Team Whoosh Generator Flight Readiness Report

2013 Regional Rocket Design Competition

Milwaukee School of Engineering
Milwaukee, Wisconsin

Kirsti Pajunen
Victoria Falcon
James Ihrcke
Eric Johnson
Christopher Larson

12 April 2013

PROBLEM STATEMENT

The objective of the 2013 Regional Rocket Competition is to design, build, and fly a single-stage, high-powered rocket to most accurately reach an apogee of 3000 feet (but must be between 2500 and 3500 feet) with certain design restrictions. The rocket must also be safely recovered in a flyable condition by an electronically deployed parachute system. The rocket must use a Cesaroni I540 motor, have a maximum length of 72 inches, have a maximum body tube diameter of 4 inches, use a Flight Data Recorder provided by the consortium and have a maximum weight of 7.5 pounds (without the motor).[1] This report describes the Team Whoosh Generator rocket design and anticipated performance based on these restrictions and the competition objective.

EXECUTIVE SUMMARY

The objective of the 2013 Regional Rocket Competition is to design, build, and launch a single-stage high powered rocket that must reach a target altitude of 3000 feet and deploy a parachute(s) electronically for a successful recovery. Upon recovery, the rocket must be determined to be in a flyable condition to be considered a successful launch. Team Whoosh Generator has designed and built a rocket that will hopefully perform well in this competition, meeting all requirements.

The rocket design uses a Cesaroni I540 motor and a 4.0-in airframe diameter. The rocket is 55 inches long and weighs approximately 6.2 pounds (without motor). A nose cone and 4 fins were selected for optimum stability of the rocket. An RRC2 mini altimeter (from last year's rocket) and an ALTS25 altimeter were selected to complete parachute ejection requirements. Upon reaching apogee (estimated around 3080 feet) a 24-inch drogue chute will deploy under which the rocket will descend until it reaches an altitude of 600 feet. A second, 44-inch main chute will then deploy such that a slow decent speed (around 16 ft/s) is obtained for landing. A GPS locator is placed in the payload bay to aid in the rocket retrieval. The rocket was built entirely at the Milwaukee School of Engineering (MSOE), and rocket parts were purchased from reputable rocketry vendors.

The rocket is expected to reach apogee around 3080 feet, as predicted by OpenRocket and a MATLAB simulation, with a maximum acceleration around 575 ft/s^2.

Included in this report are design details considered, anticipated performance, and details of the construction process. All references are acknowledged in Appendix C.

[1] Wisconsin Space Grant Consortium 2013 Rocket Competition Handbook

TABLE OF CONTENTS

PROBLEM STATEMENT 2
EXECUTIVE SUMMARY 2
ROCKET DESIGN AND CONSTRUCTION 4
  Assumptions and Limitations 4
  Airframe Design 4
    Body Tubes and Length 4
    Center of Gravity and Center of Pressure 5
    Nose Cone 6
    Fins 6
    Pressure Relief 8
  Parachute Design 9
  Payload Bay Design 9
  Rocket Construction 10
ANTICIPATED PERFORMANCE 13
  Assumptions and Limitations 13
  MATLAB Simulation 14
  OpenRocket 16
  Flight Predictions 17
CONCLUSION 19
APPENDIX A: DETAILED EXPENSE REPORT 20
APPENDIX B: BARROWMAN'S THEORY 21
APPENDIX C: RESOURCES AND ACKNOWLEDGEMENTS 23

ROCKET DESIGN AND CONSTRUCTION

The following sections detail the assumptions and limitations taken into consideration in this year's rocket design, the rocket airframe, parachute, and payload bay design, and the construction of the rocket. All rocket parts were purchased from reputable high-rocketry vendors, and the rocket was designed thoroughly and carefully with a knowledge of engineering principles. It was also simulated using two methods. Therefore, the team is confident that the rocket design has provided for a safe rocket to launch.

Assumptions and Limitations

There were several assumptions and limitations taken into consideration in the design of this rocket. Seven assumptions were made, based on Barrowman's Theory, which is described in depth in Appendix B. Such assumptions include that the fins are thin flat plates, and that the rocket is thin compared to its length. Also, the rocket needed to follow the competition restrictions, outlined in the problem statement of this report.

Realistically, the rocket will need to withstand certain conditions that the rocket design itself will not be able to take into consideration. For example, the rocket will leave the launch pad at an angle deviated from the vertical, whereas the rocket simulation and design assumes that the rocket leaves it perfectly vertically. Also, certain environmental conditions, such as wind speed and air pressure constantly change and could not be correctly accounted for in the rocket design, so a constant air pressure and wind speed are assumed.

Airframe Design

It was decided to build the rocket from the selection of individual components and not the use of a kit. This seemed most logical because of the many design restrictions (weight, length, diameter, and motor restrictions) and the necessity to reach an altitude between 2500 and 3500 feet. The following sections describe how the airframe of the rocket was designed using these parameters.

Body Tubes and Length

Several of the team's members attended the Wisconsin Space Grant Consortium (WSGC) Altimeter Conference on December 1, 2012. At this conference, the team received a constructed payload bay, built to fit a 4.0-inch outer diameter body tube. Since it was not desired to build an alternate diameter payload bay, it was decided to design a rocket with a 4.0-inch outer diameter body tube to fit the payload bay received at the altimeter conference. With this parameter set, fewer independent variables remained, making the subsequent rocket design easier.

The body tubes could be selected from several different kinds of materials, including cardboard, fiberglass, and PVC. Cardboard was selected as the body tube material for the rocket because of its simplicity, strength, price, and ease of cutting and drilling. Cardboard has proven to work well from previous years' rockets.

The body tube lengths were heavily dependent on the design restriction of a maximum total rocket length of 72 inches. OpenRocket, a free rocket design software program, was the primary software used to design much of the rocket. OpenRocket was used to calculate optimum body tube lengths. It was found that the lower body tube (to house the motor mount and drogue parachute) would have a length of 25 inches. The upper body tube (to house the main parachute) would have a length of 19 inches. These lengths help to bring the rocket to an apogee of approximately 3000 feet, with favorable centers of gravity and pressure. The total length of the rocket is 55 inches, which is below the 72 inch maximum restriction.

Center of Gravity and Center of Pressure

The relationship between the center of pressure (CP) and center of gravity (CG) is one of the most important relationships in high-powered rocketry. The center of pressure is defined as the point at which aerodynamic forces on the rocket are centered. The center of gravity is the location at which the whole weight of the rocket can be considered to act as a single force. The ratio between the locations of relative to the rocket diameter can be used to predict the stability of the rocket during flight. Generally, the center of pressure must be at least one (but not more than two) body tube diameters in front of the center of pressure, and both should be in the bottom half of the rocket.

The center of pressure and center of gravity was determined for this design using the OpenRocket software. The results were then compared against the results using Barrowman's Theory, and the two agreed acceptably.

The following assumptions were made during the derivation of Barrowman's theory for predicting the center of pressure:

1) The flow over the rocket is potential flow.
2) The point of the nose is sharp.
3) Fins are thin flat plates.
4) The angle of attack is near zero.
5) The flow is steady and subsonic.
6) The rocket is a rigid body.
7) The rocket is axially symmetric.[2]

The rocket design presented in this paper did violate some of these assumptions, particularly assumptions 2, 6, and 7. However, the theory was still applied with the understanding that minor uncertainties will be present as a result. Details into the equations used can be found in Appendix B.

[2] Culp, Randy. "Barrowman Equations." *The Space Web*. N.p., 25 Feb. 2000. Web. <http://my.execpc.com/~culp/rockets/Barrowman.html>.

Table 1 shows the locations of the CP and CG and the caliber stability at ignition and at burnout according to the OpenRocket simulation.

Table 1: Locations of CP and CG (In Inches from Nose Cone Tip)			
	CP	**CG**	**Stability (Caliber)**
Ignition	38.5	32.6	1.47
Motor Burnout	38.5	31.2	1.83

From this analysis, it can be concluded that the rocket will be stable during the entire ascent portion of the flight, and winds probably would not affect the flight very much because the stability is within one to two calibers for the entire flight.

Nose Cone

The nose cone chosen was a durable plastic 4-inch base diameter Madcow Rocketry cone. It is a short, ogive cone, 9 inches in length. This was chosen because this short, ogive cone had a low coefficient of drag combined with other parameters, allowing the rocket to achieve a desirable apogee. An eyebolt was attached to the bottom of the cone to allow for a stronger point of attachment for the recovery harness.

Fins

The fins are the main component that determines the location for the center of pressure on a rocket, and, therefore, the stability of the rocket. The design of the fins was determined by placing different shapes and sizes of fins in OpenRocket until a stable ratio between the center of gravity and center of pressure was obtained. Any fins larger than the ones selected brought the stability caliber too high (above 2). It was determined to use 4 fins spaced evenly around the rocket because 4 fins have higher drag than 3 fins.

The fins chosen were A-05 G-10 fiberglass fins from Public Missiles, shown in Figure 1. The fins were attached to the rocket using through-the-wall construction with epoxy fillets on each contact surface.

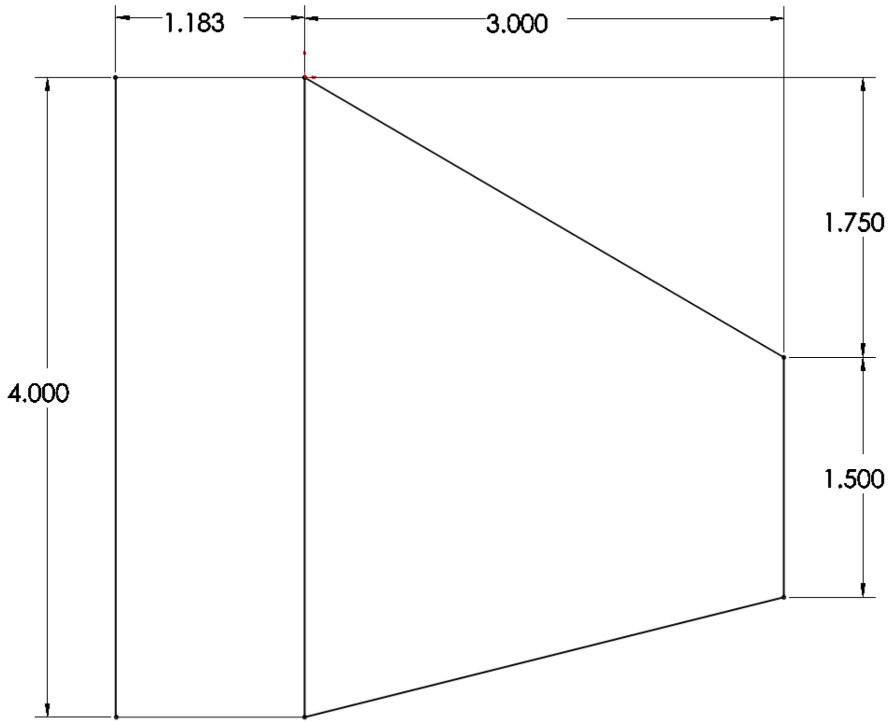


Figure 1: Fin design with dimensions

Figure 2: Assembled fins

Pressure Relief

The team decided to use two altimeters for parachute ejection, for added security in case one did not work. The two barometric altimeters used to deploy the drogue and main parachutes require static pressure port holes. The static port holes are required for pressure equalization between the air inside the bay and the outside air during flight. The parachutes could be deployed too early or too late if the static port holes are not the correct size. The general rule for port hole sizing is to use a ¼-inch diameter hole (or equivalent area if multiple holes are used) for every 100 cubic inches of volume in the bay. It is also recommended to use at least three holes spaced evenly around the body tube to help negate the effects of crosswinds. The RRC2 Mini user manual recommends the use of the following equations for port hole sizing.[3]

The volume of the bay:

$$Volume(in^3) = Bay\ Radius(in)\ x\ Bay\ Radius(in)\ x\ Bay\ Length(in)\ x\ \pi \quad (1)$$

The diameter of a single port hole:

$$Single\ Port\ Hole\ Diameter = 2\sqrt{\frac{Volume}{6397.71}} \quad (2)$$

The area of a single port hole:

$$Single\ Vent\ Area = \left(\frac{Single\ Vent\ Diameter}{2}\right)^2 x\,\pi \quad (3)$$

The diameter of multiple port holes:

$$Multiple\ Port\ Hole\ Diameter = 2\sqrt{\frac{Single\ Vent\ Area}{(\#\,of\ \ Holes)(\pi)}} \quad (4)$$

The diameter of the payload bay is 3.9 inches and the length of the bay is 8 inches. This yields a volume of 95.57 cubic inches. The diameter of a single port hole is equal to 0.24 inches with an area of 0.047 square inches. Three holes were used on the payload bay each with a diameter of 0.141 inches spaced 120 degrees apart.

One-quarter inch holes were also drilled into the upper and lower body sections of the rocket. During the rocket's ascent the atmospheric pressure surrounding the rocket decreases. If these holes are not present the higher pressure inside the rocket could cause the rocket to separate and deploy its parachutes early.

[3] "RRC2 User Manual." *Missile Works*. N.p., 2006. Web. <http://www.missileworks.com/user_downloads/RRC2X_RevC.pdf>.

Parachute Design

The rocket will use a dual deployment system. This means the rocket will deploy a small drogue parachute at apogee and then a main parachute at a lower altitude to minimize the drift of the rocket, allowing for easier retrieval of the rocket. We will be using a 24-inch drogue chute that will deploy at apogee and a 44-inch main SkyAngle Classic parachute that will deploy at 600 feet. The rocket will have a descent rate of 16 feet per second once the main cute has opened. As stated, two altimeters will be used for redundancy to ensure the parachutes deploy. The parachutes are shown in Figure 3.

Figure 3: Drogue and main parachutes

Payload Bay Design

The payload bay was made from a Giant Leap Rocketry avionics bay kit provided to the team at the WSGC Altimeter Conference. It is 8 inches long and has an outer diameter of 3.9 inches allowing it to fit perfectly into a 4 inch diameter airframe. A small piece of airframe, measuring 1.5 inches in length, was cut from a body tube and epoxied in the center of the payload bay to turn the bay into a coupler. Two barometric altimeters were used in the payload bay a RRC2 mini used in previous years and an ALTS25 given to the team at the Altimeter Conference. These altimeters will be used to deploy the drogue and main parachutes as well as record the altitude of the rocket. The payload bay also holds the Raven III (WSGC flight data recorder) along with a GPS. The GPS will be very useful in retrieving the rocket. Two key switches were placed 180 degrees apart on the payload bay to allow easy arming of devices on the launch pad. One key switch is for turning on the WSGC flight data recorder and the other is for arming both altimeters. Terminal blocks were placed at either end of the bay to allow easier attachment of black powder charges on launch day. The assembled payload bay is shown in Figure 4.

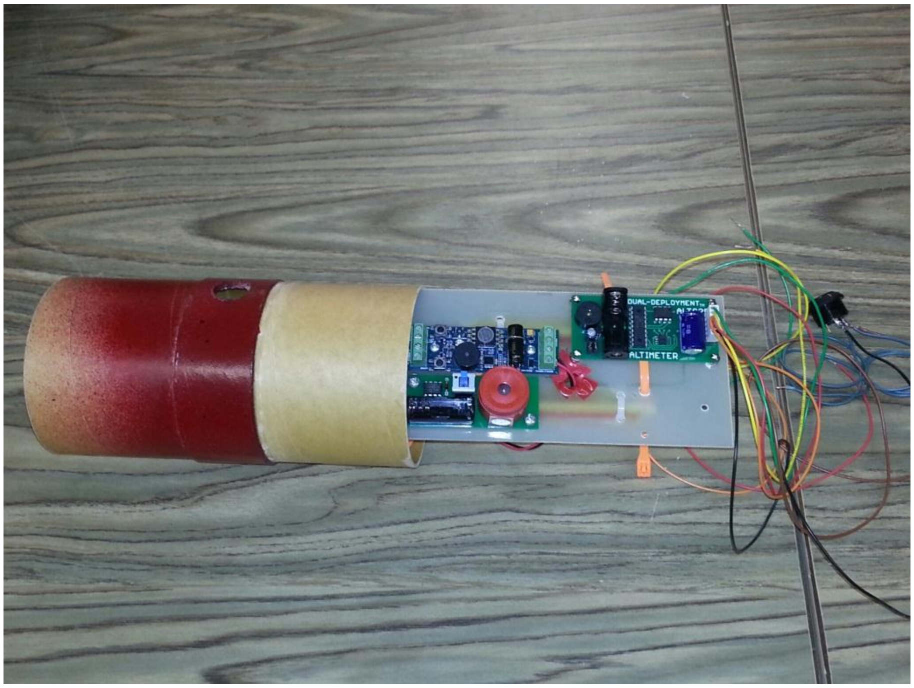


Figure 4: Payload bay assembly

Rocket Construction

For the 2013 rocket competition the aim was to provide each competing team with the same motor and for the teams to design a rocket to reach an altitude as close to 3000 feet as possible. Some of the design constraints include the motor type (Cesaroni I540), a body tube diameter of no more than 4 inches, an overall rocket length of 72 inches, and a weight restriction (not including the motor) of 7.5 pounds. Using OpenRocket, the design was determined and calculations proved the performance of the rocket to meet the specifications of the competition. Taking the results from OpenRocket, the parts and supplies were then purchased and the construction of the rocket began.

It had been determined to utilize cardboard as the team members had worked with this material in previous years. This material allowed for the ability to cut tube lengths, fin slots, holes for key switches and to apply epoxy and paint easily. The team also knew the performance that it would provide. Two body tubes were purchased and then cut to the specified lengths determined in OpenRocket. It was determined that a razor blade provided a smother, straighter, and more accurate cut rather than the band saw on the first attempt in the MSOE machine shop. Once the two sections of body tubes and the coupler were cut to 25, 20 and 1.5-inch pieces, the sizes were confirmed and each section was slid together to get an idea for the size of the rocket. Once all measurements were confirmed the 1.5-inch piece of body tube was glued in the middle of the coupler using a two part two-ton epoxy. The coupler houses the altimeter bay with all altimeters, data recorders, batteries, locating devices, and electronic key switches to turn all these devices on before the launch of the rocket. The motor side and nose cone side of the body tubes were then placed onto the coupler to confirm all fits remained the same. Due to the way the epoxy dried, some of it had to be sanded down so that they two body tubes would create a tighter seal with the coupler.

In the design of the rocket it had been determined that 4 fins sized as shown in Figure 1 would then be placed evenly around the body tube at 90 degree intervals and with no angle applied. The locations of the fins were marked on the body tube with pencil and then the slots 4-inch tall and 0.062-inch wide were cut using a razor blade to allow for a snug fit. With each of the 4 fin slots cut, the motor mount and centering ring were placed into the end of the body tube and epoxied with the same two part two-ton epoxy used in the coupler. Once the motor mount was dry and in place, each fin was placed into position and epoxied. Since the team is using four fins, it was very important to have the angles of each fin be as close to 90 degrees as possible. Each fin was epoxied one at a time and completely dry before the next one was set into place. Once all four fins were epoxied, the last centering ring was epoxied and the motor retainer was welded to the motor tube. This allows for a strong and secure bond under the strong forces and heat that the motor will produce during launch.

Figure 5: Measuring fin slot locations

Figure 6: Assembling fins

Having all parts now cut and the essential pieces epoxied, the rocket was then assembled bringing all pieces together to form the completed rocket. The altimeter bay had been built during the altimeter conference that was held earlier in the year. With all parts placed together, the team decided to paint the rocket with a black fading into red paint theme. Additionally, in white paint the name Whoosh was lettered onto the top body tube. This was done in the MSOE paint booth located in the student center campus building. With the rocket painted, the switches were placed into the coupler, the shock cord, drogue chute, and parachute were then attached to the eye bolt on the nose cone and the U-bolt placed on the top centering ring of the motor mount. With all the chutes, cords, altimeters, data recorders, and locating devices placed in the rocket assembly, the construction of the team Whoosh Generator rocket was completed and is shown in Figure 7.

Figure 7: Final rocket assembly

ANTICIPATED PERFORMANCE

The anticipated performance of the rocket was simulated using two programs: MATLAB and OpenRocket. The results of both simulations were compared to estimate the performance of the rocket on launch day. The following sections detail these simulations.

Assumptions and Limitations

The motor thrust curve for the Cesaroni I540 motor used for the competition is shown below in Figure 8, made available from ThrustCurve.org.[4]

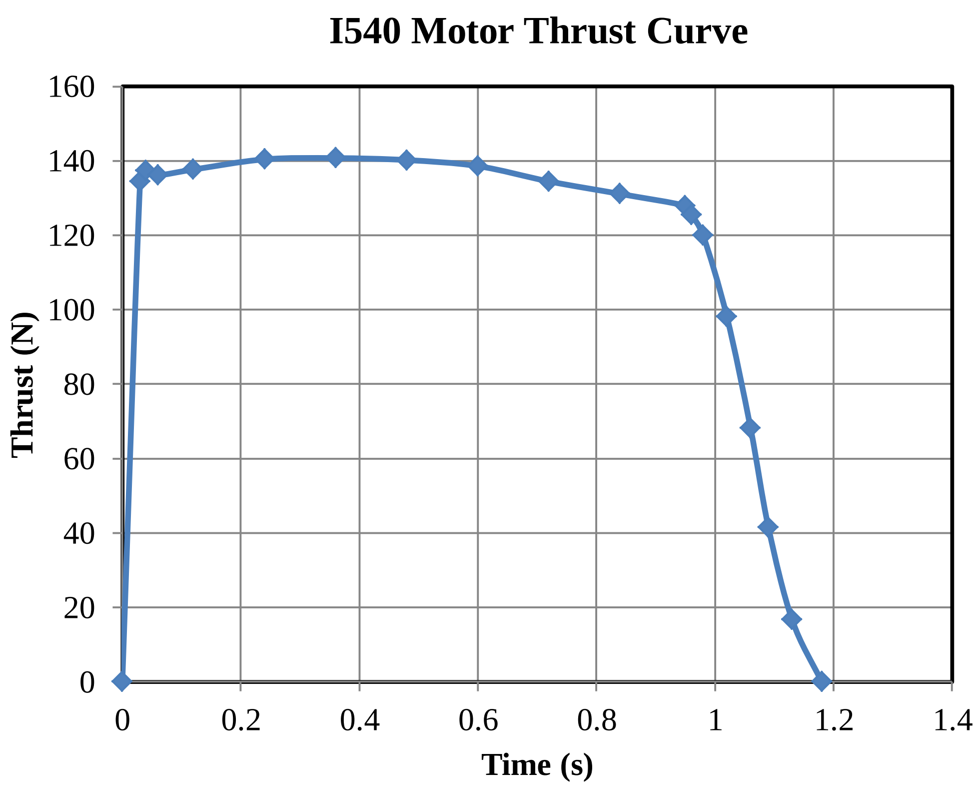


Figure 8: Motor thrust curve

From the thrust curve, the weight of the propellant at any given time can be approximated as being equal to the area under unburned portion of the thrust time curve relative to the total area, which is then multiplied by the initial propellant mass. The assumption that this thrust curve is accurate was used for the simulations.

[4] "Cesaroni I540." *Thrust Curve*. N.p., 2009. Web. <http://www.thrustcurve.org/motorsearch.jsp> .

The primary assumption for the simulations was that the rocket would be launched vertically and would follow a vertical flight path. Standard temperature and pressure were also assumed to find air density, which was also assumed to be constant throughout the flight. When approximating the performance of the rocket, the only forces acting on the rocket are aerodynamic drag, mass change of the rocket, and gravitational forces. Other forces, such as from wind, are not taken into account (for the OpenRocket simulation, wind was taken into account). For both simulations, the body tube diameter was assumed to be 4.0 inches, and the motor was an I540 motor.

There are, of course, factors that could not be taken into account in these simulations, such as stability, rotation, and deviation from vertical flight. Because of this, the estimates obtained are very likely overestimates of the likely flight performance. To account for this, a buffer of around 100 feet was added to the desired apogee altitude in OpenRocket.

MATLAB Simulation

MATLAB was used to estimate the desired weight of the rocket to reach an apogee closest to 3000 feet. A MATLAB program written and revised through previous year's competitions was used to find this. Figure 9 shows the outcome of this simulation.

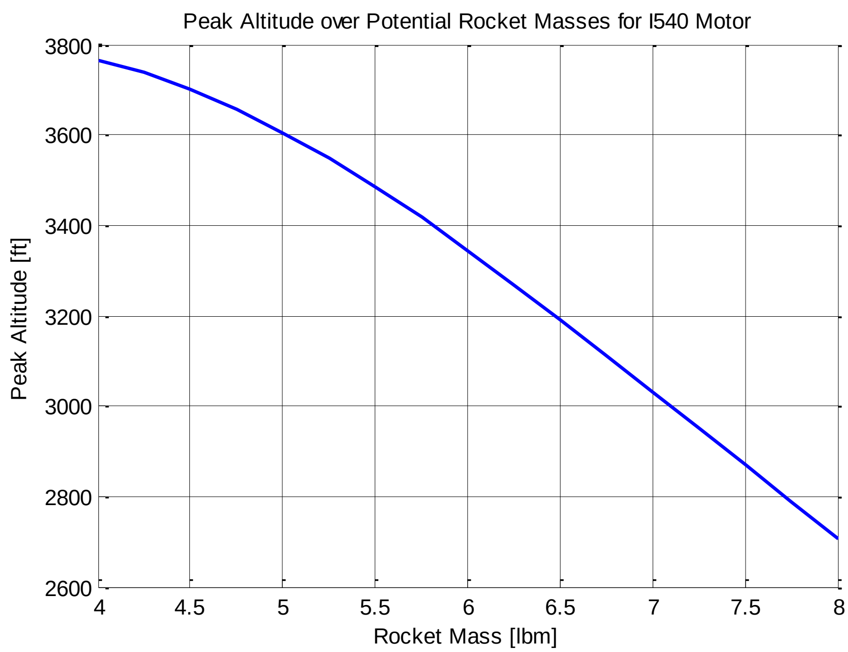


Figure 9: Simulation outcome of peak altitude compared to potential mass

As seen from the Figure 9, to reach a simulated altitude of around 3100 feet, the rocket mass (total without propellant) must be around 6.8 pounds. This is useful for finalizing the weight on launch day, as well as cross-checking the results from the OpenRocket and MATLAB flight simulations. As will be seen later, both the OpenRocket and MATLAB simulations show that a rocket mass around 6.8 pounds produces favorable flight outcomes (including apogee near 3000 feet).

A MATLAB simulation for the rocket flight performance was then developed using numerical methods. The main function used is from previous years of rocket competitions, but the simulation program itself was developed by the Team Lead this year. The function developed was designed to perform the following:

1) Load thrust data obtained from ThrustCurve.org.
2) Interpolate thrust curve for more discrete steps.
3) Calculate change in mass resulting from burnt propellant.
4) Calculate velocity from the combined impulse from drag, gravity, and thrust.
5) Calculate altitude and acceleration from velocity.

The rocket simulation function operates in the following way.
The velocity of the rocket was determined from the previous momentum plus the impulse. This relationship is shown in Eq. 5:

$$m_i v_i + F_i \Delta t = m_{i+1} v_{i+1} \tag{5}$$

Where F_i is the net force acting on the rocket and Δt is the time step between calculations. The net force acting on the rocket during accent is expressed in Eq. 6:

$$\begin{aligned} F_{net} &= F_{grav} + F_{drag} + F_{thrust} \\ &= m_i g + \frac{1}{2}\rho v_i^2 C_d A + T_i \end{aligned} \tag{6}$$

Where:

ρ is the density of air

C_d is the coefficient of drag

A is the frontal cross sectional area of the rocket

T_i is force from the motor

Substituting Eq. 6 into Eq. 5 and solving for v_{i+1} yields:

$$v_{i+1} = \frac{1}{m_{i+1}}\left[v_i m_i + \frac{1}{\Delta t}\left(T_i - m_i g - k v_i^2 \right) \right] \tag{7}$$

Where:

$$k = \frac{1}{2} C_d A$$

Acceleration was calculated using Newton's second law which is expressed in Eq. 8:

$$a_i = \frac{F_i}{m_i} \tag{8}$$

The trapezoidal method for approximating the area under a curve was used to calculate the altitude of the rocket during the flight.

The simulation calculated the altitude, velocity, and acceleration versus time for the flight until apogee, based on the assumptions as stated in the Assumptions and Limitations section. The drag coefficient for the MATLAB simulation was found in OpenRocket. The drag coefficient used was 0.43. These versus time were then plotted against the OpenRocket simulation results. These plots are shown in the Flight Predictions section.

OpenRocket

OpenRocket is a free, open source, software similar to RockSim. It is capable of calculating acceleration, velocity, and position data while accounting for variables including elevation, wind speed, and the effects of individual components on performance such as surface roughness and leading edge fin radii on drag and stability.

Also included in the program is the ability to construct full scale schematics of the rocket design. From this schematic the CP, CG, stability, and apogee can also be approximated.

OpenRocket was the main source used in designing the rocket. The rocket was modeled entirely in the program, providing a way to design and calculate proper lengths of body tubes, optimal fin and nosecone designs, rocket weights, acceptable locations of the CP and CG, and drag coefficients. This was an extremely powerful tool, and it has already been mentioned in several previous sections.

From the finished rocket model, the flight predictions were simulated (altitude, velocity, and acceleration). For the OpenRocket simulations, different wind speeds were taken into account. Wind speeds varying from 0 mph to 20 mph produced an apogee altitude difference of only 52 feet. From this, it can be concluded that an assumption of 0 mph winds is a suitable assumption to be made in these simulations, including in the MATLAB simulation. At 0 mph winds, the predicted apogee is 3083 feet, which is acceptable for the 100 foot buffer mentioned previously.

Figure 10 shows the full assembly of the rocket, as modeled in OpenRocket, with a side cross-section view and a 3D component view.

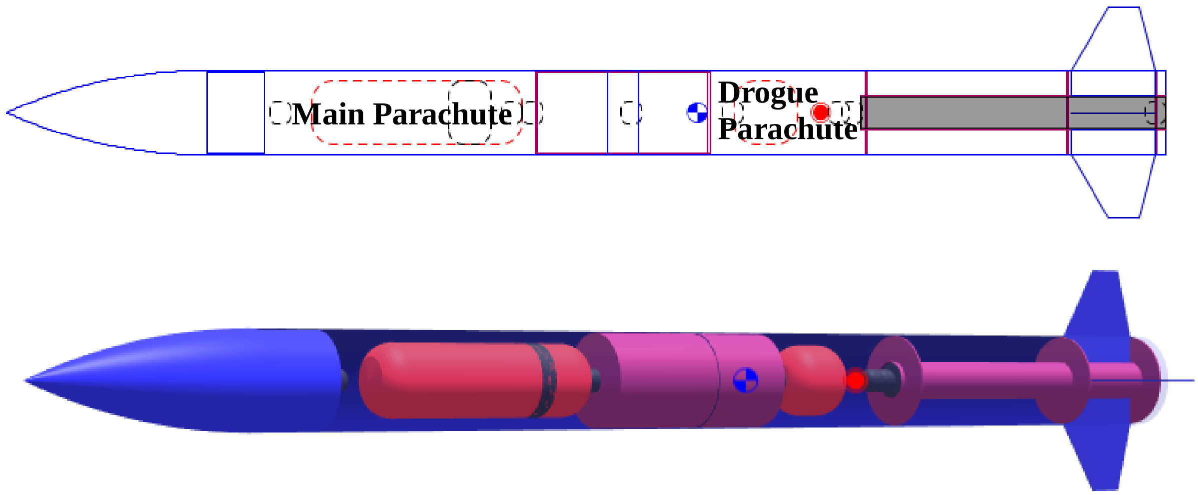


Figure 10: Fully rocket assembly with a side cross-sectional view and three dimensional model

Flight Predictions

Altitude, velocity, and acceleration predictions to apogee from MATLAB and OpenRocket are compared in Figure 11. Time to apogee is approximately 13 seconds. The peak altitude, acceleration, and velocity for both simulations are shown in Table 2.

Table 2: Maximum Flight Predictions		
	OpenRocket	**MATLAB**
Altitude (ft)	3082	3011
Velocity (ft/s)	566	562
Acceleration(ft/s^2)	574	575

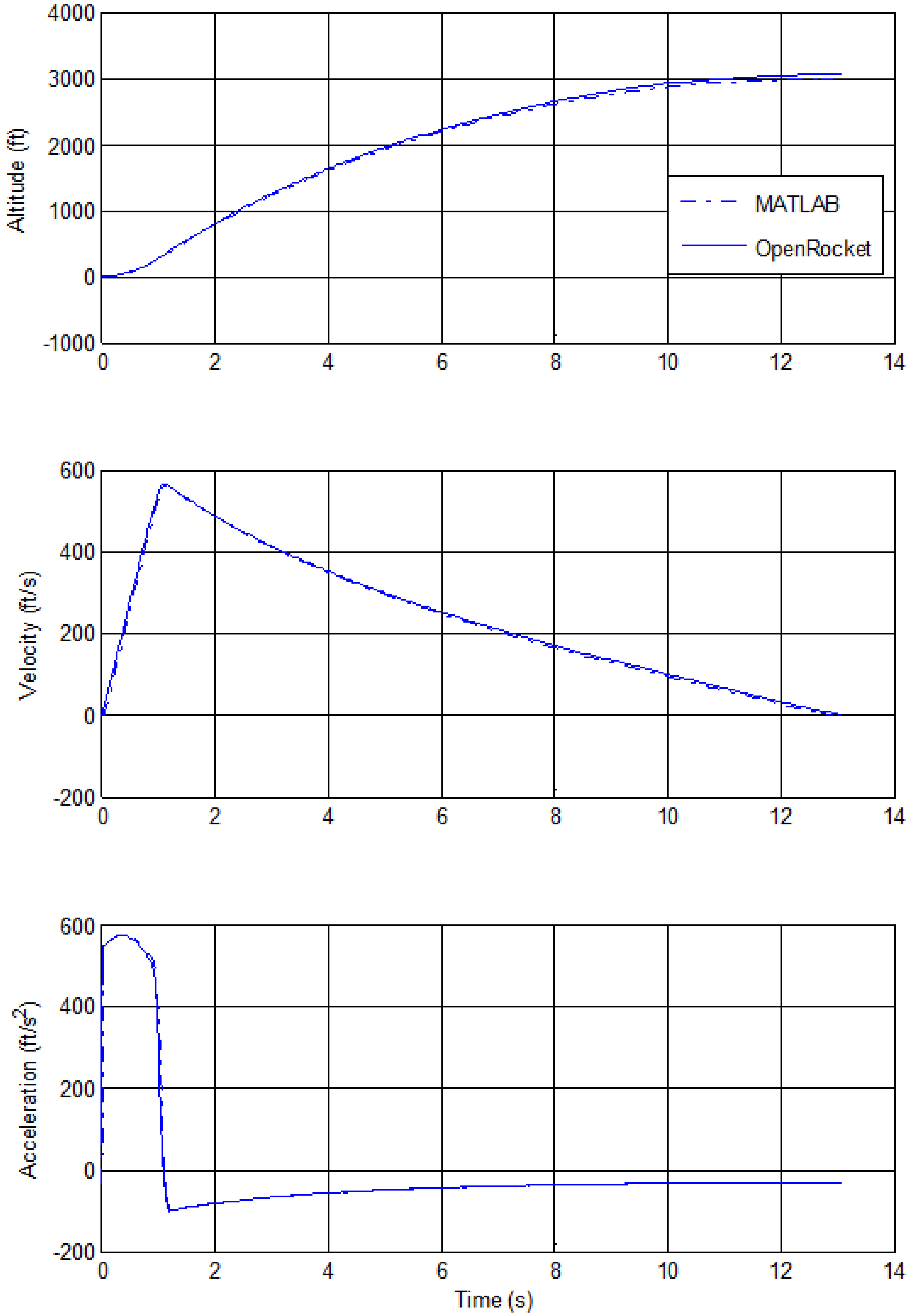


Figure 11: MATLAB and OpenRocket predictions of altitude, velocity and acceleration

CONCLUSION

This design will provide a safe and effective flight in which the goals set by the competition are achieved. The rocket is expected to climb to an altitude of approximately 3000 ft where it will then descent by drogue chute to approximately 600-ft. At this altitude, the main parachute will deploy for a safe landing. Complying with the competition restrictions, the rocket will be 55 inches long, weigh approximately 6.8 pounds (without propellant), have a 4-inch body tube diameter, and use a Cesaroni I540 motor.

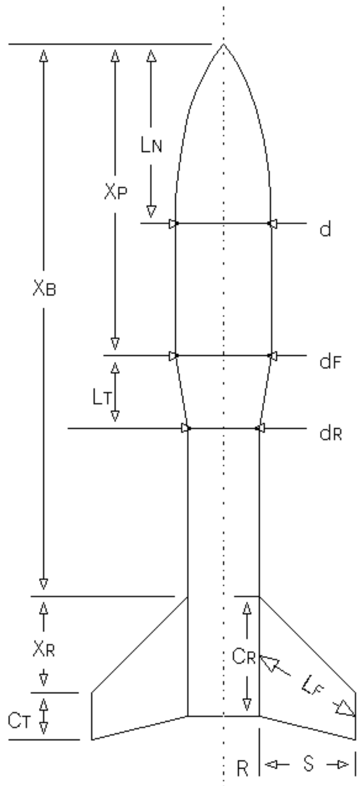
It is understood that real conditions do not match the simulated conditions used in the design of this rocket. The actual rocket performance will heavily depend on the conditions on launch day, including environmental conditions and launch rail angle. Using engineering sense, modifications to an ideal design were made to account for these conditions, and will hopefully bring the real results to closely match the desired outcome (including reaching an apogee as close as possible to 3000 feet).

APPENDIX A: DETAILED EXPENSE REPORT

This budget does not include the cost of travel.

Item	**Cost ($)**
Epoxy and Misc. Hardware & Expenses	157.77
4.00" x 9.5" Ogive Nosecone	19.95
3.9" Body Tube 2x	20.90
38 mm Body Tube	6.25
Centering Rings 2x	16.20
Motor Retainer	31.03
Parachute Protectors 2x	19.98
Terminal Blocks 2x	6.50
1500# Shock Cord 60ft	55.20
Transolve BeepX Locator	36.66
Prism Fins 4x	26.78
Key Switches 2x	12.00
Remove Before Flight Tags 2x	12.00
J-B Weld 8280 Steel Epoxy 10 oz.	13.74
4000-3/34 Dremel Rotary Tool Kit	88.00
Plano Molding Toolbox	29.84
Garmin GTU 10 GPS Tracking Unit	129.99
Educational Outreach Supplies	56.63
Team Professional Uniform Polos	158.24
ALTS25 Altimeter	99.00
Total	**996.66**

APPENDIX B: BARROWMAN'S THEORY



The Barrowman equations permit you to determine the stability of your rocket by finding the location of the center of pressure (CP). The value computed is the distance from the tip of the rocket's nose to the CP. In order for your rocket to be stable, you would like the CP to be aft of the center of gravity (CG).

The computation of CP isn't as hard as it looks at first. Check out the spreadsheet example at the bottom of this page.
You can find the CG of your rocket by simply finding the balance point after loading recovery system and motor. (Literally - balance the rocket on your hand - or finger - and that's the CG). You can then measure from the tip of the rocket's nose to the CG. The calculated CP distance should be greater than the measured CG distance by one rocket diameter. This is called "one caliber stability".

Terms in the equations are defined below (and in the diagram):

L_N = length of nose
d = diameter at base of nose
d_F = diameter at front of transition
d_R = diameter at rear of transition
L_T = length of transition
X_P = distance from tip of nose to front of transition
C_R = fin root chord
C_T = fin tip chord
S = fin semispan
L_F = length of fin mid-chord line
R = radius of body at aft end
X_R = distance between fin root leading edge and fin tip leading edge parallel to body
X_B = distance from nose tip to fin root chord leading edge
N = number of fins

Nose Cone Terms: $(C_N)_N = 2$

For Cone: $X_N = 0.666L_N$
For Ogive: $X_N = 0.466L_N$

Conical Transition Terms

$$\left(C_N\right)_T = 2\left[\left(\frac{d_r}{d}\right)^2 - \left(\frac{d_f}{d}\right)^2\right]$$

$$X_T = X_P + \frac{L_T}{3}\left[1 + \frac{1 - \frac{d_F}{d_R}}{1 - \left(\frac{d_F}{d_R}\right)^2}\right]$$

Fin Terms

$$\left(C_N\right)_F = \left[1 + \frac{R}{S+R}\right]\left[\frac{4N\left(\pi\frac{S}{d}\right)^2}{1 + \sqrt{1 + \left(\frac{2L_f}{C_R + C_T}\right)^2}}\right]$$

$$X_F = X_B + \frac{X_R}{3}\frac{\left(C_R + 2C_T\right)}{\left(C_R + C_T\right)} + \frac{1}{6}\left[\left(C_R + C_T\right) - \frac{C_R C_T}{\left(C_R + C_T\right)}\right]$$

Finding the Center of Pressure

Sum up coefficients: $\left(C_N\right)_R = \left(C_N\right)_N + \left(C_N\right)_T + \left(C_N\right)_F$ $(C_N)_R = (C_N)_N + (C_N)_T + (C_N)_F$

Find CP Distance from Nose Tip:

$$\bar{X} = \frac{\left(C_N\right)_N X_N + \left(C_N\right)_T X_T + \left(C_N\right)_F X_F}{\left(C_N\right)_R}$$

(http://my.execpc.com/~culp/rockets/Barrowman.html)

APPENDIX C: RESOURCES AND ACKNOWLEDGEMENTS

Black Powder Charge Calculator

http://www.info-central.org/?article=303

http://archive.rocketreviews.com/tool_black_powder.shtml

Model Rocket Parachute Descent Rate Calculator

http://www.onlinetesting.net/cgi-bin/descent3.3.cgi

http://www.info-central.org/?article=271

http://www.rocketreviews.com/descent-rate-calculator.html

Static Port Hole Size

http://www.vernk.com/AltimeterPortSizing.htm

RR2 User Manual

http://www.missileworks.com/user_downloads/RRC2X_RevC.pdf

Rocket Competition Manual

Collegiate Rocket Competition Handbook – Courtesy WSGC

Barrowman's Theory Information

http://my.execpc.com/~culp/rockets/Barrowman.html

Thrust Curve Information

http://www.thrustcurve.org/motorsearch.jsp

Acknowledgments

Wisconsin Space Grant Consortium