Post-Flight Performance Report

InVenTs Slinging Slashers:
High Powered Rocketry Team

Organization:
InVenTs Living Learning Community

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Executive Summary

NASA's Space Grant Midwest High-Power Rocket Competition tasked each design team to construct a high-power boosted-dart rocket that met the following design challenges: include a dual deployment system in the dart section, have the lower booster section propel the entire system upward, have the dart drag separate from the booster at motor burnout, and have the dart continue to ascend purely on its own momentum.

The primary objectives for the competition are to design the boosted dart rocket to achieve a high boosted dart apogee and have a large separation distance between the booster section and the dart at their respective apogees while meeting all safety standards. These standards require a safe landing such that the rocket may be launched again immediately after packing. The goals specified by the team are to achieve a dart apogee greater than 3000 feet, and greater than 1500 feet of separation between the dart and booster. Additionally, a video of the flight must be recorded by the rocket and an avionics package must be present to collect data from the launch.

The inVenTs High Powered Rocketry Team, nicknamed the inVenTs Slinging Slashers, was assembled to take on the challenges presented by NASA's Space Grant Midwest High-Power Rocket Competition. The team's members were of different academic levels and majors, including Aerospace, Mechanical, and Electrical Engineering, and Physics, and provided many different technical experiences and skills.

The purpose of this report is to compare the results of the competition flight to the predicted performance of the rocket and to detail any and all changes that were made to the original design.

Rocket Design

The final iteration of the rocket was constructed using traditional approaches as opposed to computer-based methods such as the use of 3D printed parts. The test launch revealed several weaknesses in the second iteration of the rocket. The Blue Tube (vulcanized fiber) body tube on the booster was unable to endure the force exerted by the ejection charge during deployment. The body tube zippered, the parachute detached from the shock cord, and the booster stage was severely damaged upon impact. The final design incorporated a uniform- diameter booster stage with a fiberglass construction. Although the fins had to be manually cut and mounted onto the body tube, which increased the risk of failure due to human error, the fiberglass did result in a successful flight. A Dremel tool was used to cut the fiberglass fins, which were then chamfered to a point on the trailing edges and filleted on the leading edges. The fins on the booster were designed with fin tabs which were glued to the motor mount, through the body tube, for extra support. Epoxy was added between the fins and the booster body tube and filleted for smoother air-flow around the body tube. The shock cord was wrapped around the motor mount, between the two sets of centering-rings, and then coated in epoxy.

The transition piece, like the second iteration, was constructed out of polystyrene and cut on a CNC router. However, to protect the outside of the transition piece upon impact, a fiberglass shell was fabricated around the polystyrene transition on the final iteration. The inside of the transition piece contained two pennies at the bottom to support the dart and prevent the dart from wedging into the polystyrene. An eye-bolt was epoxied into the bottom of the transition piece with the booster's shock cord secured to it. The shock cord was a 15-foot length of Kevlar that was sized to avoid the collision of components upon ejection and descent.

The dart was constructed from three, one-foot-long segments of 38-millimeter diameter, fiberglass tube. The rear segment supported the three fiberglass fins for the dart. The mid segment housed the two couplers and electronics bay. At the end of each coupler, eye-bolts were mounted in place to support the recovery system. However, upon further simulations, the drogue chute alone was expected to slow the dart down to a safe impact velocity, and eliminated the need for a main chute. The tail cone was constructed from a four to one, tangent-ogive nose cone with the tail-end removed. The same component was used for the nose cone of the dart. The segments were attached to the two couplers via 2-56 thread nylon shear pins. The design originally specified that the camera would reside within the tail cone. However, it permitted a clearer view to secure it to the outside of the dart's body tube.

Expected Performance

OpenRocket simulations helped predict the rocket's performance and flight characteristics. Three different scenarios were constructed for potential flight conditions the rocket may have encountered. The simulation which neglected wind expected the rocket's apogee to occur at 1209 meters (3967 ft). The simulation set for average wind conditions (2.68 meters per second (8.8 ft/s) with a standard deviation of 0.214 meters per second (0.7 ft/s)) calculated the dart's apogee to occur around 1207 meters (3960 ft). The last simulation accounted for higher winds averaging around 5.36 meters per second (17.6 ft/s) with a standard deviation of 0.536 meters per second (1.76 ft/s). This simulation calculated the dart's apogee to occur at approximately 1202 meters (3944 ft). Both the no wind and average wind simulations predicted the dart's impact velocity to measure in at 8.08 meters per second (26.5 ft/s), while, in high winds, the dart's expected impact velocity was predicted to be 8.11 meters per second (26.6 ft/s). Although the original plan was to achieve an impact velocity of around 6 meters per second (20 ft/s), further simulations did not show risk of damage to the dart at impact velocities of even greater than 8 meters per second (26 ft/s). Under all simulations, the optimum ejection charge delay for the dart was calculated at 13.5 seconds. However, the use of the AIM Altimeter 3.0 ensured that the dart's parachute deployed directly after apogee when a shift in velocity direction occurred. The booster's optimum delay was calculated at 11 seconds. However, to ensure that the parachute deployed after apogee, the ejection charge on the motor was set to occur at 12 seconds.

The entire assembly, with a loaded motor, has a stability of approximately 2.58 calipers. The center of pressure is approximately 146 centimeters (57.5 inches) from the top of the rocket while the center of gravity rests at approximately 126 centimeters (49.6 inches) from the top. For a visual representation, refer to figure 1a. The dart has a stability of approximately 3.27 calipers with its center of pressure at 72.7 centimeters (28.6 inches) from the top of the dart and its center of gravity resting at 59.1 centimeters (23.3 inches) from the top. Figure 1b shows a visual layout of the dart's stability. The booster, with an empty motor, has a stability of 0.946 calipers with its center of pressure at approximately 54.3 centimeters (21.4 inches) from the top of the booster and its center of gravity resting at 46.7 centimeters (18.4 inches) from the top. Refer to figure 1c for a visual representation of the booster.

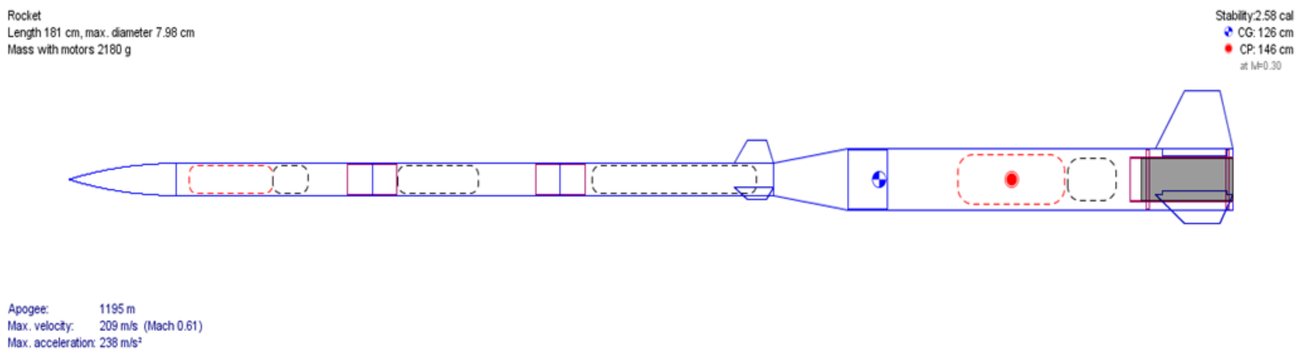


Figure 1a: Rocket assembly diagram with the center of gravity as a blue and white dot and the center of pressure as a red dot.

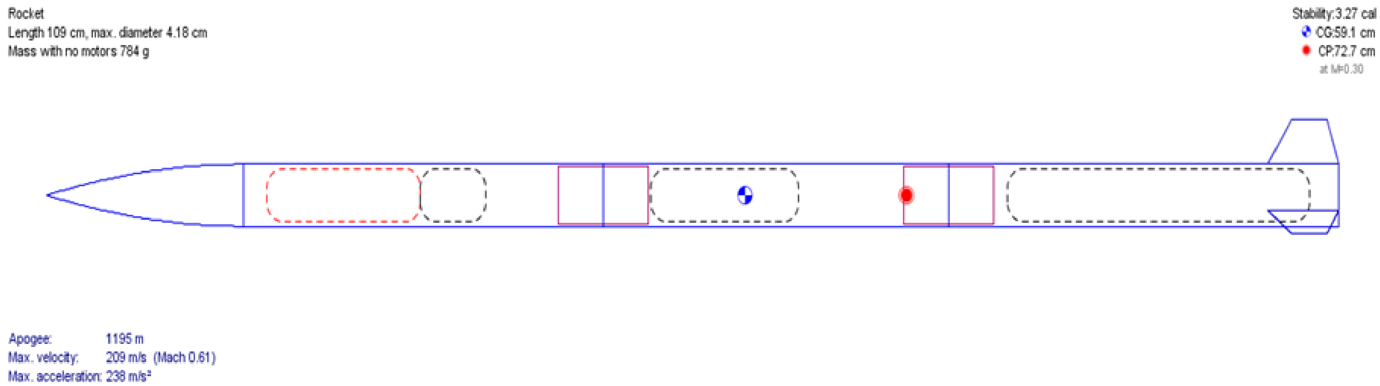


Figure 1b: dart diagram with the center of gravity as a blue and white dot and the center of pressure as a red dot.

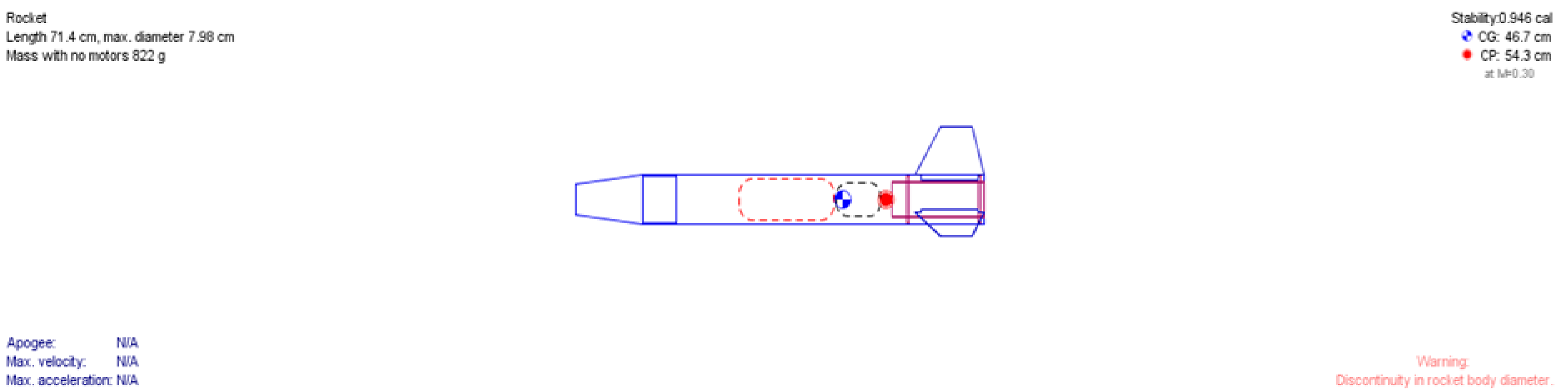


Figure 1c: Booster diagram with the center of gravity as a blue and white dot and the center of pressure as a red dot.

Rocket Operation Assessment

Launch Analysis

For the competition launch, both launches were a success in that they met the competition guidelines, but only the second launch met the goals the team set for themselves.

The rocket needed to be launched twice due to a lack of significant separation between the booster and the dart during the first launch. The altimeters placed in each rocket section only registered a one foot difference in apogee, so the transition piece was adjusted. Originally, a single penny was placed at the bottom of the hole in the transition piece to prevent the dart from compacting the polystyrene and conforming to the booster, but the dart did not separate. To fix this, a second penny was placed inside the transition piece to decrease the depth the dart went into the booster. Additionally, duct tape was added to shore up the rim of the piece due to separation between the fiberglass and polystyrene that was used for the piece. These modifications allowed the dart to have less friction with the transition piece, facilitating a successful separation during the second launch. As a result, the team goal of a separation of over 457 m (1500 ft) was reached.

Flight Anomalies

During the first launch, the rocket did not separate until after apogee, unlike what was predicted. Because of this, only 1 ft of separation was recorded. This was most likely due to the compression of the foam while the motor was burning, along with the dart being too deep in the transition piece. As it was said in the previous section, this problem was mitigated, leading to a successful second launch.

During the second launch of the rocket, the booster section separated from the dart early in flight. The inner transition piece was then exposed which caused a major disruption in airflow. Furthermore, the booster's stability was under one caliper, meaning it was only marginally stable. The combination of these two factors caused the booster to tumble. The separation between the booster and the dart was thus greater since the booster slowed due to significant drag as it tumbled on its side. This helped to increase the separation distance between the booster and the dart.

Propulsion System Assessment

The thrust curve for the Cessaroni I445 competition motor can be seen in Figure 2. The burnout for the motor occurs 1.1 seconds after ignition. The maximum thrust for the motor is 526.2 N, while the average thrust is 442.7 N. [1] Appendix 1 shows the flight data for the dart, as recorded by the AltimeterThree. The data recorded during the flight shows that burnout occurred 1.15 seconds after launch when the acceleration of the dart returned to 1 G. This closely matches the specifications of the motor. As the motor reaches max thrust (or maximum impulse) the acceleration reaches its maximum as well. The maximum acceleration of the dart was 22.79 g's of force, which occurred at the 0.6 second mark. This matches the thrust curve for the motor, with maximum thrust occurring at about the same time. As the motor begins to run out of propellant, the thrust, as well as the acceleration, begins to decrease. Eventually, the motor completely burns out and is depleted of propellant. This is evidenced by the acceleration returning to the original nominal status just before launch.

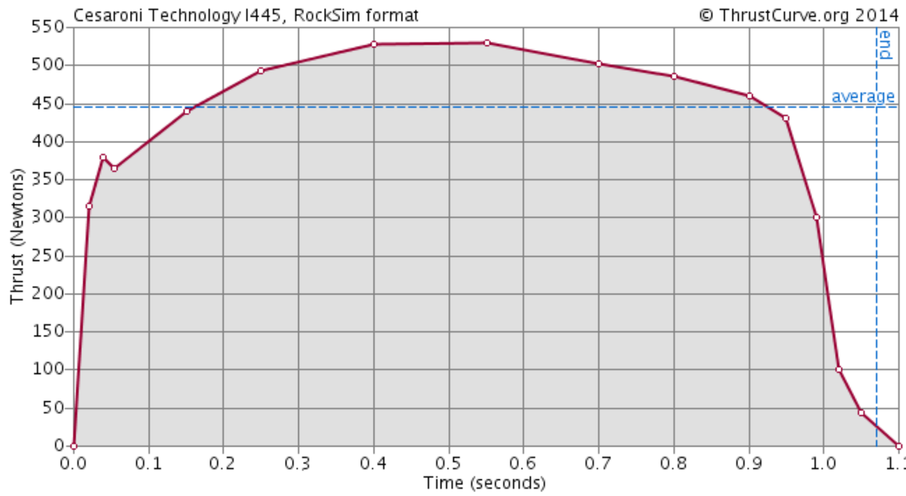


Figure 2: Thrust curve for Cessaroni I445 Motor [2]

Flight Path Assessment

Most rockets follow a straight and linear path as they accelerate upwards and then fall back down to the surface in a parabolic manner. Others can deviate from this intended path by weather anomalies and inconsistencies in construction or perhaps even design peripherals. For the purposes of this flight, the intended path was initially a linear ascent for both the booster and the dart, followed by a parabolic, curvilinear motion. The booster's parabolic movement would occur immediately after drag separation. The dart would enter parabolic flight with a narrower parabola after achieving a higher apogee.

Recovery System and Rocket location & Recovery Analysis

The recovery system for both the booster and the dart involved a parachute. As such, the descent direction and ground path was dictated by the direction of the wind. At the time of launch, the wind direction was east northeast. [3] Figure 3 shows the ground distances of both the booster and the dart, respectively. The dart drift distance was approximately 300 ft further than that of the booster. The dart drifted further because it reached a higher apogee than the booster. Recovery of both the booster and the dart was straightforward. Since parachutes deployed on both the booster and the dart, it was easy to trace them down to where they landed in the field, even without the use of a transmitter. This made it easy to recover all sections of the boosted dart.

Figure 3: Distances to booster and dart respectively. Distance to booster approximately 895 ft. Distance to dart approximately 1170 ft.

Pre and post Launch Procedures Assessment

Comprehensive checklists were created so that launch procedures could be executed quickly and safely. This allowed for efficient use of time while approaching the launch pad and recovery of rocket. Special care was taken when approaching the dart to ensure ejection charges had fully detonated. Figure 4 depicts the booster as seen during recovery. Both the preflight and post-flight checklists were reviewed and approved by the RSO. Slight changes were made to the preflight checklist. These included the installation of a pair of wires which allowed us to externally arm the ejection charges while on the launch pad. Alternatively a “safe switch”could have been used, however, this would have forced the team to drill an additional hole into the side of the body tube. Post launch procedures remained unchanged and both ejection charges in the dart were safely discharged.

Figure 4-Booster as seen upon recovery

Data Collection

<u>Rotation</u>

Some rockets use rotational motion to control the attitude of the rocket in the longitudinal principal axis. This motion, visibly indicated by rotating fins, can induce static stability and create a steady flight path to an otherwise unstable rocket. This rotary movement about the rocket's center of gravity can be caused by several phenomenon: fin cant, gimbaled thrust, and even wind. Lacking gimbaled thrust or any other form of thrust vectoring, the rocket's rotation was caused solely by fin cant and wind effects. Fin cant is the term for the angle at which the fins are attached to body of the rocket. Zero fin cant means the fins are aligned perfectly parallel to the length of the body tube; there is no angle between the fin and body tube. Assuming no wind, zero fin cant will produce zero rotation. However, if the fins are placed at an angle to the surface of the body tube, the normal force on the surface of the fin will cause an unbalanced torque about the length of the body tube. This action can be advantageous to the rocket. Like a spinning bullet, the rocket's flight path will be straighter and can therefore cover a longer distance. This moment about the principal axis, although beneficial to the stability and predictability of it's flight path, can be detrimental to the max apogee of the rocket. Optimization during the design phase saw several iterations of adding and reducing fin cant. The goal: include enough fin cant to add linearity to the flight path while mitigating losses to apogee. For the final layout of the rocket, fin cant was ultimately excluded, as the design was already suitably stable and was able to reach higher apogees without the need of rotation. Wind can be encountered at any fin cant. The wind essentially acts as another normal force to the fins, inducing rotational velocity to the system. These dispersion forces are often sources of drag. It is critical to avoid roll rates that are deleterious to the overall performance of the rocket, including the resonant frequency. Unfortunately, rotational motion was unsuccessfully recorded due to loose wiring between the microcontroller and the inertial measurement unit (sensor). Although rotational motion failed to be recorded, it can be assumed that the resonant frequency was not reached, as the rocket did not fall apart and fin flutter did not cause the fins to break off during flight.

<u>On-board Video</u>

The requirement to have a downward-facing, on-board camera proved to be a challenging task. Although the design called for a camera resting inside the bottom tailcone, uncertainties arose regarding the size of the hole for the lens and if it was secure enough to hold the camera in place during launch. To increase chances of launch success, certain measures were taken right before launch to ensure that the camera would be fully attached. The decision was made to attach the camera externally to the surface of the dart body tube using duct tape. Although certainly a large source of drag, it guaranteed that the lens would face downward with an unobstructed view. Completely isolated from the electronics in the dart, the camera contained its own battery, memory storage, and activation method. The camera was set to record by using the two external buttons. Despite verification of the camera's operability, the camera failed to capture in-flight video. The video recording only lasted for approximately eleven minutes while sitting on the launch pad and did not record the flight. Still, both the dart and booster were successfully recovered so that partial footage could be obtained and reviewed.

<u>Data Interpretation/Comparison</u>

Ultimately, the recorded data showed strong correlation with the predicted performance. The booster stage had a lower apogee than predicted, as the simulation did not account for tumbling. Figure 5 indicates the dart's apogee as recorded by the AltimeterThree. The simulation also failed to account for sources of human error (such as asymmetrical fin spacing) that could have been the reason behind a lower- than- anticipated dart apogee. Going forward, a higher apogee could theoretically be attainable with the use of the 3D printed parts from the initial design. The fiberglass proved to be strong enough to withstand the force of impact. ABS plastic appeared to have lower force resistance. When running stress analysis on the ABS plastic used in the second iteration of the rocket, a human hand could exert enough force to break two millimeter thick pieces apart. However, the same basic test was used against the fiberglass and yielded no damage to the fiberglass.

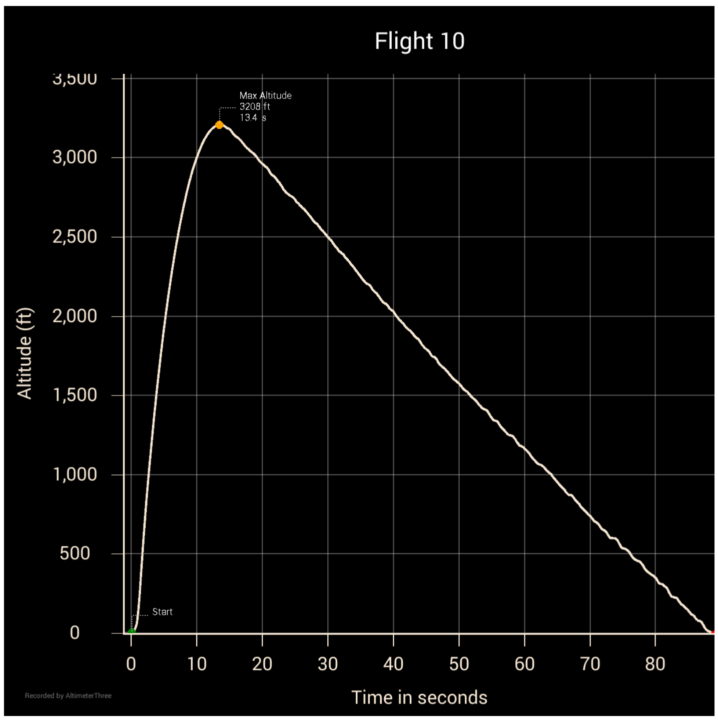


Figure 5: Graph obtained from AltimeterThree depicting maximum apogee for dart

Flight Performance Reporting Sheet

Virginia Tech inVenTs Slinging Slashers

Operation (determined by RSO or designee)

Launch……………………………………………………………………………………✔

Drag Separation………………………………………………………………………..✔

Dart

Parachute Deployment…………………………………………………………….....✔

Recovery……………………………………………………………………………….✔

Determined to be in flyable condition…………………………………………………✔

				Predicted	Actual	
1	Maximum Dart Altitude (ft)			3921	3208	
2	Maximum Dart Acceleration (G's)			24.47	22.79	
3	Maximum Dart Velocity (ft/s)			685.7	640	

Booster

Parachute Deployment…………………………………………………………………✔

Recovery………………………………………………………………………………..✔

Determined to be in flyable condition……………………………………………......✔

				Predicted	Actual	
1	Maximum Booster Altitude (ft)			2610	1103	
2	Maximum Booster Acceleration (G's)			24.47	22.79	
3	Maximum Booster Velocity (ft/s)			685.7	-	

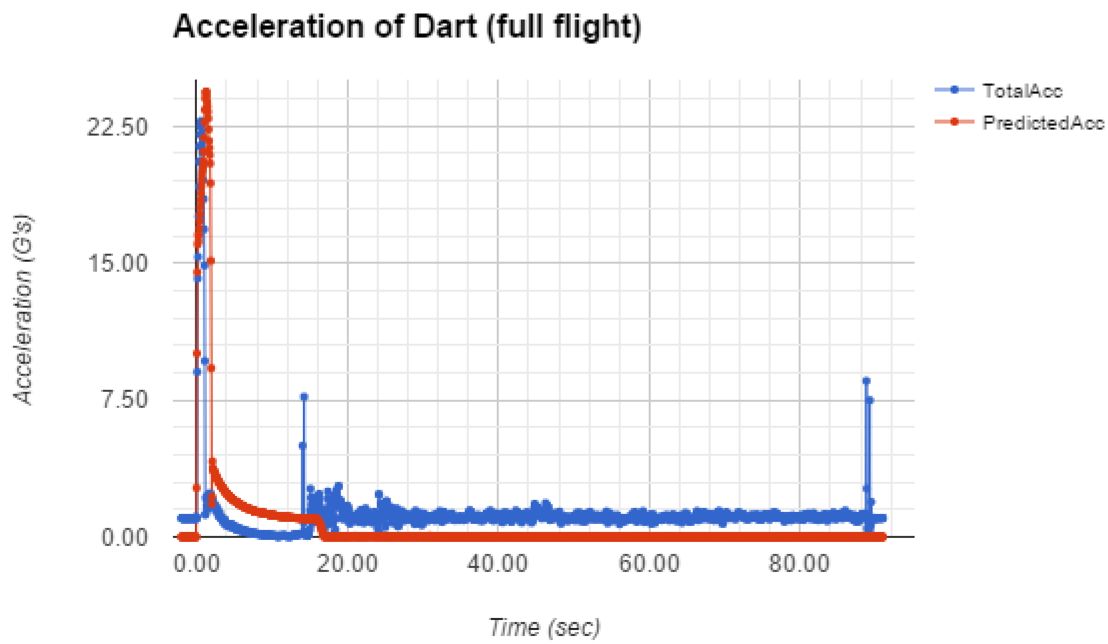


Figure 6- Graph depicting total acceleration for the dart with predicted acceleration overlayed

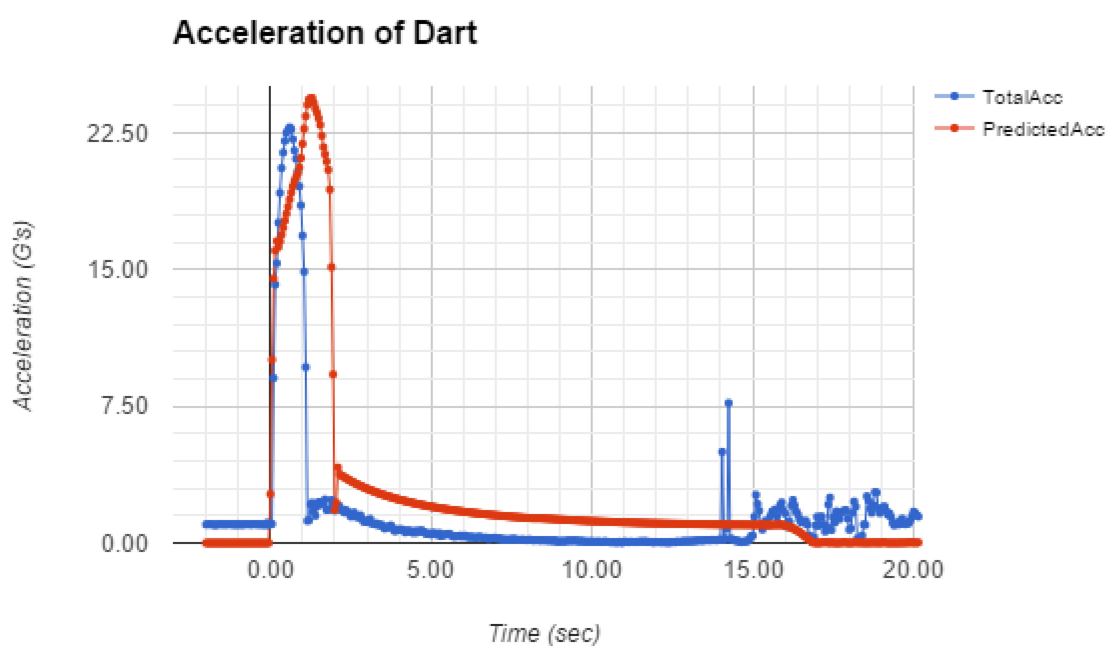
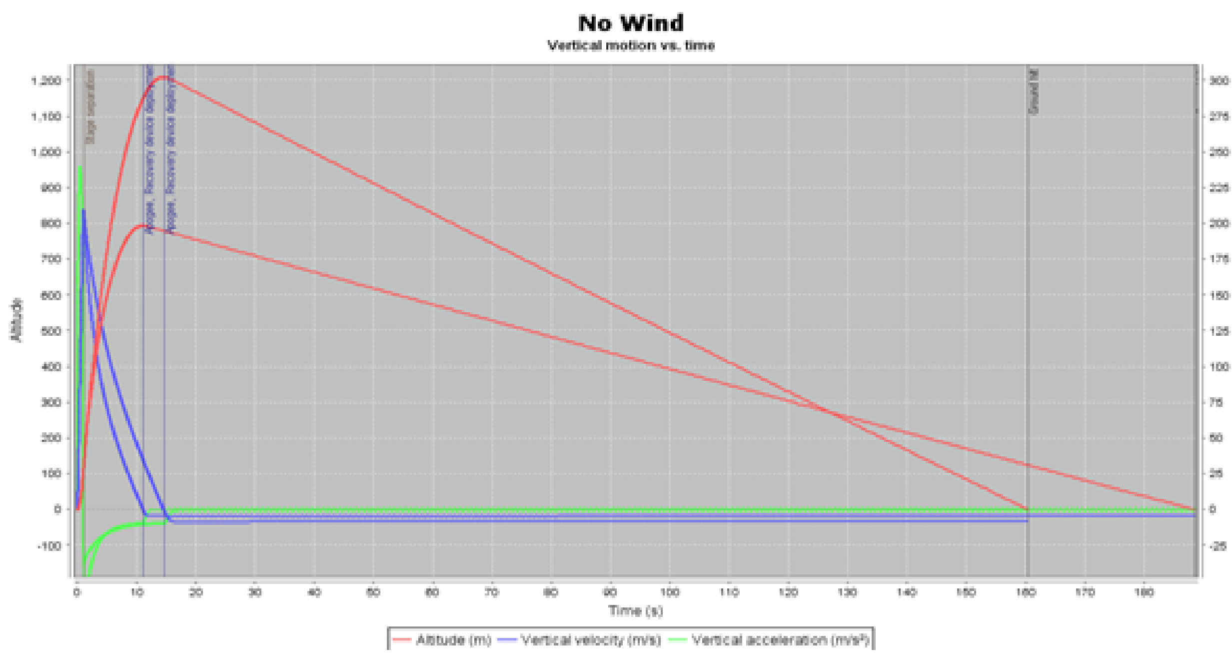


Figure 7-Magnified graph highlighting differences in actual and predicted acceleration performance

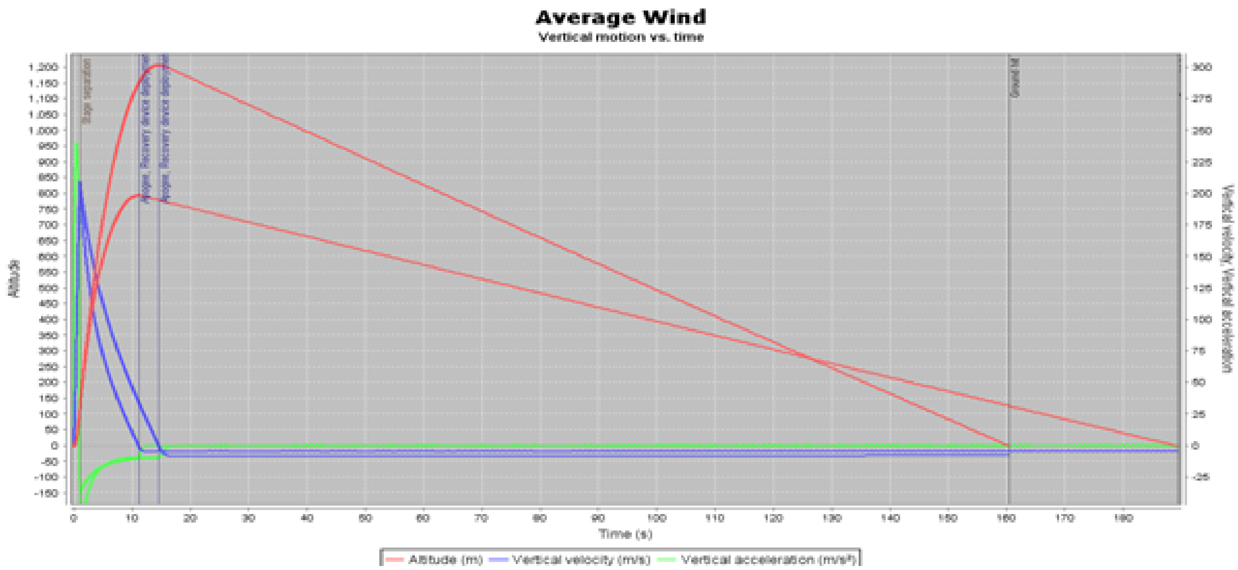
References

1. Technology, C. (2009, 06 28). Cessaroni I445. Retrieved from thrust curve.org: http://www.thrustcurve.org/motorsearch.jsp?id=704
2. Technology, C. (2009, 06 28). Cessaroni I445. Retrieved from thrust curve.org: http://www.thrustcurve.org/simfilesearch.jsp?id=1523
3. "Weather History for Rush City, MN | Weather Underground." *Weather History for Rush City, MN | Weather Underground*. N.p., n.d. Web. 29 May 2015.

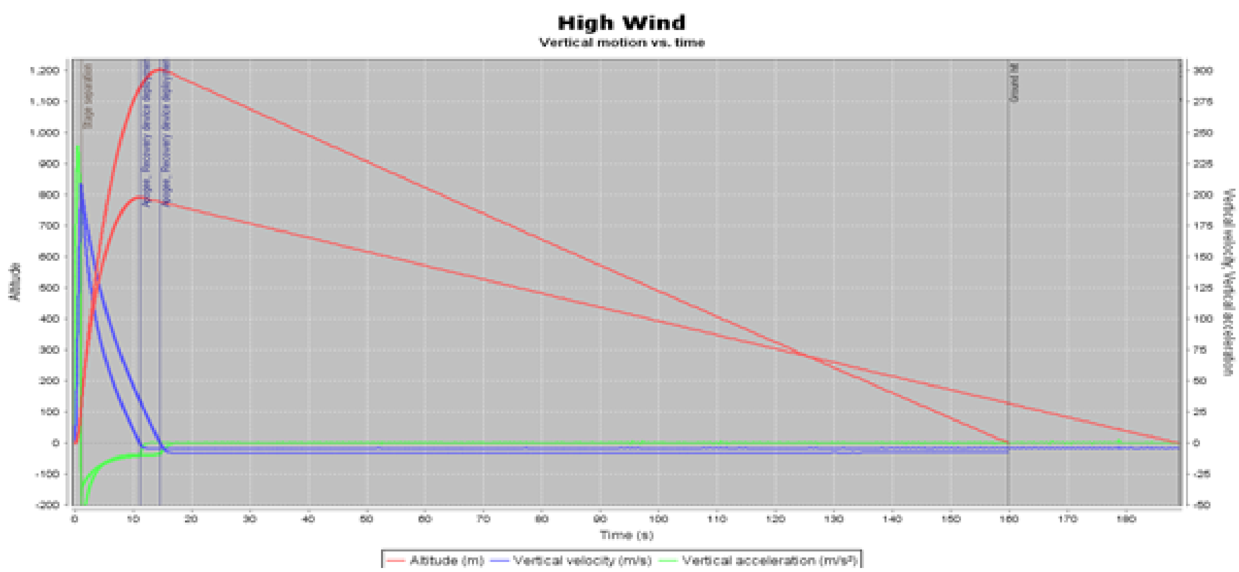
Appendices



Graph of height (red), velocity (blue), and acceleration (green) vs time for no wind.



Graph of height (red), velocity (blue), and acceleration (green) vs time for average wind.



Graph of height (red), velocity (blue), and acceleration (green) vs time for higher winds.