(KEforeSI_mat),max(KEavSI_mat),max(KEboostSI_mat)]);
```

```
KEforeST_mat = KEforeSI_mat*0.7376;
KEavST_mat = KEavSI_mat*0.7376;
KEboostST_mat = KEboostSI_mat*0.7376;

maxKE_ST = max([max(KEforeST_mat),max(KEavST_mat),max(KEboostST_mat)]);

% Calculate the KE of each component in Joules at landing
KEforeSI = KEforeSI_mat(end);
KEavSI = KEavSI_mat(end);
KEboostSI = KEboostSI_mat(end);

maxLandingKE_SI = max([KEforeSI,KEavSI,KEboostSI]);

% Calculate the KE of each component in Ft-lbs at landing
KEforeST = KEforeST_mat(end);
KEavST = KEavST_mat(end);
KEboostST = KEboostST_mat(end);

maxLandingKE_ST = max([KEforeST,KEavST,KEboostST]);

figure(6)
ax13 = subplot(3,1,1);
title('Kinetic Energy of Each Component vs. Altitude');

plot(time,KEforeST_mat,'LineWidth',2);
ylabel('KE of Fore(ft-lbs)');
xlabel('Time (s)');
grid on;
grid minor;
axis([0 max(time) 0 maxKE_ST*1.2]);

ax23 = subplot(3,1,2);
plot(time,KEavST_mat,'LineWidth',2);
ylabel('KE of Middle(ft-lbs)');
xlabel('Time (s)');
grid on;
grid minor;
linkaxes([ax13 ax23],'x');

ax33 = subplot(3,1,3);
plot(time,KEboostST_mat,'LineWidth',2);
ylabel('KE of Booster(ft-lbs)');
xlabel('Time (s)');
grid on;
grid minor;
linkaxes([ax23 ax33],'x');
```

```
vf = v(end); %Find final landing velocity

% Print Results
fprintf('The kinetic energy of the nosecone section is %4.2f ft*lbs\n', KEforeST);
fprintf('The kinetic energy of the avionics bay section is %4.2f ft*lbs\n', KEavST);
fprintf('The kinetic energy of the booster section is %4.2f ft*lbs\n\n', KEboostST);

fprintf('The velocity at landing is %4.2f m/s or %4.2f ft/s \n', v(end),v(end) * 3.281);
```

```
The kinetic energy of the nosecone section is 38.96 ft*lbs
The kinetic energy of the avionics bay section is 33.63 ft*lbs
The kinetic energy of the booster section is 45.05 ft*lbs

The velocity at landing is 5.12 m/s or 16.80 ft/s
```



Published with MATLAB® R2016a

Appendix C: Verification of OpenRocket Flight Calculations

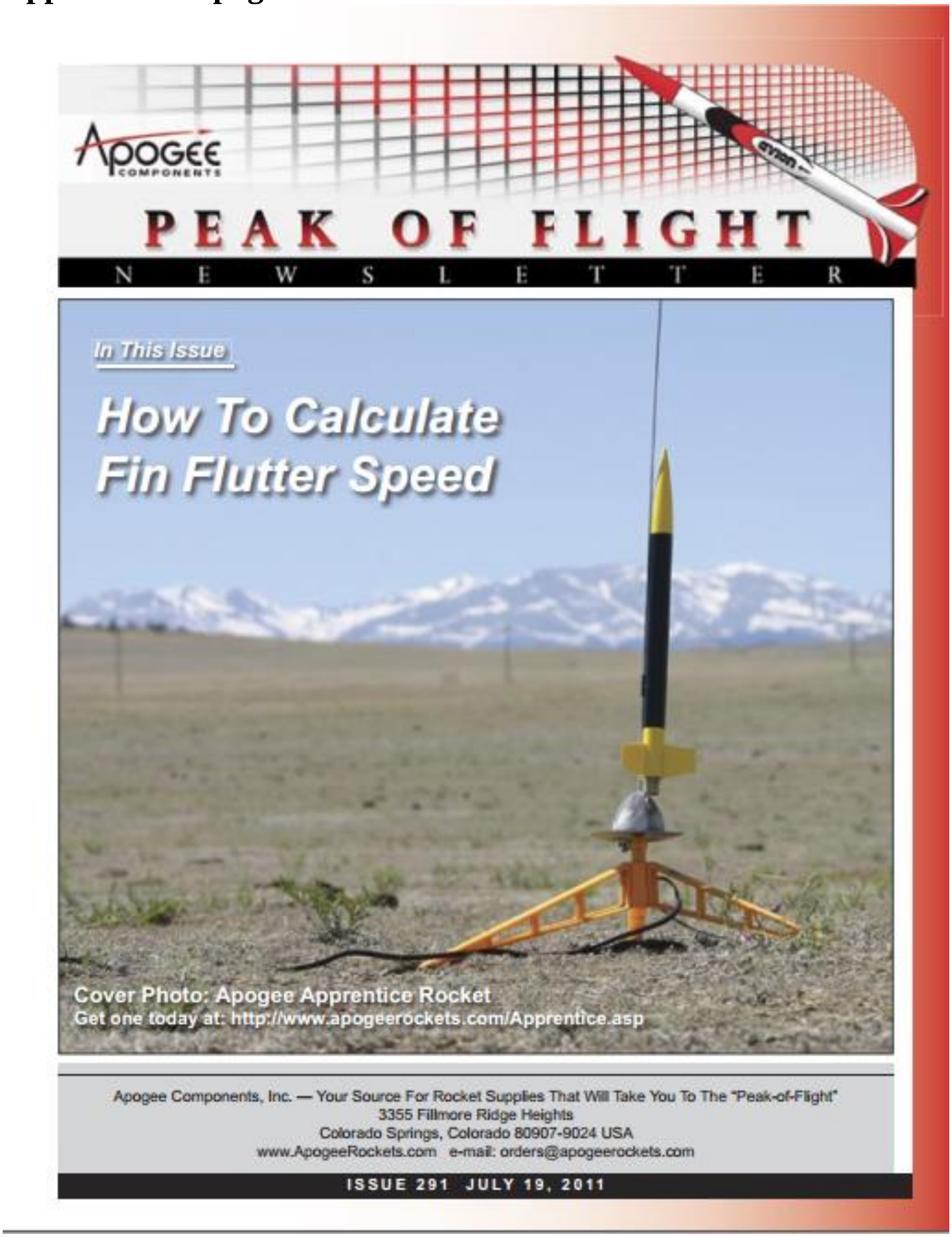
```
clc
clear

%CONSTANTS --------------------------------

%Center of Pressure
Ln  = 0.5499;      %length of nosecone [m]
Cnn = 2;           %coeficient of drag for nosecone
Xb  = 2.616;       %length from tip to fin root chord [m]
Xr  = 0.127;       %length from fin root leading edge to fin tip leading edge [m]
Cr  = 0.2032;      %fin root chord length [m]
Ct  = 0.102;       %fin tip chord length [m]
S   = 0.1778;      %fin semispan [m]
N   = 3;           %number of fins
Lf  = 0.19356;     %length of the fin mid-chord line [m]

%Center of Gravity
dn  = 0.4258;      %distance of the nose CG to nose tip [m]
mn  = 1.607;       %mass of the nose [kg]
dp  = 0.8766;      %distance of the payload CG to nose tip [m]
mpayload  = 2.379; %mass of payload [kg]
dm  = 1.5316;      %distance of the main CG to nose tip [m]
mm  = 4.848;       %mass of main [kg]
dd  = 1.9379;      %distance of the drogue CG to the nose top [m]
md  = 0.907;       %mass of drogue [kg]
db  = 2.563;       %distance of the booster CG to nose tip [m]
mb  = 6.065;       %mass of the booster (with motor) [kg]
M   = mn + mpayload + mm + md + mb;   %mass of the rocket (with motor) [kg]

%Apogee
mr  = 11.964;      %mass of rocket (no motor) [kg]
me  = 3.5635;      %mass of motor [kg]
mprop  = 1.582;    %mass of propellant [kg]
rho = 1.225;       %density of air [kg/m^3]
Cd  = 0.55;        %drag coefficient
D   = 0.1397;      %diameter of body tube [m]
R   = D/2;         %radius of body tube [m]
g   = 9.81;        %gravity constant [m/s^2]
T   = 1405;        %average thrust of motor [N]
t   = 3.63;        %motor burnout time [s]

%CALCULATIONS ------------------------------------
```

```
%Center of Pressure
Xn  = 0.466 * Ln;   %CP location for fins, from tip [m]
Xf  = Xb + ((Xr*(Cr + 2*Ct))/(3*(Cr + Ct))) + (1/6)*((Cr + Ct) - ((Cr*Ct)/(Cr+Ct)));    %CP location of fins, from tip [m]
Cnf = (1+R/(S+R))*(4*N*(S/D)^2/(1+sqrt(1+(2*Lf/(Cr+Ct))^2)));   %CP of fins, from tip [m]
X   = ((Cnn*Xn + Cnf*Xf)/(Cnn+Cnf));    %CP location of rocket from tip [m]

%Center of Gravity
cg = (dn*mn + dp*mpayload + dm*mm + dd*md + db*mb)/M; %CG location of rocket from tip [m]

%Static Stability Calculation
stab = (X - cg) / D;    %static stability margin [calibers]

%Apogee

%Burn Calculations
ma  = mr + me - (mprop/2); %(average) burn mass [kg]
A   = pi*(R^2);         %cross-sectional area of rocket [m^2]
k   = (1/2)*rho*Cd*A;   %aerodynamic drag coefficient [kg/m]
q1  = sqrt((T - (ma*g))/k); %burnout velocity coefficient [m/s]
x1  = (2*k*q1)/ma;      %burnout velocity decay coefficient [1/s]
v1  = q1*((1-exp(-x1*t))/(1+exp(-x1*t)));   %burnout velocity [m/s]
y1  = (-ma/(2*k))*log((T - (ma*g) - (k*v1*v1))/(T-ma*g));   %burnout altitude [m]

%Coast Calculation
mc  = mr + me - mprop;     %coast mass [kg]
qc  = sqrt((T-mc*g)/k); %coast velocity coefficient [m/s]
xc  = ((2*k*qc)/mc);    %coast velocity decay coefficient [1/s]
vc  = qc*((1-exp(-xc*t))/(1+exp(-xc*t)));   %coast velocity [m/s]
yc  = (mc/(2*k))*log((mc*g + k*(vc^2))/(T-mc*g));  %coast distance [m]

%Total Calculation
PA  = y1 + abs(yc);     %apogee [m]

%PRINT VALUES

fprintf('Center of Pressure: %2.4f inches \n', X*39.37);    %print CP [in]
fprintf('Center of Gravity: %2.4f inches \n', cg*39.37);    %print CG [in]
fprintf('Static Stability Margin: %2.4f calibers \n', stab);   %print static stability margin [calibers]
fprintf('Apogee: %2.4f feet \n', PA*3.281);                %print aprogee [ft]
```

Attempt to execute SCRIPT fullscale_simulations as a function:
C:\Users\Evan\Downloads\fullscale_simulations.m

Published with MATLAB® R2016a

Appendix D: Apogee Rockets Fin Flutter



PEAK OF FLIGHT

How To Calculate Fin Flutter Speed

By Zachary Howard

After construction completed on July 1, 1940, the Tacoma Narrows Bridge was the third largest suspension bridge in the entire world, behind the Golden Gate Bridge and the George Washington Bridge. Its infamy lies not with historic length but in its nickname, Galloping Gertie. The nickname arose from the bridge's easily excitable bending mode. Drivers would watch the oncoming cars rise and fall with the violent motion of the bridge. During a particularly strong forty-mile per hour gust the newly excited torsion mode of the bridge caused a violent twisting along the centerline of the bridge. Figure 1 below shows the bending and torsional modes of the bridge. Despite being made from carbon steel and concrete on, November 7, 1940 the growing torsional oscillations overwhelmed the natural damping of the bridge and Gertie plunged 300 ft into the ocean below. After months of research NACA engineers diagnosed the cause of the vibrations as aeroelastic flutter.

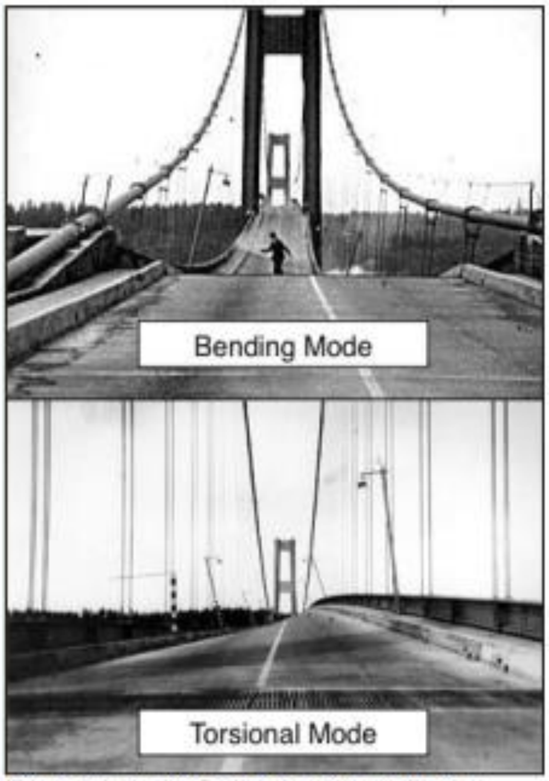


Figure 1. Galloping Gertie's Bending and Torsion Modes

Background

In textbooks aeroelastic flutter is defined as "a dynamic instability associated with the interaction of aerodynamic, elastic and inertial forces." The essence of this definition involves understanding the interaction between an object and the surrounding air. Let's start with the simple aerodynamic concept of lift. In the case of Galloping Gertie, the bridge construction did not allow air to pass through the bridge; rather it was diverted above and below. This diversion of air creates lift and a pitching moment around the aerodynamic center. Due to the coupling between an increase in pitching moment and an increase in lift, a positive feedback loop is created. This means that the increase of one variable drives the increase of the other in an infinite loop. If not damped, the positive feedback loop leads to uncontrolled aeroelastic flutter and ultimate failure of the structure. In

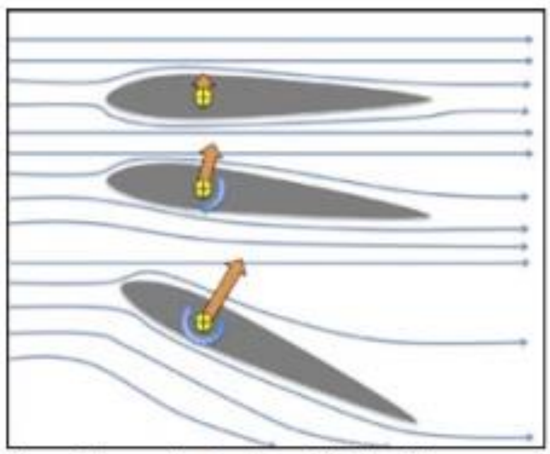


Figure 2. Increasing Torsion on Pitching Wing

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How To Calculate Fin Flutter Speed

Figure 2 notice how an increase in the lifting force (orange arrow) creates a clockwise rotation of the wing and an increased torsional moment (blue arrow).

Unlike the Tacoma Narrow bridge, a fin attached to a rocket does not have large mechanical dampers. Instead, rockets need to rely on thoughtful construction and air to damp out any vibrational energy in the fins. Air is very efficient at reducing the amplitude of the vibration while the rocket remains under the flutter velocity. However, once the flutter velocity is exceeded the air will exponentially amplify the oscillations and rapidly increase the energy in the fin to the point of destruction. Figure 3 shows the exponential damping and amplification of vibrational energy in a rocket fin below and above the flutter speed. For the remainder of this article we will establish an equation for predicting the flutter boundary and discuss all variables involved.

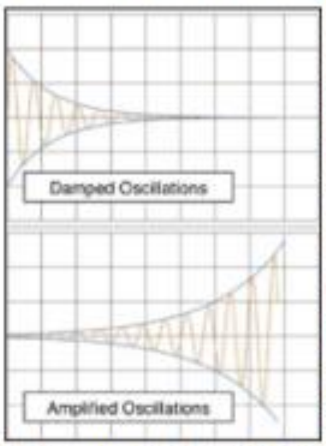

Figure 3. Damped and Amplified Oscillations

Flutter Boundary Equation

The Flutter Boundary Equation is based on an earlier calculation published in NACA Technical Paper 4197. If you are familiar with that paper you will notice that Equation 1 listed below is slightly different than the one presented in the technical paper. The most significant mathematical change is the use of a more accurate term for torsional modulus. This accuracy was gained by the inclusion of plate theory. Due to the complex nature of the flutter boundary equation we will focus our efforts on learning to understand the variables rather than trudging though the derivation.

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

Equation 1. Flutter Boundary Equation

To begin our dissection of the Flutter Boundary Equation we will analyze the sole material property included in this equation, the Shear Modulus. Identified by the letter (G) it has units of pounds per square inch or PSI, and is the representation of the amount of deformation associated with a particular amount of force. Simply, the higher the Shear Modulus the more force it can handle.

Continued on page 4

Continued from page 3

How To Calculate Fin Flutter Speed

For the purposes of this equation the materials are assumed to be isotropic, which means that the mechanical properties of the material are the same in all coordinate directions. This assumption is very accurate for metals because they are manufactured in a relatively uniform way, but for wood and hand laid composites isotropy cannot be assumed. In wood, shear stresses are unique to each axis, making the material orthotropic. You have probably noticed how it is easier to split wood along the grain rather than trying to cut it perpendicularly.

Additionally, there is no guarantee that two pieces of wood, even from the same tree, will have the same material properties. The same is true for all hand laid composites as well, because of the variability in cloth fibers and epoxy application. Therefore, when using published shear data on orthotropic materials, add an additional safety factor.

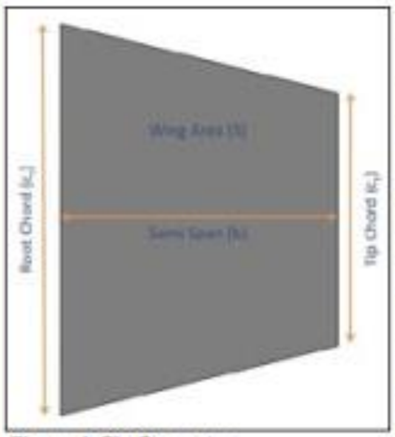

Figure 4. Fin Geometry

From Equation 1, the variables under the square root describing the geometry of the wing are the thickness of the wing (t), root chord (c), Aspect Ratio (AR) and the Taper Ratio (l). The equations for these variables are listed below, along with a wing geometry guide shown in Figure 4. All units should be in inches.

In a recent optimization study done by the Air Force they found that semi-span had the most impact in flutter speed calculations. Logically this makes sense, because a stubbier fin will be stiffer and more able to resist torsion as compared to a longer, more flexible fin. However, there is a trade off here with the minimum effective area needed to keep your rocket going straight. Through multiple design iterations using the RockSim software (www.ApogeeRockets.com/rocksim.asp), you should be able to come up with the right mixture of all desired values.

$$S = \frac{1}{2}(c_r + c_t)b$$

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

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

Equations 2. Geometric Equations

Next we come to Air Pressure (P). Using static atmo-

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How To Calculate Fin Flutter Speed

spheric models you will find that in the Troposphere, which is below 36152 ft, temperature and pressure vary linearly with altitude according to those listed in Equations 3. There are more equations that model temperature and pressure changes in the Upper and Lower Stratosphere, which you can find at http://www.grc.nasa.gov/WWW/K-12/airplane/atmos.html. The answers to the pressure calculations need to be converted into pounds per square inch in order to make sure that all the units under the square root cancel out.

$$T(°F) = 59 - .00356h$$

$$P(lbs/ft^2) = 2116 \times \left(\frac{T + 459.7}{518.6}\right)^{5.256}$$

Equations 3. Temperature and Pressure Variations

The last variable of the Flutter Boundary Equation is speed of sound (a). Dependent only on the temperature of the medium, the equation for the speed of sound is given in Equation 4.

$$a = \sqrt{1.4 \times 1716.59 \times (T(°F) + 460)}$$

Equation 4. Speed of Sound

This equation already has the Ideal Gas Law constants associated with air inserted, making the temperature calculated through Equations 3 the only variable. The unit on this calculation is feet per second, which due to cancellation among all other units makes the Flutter Boundary Equation in terms of feet per second.

Equation Verification and Safety Factor

In order to verify this equation, I have tested the Flutter Boundary Equation with data published in an article called *"Fin Flutter"* at http://www.info-central.org/?article=138 by Duncan McDonald. Although his attempt at calculating fin flutter was wrong (He forgot to add in the pressure terms and to keep consistent units. Also, some of the constants in the equation are deceiving because they are actually a combination of a bunch of constant terms), he had valuable test data from contributor Jeff Taylor who flew accelerometers in his rockets and recorded their maximum speed.

Based on the article's data, my Flutter Boundary Equation successfully predicted the two instances of flutter and the three safe flights of Jeff's rocket. That is a 100% success rate in five test cases. Without more significant testing the true accuracy of this equation will not be known, but preliminary calculations suggest that a comfortable safety margin is anything 20% below the flutter velocity speed. However, there have been instances of accuracy to within 5%.

The one major prediction problem is that the flutter velocity changes with altitude; therefore, to accurately predict flutter speed the altitude at which maximum velocity is achieved must be known. Usually this is not known, so keeping the rockets velocity under the maximum allowable at sea level is advised.

Root Chord (c_r)	9.75 in
Tip Chord (c_t)	3.75 in
Thickness (t)	.125 in
Semi-Span (b)	4.75 in
Shear Modulus (psi)	380000psi

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Appendix E: Testing Procedures

Carbon Fiber Airframe Testing Procedure

Abstract:
The current design is similar to previous models that LionTech Rocket Labs has used in the past. The only failure that previous designs have experienced was zippering of the body tube. Two testing procedures are to be done to ensure the rocket is capable of withstanding any and all forces seen during takeoff, flight, parachute ejection, and landing.

The first procedure is a tensile test. The objective of a tensile test is to exert tensile forces on a test piece that is structurally identical to the material used in the final design. These forces are to be increased until the test piece fails. In the case of this procedure, failure is when the material initially begins to permanently deform. Once the material fails, the force needed to cause this outcome is recorded and compared to the maximum force that the rocket is expected to experience during operation. If the expected maximum force is less than the force recorded with the test, then the current design is sufficient enough to be used. If the expected maximum force is greater than the test result, then a new design must be created and tested. This process is to be continued until the test results exceed the estimated maximum values.

Objective:
Determine the tensile load that can be applied to the wrapped tube before failure for blue tube wrapped in 1 layer, 2 layers, and 3 layers of carbon fiber wrapping. Using these results and predicted loads experience during flight, a safety factor can be obtained to validate the design choice.

Necessary Equipment:

- Sample of 3, 3-inch diameter tubes wrapped with 1 layer, 2 layers, and 3 layers of carbon fiber
- 2 Aluminum blocks machined to fit the interior of each body tube and contains 4 threaded holes for machined screws
- 2 Aluminum rods machined to fit through the blocks. These rods are used as attachment points for the tensile equipment
- Minimum of 8 machine screws
- Tensile loading equipment (to be determined by equipment faculty/provider)
- Carbon Fiber Airframe Testing Procedure Document

Assembly
For reliable results, proper assembly of testing equipment is imperative. The assembly procedure shall go as follows:

1. Prepare each tube section for testing; this includes cutting the tube to necessary length (as required by testing equipment or faculty), drilling 4 holes on each end of the tube and ensure alignment of those holes with the aluminum block
2. Align one end of the tube with an aluminum block and secure it using 4 machined screws.

3. **(Important)** Check that the aluminum is aligned perpendicularly to the tube. *Misalignment will disturb testing results as the load will no longer be purely tensile.
4. Feed aluminum rod through the aluminum block with the stop on the interior of the tube; clamp the block once fed through so it cannot fall into the tube.
5. Feed second aluminum rod into second aluminum rod, again with the stop on the side of the block to the interior of the tube. Again, clamp the rod so it won't slide out of the block.
6. Align the other end of the tube with the second block-and-rod assembly.
7. **(Important)** Check that the aluminum is aligned perpendicularly to the tube. *Misalignment will disturb testing results as the load will no longer be purely tensile.
8. If alignment is true, this assembly is ready to load into the testing equipment. Load the assembly into the testing equipment by attaching each end of the rod to the testing grips (or similar mechanism depending on tensile equipment).
9. Run the experiment
10. Record the load at failure in the table below.
11. Repeat steps 1-10 for the remaining configurations

Provide sample images of each of the completed steps here for future use

Results:

Configuration	**Load at failure**
1 layer of wrapped carbon fiber	
2 layers of wrapped carbon fiber	
3 layers of wrapped carbon fiber	

Success of results:

The test can be deemed successful if all the following are true:

a) Results are realistic
b) A trend can be examined (i.e. load at failure for 2 layers is higher than 1 layer and strength of 3 layers is greater than 2 and 1 layer)
c) Failure is at the screw holes as expected

Validation of design

Using the data recorded, scale the strength of the carbon fiber wrapped tube up to the diameter of full scale. Determine the safety factor of full scale design using the scaled failure strength and expected maximum load experienced during flight.

Motor Testing and Checkout Procedures

Local Environmental Conditions
Temperature:
Humidity:
Air pressure:

Hardware Installation

1. Assemble load cell fixture as follows:
    a. Fasten the load cell to the load cell mount with screws on the inner set of holes.
    b. Fasten a threaded rod to the top of the load cell and secure the connection with a nut and washer.
    c. Place bolts and washers through the outer set of holes on the load cell mount, with the bolt head facing upward.
2. Screw the threaded rod upwards through the cantilever beam of the reaction fixture, securing the connection with a nut and washer on top of the cantilever beam.
3. Refer to and follow *Motor Preparation Procedures* to prepare the motor for this test.
4. Install the prepared motor as follows:
    a. Insert loaded motor into motor mount tube.
    b. Position the motor retainment tabs on the aft end of the motor mount tube underneath the motor and tighten their screws to secure them in that position.
5. Locate ignition Power Supply a safe distance from the test stand.
6. Locate miscellaneous hardware and tools a safe distance from the stand.

Instrumentation Installation

1. Take the wires from the load cell and wire them into the Data Acquisition System (DAQ) as follows in Table XXXX.

Ch	1	2	3
GND	Vin(+)	Vin(-)	Vout
Bl	W	G	R

2. Locate the DAQ a safe distance from the test stand and opposite the plume direction. Secure wiring to the test fixture where appropriate to prevent damage to the wires.
3. Set InstruNET sample rate to 1000Hz.
4. Set number of channels to 3.
5. Verify all channels are enabled for digitizing.
6. Configure InstruNET network and sensor settings per Tables XXXX through XXXX.

	Network	Device	Module	Channel
Load Cell	1	1 i100	1 #100	Ch1 Vin+

Sensor	Units	Range (Low, High)	Mex Force (lbf)	Manf. Rec. Voltage (V)	Sensitivity (mV/V)	Resistance (Ohms)	Excitation Voltage (V)	Low-Pass Filter (Hz)	# Ch.
Load Cell	lbs	(0, 500)	500	10	2.00654	352.60	1.3	4000	1

1. Verify that sensors are outputting correct nominal readings and units.
2. Save InstruNET sensor settings.
3. Position and test digital video cameras a safe distance from the test stand.

Testing Preparation
Test Date:
Test Number:

1. Refer to and follow *Initiator Installation Procedures* to install the initiator for this test.
2. Move all personnel and remaining equipment a safe distance away from the test stand.
3. When test director is ready and all personnel are in a safe area, they will vocally announce the impending test.
4. The test director then provides power to the initiator.

Appendix F: Payload Launch Procedures Sign-Off

PSU LTRL Payload Launch Procedures Sign-Off

Assembly:

1. Indicates that the rover and the ground station are verified to be communication with each other properly.
    a. Signature of lead: ____
    b. Print name: ____

2. Indicates that the initiator has been tested
    a. Signature of lead: ____
    b. Print name: ____

3. Indicates that the CO2 ejection mechanism has been assembled correctly.
    a. Signature of lead: ____
    b. Print name: ____

4. Indicates that the rover is still operating correctly before connecting power to the initiator circuit.
    a. Signature of lead: ____
    b. Print name: ____

5. Indicates that the battery for the initiator circuit has been tested.
    a. Signature of lead: ____
    b. Print name: ____

6. Indicates that the tested battery has been connected to the initiator circuit
    a. Signature of lead: ____
    b. Print name: ____

7. Indicates that the assembled rover has been attached to the containment mechanism and inserted into the rocket body.
    a. Signature of lead: ____
    b. Print name: ____