2015-2016
NASA Space Grant Midwest High-Power Rocket Competition

Team Rocket Design Report

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Table of Contents

I. **Executive Summary** 3

II. **Design Features** 3

A. Rocket Airframe 3

B. Active Drag System 5

C. Electrical and Controls 7

D. Construction Methods 11

III. **Predicted Performance** 15

A. Launch and Flight Analysis 15

i. Velocity vs. Time

ii. Coefficient of Drag vs. Velocity

iii. Coefficient of Drag vs. Time

B. Recovery Analysis 19

IV. **Safety** 20

V. **Budget** 20

VI. **References** 22

I. Executive Summary

Team Rocket, in coordination with Badger Ballistics of the University of Wisconsin-Madison, was presented with a unique challenge in this year's NASA Midwest High-Power Rocket Competition - one which we were all very excited to tackle. The competition's unique requirement of video documented active drag implementation combined with on-board data collection characterizing drag coefficient and flight performance prediction pushed our collective rocketry, engineering, and electronics knowledge to its limits, demanding an innovative, multidisciplinary construction. This report outlines the design and fabrication of the team's rocket and underlines the complex challenges and solutions encountered throughout the process.

II. Design Features

Rocket Airframe

When competition motor sizes were released, our team quickly fell in love with one of the largest motors that was available for use, the Cesaroni K711. From preliminary design considerations to special fabrication methods, designing a rocket airframe to handle the high stress levels that a class K motor would present would be a great learning experience throughout the entire competition. In addition to meeting competition requirements for altitude, the rocket we have designed is specifically tailored to handle the stresses a supersonic flight presents and is constructed with paramount fabrication practices.

Preliminary design considerations dealt with rocket dimensions and mass positioning within the rocket. 98mm was ultimately chosen as the main rocket body diameter since it was large enough to house all of our necessary components without much hassle, but also small enough to decrease drag noticeably compared to the next largest tube size. The relationship between cross sectional area and force due to drag can be seen in Equation 1. Minimizing cross sectional area was a major concern of ours - increasing tube radius linearly would increase the force of drag our airframe would be subjected to quadratically.

$$Fd = \frac{1}{2}(p)(Cd)(V^2)(A)$$

Equation 1 *– Drag Equation.* p *= density of fluid, Cd = drag coefficient, V = body velocity, A = frontal area, Fd = force due to drag.*

Total rocket mass could only be minimized to a point. Much care was taken to determine mass position within the rocket to offset the extremely massive motor, casing, and motor mount tube. Since electronics will be mounted around the motor mount tube between centering rings, increasing mass below the center of pressure became a significant concern in terms of stability. To offset this, rocket length was increased, with around 1.2 kg of mass added to the nosecone and our main electronics bay positioned as close to the nosecone as possible. Through these various means, rocket length, stability, and mass was optimized for a supersonic flight.

As far as structural features are concerned, the main body tube is made of blue tube, which is essentially a type of wound cellulose fiber impregnated with resin. Considering the incredible amounts of airframe stress that will arise during the competition flights, regular cardboard/phenolic tube was ruled out, and for ease and safety of fabrication, fiberglass was also ruled out (no dangerous dusts arise during sanding/cutting, no mixing of resin is necessary, less rocket mass than with fiberglass, etc.). Blue tube provides just enough strength and durability without being overly massive. It is also flexible enough to absorb and distribute impact loads when the rocket has a hard landing, and will likely not shear when struck with a fast moving shock cord in tension. The team did not look into other composite materials for the rocket body due to time and budgetary constraints. From a fabrication standpoint, connection points on the tube will be layered with epoxy for extra strength, especially around the lip where zippering due to shock cord collision usually occurs. The fins are constructed of 3/16-inch thick tempered Masonite (hardboard), which has been smoothed on both sides. The chosen thickness combined with the rigidity of tempered Masonite helps to prevent fin flutter and rounded fin edges will help to reduce drag and increase maximum altitude. Through the wall, fin tabs will be constructed between three of the four centering rings for added strength, along with full length epoxy clay fillets where the fins meet the tube exterior. The fin tabs will extend to the motor mount tube housed within the lower most body tube section. Due to the increased stress concentration in the body tube around the motor mount tube from numerous "hatches" cut out of the main body tube to house various electronic components, four centering rings were added and will be epoxied to the fin tabs for added strength.

Active Drag Components

Aside from the control system, the hardware for the active drag system consists of two servos (19.2 kg-cm of torque per servo), two metal pull rods (linkages), two plastic control horns for connecting the servo linkages to the drag tabs, a plastic transmission arm for each servo, a separate 2S LiPo battery, and two drag tabs which are cut out of extruded polyurethane foam insulation, reinforced with aluminum plates, and covered with a carbon fiber and epoxy shell layer. We estimated the maximum drag force per drag tab to be approximately 35 lbs. (assuming drag tabs perpendicular to airflow, rocket at max velocity, tabs perfectly square and of uniform material), so a composite structure was needed for extra strength. The aluminum plates on the drag tabs will also serve as mounting points for the hinges, which will be secured to the farthest aft centering ring. The motor mount tube extends approximately five inches past the base of the aft most centering ring – the drag tabs are conically shaped to shroud the protruding motor mount and act as a boat tail when stowed. The hinge system consists of a bent u-shaped aluminum bracket screwed to the bottom centering ring. There is a hole in the aluminum bracket as well as the aluminum reinforcing plates on the drag tabs, and a pin is inserted through the holes to fasten the drag tabs to the rocket. As the servos pull on the linkages, the drag tabs will extend outward into the airstream at an increasing angle relative to the vertical axis. Having the drag tabs at the far aft end of the rocket helps to keep the rocket stable during deployment and allows for gradual, rather than sudden, loading. All of the mechanical components for the active drag system will have removable cowlings over them to minimize drag during the flight and to reduce potential damage to delicate linkages. At standard temperature and pressure, assuming the maximum acceleration experienced by the rocket is 20 Gs, the maximum velocity of the rocket is Mach 1.1, and the total cowling weight is less than three pounds, our rocket will have a higher maximum altitude with the cowling in place rather than not (see Equation 1). An attempt was made to keep the linkages from the servos to the drag tabs completely internal, but given the remaining mounting space available, complete internal routing was not feasible. The team felt that external routing was more practical, allowing easy access to components that may need to be removed for replacement or repair.

Electrical and Controls

The main goal of the competition is to utilize a scratch built computer system to actively control drag deployment and to characterize the drag coefficient over the entire flight. These systems can be broken down into two major categories: systems that do not require real time feedback from the rocket and systems that do. Systems with real time data (such as velocity and altitude) are advantageous since they are much more effective at controlling the rocket's drag. Therefore, the team tried extremely hard to implement such a system. In order to accurately understand the rocket's flight, the on-board computer would need velocity, position and acceleration data. Several different combinations of sensors and ways of calculating these parameters such as barometric altimeters, real-time GPS positioning, and pitot-static airspeed measurements were considered. After consulting with faculty advisors and industry professionals, we determined that such sensors would be unlikely to provide accurate data due to incredibly high speeds and rapid pressure changes in flight. GPS refresh rates were not nearly fast enough at 10 Hz to provide adequate data points in flight early on, where small drag adjustments have a considerably larger impact on total apogee altitude. Our chosen method of controlling the active drag system is simplistic yet extremely effective – using nothing but a timer. A simple equation can be used to relate position, final velocity, initial velocity, and acceleration.

$$s = (v_f^2 - v_i^2)/2a$$

Equation 2 – *Relationship between velocity, position, and acceleration. S = position, vf = final velocity, vi = initial velocity (after motor burnout), a = rocket vertical acceleration.*

If we apply this equation to the flight of the rocket after motor burn out (all parameters of each flight will be identical for this segment of data – drag tab deployment will not happen until the coast phase), initial velocity will be the velocity at motor burnout and final velocity will be the rocket's velocity at apogee (which will be 0 m/s). Therefore, we can equate the ratio of s1 to s2 and a1 to a2 (where case one signifies the deployment flight without drag and case two signifies the flight with drag deployment). Since our predicted apogee without the drag system activated is approximately 2500 meters AGL, motor burnout occurs at 750 meters AGL, and since the second flight's apogee must equal 75% of the non-drag deployment flight's apogee, the distance travelled by the rocket after burnout on its second flight has to equal 0.643 times the apogee of the rocket on the initial flight. This is due to the fact that we are comparing the flight behaviors of the rocket only after motor burnout – we cannot equate the 75% altitude ratio directly. Therefore, the deceleration of the rocket with the drag system activated has to be 1.556 times the deceleration of the rocket without the drag system activated. This parameter can be changed for any given percentage of initial non drag deployment flight altitude and will be employed into our onboard computer system coding scheme. After the first deployment flight without drag has been fully characterized, a vertical acceleration vs time curve will be mathematically created. The onboard computer system will use the acceleration vs time curve to adjust the drag petals and attempt to re-create the modeled flight. The second half of each flight closely parallels that of a ballistic trajectory – the only major acceleration affecting the rocket is gravity. For this time period, the drag petals will have little effect on the deceleration on the rocket. As the rocket's speed slows the effect of aerodynamic drag becomes less important (see Equation 1). From the plot of acceleration vs time (see Figure 1), it is clear that aerodynamic affects have the largest impact on the deceleration of the rocket during the first quarter of the rockets flight, again still assuming after motor burn out during the coast phase. Therefore, the team assumed that if we increased the factor of drag during the first quarter of coasting flight by a factor of 1.556 (assuming we are meeting the 75% of deployment without drag flight apogee requirement), the rocket's apogee will be close to ideal

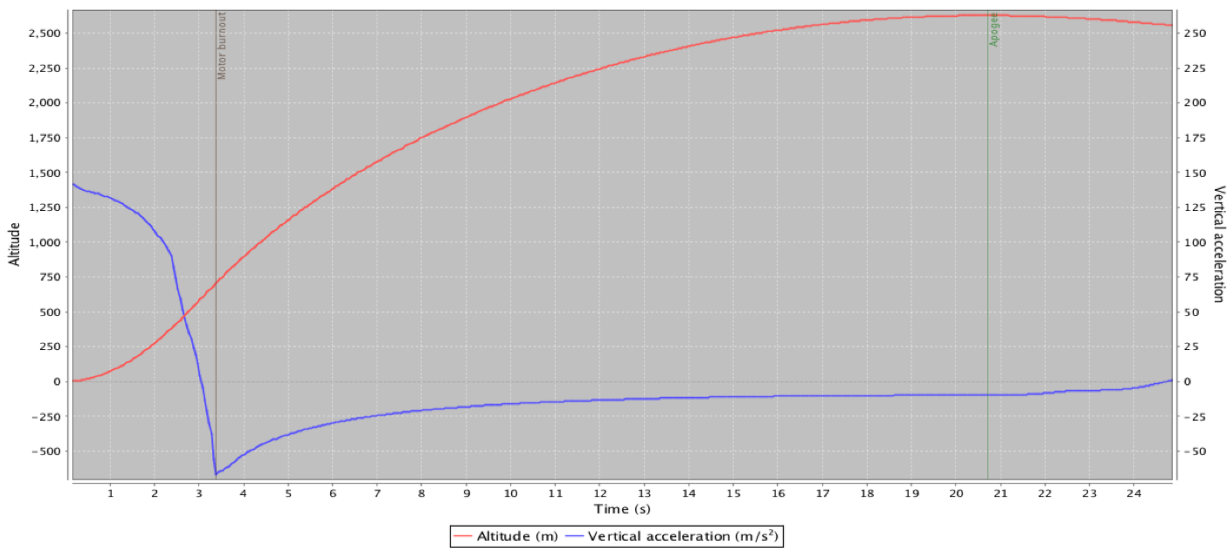

Figure 1 - *Vertical Acceleration vs Time and Altitude vs Time graphs from Open Rocket simulation on a Cesaroni K711 motor – non drag deployment flight.*

to meet competition requirements. A major advantage to a timer only system is that the this can be fully tested and validated on the ground before flight. We will be starting the on-board timing system with an accelerometer (which will sense motor ignition) and will assume that motor burn time is identical for each flight. Initially, when the drag petals are entirely stowed, their drag coefficient can be approximated as that of a streamlined body: Cd = 0.04 (see Figure 2). When the drag petals are fully activated, they can be approximated as a cone: Cd = 0.5 (see Figure 2). Full drag petal deployment is complete when they reach 60° from the vertical. To characterize this over the entire flight we will combine the estimations shown below with our mathematical model of the flight.

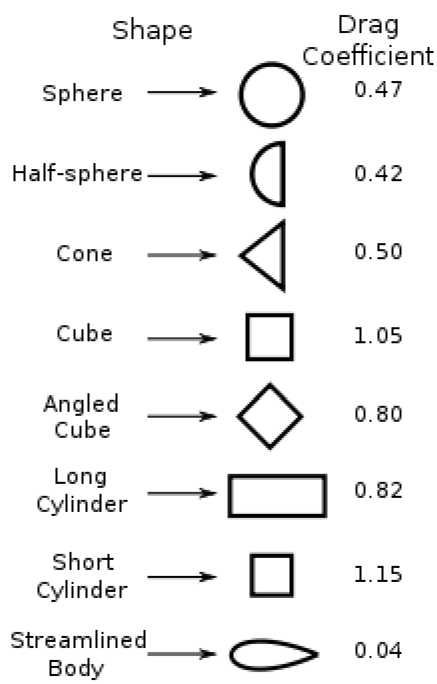

Figure 2 *- Table of common shapes and related drag coefficients.*

The entire drag system will be powered by a separate battery that is located in the aft section of the rocket and mounted with a small video camera system that will record and stream live video of the rocket's ascent, drag tab deployment, and descent. The team is also going to use a standalone GPS sensor and transmitter (with a refresh rate of 10 MHz) located in the nosecone to aid in rocket recovery after the flight. Housed in the main electronics bay will be an accelerometer, standalone altimeter (which will also fire ejection charges), competition altimeter, a 2S LiPo battery, and an Arduino 101. Since critical flight information will need to be relayed to the active drag system separately from the Arduino, the team has furnished a system of spring loaded electrical connections, similar to circuit board test probes, that will pop off during parachute deployment. The spring loaded connections and wiring are fixed to the inside of the main body tube with circular conductive surfaces for them to mate with on the bottom of the electronics bay. This setup means more direct wire routing and more secure connections compared to running cords along the entire shock cord length. Since active drag control is no longer needed after apogee has been reached, splitting the data connection between the controller and drag system is not an issue. Please note that no power will be transmitted via these connections – only data.

Construction Methods

After the final computer models were complete and met expected flight behavior, parts were ordered that would meet design specifications. The entire design process took roughly two months and came close to the maximum allotted budget. The University of Wisconsin – Madison College of Engineering provided the necessary facilities and tools to begin fabrication. Construction of the rocket began with the aft most tube section, as it was the most technically complex and most difficult system to integrate. Centering rings were drilled for wire routing, and eye hooks were placed and epoxied using RocketPoxy.

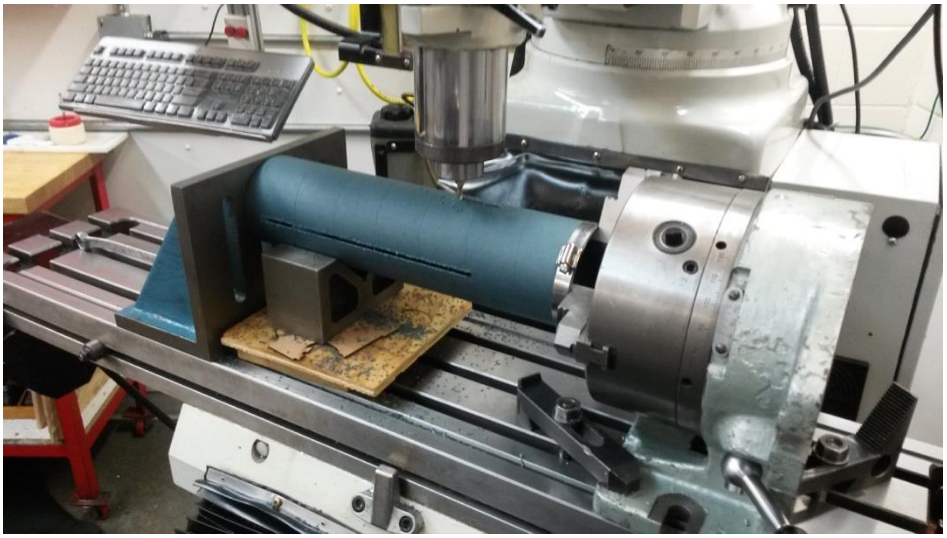

Figure 3 *- Aft rocket body section fin tab and servo mounting hatches being milled.*

The foot-long fin tabs and servo hatches were then milled into the blue tube, filed and sanded down for smoothness, and components were test-fitted. The centering rings were then

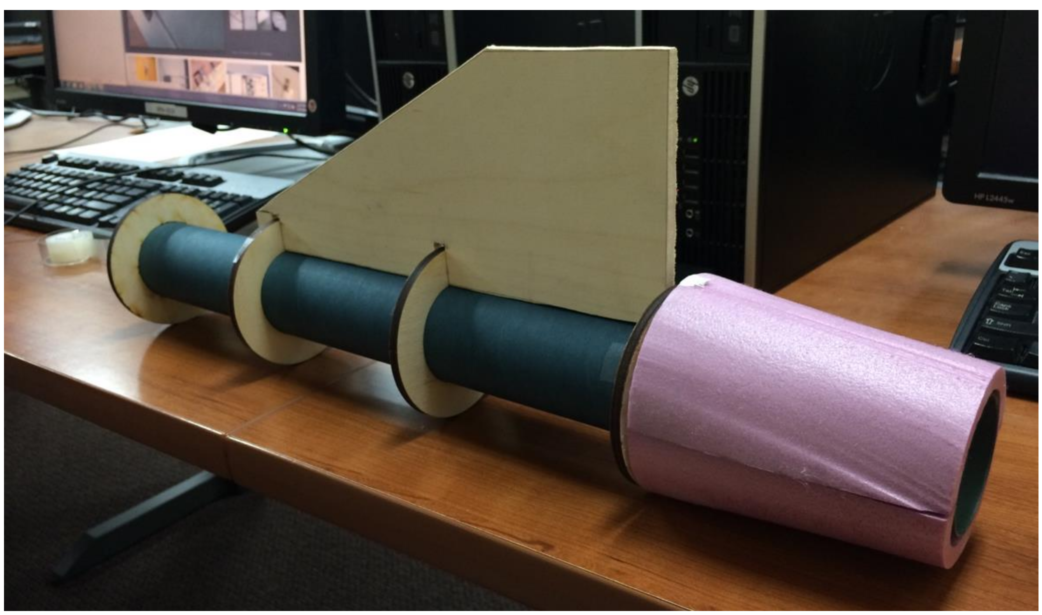

Figure 4 *- Test fit of the engine mounting components. Note – fin and drag tabs shown are NOT the ones that will be flying.*

epoxied in place, the motor mount tube was inserted, and the base of the motor retainer was epoxied into place. Once all of these components were assembled, fabrication began on version one of the drag tabs which were cut via hot wire from polyurethane foam insulation and guided by cardstock forms. The tab edges were smoothed and contours were cut to allow space for the motor retainer, aluminum strengthening tabs, and hinges. The main aluminum support structure for the drag tabs was then inserted and the carbon fiber sheet material was cut to the correct dimensions. Epoxy was applied above and below the carbon fiber to allow it to cure throughout and adhere to the insulation. Holes for one-inch rail buttons were then cut into the forward and aft sections of the tube.

***Figure 5** – Carbon fiber layup for the drag tab shell.*

Unfortunately, the fabrication process is only partially complete. The next step will be to mount the hinges that the drag tabs will be attached to, and secure the drag tabs to the hinges. The mounting brackets for the servo motors, video transmission hardware, and aft battery will then be assembled and epoxied into the rocket. After the brackets are in place, the servos can be screwed into place, the linkage arms and control horns will be connected, and the testing process can begin. In conjunction with the drag system assembly fabrication, the control system housed inside the nose cone and main electronics bay will be assembled. This involves routing data transmission wiring from both the electronics bay to both the nose cone and aft drag system. The wire will be routed through a small, rigid, and hollow tube that runs the entire axial length of the rocket, which will facilitate easy replacement should the need ever arise. The wire routing tube will be epoxied in place, and will help to protect the wiring from the ejection charge blasts. We are using a standard blue tube electronics bay kit for our main bay, which consists of a tube coupler exterior, two inner threaded rods, and a tray that sits between the two rods, used for mounting electronic components. The electronics bay will have bulkheads and eye hooks on both sides, but will only be epoxied closed on one end for quick and easy access. Both the forward and aft ejection charges will be routed through each bulkhead and affixed to them, along with both the forward and aft circular conductive surfaces used in the spring loaded electrical connection system. The aft segment of the nose cone will then be cut off and a bulkhead/eyebolt assembly will replace it to create a makeshift electronics bay which will be used to house our GPS sensor and transmitter. A custom electronics tray, similar to the one shown above , for the nose cone electronics bay may be built, depending on time and budgetary constraints. Our tempered Masonite (hardboard) fins will be laser

Figure 6 *- Example of a potential design for a nose cone electronics bay with GPS integration.*

cut for precision, and then epoxied into the fin holes that were milled into the tube earlier. Fin fillets made from epoxy clay will be applied for extra strength and durability, and the leading edges of each fin will be sanded down to produce a rounded edge. 1500 lb. Kevlar shock cord will then be tied to the eye bolts on the electronics bay, the nose cone, and the top of the motor mount tube, along with two squares of Nomex for parachute protection. Three times the length of the rocket was chosen as the appropriate amount of shock cord based on industry recommendations. The rocket was then painted, rail buttons were installed, and pressure relief holes were drilled in all sections. Lastly, both our drogue parachute and main parachute were tied into eyebolt connections and packed neatly into the rocket.

III. Predicted Performance

Launch and Flight Analysis

Predicted performance analysis was completed mainly through Open Rocket simulation software and validated in Rocksim. All analysis done assumed “standard” weather conditions, with no more than 10% cloud cover and 5 mph wind. As seen in Figure 7, our rocket has a predicted altitude of 2629 m or about 8625 ft. Our mathematical estimates for altitude with the drag system deployed resulted in about 1650 m. Expected max velocity with no drag

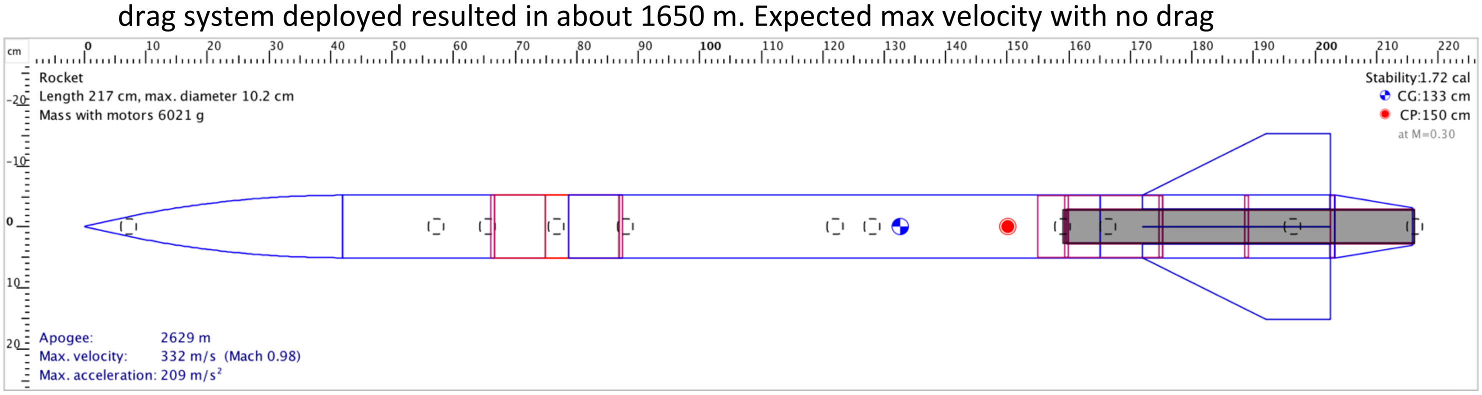

Figure 7 *- Dimensioned model detailing location of center of gravity and center of pressure with motor installed.*

deployment will reach 332 m/s or about Mach 0.98. With drag deployment this decreases to about 270 m/s. Above in figure 8 is an analysis of velocity over the duration of our flight, which

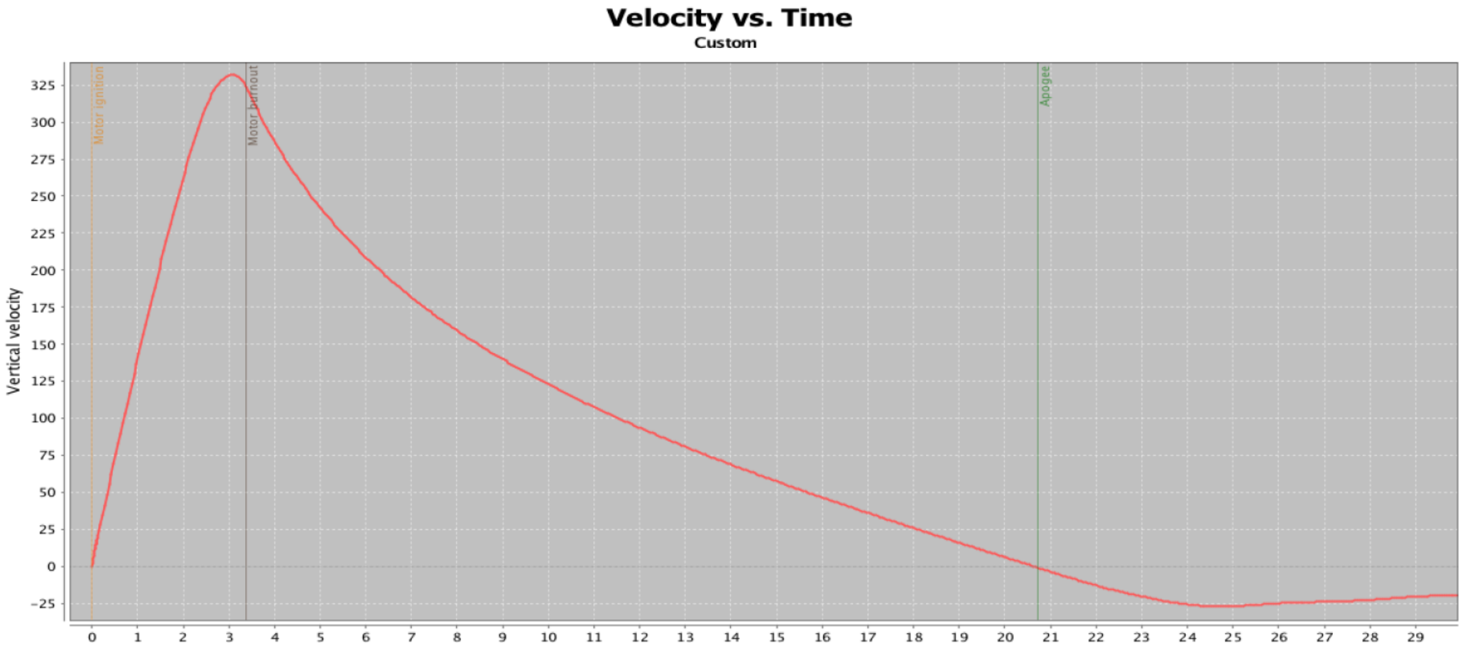

Figure 8 *– Estimated vertical velocity vs. time plot – drag tabs in stowed position.*

will be about 20 seconds. Figure 9 below depicts velocity vs. time with the drag system deployed. Center of gravity and center of pressure were found to be at 133cm and 150 cm from the tip of the nose cone, respectively, which we found to be ideal. Stability was established at

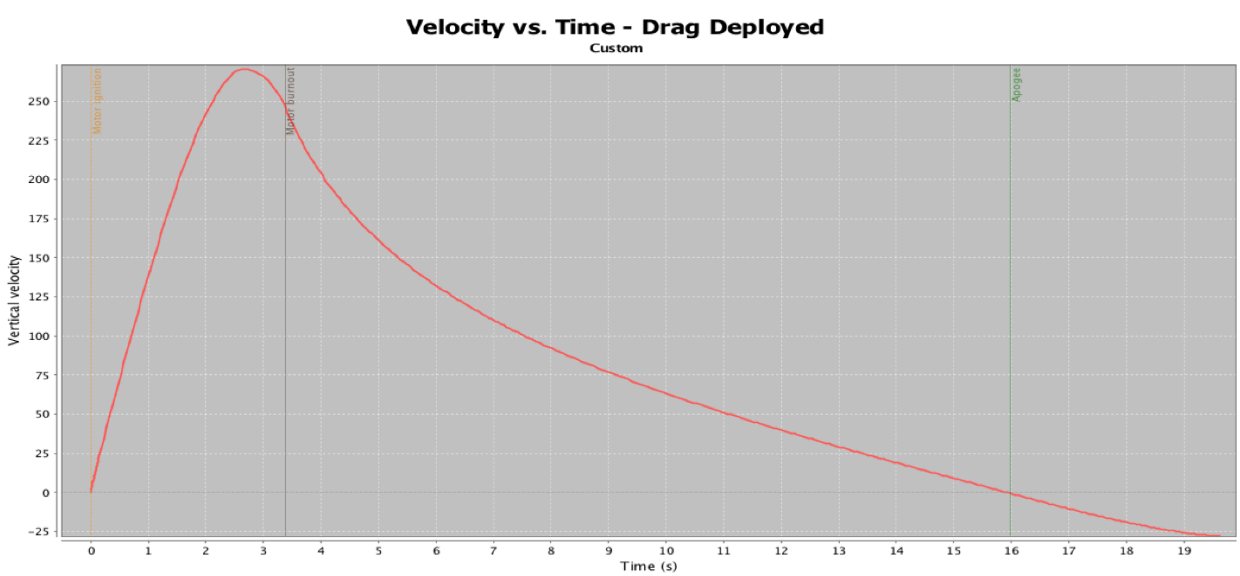

Figure 9 *- Vertical velocity vs. time plot – drag tabs deployed*

1.72 cal, a value which we have accepted and believe is adequate for a stable launch. Drag coefficient estimates were done in Open Rocket and confirmed mathematically, represented for no drag deployment in upcoming figures 10 and 11 as drag coefficient vs. time and vs. velocity, respectively. Figures 12 and 13 characterize these as well for the launch with the drag system deployed.

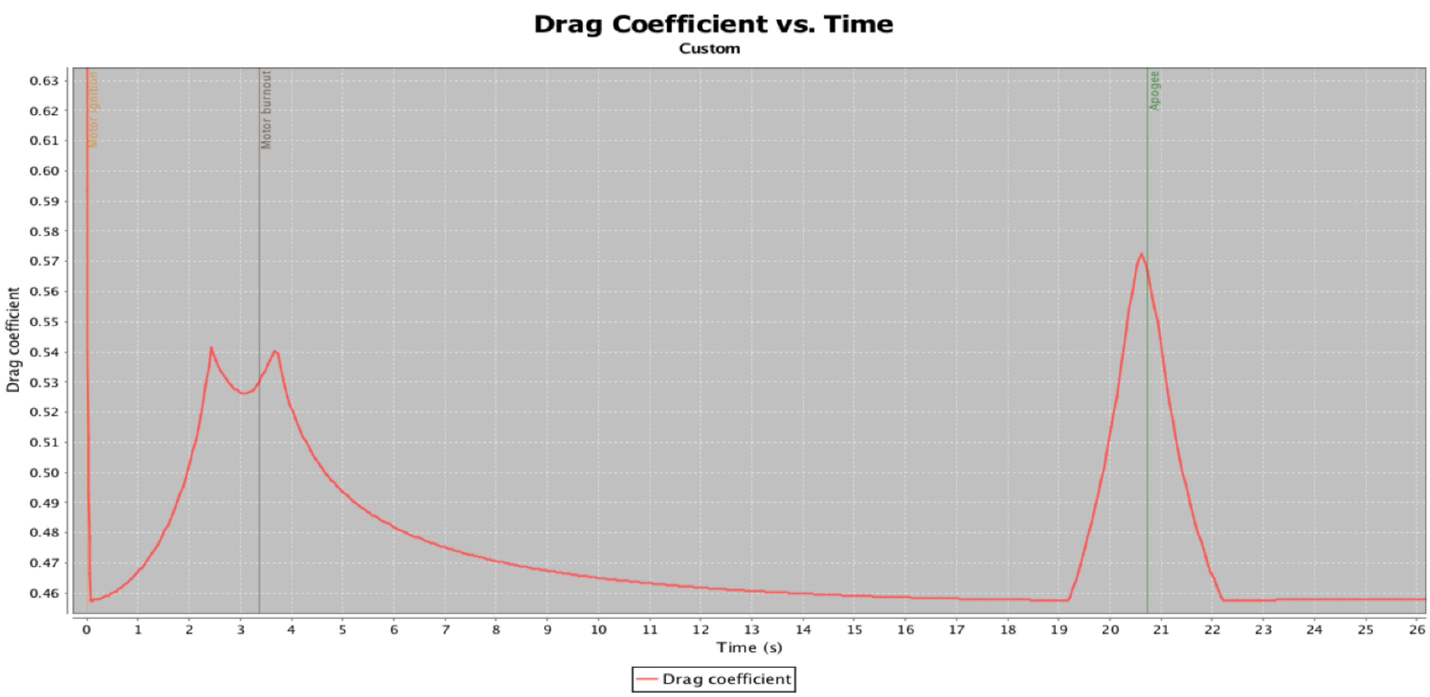

Figure 10 *- Estimated drag coefficient vs. time plot – drag tabs in stowed position.*

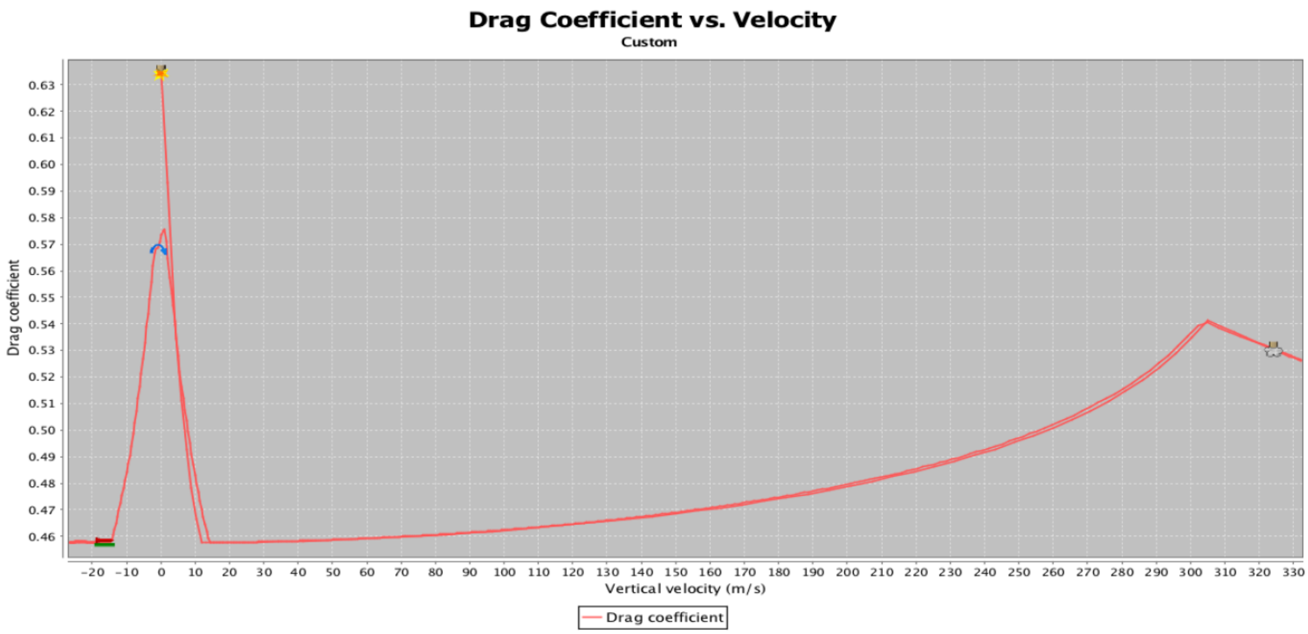

Figure 11 *- Estimated drag coefficient vs. velocity plot – drag tabs in stowed position. Data is plotted in chronological order despite the x-axis designation of vertical velocity.*

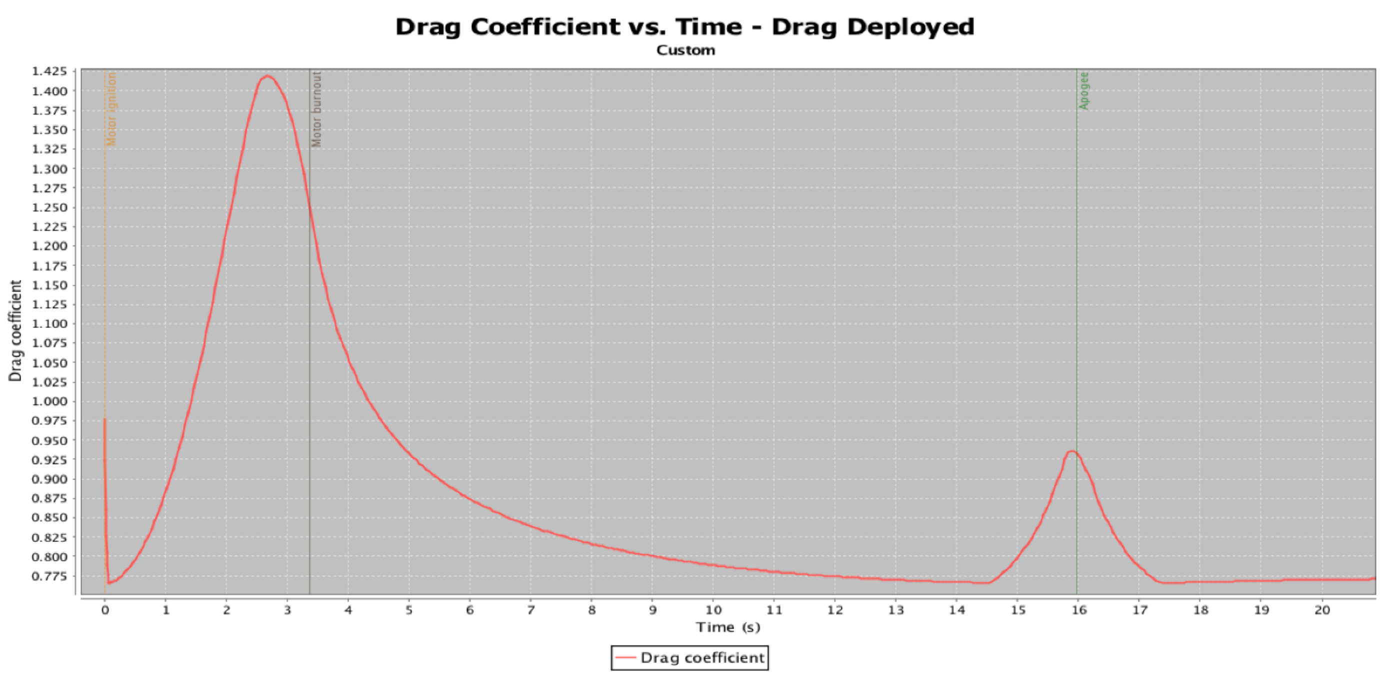

Figure 12 *- Estimated drag coefficient vs. time plot – drag tabs deployed position.*

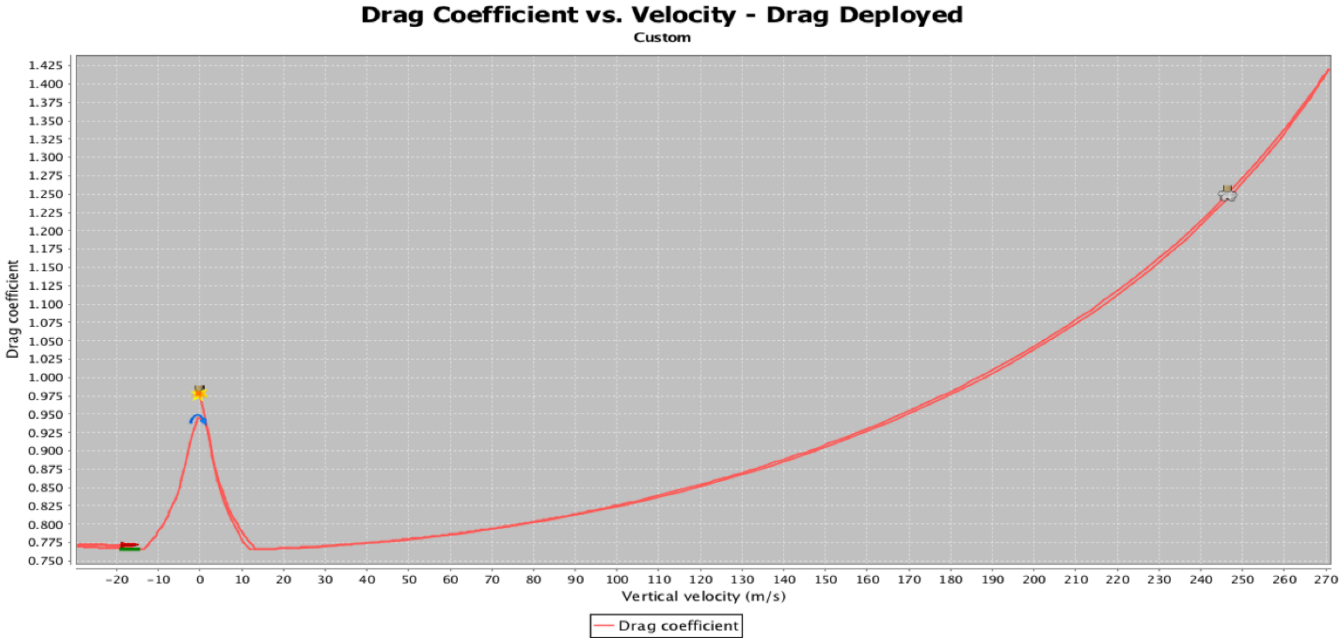

Figure 13 - *Estimated drag coefficient vs. velocity plot – drag tabs deployed. Data is plotted in chronological order despite the x-axis designation of vertical velocity.*

Recovery Analysis

In order to locate our rocket after landing we are using GPS tracking combined with live video telemetry data. The rocket is currently setup for dual deployment, with a drogue chute deployed from the main body tube at apogee and a main parachute deployed at 200 ft. above ground level from the upper body tube. This method insures that the un-capped ejection charge on the motor will deploy a parachute in the event our ejection charges fail to detonate and also allows the video transmission system to be in a ground facing orientation throughout the entire recovery process. After recovery our team will conduct an extensive and thorough analysis of the rocket to assure it is in flyable condition.

IV. Safety

Safety considerations are at the focus of our team's concerns, in order to assure a successful launch and prevent possible injury or damage. At launch our team will be insuring the safety of our rocket by test firing an ejection charge, prepping the motor and installing it into the casing, and fine tuning all of our electronics. Doing this all at launch greatly reduces risk of error and failure potential. Additionally, we will be taking precautions handing all motors and ejection charges by keeping them packaged and stored until launch and careful handling thereafter. After launch we will be carefully approaching and inspecting our downed rocket to insure it is in safe and flyable condition. All other safety aspects, including manufacturing safety, have been previously outlined.

V. Budget

Our rocket and final travel expenses are budgeted to be near $2000. In addition to the $2000 funding provided by the Wisconsin Space Grant Consortium our group was funded for $500 to purchase parts from the UW-Madison College of Engineering. The table below documents all parts ordered and other fees associated with the competition.

Purchase	Cost
4" Blue Tube Coupler x 2	21.90
44" Angel Parachute	69.00
54mm Retainer	31.03
54mm to 98mm Centering Rings x 4	32.40
98mm Blue Tube	38.95
98mm Coupler Bulkhead x 5	21.25
ALTS25 Altimeter	99.00
Arduino 101	30.00
Cesaroni 54mm 6-Grain Case	105.93

Cesaroni K711-18A Motor (after discounts) x3	307.94
Drogue Parachute Protector	8.15
Electronics Bay x 2	69.90
Eyebolts with Washers and Nuts	4.50
FIXIT Epoxy Clay	11.95
GPS Module	80.00
Hi-Speed Servo	32.93
Hotel and Travel Expenses	300.00
Kevlar Shock Cord	46.00
Mini Camera	40.99
Nylon Shear Pins	2.95
Parachute Protector	10.49
PNC-4” Nosecone	21.95
Rail Button	3.07
Registration Fee	400.00
Retract Servo x 2	72.00
RocketPoxy Epoxy	38.25
Servo Wire	14.68
Wireless AV Transmitter	45.80
Total Cost:	$1961.01

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2. Common shapes and related drag coefficients - figure 2 https://en.wikipedia.org/wiki/Drag_coefficient#/media/File:14ilf1l.svg
3. Potential design of a nose cone electronics bay – figure 6 http://www.vernk.com/images/Angelfire/Electronics/AngelfireNoseconeAndGpsRadioPayload_LoRes.jpg