ISS Space Grant Team

TRAPPIST-1

Illinois Space Society
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Executive Summary

As of May 5, the Illinois Space Society's "Trappist-1" rocket is ready for flight. Many of its subsystems need refinement and further testing, but the capability of flight has been proven through its test flight. The rocket surpassed the 3000 ft altitude constraint, and was recovered in a condition that could warrant flight with minimal repairs.

The drag system has been reworked to be simple yet effective and should slow down the rocket enough such that it reaches the same altitude on both competition flights. Further testing using fluid simulations in Solidworks, scripts in Matlab, and simple hand calculations have proven that the servos will be able to apply necessary torque to the flaps to provide stable and controllable deceleration.

The Arduino pressure sensor-based velocity sensor is well on its way to being operational and only requires a new sensor as an original one burnt out. However, preliminary results show that the sensor is accurate to within a few tenths of a meter and can take readings at a rate that offers a reasonable level of precision for the overall computer system.

The avionics bay has been proven to record accurate data and protect the delicate electronics inside of it from the harsh blasts of the ejection charges. It also held together when the tube separation occurred from either end, ensuring the rocket holds together as one piece on its descent.

The rocket proved to be stable throughout its whole flight even with its unconventional flap and fin configuration. OpenRocket has proven to be a useful tool in calculating the stability of the rocket along with other flight characteristics.

The team has put a lot of work into the rocket over the past weeks and it shows with the quality of the test flight and general construction. The design still requires some optimization to save weight and increase ease of assembly, but these are small details and will be accomplished soon.

Vehicle Design Overview

Airframe Discussion with Dimensions

The rocket has a total length of 86.5 in and a total mass of 209 oz without any motors installed. A diagram of the model can be seen in *Figure 1*.

The top of the rocket begins with a 12 in nose cone. This size was picked for the nose cone because OpenRocket estimated it would allow the rocket to reach the highest altitude. However, a longer nose cone of 15 in is being researched on the basis that it will decrease drag enough to warrant the slight increase in weight.

The upper body tube was originally 21 in long, but 21 in was not enough to reliably pack the main parachute. The upper body tube was extended to 26 into have enough room to reliably and safely pack in the main parachute.

The coupler between the upper and lower body tube is 12 in long. 4 in of tube is used on each side to attach the coupler to the upper and lower body tubes, respectively, providing additional stability. The extra 4 in is used to provide additional space for the electronics and other parts.

The lower body tube is 26 in long. Originally 2 parachutes were to be in the lower body tube and the lower body tube was 29 in long. However, when plans changed to only have 1 parachute in the lower body tube, the size of the lower body tube was reduced to 26 in to save weight while at the same time maintaining stability, as calculated by OpenRocket.

The motor assembly at the bottom of the rocket is 18 in long. 6 in of coupler tube connects it to the lower body for a strong attachment instead of the 4 in coupler piece used to connect the upper body to the lower body. The motor assembly was made a separate piece to assist the servicing of the servos in case one or more fail.

The fins are 1/8th in fiberglass with a root chord of 5.75 in, tip chord of 3.9 in, height of 5.6 in, and sweep of 32.5 degrees. The fins had a flutter analysis performed on them and they were shown to be stable through a maximum velocity of 800 ft/s.

The 4 in diameter of the rocket was picked to maximize stability as dictated by OpenRocket while still leaving enough space to fit a hand inside to make the rocket easier to work with. It is also wide enough to fit the large amount of equipment required in the avionics bay and motor assembly.

Figure 1 - OpenRocket Model

Propulsion System

The rocket is powered by one J level motor and one K level motor. The J level motor is a J415W-14. This motor has an impulse of 1232 Ns, an average thrust of 415 N, and a maximum thrust of 733 N. It has a burn time of 2.9 s. Its delay is 14 s, or the "L" Aerotech designation. The K level motor is a K1103X-14. This motor has an impulse of 1789 Ns, an average thrust of 1103 N, and a maximum thrust of approximately 1780 N. It has a burn time of 1.6 s. Its delay is 14 s as well. These motors were chosen due to their burn times and impulse difference. These two values are critical to increasing the score as much as possible, and they provided the rocket with the needed launch rail velocity and altitude as constrained by the competition. Thrust curves for each motor can be seen in *Figure 2*.

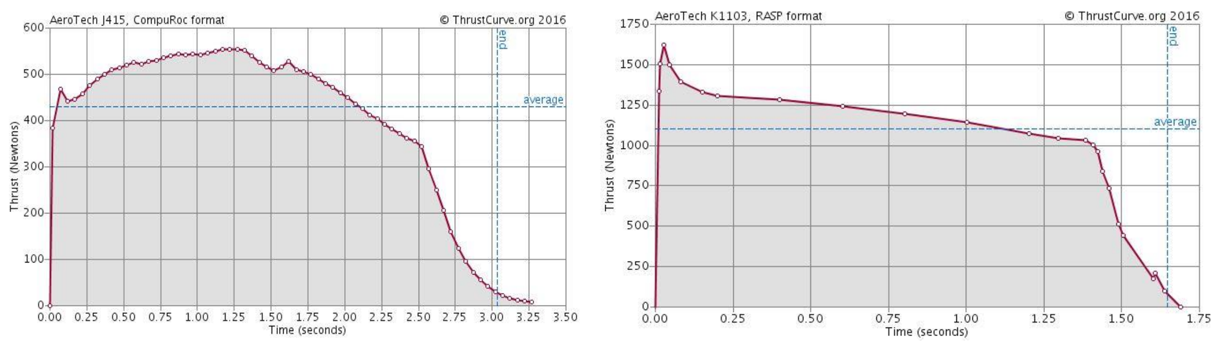


Figure 2 - J415W and K1103X Thrust Curves

The motor casing is a RMS-54/1706 Aerotech casing. It uses a motor adapter system provided by Apogee rockets to accommodate for the differing motor lengths (1280 and 1706). Each motor reload has the same diameter of 54 mm. This system makes use of a floating forward closure. Reloading will be practiced prior to the competition to ensure ease of use.

The motor mount tube is a 22 in long piece of blue tube with a 54 mm inner diameter to fit the motor casing. This motor mount is centered and held in place with 4 x 1/4th in plywood centering rings.

The motor casing is held in place by a tail-cone retainer. This reduces drag while at the same time keeping the motor casing in place during flight. This kind of retainer requires the motor mount tube to stick out past the end of the bottom centering ring such that when the retainer is screwed on, it will be flush with the bottom of the rocket.

Avionics Bay and Electrical Circuit Mapping

The avionics bay is a very dense part of the rocket. It includes two StratoLogger altimeters, one AltimeterTwo, one Arduino Mega board, three 9-Volt batteries, a 7.4 V 800 mAh lithium polymer battery, two cameras with mounts, the custom velocity sensor, and two light sensors. It also contains wires for connecting rotary switches to the Arduino and two StratoLoggers. The StratoLoggers control the dual deployment system of the rocket, activating the black powder charges outside of the coupler. They are powered by one 9-Volt battery each. The Arduino controls the flap system, velocity sensor, and light sensors. It is powered by another 9-Volt battery. The servos are powered by the 7.4 V lithium polymer battery but controlled by the Arduino. They communicate from the bottom of the rocket via breakaway servo extensions inside the lower body tube. The two cameras are mounted inside 3D printed mounts and run on their own internal power. The velocity sensor will be powered by the Arduino and relay information back to it via a multiplexer that handles the two incoming streams of pressure data, and it stores data on a micro SD card after being formulated into velocity readings. The two light sensors will also be powered by and communicate with the Arduino. A diagram can be seen in *Figure 3*.

The avionics bay also has 3 x 1/8th in holes that allow for static pressure measurements to ensure accurate deployment of the parachutes and velocity sensor readings. Immediately before flight, the holes where wires thread through a bulkhead are covered in putty to ensure there are no pressure leaks and that the hot gases from the ejection charges do not harm the delicate electronics inside. All replaceable parts such as batteries will be held down with zip ties, while the more permanent installations such as the Arduino and StratoLoggers will be held down with small screws and nuts.

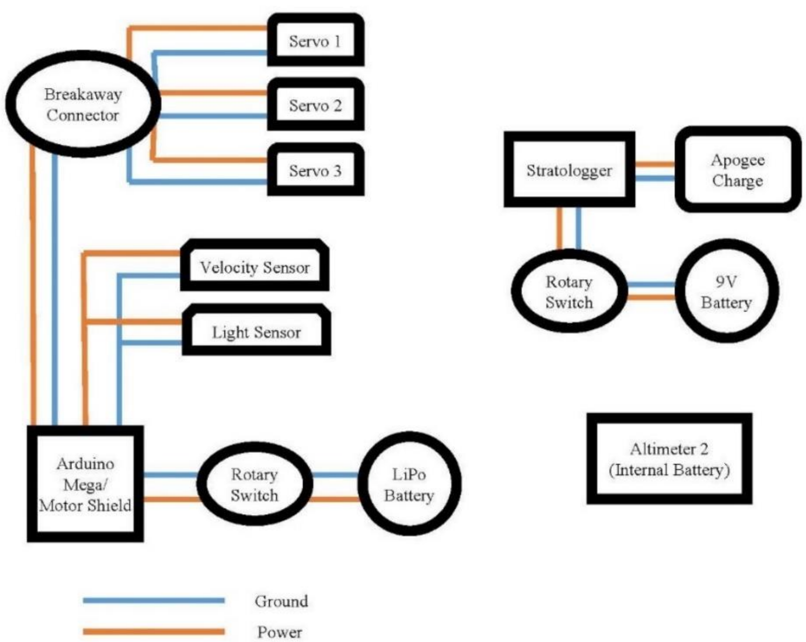


Figure 3 - Electronics Layout

Velocity Sensor

A pitot tube as shown in *Figure 4* measures the velocity of a fluid by comparing the static pressure and the stagnation pressure. Static pressure is the air pressure inside the rocket and outside the airflow. Stagnation pressure occurs where the velocity of the airflow has reached zero, meaning that all kinetic energy has been transformed to pressure.

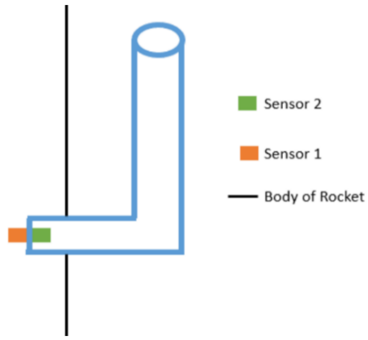


Figure 4 - Pitot Tube Layout

To compute velocity from the pressure difference, a form of Bernoulli's equations will be used:

$$\mu = \sqrt{\frac{2(p_t - p_s)}{\rho}}$$

Where:
μ = fluid velocity
p_t = stagnation pressure
p_s = static pressure
ρ = fluid density

Under standard conditions, the density of the atmosphere is about 1.225 kg/m^3. However, since the rocket will undergo a rapid change in altitude, additional parameters must be accounted for. Fluid density will be calculated as:

$$\rho = \frac{PM}{RT}$$

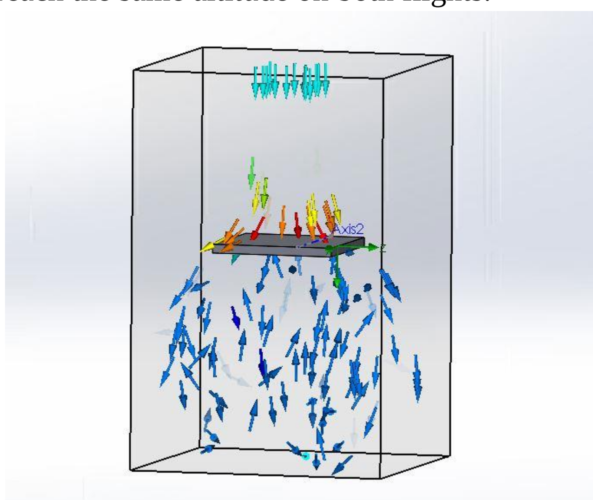
Where:
P = pressure at given altitude
M = molar mass of air
R = ideal gas constant of 8.134 $\frac{J}{molK}$
T = temperature at altitude h

Drag System

The drag system consists of three 1.75 in x 1.75 in flaps rotated by servos seated in servo mounts. These servo mounts are directly epoxied into the rocket body such that the servos themselves are serviceable and replaceable in the event that one or multiple fail. These servos have a wire that runs up the length of the lower body tube to the coupler where a small connector allows the servos to communicate with the Arduino inside the avionics bay. The wires will separate without excessive resistance when the ejection charge activates. These wires are also protected by tape running up the body tube.

The drag system will be controlled by the Arduino via pressure data. The static pressure used to determine the altitude will also be used in conjunction with measured time steps to calculate an estimated velocity. These two measurements will allow a program to compare previous flight data from the J-powered flight to actual flight to determine when the drag system needs to deploy. Thus, the drag system is an active one and should provide results accurate within the same order of magnitude as the custom velocity sensor.

An analysis of the force on a 3-dimensional square plate was done using both the drag equation and Solidworks flow simulation. Pictures of these results are shown in *Figure 5.* When the flaps are activated (face perpendicular to the flow at maximum velocity of 800 ft/s, the proposed maximum velocity with a 10% positive margin), the force acting on the plate is approximately 75 N. This force creates a torque of 1.66 Nm, or 16.94 kgcm. The servo can provide up to 20 kgcm of torque, so it should be capable of deploying and maintaining the flap position during initial activation after motor burnout on the K-powered flight. As predicted by a custom MATLAB program, three 1.75 in x 1.75 in square flaps deployed at motor burnout create enough drag to slow the rocket down to reach the same altitude on both flights.



Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value
GG Max Velocity (Y) 1	[m/s]	254.656	253.999	249.292	257.159
GG Normal Force (Y) 1	[N]	74.695	73.440	72.376	74.707
GG Torque (Y) 1	[N*m]	-0.005	-0.007	-0.011	-0.002
GG Torque (X) 1	[N*m]	1.661	1.636	1.604	1.667
GG Torque (Z) 1	[N*m]	-0.994	-0.980	-0.994	-0.969

Figure 5 - Flap Fluid Simulation and Results

Each of the servo mounts was 3D printed with a 0.1 mm layer height and full infill, increasing the strength as much as possible. This mount was epoxied into a test piece of blue tube in the same manner as it would be mounted on the actual rocket. After putting one of the servos in the mount, it was securely fastened using four screws. This assembly was then fastened into a vice grip. To test the ability for the servo mount to withstand similar forces as to those experienced in flight, a small luggage weighing device was secured about the axle of the servo as depicted in *Figure 6.* This was to simulate the force being applied by the flap, as its force is centered about the axle of the servo. This was then pulled on with a force greater than the force that would be experienced during flight, and the servo and mount showed no indication of cracking, slipping, or displaying other weaknesses. The maximum force applied was approximately 35 pounds, or 155 N, over twice what the estimated drag will be. The action of the servo was also tested afterward, and proved to be in working order just as before the test. This testing method was used due to the complexity that might arise from trying to model 3D printed plastics. It proved to be simple and time saving.

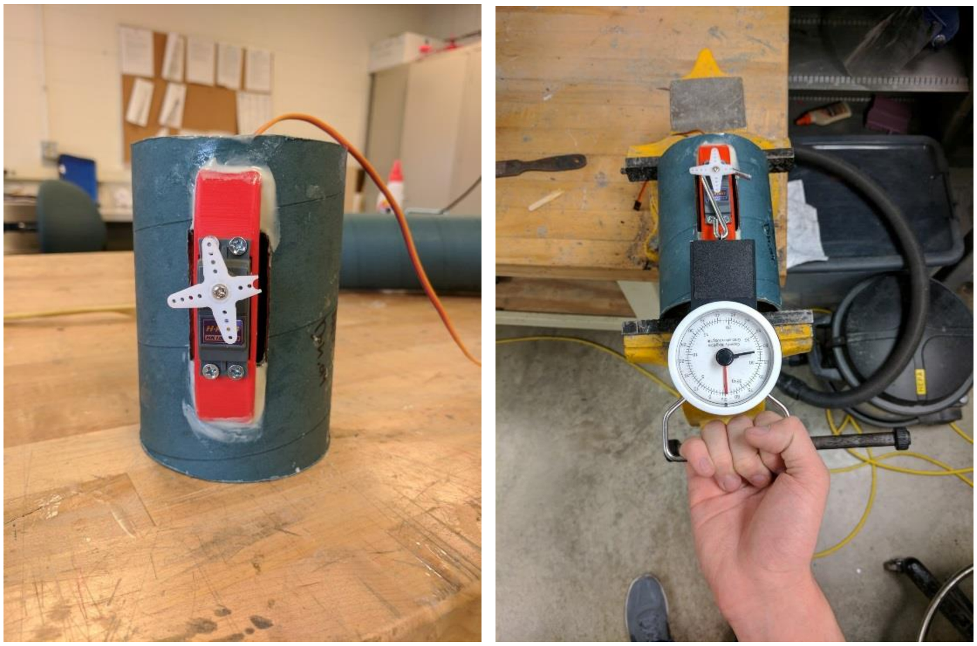


Figure 6 - Testing of the Servo

This system is far different than the original pushrod system that was meant to be employed when the preliminary design report was submitted. This current design proved to be simpler, increase stability, and come closer to convention in terms of the rocket body design. It did require larger holes to be cut out of the body tube where the motor is mounted, increasing the risk of rapid unplanned disassembly during flight. However, this risk is still minimal as the point at which the hole is cut is where both a coupler piece and normal piece of blue tube intersect, thereby increasing the strength. The wires do pose a risk to impeding separation of the body tube, and this will be countered for by using a larger than needed black powder charge (2g) and easily undone connections.

Cameras

Cameras will be mounted onto the rocket using a custom designed and 3D printed mount. The mount conforms to the shape of the body tube, allowing minimal space to be taken up in the coupler. The mount has four holes allowing for it to be screwed onto the body tube and secured. A small catching arm keeps the cameras held in the mount. The camera can then be zip-tied or velcroed onto the mount and secured in place. Two mounts will be installed, with one facing upwards and one downwards so that two cameras can view both above and below simultaneously. An aerodynamic cover will then be glued onto the rocket over the mount to keep drag produced to a minimum and protect the cameras from the airflow.

Mass Statement

The mass of the rocket when fully assembled and fully loaded with the J motor is 251.3 oz. while with the K motor is 260.5 oz. loaded. Unloaded, the full assembly is 209.4 oz. ∓ 10.5 oz. with a 5% error margin. The mass budget for the rocket can be seen in *Table 1*.

Part	Mass (oz.)	Notes
Casing with closure	15.6	
Main Parachute	11.8	
Main shock cord	13.5	
Nose Cone	8.6	
Flap (1)	1.2	(x3)
Launch Rail Guide (1)	0.4	(x2)
Rotary Switch (1)	0.4	(x3)
Motor Adapter Piece	1.6	
Nut (1)	0.2	(x10)
Electronics Board	2.0	
Arduino Mega	1.6	
Servo (1)	2.4	(x3)
9V Battery (1)	1.6	(x3)
Camera (1)	1.4	(x2)
Servo Connection (1)	1.0	(x3)
StratoLogger (1)	0.6	(x2)
Lithium Polymer Battery (1)	1.6	(x2)
Drogue Parachute	3.2	
Drogue Shock Cord	11.6	
Upper Body Tube	13.6	
Lower Body Tube	13.8	
Motor Assembly	50.0	Including tail cone
Miscellaneous Wiring	3.0	
Electronics Sled	3.0	
Coupler with Bulkheads	25.4	
Camera Mount (estimate)	3.0	
Velocity Measuring Device	3.0	
Total	**209.4**	219.8 oz. with 5% error margin

Table 1 - Mass Statement

Budget

The team originally planned on a budget of $1,000. However, after discovering that the original motor casing was incompatible with the motor adapter system, a new casing had to be ordered. It was also realized that the rocket may need many extra parts in the event that a few break in the case of a hard or awkward landing. As a result, the team went slightly over the $1,000 budget for a total cost of $1,305. The budget can be found in *Table 2*.

54 mm Seal Disk	$16.05	Motor Casing (54-1706)	$161.5
6 V Nickel Battery	Owned	Motor Mount Tube (Blue Tube)	$23.95
Active Drag Servos	Owned	Motor Retainer Tail-cone	$57.78
Anemometer Fins	Owned	Mounting Brackets for Flaps	$5.00
Anemometer Motor	Owned	Mounting Screws for Flaps	$5.00
Arduino Mega	$45.95	Multiplexer	$6.95
Arduino Pressure Altimeter	$39.80	Nose Cone	$23.05
Bigger Servos	$81.80	Nuts and Threaded Rod	Owned
Body Tube (Blue Tube)	$77.90	Drogue and Main Parachute	Owned
Cameras	Owned	Parachute Protectors	Owned
Centering Rings	Owned	Quick-links	$15.76
Chute Swivel	$14.70	Rail Buttons	$10.00
Control Horns	$2.58	Resistors	$0.42
Copper Wire	Owned	Rocket-Epoxy	$38.25
Coupler (Blue Tube)	$39.95	Rotary Switches	$19.86
Electronics Bay (Plywood)	Owned	Servo Extension Wires	$9.90
Eyebolts	$16.53	Servo Extension Wires	$5.86
Fiberglass	$40.00	Shear Pins	$3.10
Heat Shrink Tubing	Owned	Shock Cord	$24.00
J Motor (J415W-L)	$158.08	StratoLogger Altimeters	Owned
K Motor (K1103X-14)	$192.08	U-Bolts	$3.90
Light Sensors	$3.00	Tube Fasteners	$31.66
Metal Servo Arms	$26.25	USB Adapter for Arduino	$3.95
More Tube Couplers	$34.54	Voltmeter	Owned
Motor Adapter	$59.00	Pushrod (1.2 mm)	$6.99

Total	**$1,305**

Table 2 - Budget

Construction of Rocket

Practices

The rocket itself has five distinct pieces, each requiring their own construction process. These include the motor mount assembly, lower body tube, coupler, upper body tube, and nose cone. The first step of construction was to cut each piece to the proper length as listed in the Vehicle Design Overview section. These pieces of blue tube with diameter 4 in were the basis for all other construction techniques following.

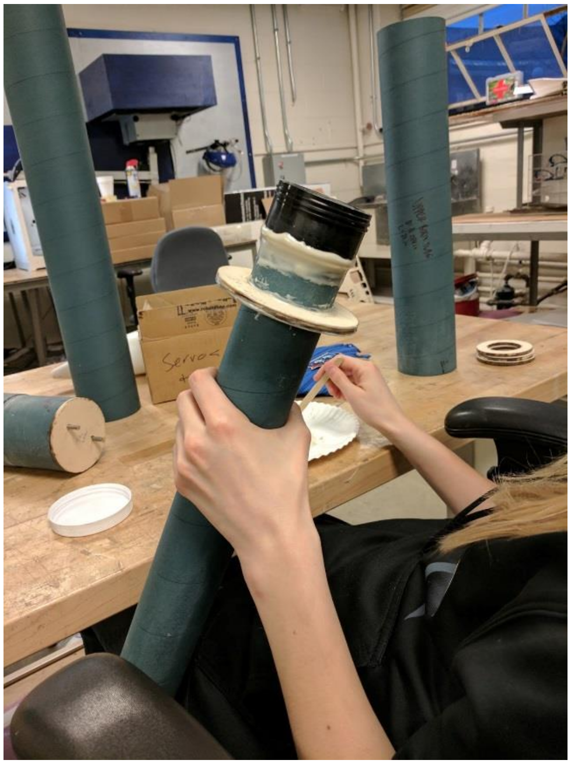


Figure 7 - Construction of the Motor Mount

The motor mount assembly in *Figure 7* was built consisting of the outer body blue tube, a coupler blue tube, four centering rings, an inner motor mount tube, three fins, the drag system, and the tail-cone retainer. Using rocket epoxy, the retainer was placed on one end of the motor mount tube. Then four centering rings were placed on the tube with similar spacing starting from 2 in above the retainer. The fins are sandwiched between the lowest and second centering rings. After applying the epoxy, it was left to dry for twenty-four hours while the next piece was worked on.

Following the basic construction of the motor mount assembly, the outer piece of blue tube was then cut using a dremel to make three vertically oriented, equally spaced slits for the fins to slide into and attach to the center tube. Both the outer tube and the fins were sanded down by hand to allow for easy attachment. Once placed properly, multiple layers of epoxy were applied to create strong filets.

The drag system was then placed in the middle of the motor assembly. The servos were offset 60 degrees from the fins so that the airflow around them does not disturb the airflow about the fins

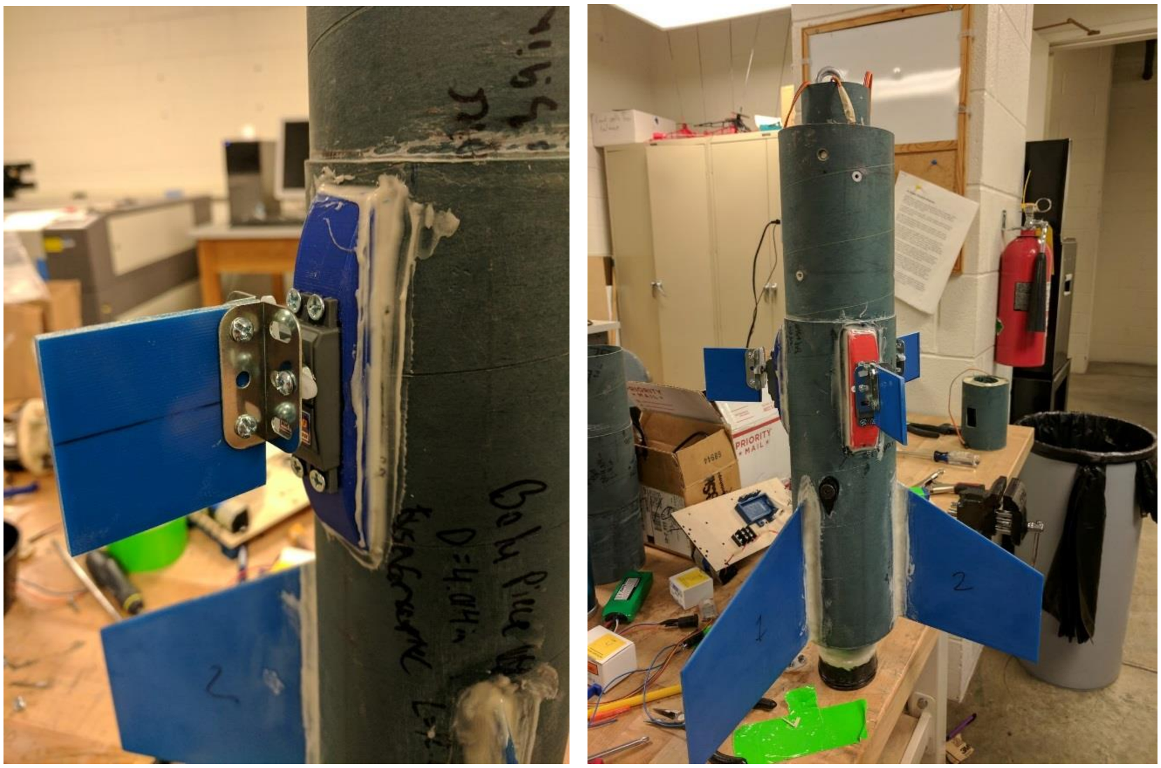


Figure 8 - Close-up of a Mounted Flap and the Motor Assembly

greatly. Using the 3D printed mounts and wood screws to secure the servos into the rocket, the three servos were properly placed and ready for the attachment of drag flaps. The drag flaps are a simple square shape with a mount placed on one edge using four screws. This allows for proper strength and simple adjustments which can be seen in *Figure 8.*

The lower body tube was cut to the specified length as given in the Vehicle Design Overview section. Tube couplers (the small inlaid metal circles) were placed in the same fashion as the slits in the motor assembly. At the bottom of the lower body tube, three of six of the tube couplers are embedded in the blue tube each 120 degrees apart. Placed above but offset by 60 degrees are the other three tube couplers, totaling six spots. On the assembled rocket, six countersunk screws hold the lower body tube to the motor assembly section through these tube couplers. Once constructed, the lower body tube will hold the shock cord and drogue parachute.

The coupler piece in *Figure 9* allows for separation of the rocket once the ejection charge goes. The outer body tube piece is the same diameter as the upper and lower body tubes; however, there is another tube that has the outer diameter equal to the upper and lower body tubes' inner diameter, allowing for a snug fit yet easy separation for access to parachutes and other electronics. This is necessary because the coupler contains shock cord on either end, resulting in large amounts of force on each end of the piece at once. The inside of the coupler contains the electronics sled. The electronics sled was built out of two pieces of 1/8th in plywood, each glued together using wood glue, and four squares with holes aligned on the outer edges to allow the sled to slide on rods on either side for easy access and removal.

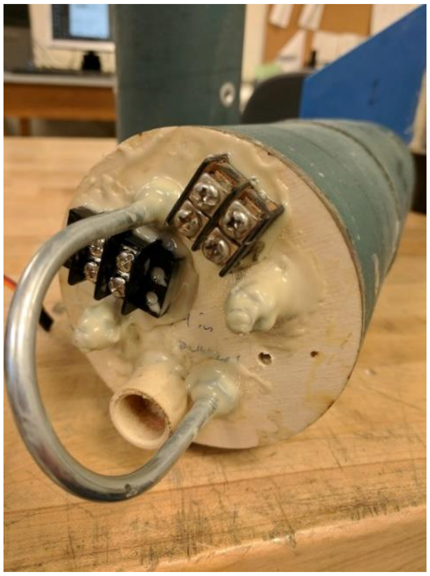


Figure 9 - Close-up of Upper Bulkhead

The upper body tube and the nose cone may be considered as one piece for this project. This is because the nose cone was screwed into the upper body preventing it from disconnection from the rocket using three screws. The inside of the upper body tube contains the main parachute and shock cord. On the first launch, the upper body tube broke. Increasing the length will prevent this in the future to allow for more room for the parachute. There are also five evenly spaced shear pins connecting the upper body tube to the coupler.

Each shock cord segment in both the upper and lower body tube is approximately 20 ft long, minimizing the risk of the different body sections of slamming into one another.

Stability Analysis

Because the rocket design has changed substantially since the submission of the preliminary design report, it is in the best interest of the team to redo the stability analysis. A stability analysis was performed using measured values for the center of mass for the rocket with the J and K motors and given values from OpenRocket about the center of pressure. The OpenRocket design is fairly accurate, but having a value as close as possible to reality is beneficial to ensuring the safety of the rocket. The center of pressure from the tip of the nose is 68.9 in. The centers of mass measured from the tip of the nose with J and K motors are 57.3 in and 57.8 in, respectively.

$$Stability\ Margin_J = \frac{68.9 - 57.3}{4.0} = 2.89$$

$$Stability\ Margin_K = \frac{68.9 - 57.8}{4.0} = 2.78$$

The calculation for the stability margin of the rocket indicates that the rocket will remain stable through both flights. The stability margin must remain between 1 and 5 to ensure that the rocket will be stable, but not overly stable, resulting in unwanted rotation or spin of the rocket. If unstable, the rocket would not recover from changes in wind directions and could change directions during the flight. Because the active drag system was changed and weights were shifted, this margin is one with more room for error or variance, as opposed to the margin of the initial design, which was much closer to 1.

The drag system is also placed in a way such that even after deployment, the rocket maintains its high stability. It can be assumed that once the flaps are deployed, the center of pressure moves to where the flaps are mounted. When this happens, rocket stability should increase to approximately 3.55, ensuring the rocket still stays within the designated range.

Parachute Deployment and Detection Scheme

The parachute system is composed of two parachutes. The drogue parachute has a 20 in diameter. It is stored in the lower body tube of the rocket above the motor assembly section. This will slow the rocket down to approximately 80 ft/s. This parachute is deployed at apogee either by a StratoLogger or the backup motor ejection charge. This parachute will be ejected out of the tube using 2 g of black powder. It is attached to the shock cord by a 500 lbs quick-link connector knotted such that the parachute is a third of the way down the shock cord. When the parachute is deployed, the two halves of the rocket should not slam into each other as the rocket settles into descent.

The main parachute has a 52 in diameter. It is stored in the upper body tube of the rocket above the coupler section. The nose cone stays attached to the upper body tube during descent and deployment and is also the mounting point for the shock cord. The nose cone was drilled through so that the shock cord could be threaded through and knotted. The nose cone will also be held in via three steel screws drilled through metal plates that are epoxied to the nose cone. This parachute will slow the rocket down to approximately 20 ft/s. This is below the maximum descent rate allowed by the competition of 24 ft/s. This parachute is deployed at approximately 600 ft above the ground by the same StratoLogger as the drogue charge. There will also be a second chance for this parachute to open at 500 ft above the ground via a backup StratoLogger. The first ejection charge is 1.5 grams of black powder, while the backup charge is 1.75 grams of black powder.

The ejection charges were sized using a combination of online calculation, ground testing, and drag estimates. The online calculation gave the team a starting position for charge sizes to be used in testing and the force that should be used to hold the body tubes to the coupler. The team used 5 x 2-56 shear pins to hold each tube onto the coupler section while in flight. Each 2-56 shear pin holds up to 21.6 lbs of force before splitting. Using 5 shear pins offers up to 108 lbs, or approximately 475 N of force. At the time of flap deployment, the rocket experiences a maximum drag force of 393 N (225 N from three flaps, and 168 N from the rocket body).

However, most of the drag force from the body of the rocket acts to hold the rocket together, so the force on the shear pins should be much lower at the point of maximum drag.

This system was changed since the submission of the preliminary design report. It no longer uses a chute release, instead going for conventional dual deployment. The velocity measuring system uses less space than originally allotted, so the main parachute can be put in the upper body tube.

The parachute detection scheme is relatively simple. Wired to the Arduino inside the coupler will be two photoresistors. One will go to the top of the coupler and the other will go down to the bottom of the coupler. Each will poke out slightly from the bulkhead. These sensors will have an initial resistance of roughly 200 kΩ when they are inside the rocket (stowed parachutes). When the parachutes are ejected, the resistance drops to approximately 10 kΩ. In conjunction with measuring the resistance, the Arduino will be measuring a time step during flight. As soon as the parachute is deployed, the sensors will be exposed to sunlight, and the time at which this occurs will be seen by saving the time step at that instant. This will capture deployment of each individual parachute. *Figure 10* displays how the photoresistor changes resistance when exposed and hidden from light. This is the method by which the Arduino detects tube separation.

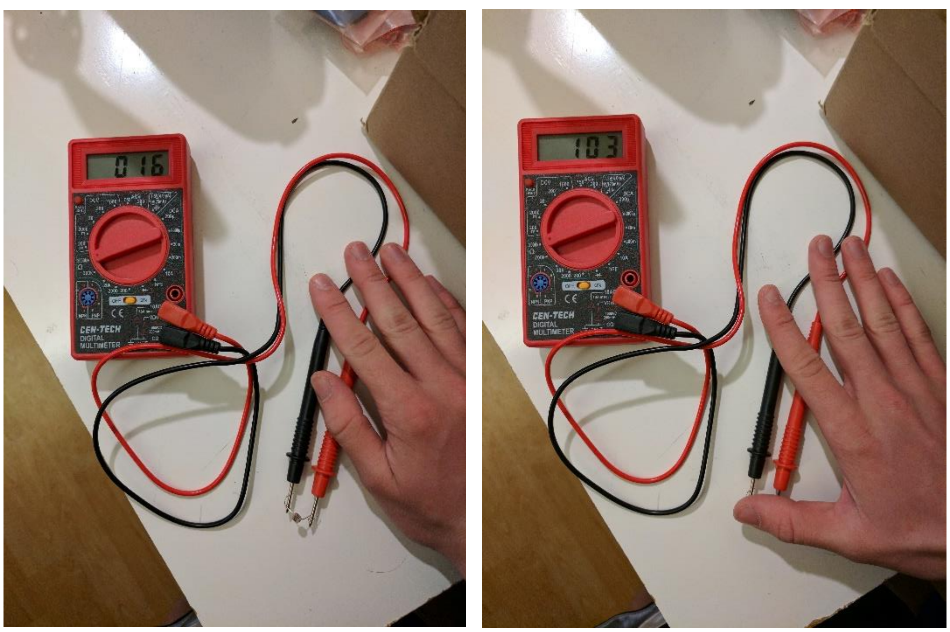


Figure 10 - Testing of the Photoresistor

Finished Rocket and Test Flight Photos

Figure 11 - Launch Site Photos

Test Flight Reports

Overview

The rocket test flight took place on April 25, 2017 and took approximately six hours to complete. The team successfully assembled the rocket, performed black powder charge tests on both the lower and upper sections, launched the rocket with the J415W-14 motor with an onboard altimeter for data collection, and tested parachute deployment. The cameras, activation of drag system, custom velocity sensor, and parachute detectors were not tested on the test launch. Some photos from the launch can be seen in *Figure 11*.

Launch Setup

The rocket setup procedures included wiring the avionics, black powder charge testing, packing the parachutes, and assembly of the upper and lower sections of the rocket. Two altimeters were used on the rocket, one controlling the primary drogue and primary main, and the other controlling the backup main. The team had configured the altimeters before launch day to deploy the drogue without any delay at apogee and have the primary main deploy at 600 ft altitude. In the event the primary main failed, the second altimeter was configured to deploy the backup main at 500 ft. On the launch day, a quick check was done to ensure the correct settings for parachute deployment.

Once the avionics were properly configured, the team performed black powder charge testing on both the upper section and lower section. The team removed all electronics from the avionics bay and equipped the lower body tube with a 1.5 g black powder capsule. During the test, the tube did not separate, and there were visible smoke leakages. The team found holes in the coupler that allowed the charge to travel through the coupler and into the lower body tube, so putty was used to block the holes on the coupler. A second black powder test was done on the lower body tube with 1.5 g of black powder, and again the body tube did not separate from the rocket. Smoke was observed to leak in three distinct spots near the servos. After disassembling the rocket, the team determined that the charge had passed through holes that were used to run wires from the avionics bay to the servos. It was then able to leak out between the servo and servo mount. The holes were sealed with putty, and a brief check was done to ensure success of the next black powder charge test for the lower body tube.

The upper body tube was tested before the third lower body tube test. A 1.25 g black powder test charge was prepared and placed inside the upper body tube. All holes in the coupler were sealed before the test, and the upper body tube was attached with five shear pins. The upper body tube successfully separated from the rocket when the test was performed.

The final black powder charge test was performed on the lower body tube with a 1.5 g black powder charge. The charge was taped to the coupler outside the avionics bay and inside the lower body tube. The lower body tube was connected to the coupler with five shear pins. The test was successfully completed with separation of the lower body tube from the rocket. The black powder charge testing took approximately five hours to complete.

The team then began preparing the rocket for the test launch. A final check was done on the altimeters to ensure they were configured correctly, and the avionics were connected to the switches and black powder charges. A 2 g charge was used for the lower body tube, and a 1.5 g main and 1.75 g backup charge was used for the upper body tube. After the coupler was sealed, the black powder charges were taped to bulkheads on their respective sides. The rocket was then assembled and held together with five shear pins on the upper section and five shear pins on the lower section of the coupler.

The motor was difficult to assemble because the O-ring on the top of the J motor was too large and would slide out of its proper place when the motor was inserted into the motor casing. Grease was applied over the O-ring to help the casing slide over it easier, and the casing was slid over the O-ring without dislodging it from its groove. The loaded casing was taken down to the launch pad with the rocket. Due to O-ring complications, assembly of the motor took approximately 30 minutes. The team set up the rocket on the pad and inserted the J motor. The rocket was then ready for launch.

One-eighth inch vent holes were also included in the upper and lower body tubes. In the event the tubes are unable to separate, the vent hole is able to release the pressure gradually. Even with a hole in the tubes, the initial pressure created during the ejection event separates the tubes.

Launch and Boost Phase

The rocket launched successfully on the first attempt. The maximum acceleration experienced by the rocket was 294 ft/s^2 at 0.1 s, and the maximum velocity of 474 ft/s at 2.9 s. The smoothed data for velocity versus time and acceleration vs time are shown below in *Figure 12*

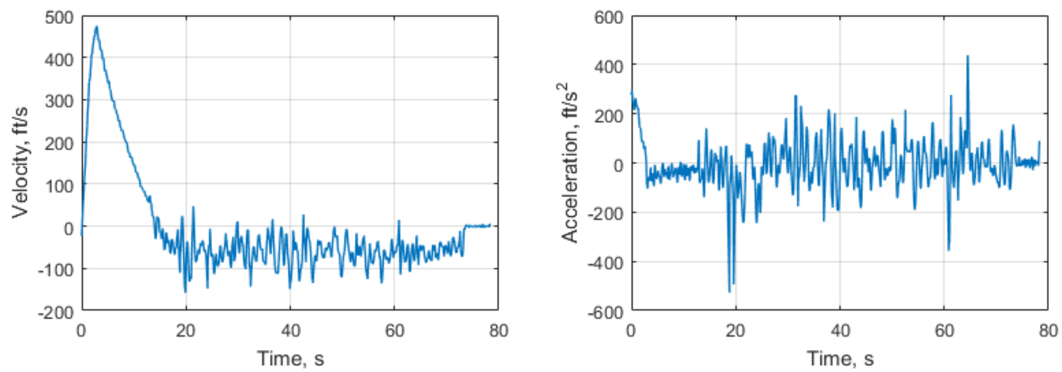


Figure 12 - Graphs of Velocity and Acceleration Data from the StratoLoggers

The rocket achieved an apogee of 3233 ft approximately 13.95 s into flight, as measured by the primary altimeter. The backup altimeter registered a final apogee of 3232 ft 13.95 s into flight. The altimeters matched data closely throughout the entire flight with the exception of the time at which the black powder charges deployed and near the end of the flight. The backup altimeter terminated its data collection 68.35 s into flight while the primary altimeter continued logging data for 78.35 s. The co-plotted altitude versus time data for the altimeters can be shown in *Figure 13*.

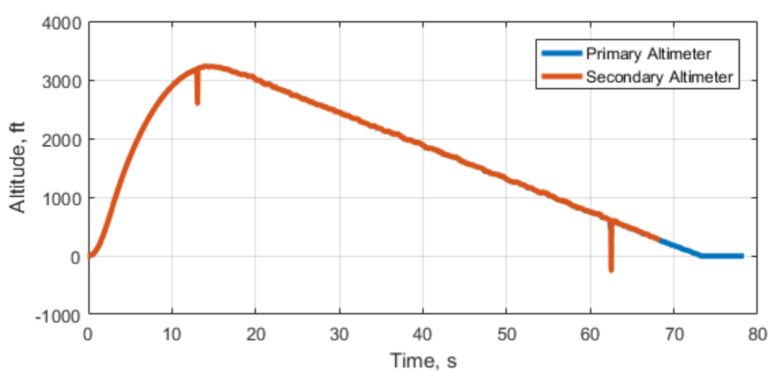


Figure 13 - Graph of Altitude from Both StratoLoggers

The altimeters also successfully ignited the black powder charges at the correct altitudes. There is a noticeable voltage drop in the primary altimeter at approximately 14 s for the drogue parachute deployment, which occurs near the detected apogee time of 13.95 s in *Figure 14.* The altimeter was set to deploy the drogue without a delay after apogee, so the drogue parachute deployed at the correct time. The voltage data for the primary altimeter continues at a constant 9.4 V until approximately 62.5 s into flight, when there was a voltage drop that indicated the ignition of the main parachute black powder charge. The deployment occurred when the primary altimeter detected an altitude of 599 ft, which nearly matched the expected deployment altitude of 600 ft.

The backup altimeter was programmed to deploy the main at 500 ft altitude. The subplot of the backup altitude and voltage over time is shown in *Figure 14*. The voltage remains at a constant 9.3 V until 63 s, when the first main parachute black powder charge ignited. This occurred at an altitude of approximately 600 ft and was due to the settings of the primary altimeter. There is a second discontinuity where the backup voltage remains at 9.2 V briefly before returning to 9.3 V at approximately 64 s when the backup altimeter registered an altitude of 513 ft. Because the time of the voltage drop cannot be accurately measured, the altitude at which the main parachute backup charge is ignited cannot be determined with absolute certainty; however, the results indicate that both the primary altimeter and backup altimeter performed with the precision required for a successful rocket launch.

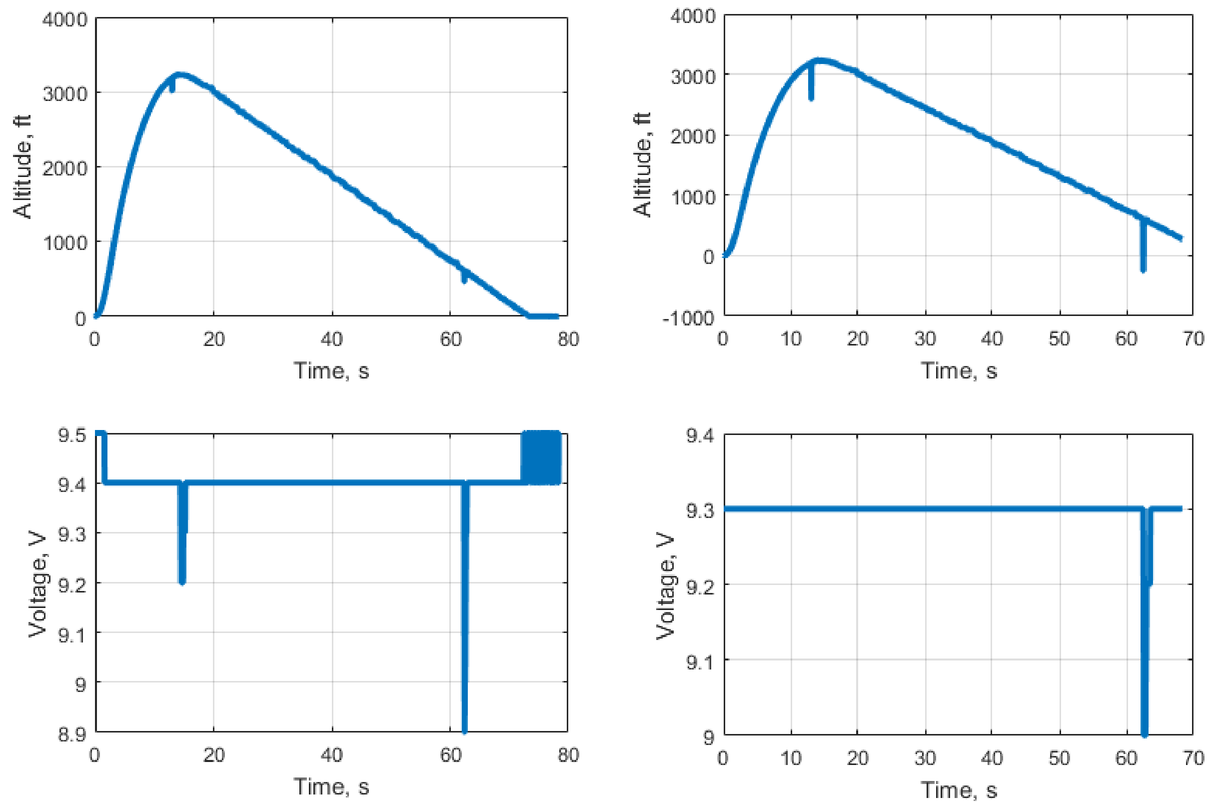


Figure 14 - Graphs of Altitude and Voltage from Primary StratoLogger (Left) and Secondary StratoLogger (Right)

Recovery

The rocket was recovered approximately 500 ft away from the launch site. The drogue parachute deployed successfully and is shown in *Figure 15*. The main parachute did not successfully deploy, but all three of the black powder charges went off and both the lower and upper body tubes separated. The reason for deployment failure of the main was determined to be tight packing in the upper body tube. It was found approximately 2 in inside the upper body tube at the end of the flight, and this can be readily fixed for the competition flight. Photos of the main parachute inside the upper body tube and the deployed drogue parachute can be seen in *Figure 17*. Minor damages were inflicted on the rocket due to a high velocity impact from the main deployment failure. A crack was observed starting from the bottom of the upper body tube and ending approximately a quarter the way up the tube due to impact with the ground. The servo horn on one of the servos broke in two pieces, but the flap remained intact. The cracked servo horn can be seen in *Figure 16*. The crack and servo horn were the only damage that the rocket incurred. Photos of the rocket recovery are included below. With minimal repairs, the rocket is capable of flight. The upper body tube of the rocket has already been lengthened to allow for a longer parachute packing such that the diameter of the packed parachute is reduced, and the parachute slides into and out of the tube easier. Aluminum flap mounts have also been ordered to replace the original plastic arms used in testing.

Figure 15 - The Rocket Descending Under Drogue

Figure 16 - The Broken Flap

Figure 17 - Landing Site Photos of the Upper Body Tube and Drogue Parachute

Test Flight Discussion

OpenRocket

The rocket was designed in OpenRocket before construction began to provide an estimate of the rocket's apogee and maximum velocity. The model was 82.7 in in length and 4.0 in in diameter. The nose cone was 12.0 in in length, the upper body tube was 26 in, the coupler was 4.0 in with the outer wall, the lower body tube was 26.0 in, and the motor assembly was 12.2 in. The drag reducer added 2.5 in to the length. The main parachute was assumed to be 18 oz. and packed 6.6 in from the top of the upper body tube. The drogue parachute was 5 oz. and was packed 11.6 in in the lower body tube relative to the top of the lower body tube. Various mass components were placed inside the coupler where the avionics bay would be located, including epoxy, two StratoLoggers, an Arduino, two cameras, a velocity sensor, two 9 V batteries, and an I-Bolt. The lower body tube contained the drogue parachute, epoxy, quick-links, and three servos for the active drag system. The active drag system remained in the dormant configuration throughout the simulation and was modelled as three 2x2 in fiberglass fins equally spaced around the rocket that were ⅛ in in width. The three rocket fins had a root chord of 5.75 in, a tip chord of 3.9 in, a height of 5.6 in, and a sweep angle of 32.5 degrees. The fin thickness was 1/8th in, and they were made of fiberglass. The rocket final mass was 192.8 oz., but the mass was adjusted to the actual rocket mass after construction was completed to be 209 oz. The rocket was predicted to achieve a maximum altitude of 2923 ft and maximum velocity of 430 ft/s with a J415W-14 motor. OpenRocket also predicted a velocity off the launch rail of 55.2 ft/s with the J415W, ensuring that the rocket is achieving a safe launch speed in all cases.

During the actual test flight, these values differed from the predicted values, with the maximum altitude achieved being 3233 ft and a maximum velocity of 475 ft/s. The velocity of the rocket off the launch rail is ensured to have been at least the predicted value as the thrust curve for the motor is not believed to differ greatly from the values OpenRocket follows. Discrepancy between actual values and predicted values could have arisen for several reasons. During the test flight, not all systems were flown that were included in the model. The camera mounts and cameras were not flown during the test flight, and other last minute changes with deciding not to fly certain electronics could have resulted in the recorded altitude being higher than the predicted altitude due to the mass of the rocket being lower than predicted. In addition, conditions of flight were not exactly consistent with flight predictions. Wind speeds, launch angle, and other various parameters that differed from flight simulations could have led to the measured values being different than the predicted values as well. Overall, however, the predicted values remain relatively consistent with the measured values from the test flight.

During the flight, at apogee the drogue chute deployed with no issues; however, despite the dual deployment being successfully installed, the main chute was not folded into the rocket properly. As a result, the main chute did not deploy due to it not being able to unravel. Damage due to this anomaly was minimal, with the only main damage being a small crack on the upper body tube, which was replaced with a new upper body tube shortly after.

Planned Changes/Improvements

During the test flight, the dual deployment system was successfully installed. However, due to improper folding of the main parachute, the chute did not deploy properly. As a result, the rocket now has a longer upper body tube and modified parachute protector to allow for the chute to have more space in the body tube. When readying the chute for flight, the chute will be folded in such a manner that it is much more compact and thin, which will also help prevent any future improper deployment.

Due to time constraints with potential test launch opportunities, the camera mounts were not installed during the test flights. As such, future test flights will include the camera mounts and cameras in to be able to test the system and ensure it functions before the competition.

Due to time constraints, despite the active drag system being installed on the rocket, it was unable to be tested during the test launch. Future plans will involve testing the drag system to ensure it functions properly and matches the team's predictions and models.

The shock cords were originally connected to the coupler using two large quick-links. These quick-links together accounted for 7 oz. of weight on the rocket, which negatively impacted the maximum altitude achievable by the rocket. To negate this, a simple self-tightening knot will be wrapped around the U-bolts and I-bolts instead of the large quick-links. It may take slightly more time, but it will save weight and space in the rocket body tubes.