Team Whoosh Generator
2014 WSGC Collegiate Rocket Competition

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Abstract
The objective of the 2014 Wisconsin Space Grant Consortium (WSGC) Collegiate Rocket Competition is to design, build, and fly a single-stage, high-powered rocket to accurately reach an apogee of 3000 feet, along with design restrictions and two added design objectives. The rocket must use a motor as specified by WSGC, have a maximum length of 72 inches, have a body tube diameter between 4 and 6 inches, use a flight data recorder provided by WSGC, and be safely recovered in a flyable condition by an electronically deployed parachute system. Also, a system in addition to the altimeters already on board must be implemented that records data which can be used to find the rocket's velocity and acceleration during ascent. Finally, the time to rocket recovery must be minimized.

Included in this report are design details considered, anticipated performance, photos of constructed components, and flight results.

Team Whoosh Generator thanks the Wisconsin Space Grant Consortium (WSGC) for the funding to make this project possible.

1.0 Rocket Design and Construction

The following subsections will detail the airframe design, nosecone and fin design, rocket stability, electronics bays, pressure relief considerations, and recovery method.

1.1 Motor selection. Several different motors were available for use in the competition. In order to determine which motor would work best, a MATLAB program was run. The code uses the thrust curves of the various motors, the propellant masses, the drag coefficient of the rocket, and also the outside diameter of the rocket. All possible motor choices for the competition were placed in the code and a plot of possible rocket masses versus altitude of the rocket's flight was created. This is shown in Figure 1 for a diameter of 5 inches. To achieve an altitude of 3000 feet and still have room for the extra mass added from the Alternate Velocity Measurement System (AVMS), which is described later, a large motor was necessary. The chosen motor was the Cesaroni K454 because it was the lowest power motor that would achieve an apogee of at least 3000 feet and allow for extra weight, with a total rocket weight (without fuel) of around 16 pounds.

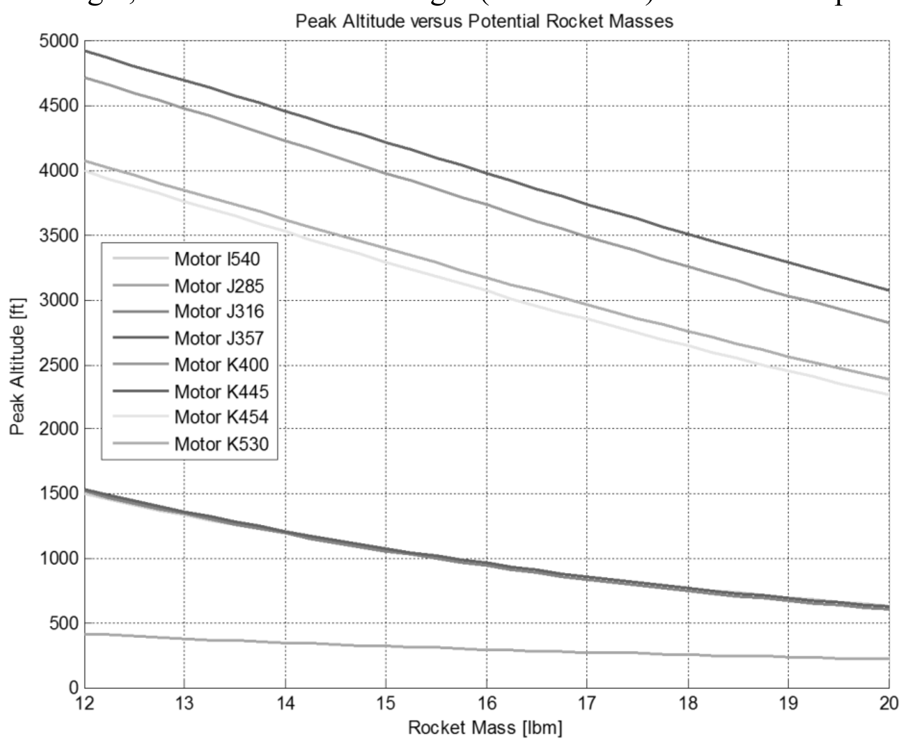

Figure 1: Altitude versus Rocket Mass for each Motor Option

1.2 Airframe design. 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 rocket's diameter was determined using the same MATLAB code used to determine the motor. The possible rocket body diameters for the competition were between 4 to 6 inches. Since the body tubes are normally available in one inch increments, diameters of 4, 5, and 6 inches were run along with the MATLAB code. It was determined that a 5 inch diameter body tube would cause the rocket to have an apogee closest to 3000 feet and still be flexible with the mass of the rocket. Unfortunately the team was unable to find cardboard tubing that was available at 5 inches in diameter. The closest to the 5 inch diameter tubing without going down to 4 inches or up to 6 was 5.54 inches in diameter. Inputting 5.54 inches into the program still proved this to be a viable option, so this was chosen for the rocket.

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 25.5 inches. The upper body tube (to house the main parachute) would have a length of 16.5 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 65.5 inches, which is below the 72 inch restriction.

1.3 Nose cone. After choosing a body tube size of 5.54 inches, nose cone options were limited to a 5.38 inch diameter. Only two durable plastic options were found with an ogive shape, both made by LOC Precision Rocketry; the PNC Short and the PNC Long. With the short length measuring 13 inches and the long length measuring 21 inches, the 13 inch length was chosen in order to maximize the available space for electronics bays, parachutes, and other miscellaneous items while remaining inside of the maximum overall rocket length. The ogive shape was chosen because it has a low coefficient of drag which will allow for a higher apogee with the increased weight of the payloads.

1.4 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. It was determined to use 4 fins spaced evenly around the rocket. The fins chosen were C-08 G-10 fiberglass fins from Public Missiles shown in Figure 2. The fins were attached to the rocket using through-the-wall construction with epoxy fillets on each contact surface.

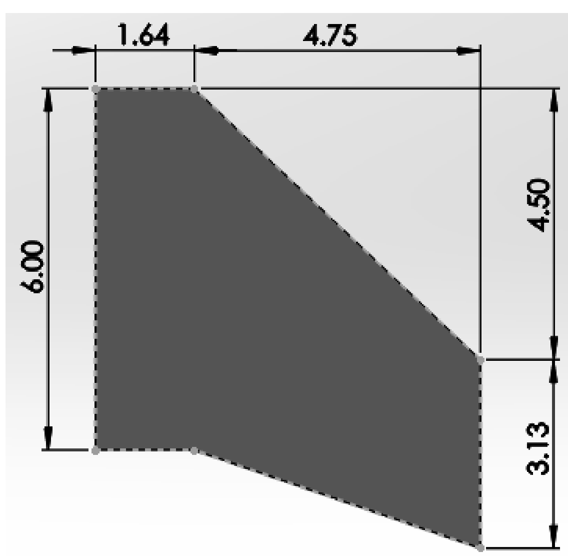

Figure 2: Fin Dimensions

1.5 Rocket stability. 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 relative to the rocket diameter can be used to predict the stability of the rocket during flight. Generally, the center of gravity must be at least one (but not more than two) body tube diameters in front of the center of pressure.

The center of pressure and center of gravity were 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 (Barrowman, 2014):

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.

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.

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	47.9	41.3	1.19
Motor Burnout	47.9	39.4	1.53

From this analysis, it can be concluded that the rocket will be stable during the entire ascent portion of the flight.

1.6 Lower payload bay. The Lower payload bay was made from a 5.372 inch OD tube that is reinforced with a 5.24 inch OD stiffy tube. It was 6.5 inches long and since the outer diameter of it was 5.372 inches, it fit perfectly into the 5.38 inch ID 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 two 9 volt batteries that will power the previously mentioned electronics. 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 3.

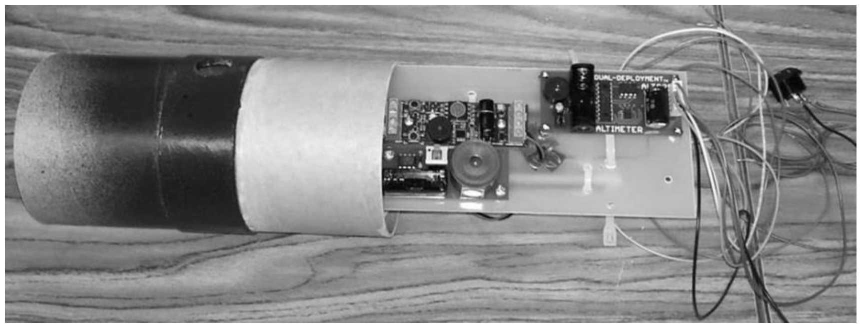

Figure 3: Lower Payload Bay Assembly

1.7 Alternate velocity measurement system (AVMS). A requirement of this year's competition was to record data that can be used to find the rocket's velocity and acceleration during its ascent using a device other than the altimeters used for electronic deployment of the parachutes.

The design that was chosen involves calculating the velocity using the drag force on the main nose cone. An aluminum rod was attached to the nose cone and rested on a force sensor. The device works using a pressure sensor that can read between 0 and 1000 pounds of force depending on the size of the resistor used in its amplifier circuit. The pressure sensor is a variable resistor that will decrease in resistance as the force applied to the sensor goes up. The pressure sensor feeds into an analog pin on an Arduino Uno board with an Ethernet shield attached to it. The pressure sensor is shown in Figure 4. The Arduino Uno reads the voltage across the pressure sensor and then saves it to a micro SD card inserted on the Ethernet shield. This voltage has a known relationship to the force being applied to the pressure sensor, which was calibrated. The Arduino Uno also has a piezo buzzer attached to one of its digital pins that beeps at a regular interval to show the force sensor is connected and recording data.

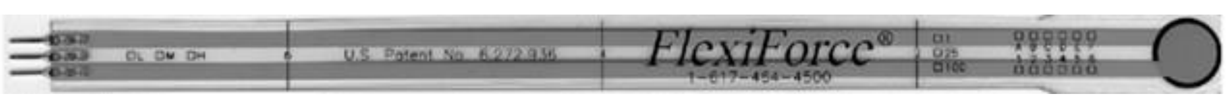

Figure 4: Pressure Sensor for AVMS

The payload bay that houses the AVMS has 2 fiberglass boards in it to support the electronics. The electronics that are housed in the upper bay are the force sensor, the force sensor's amplifier circuit, the Arduino Uno with attached Ethernet Shield, the Garmin GTU 10 Global Positioning System, and three 9-Volt batteries: two used for the force sensor's amplifier circuit, and one used to supply power to the Arduino Uno. The force sensor's amplifier circuit and the Arduino Uno will be turned on at the launch pad using key switches. The boards are centered around an aluminum rod running from the nose cone down to the force sensor. Conduit is attached to the bottom bulkhead to guide the aluminum rod in the bay. The nosecone is free to move down one eighth of an inch but a removable pin in the aluminum rod stops the nose cone from going upwards. A diagram of the upper bay without the boards or electronics is shown in Figure 5.

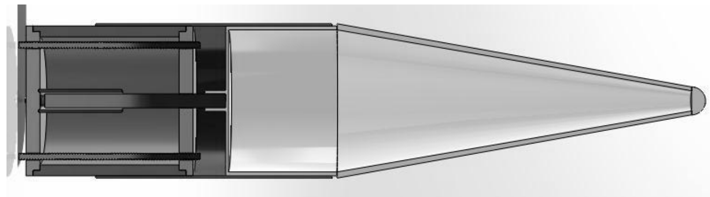

Figure 5: AVMS Setup

The voltage across the pressure sensor was recorded and related to the force applied using the sensor's calibration. The velocity was found using the drag force equation shown in Equation 1.

$$F_d = \frac{1}{2}\rho V^2 C_d A \tag{1}$$

where F_d is the drag force on the nose cone, ρ is the density of air, V is the velocity of the rocket, C_d is the coefficient of drag of the nose cone, and A is the cross sectional area of the nose cone. The velocity was solved for as shown in Equation 2.

$$V = \sqrt{\frac{2F_d}{\rho C_d A}} \tag{2}$$

Using Equation 2 and the recorded data on the SD card, the velocity of the rocket's ascent was determined.

1.8 Pressure relief. The two barometric altimeters used to deploy the drogue and main parachutes require static pressure port holes. Static port holes are required for pressure equalization between the air inside the bay and the outside air during flight. This is very important since 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 smaller holes are used) for every 100 cubic inches of bay volume. It is also recommended to use at least three holes spaced evenly around the body tube to help negate the effects of crosswinds.

The diameter of the lower payload bay is 5.38 inches and the inner length of the bay is 5.75 inches. This yields a volume of 130.7 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 drilled into the payload bay each with a diameter of 0.141 inches spaced 120 degrees apart.

During the rocket's ascent the atmospheric pressure surrounding the rocket decreases. In order to relieve the pressure, a quarter inch hole was drilled into both the upper and lower body sections of the rocket. If these holes are not present the higher pressure inside the rocket could cause the rocket to separate and deploy its parachutes early.

1.9 Recovery. The rocket used a dual deployment system. This means the rocket deploys a small drogue parachute at apogee and then a main parachute at a lower altitude to minimize the drift of the rocket allowing easier retrieval of the rocket. A 24 inch drogue chute that deploys at apogee and a 60 inch main SkyAngle Classic parachute that deploys at 600 feet were used. The rocket has a descent rate of 18 feet per second once the main cute has opened. Two altimeters were used for redundancy to ensure the parachutes deploy. The parachutes are shown in Figure 6.

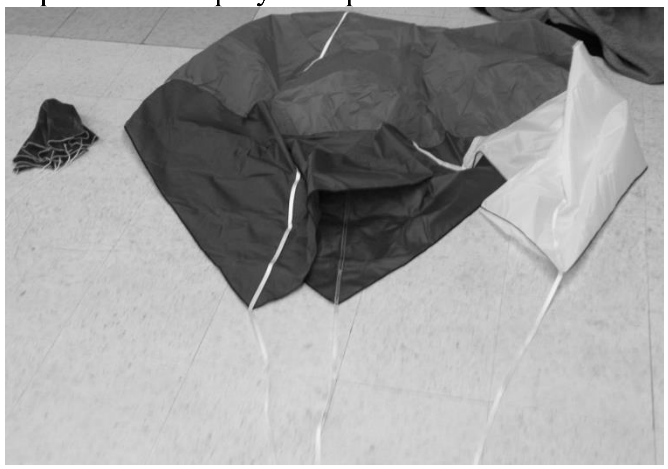

Figure 6: Drogue and Main Parachutes

2.0 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.

2.1 MATLAB Simulation. The primary assumptions made were that the rocket would be launched vertically and that the rocket would follow a vertical flight path. Additionally, standard temperature and pressure were assumed to determine air density, which was also assumed to be constant throughout the range of flight.

A MATLAB simulation for the rocket's flight performance that was used in previous years and improved upon this year was run. The function 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 Equation 3:

$$m_i v_i + F_i \Delta t = m_{i+1} v_{i+1} \tag{3}$$

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 Equation 4:

$$
\begin{aligned}
F_{net} &= F_{grav} + F_{drag} + F_{thrust} \\
&= m_i g + \frac{1}{2}\rho v_i^2 C_d A + T_i
\end{aligned} \tag{4}
$$

where ρ is the density of air, C_d is the coefficient of drag, A is the frontal cross sectional area of the rocket, and T_i is force from the motor. Substituting Equation 4 into Equation 3 and solving for v_{i+1} yields:

$$v_{i+1} = \frac{1}{m_{i+1}}\left[v_i m_i + \frac{1}{\Delta t}\left(T_i - m_i g - k v_i^2\right)\right] \tag{5}$$

Where:

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

Acceleration was calculated using Newton's second law which is expressed in Equation 6:

$$a_i = \frac{F_i}{m_i} \tag{6}$$

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 0.41.

2.2 OpenRocket. OpenRocket is a free, open source, software similar to RockSim. It is capable of calculating acceleration, velocity, and position data. This is done while accounting for variables including: elevation, wind speed, and the effects of individual components on performance. Also included in the program is the ability to construct full to-scale schematics of the rocket design. From this schematic the CP and CG 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.

2.3 Flight Predictions. The peak altitude, acceleration and velocity for both simulation methods are shown in Table 2.

Table 2: Maximum Flight Predictions

	OpenRocket	MATLAB

Altitude (ft)	3012	2996
Velocity (ft/s)	462	465
Acceleration(ft/s^2)	201	197

3.0 Results

Simulations were run to design and estimate flight performance of the rocket. The two programs that were used were OpenRocket and MATLAB code written by the team. Actual flight data was recorded using a Raven 3 flight data recorder provided by WSGC. The flight of the rocket matched well with the estimates of both simulations. A comparison between predicted and measured results is shown in Table 3.

Table 3: Flight Performance Comparisons

	Apogee (ft)	**Maximum Velocity (ft/s^2)**	**Maximum Acceleration (ft/s^2)**
MATLAB	2996	465	197
OpenRocket	3012	462	201
Actual	2967	400	228
Percent Error From Actual (%)			
MATLAB	1	16	14
OpenRocket	1	16	12

Predicted and actual acceleration data is shown in Figure 7.

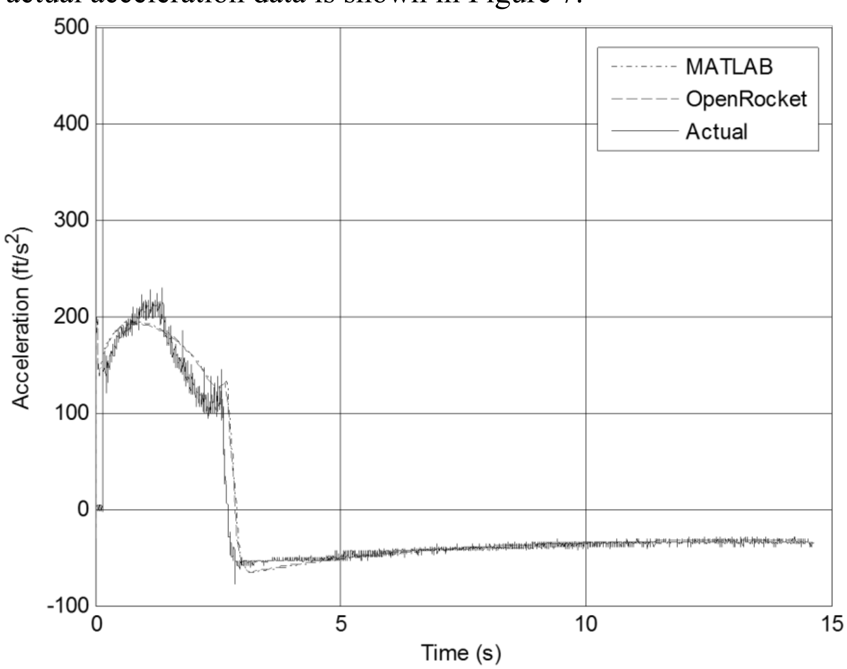

Figure 7: Comparison between Predicted and Actual Acceleration

Velocity data from the AVMS is shown in Figure 8.

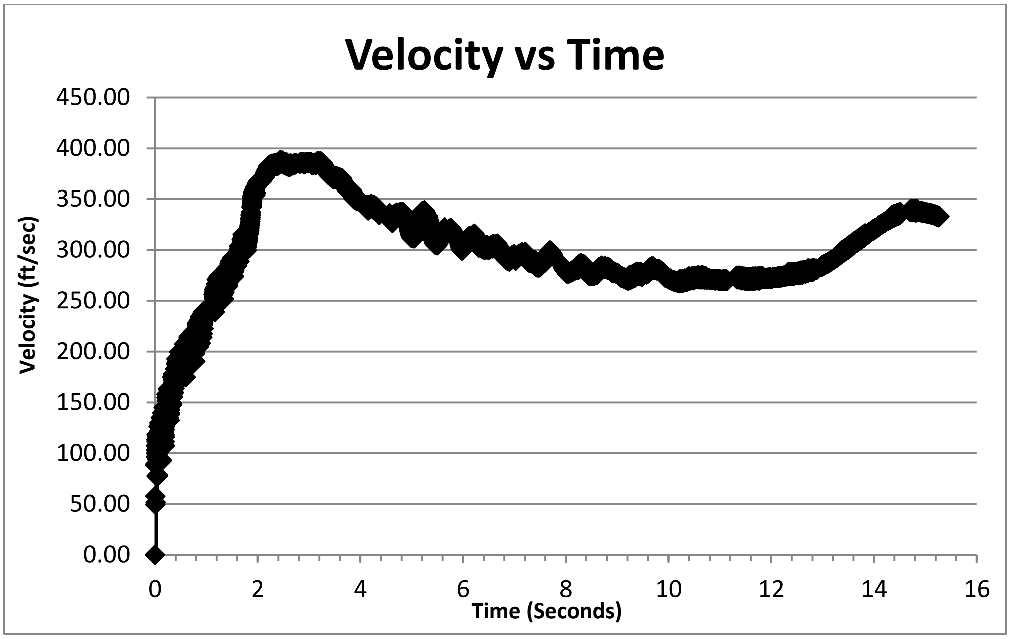

Figure 8: Velocity Data from AVMS

From Figure 8 it can be seen that the velocity data from the AVMS has a steady increase while the motor is burning. The velocity begins to decrease as the rocket approaches apogee. There is some noise in the data near apogee probably due to the nose cone rattling on the force sensor. The calculated maximum velocity by this method was 388.17 ft/s compared to the actual maximum velocity of 400 ft/s.

The time to apogee was about 14.5 seconds, which was as predicted. The rocket undershot the desired altitude of 3000 feet by 33 feet. This was fairly good because MATLAB predicted an apogee of 2996 feet and OpenRocket predicted 3012 feet. Since the actual apogee and these two predicted values had a percent error of 1%, the simulations were good representations of the actual flight. The undershoot was expected because there was a burst of about a 15 mile per hour wind right before the rocket launched. This caused the rocket to reach below the expected apogee.

4.0 Conclusion

The rocket was successfully recovered in a flyable condition in compliance with the competition rules. The software utilized for this design predicted the altitude of the rocket to an exceptional margin given the uncertainties present in the launch and design. The AVMS recorded velocity data closely matched the actual data showing that this method works as a possible alternative to recording the velocity using accelerometers. Lessons learned through this design will be incorporated into future competitions by returning team members.

5.0 References

Barrowman, James. "The Theoretical Prediction of the Center of Pressure." (1966). Apogee Rockets. Web. 13 Apr. 2014.
<http://www.apogeerockets.com/downloads/PDFs/barrowman_report.pdf>.