NUSTARS

NORTHWESTERN UNIVERSITY SPACE TECHNOLOGY AND ROCKETRY SOCIETY

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Flight Performance

Flight Trajectory Assessment

Flight 1

The flight trajectory started with burnout. After burnout, the rocket had to autonomously self correct any rotation from burnout until the rocket reached apogee. This meant that the rocket should have flown in a very straight line with little rotation. This was shown to have happened in the video and the flight data (see the Roll Angle vs. Time v.s Command State sub-section in the Discussion of Flight Results section below). After a successful coast phase, the rocket deployed drogue parachute at apogee and set off its ejection charges for a main parachute, which didn't deploy at 800 ft.

Flight 2

The trajectory of the rocket started with the motor burnout. After burnout, the rocket was supposed to rotate according to a series of commands during the coast phase. However, the rocket got stuck on the first command and did not rotate at all during the coast phase (see the Roll Angle vs. Time vs. Command State sub-section in the Discussion of Flight Results section below). Once the rocket reached apogee, the drogue parachute deployed. The main parachute deployed successfully this time at 800 ft.

Table of Flight Characteristics

First Flight

Mass with Motor	240 oz
Mass without Motor	200 oz
Motor	J800T
Maximum Altitude	3660 ft
Maximum Velocity	505 ft/s
Maximum Acceleration	520 ft/s^2
Ascent Time	15.6 s
Main Descent Rate	27 ft/s

Second Flight

Mass with Motor	238 oz
Mass without Motor	198 oz

Motor	J800T
Maximum Altitude	3659 ft
Maximum Velocity	498 ft/s
Maximum Acceleration	490 ft/s^2
Ascent Time	14.65 s
Main Descent Rate	18 ft/s

Analysis of Flight and Flight Anomalies

The data collected from the flight computers during both flights was very similar. The two important pieces of data to notice are the differences between main descent rates and the mass of the rocket. The main descent rate was 27 ft/s in the first flight because the main parachute got stuck in the nose cone, even though both ejection charges successfully deployed. This was because we used an old nomex to protect the parachute and the loop that connected the parachute to the shock cord ripped during descent. This caused the parachute to get stuck in the nose cone and not deploy. However, with only a drogue parachute deployed, the rocket came down relatively slowly at 27 ft/s. To ensure that this mistake didn't happen again during the second flight, a new nomex was used around the same main parachute. The main parachute was inspected for holes and burns, and, because none were found, we decided it was safe to use the same parachute. To ensure the main parachute didn't get stuck, we also took off one foot of shock cord from the nose cone. This left 6 feet of shock cord in the nose cone and reduced the weight of the rocket by two. The descent rate on the second flight was 18 ft/s, different from the first because the main parachute did not get stuck in the nose cone on the second flight.

As stated in the previous paragraph, the weight difference of the rocket was due to the removal of one foot of shock cord in the main nose cone during the second flight. This was done to ensure that the main parachute had enough room to fit inside the nose cone and not get stuck so it could successfully deploy on the second flight.

The rocket flew to approximately the same apogee of 3660 and 3659 ft. This difference is most likely caused by wind or the rocket having a slight angle as it launched off the launch pad on the second flight. Because there was less weight in the rocket on the second flight, we expected the rocket to fly higher on the second flight than on the first flight. However, given that the maximum velocity was also lower on the second flight, this indicates that either there was more wind on the second flight or the motor was a little bit less powerful which happens when manufacturing within a certain tolerance.

The maximum velocity in the first flight was 505 ft/s and faster than the second flight by 7 ft/s (498 ft/s). There are three reasons why this could happen: the motor for the second flight was manufactured with an impulse on the lower side of the tolerance range, the wind was stronger for the second flight, or the launch rod on the second flight was not at a 90 degree angle. The most likely explanation is probably that there was more wind on the second flight than on the first flight. The other two factors could also have contributed, but wind or an angled launch rod probably affected it the most. The increase in wind speed explanation is supported by the behavior of other flight data as well.

The maximum acceleration for the first flight was 500 ft/s^2 which was faster than the maximum acceleration for the second flight by 10 ft/s^2 (490 ft/s^2). Because the flight computers don't directly record the maximum acceleration, these values were found by taking the slope of the velocity curve. For the first flight, the velocity changed approximately 100 ft/s in 0.2 seconds (so 100/0.2), and the velocity of the second flight changed approximately 98 ft/s in 0.2 seconds (so 98/0.2). These calculations produced the maximum acceleration numbers described in the table above. Because our method for calculating the acceleration isn't exact, these numbers may vary. Since the rocket was lighter on the second flight, we expected it to have a larger acceleration then. However, a stronger wind in the second flight would explain why the maximum acceleration in the second flight was smaller than the maximum acceleration in the first flight.

The ascent time was also very different: 15.60 seconds for the first flight and 14.65 seconds on the second flight. This supports the theory that the second flight had more wind because the rocket would have less resistance which would allow it to maintain its momentum for a longer period and fly higher. In addition, because the rocket was lighter on the second flight, the rocket would need less time to reach approximately the same apogee. This would make sense because if there was more wind, normally the rocket should have a smaller flight time and a smaller apogee. However, the rocket had less weight which appears to have made up for most of that difference in this case.

The graphs for the flight data can be found in the Appendix.

In-Flight Recovery System Analysis

The in-flight recovery system worked pretty well during the competition. For both flights, the drogue parachute deployed properly at apogee and both ejection charges were blown. For the first flight, the hole on the nomex for the main parachute ripped so the nomex got stuck in the nose cone. This prevented the main parachute from deploying even though both ejection charges blew. However, the rocket still descended at a rate of 27 ft/s, which was only 3 ft/s over the limit for rocket descent rates set by the competition. The nomex ripped because it was old and frayed. For the second flight, the new backup nomex was used and the recovery system worked perfectly. The main parachute was deployed at 800 ft and the rocket landed with a main descent rate of 18 ft/s, well within the limit set by the competition.

Ground Recovery Assessment

The rocket was covered safely and quickly during the competition. The rocket was found by using the tracker to identify where the rocket landed. In addition, two members of the team watched the rocket as it descended to make sure we knew approximately where to look for the rocket. The checklists were followed to ensure that students recovered the rocket in a safe manner. When recovering the rocket, the ejection charges were checked first to make sure that they all had exploded and there were no live explosives on the rocket. Next, the students disarmed the flight computers for extra safety. The rocket was then carried back to the judges to be inspected and to have data collected.

Plots of Roll Angle (sensed) vs Time from Sensor Data

Flight 1

The data for the roll angle collected from flight 1 shows the rocket autonomously self correct back to its preset starting orientation (Figure 1). The rocket's starting orientation was manually set on the launch pad to be zero. This is the orientation that the rocket would autonomously self correct to, which is why theta goes from -30 degrees to zero degrees in between time t=3 and t=15. The rocket goes from 0 to -10 degrees in between times t=0 an t=3 because this is the amount the rocket rolled during burnout. The data also reflects the rocket rotating and autonomously self correcting during the last few seconds before apogee, which is consistent with the video data. Note that negative angles just indicate the direction of rotation.

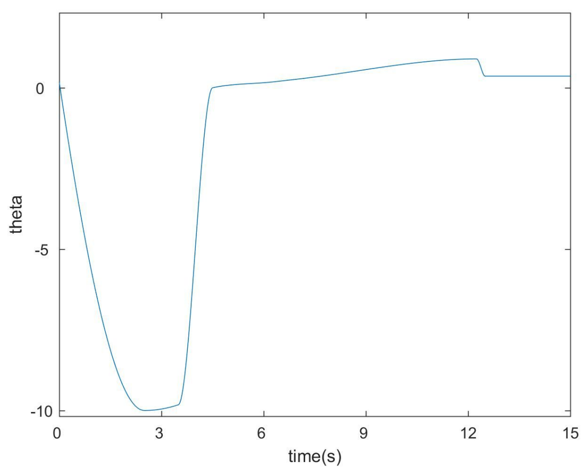


Figure 1: Flight 1 Roll Angle Data

Flight 2

The data for flight 2 shows theta being zero for the entire flight (Figure 2). This is because during the second flight, the rocket did not actually rotate at all. This is consistent with the video footage during the second flight. The looks a little wiggly because Y axis is scaled down to be from -0.25 to 0.25 degrees. This is a very small range, so it looks like the rocket is spinning back and forth much more than it actually is.

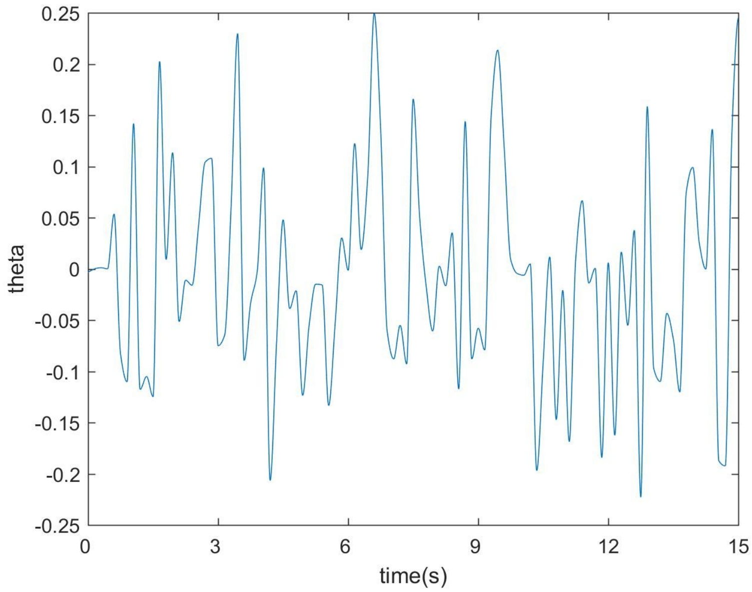


Figure 2: Flight 2 Roll Angle Data

Links to the Flight Videos
Flight 1

Off Launch Pad
https://drive.google.com/file/d/1qcXh8GKpAj40faFhSSeE_1ar88wrsQof/view?usp=sharing

Rotation and Landing
https://drive.google.com/file/d/13dyhZ5-aai2UG4Hi-f5Wegz3fRy0UHhn/view?usp=sharing

Flight 2
https://drive.google.com/file/d/1I7tmqeNGSdbBFK7O_jL22WjtK8ssJVN9/view?usp=sharing

Alternative Link for all Flights
https://www.dropbox.com/sh/mbz1rwr75d08e6s/AAAFq7Xkf8tIyFsUbpA3E1lZa?dl=0

Roll Angle (based on video) vs Time
Flight 1
For flight 1, there was interrupted footage of the rocket's flight. The first video shows the rocket right as it is lifting off. The second video shows the last few seconds of flight before burnout. These few seconds are more descriptive of the rocket's movements. The rocket starts by holding its position and then it rotates approximately 15 degrees to the right (Figure 3). It then immediately rotates back to its original position (Figure 4). This shows that even though the wind caused the rocket to rotate during flight, the rocket was able to successfully autonomously self correct during the flight. Unfortunately, only the middle LED was captured during the first video. It seems to be off for most of the rotation and sort of turns back on when it stops.

However, the sun glare makes it difficult to determine if the light is on or off (Figure 3). Overall, flight 1 was consistent with its task of autonomously self correcting during the first flight.

Figure 3

Figure 4

Flight 2

For the second flight, the flywheel system successfully held the first command for the entire flight. The middle light was on almost the entire time. The sunlight made it difficult to see what color the LEDs were, however, in Figure 5, the shadow from the rocket shows that the middle LED light was on when the rocket was going straight up. The rocket was commanded to hold four different commands after the flight. However, the video shows that the rocket appears to have gotten stuck on the first command and not rotated at all during the flight (Figures 5 and 6). This is consistent with our LED light system because the middle LED was on and the rocket was not rotating. However, the rocket should have been rotating, therefore the video results and the given commands are not consistent.

Figure 5

Figure 6

Discussion of Flight Results

Flight Data vs. Expectations

The predicted flight data from OpenRocket is given in the table below.

Mass with Motor	240 oz
Mass without Motor	200 oz
Motor	J800T
Maximum Altitude	4022 ft
Maximum Velocity	566 ft/s
Maximum Acceleration	562 ft/s^2
Ascent Time	15.5 s
Main Descent Rate	18.9 ft/s

Mass
The mass of the rocket was the same as the simulation for the first flight because we simulated it with the correct masses of each part of the rocket. The mass of the rocket for the second flight was less than the mass of the rocket for the first flight because we removed some of the shock cord from the nose cone.

Maximum Altitude
The maximum altitude of the rocket was approximately 362 ft lower than the OpenRocket simulation predicted. Even though there wasn't that much wind on launch day, rocket simulations tend to predict a higher apogee than actually occurs. This is consistent with the data collected from the flight computers after the launch. The apogee during the launches was about 140 ft less than the apogee predicted using the ratios in the FRR. This shows that while our predictions were not very accurate for estimating the actual apogee of the rocket. In addition, another possible explanation for the difference could be larger winds than simulated.

Maximum Velocity
The maximum velocity of the rocket was predicted to be 57 ft/s and 64 ft/s faster than the actual maximum velocities of both launches. This is consistent with the rocket having a smaller maximum altitude than predicted by the simulation. This could be because OpenRocket tends to overestimate rocket flight data and because it could have been more windy than the simulation accounted for. Even though the maximum velocity was not consistent with the maximum velocity predicted by OpenRocket, the maximum velocities of the two launches were consistent with each other, which makes sense because the rocket was subjected to relatively similar conditions for the two launches.

Maximum Acceleration
The maximum acceleration from the first and second flights was also much higher than the maximum acceleration predicted by OpenRocket (approximately 72 ft/s^2 and 62 ft/s^2 higher). The difference between the maximum acceleration simulated and the maximum acceleration observed, like maximum velocity and altitude, could be because OpenRocket overestimates maximum accelerations and because of the larger wind. However, the difference between the maximum accelerations and the maximum velocities is similar: the maximum acceleration for the test flights is very close to the maximum velocity of the test flights, just like OpenRocket.

Ascent Time
The actual ascent times were somewhat similar to the predicted ascent time. The first flight had an ascent time of 15.6 seconds, which was actually only 0.1 seconds above the predicted ascent time. However, the ascent time of the second flight was 14.65 seconds, which was much less than both the ascent time from the OpenRocket simulation and the first launch. This could be due to winds which prevented the lighter rocket from reaching a higher apogee and therefore took less time to reach apogee.

Main Descent Rate
OpenRocket predicted that the main descent rate would be 18.9 ft/s. This is consistent with the data collected from the second flight with a main descent rate of 18 ft/s. This isn't consistent

with the data from the first flight because the main parachute did not deploy for the first flight because the nomex ripped and got stuck in the nose cone.

Propulsion System Assessment

Discussion on the specifics of our launch (apogee, velocity, acceleration) were discussed in the “Analysis of Flight” section. This flight data was compared to the predictions made by OpenRocket in the section Flight Data vs. Expectations. The rocket was a single staged rocket which meant that the rocket would stay connected throughout the flight until apogee. A single staged rocket was used for the competition because it best fit the guidelines and a two stage rocket would have been too difficult for our team. Apogee for the first flight was 3660 ft and 3659 ft for the second flight. The maximum velocity for the first flight was 505 ft/s and 498 ft/s for the second flight. The maximum acceleration was 500 ft/s^2 for the first flight and 490 ft/s^2 for the second flight. It is possible that the two J800T motors used had slightly different total impulses because the maximum velocity, acceleration, and altitude was lower than the first flight even though the mass of the rocket decreased by 2 ounces. The burn time for the J800T motor was 1.76 seconds and it had a maximum thrust of 1001 Ns or 156.58 lb-s. The total impulse for the motor was 1229.11 Ns or 276.31 lb-s. The diameter of the motor was 54 mm. The J800T motor was used successfully on both flights. The thrust curve is shown in Figure 7 below.

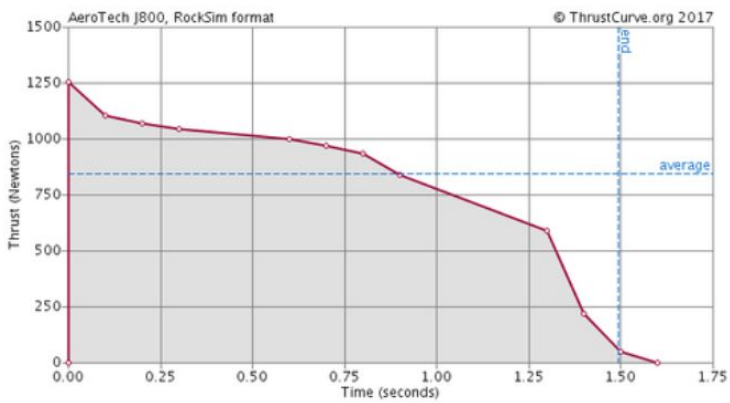


Figure 7: J800T motor thrust curve. Source: wildmanrocketry.com

Roll Angle vs Time vs Command State

Flight 1

The command state for the first flight was to autonomously self correct for any natural rotation of the rocket or any rotation caused by wind. Even though our video cut out for most of flight 1, the last few seconds of the coasting phase before apogee show the rocket get hit by a gust of wind and immediately self correct back to its original orientation. The data received by the sensors plotted in Figure 1 shows the same thing: the rocket would get knocked off of its starting orientation and would self correct back to that same starting orientation. Therefore, both sets of data show that the rocket autonomously self corrected for any roll after burnout.

Flight 2

The command state for the second flight was to start by rolling the rocket clockwise until the camera is pointing north and to hold that orientation for 1 second, then rotate the rocket counter-clockwise 90 degrees and hold for 1 second, roll the rocket counter-clockwise 180 degrees and hold it for 1 second, and finally have the rocket rotate counter-clockwise by 90 degrees and hold it for 1 second. As the rocket is moving, it should send its corresponding LED light signals so the LED lights turn on depending on how the rocket is or isn't rotating. If there is more time after these commands are executed, repeat the commands. The video and the flight data for the second flight revealed that the rocket did not successfully complete these commands. The rocket appeared to get stuck and just hold the first command instead of switching commands after one second. This could be because of faulty code, disconnected wires, electronics failures, or the flywheel not spinning correctly. The flywheel could break if several screws came undone or the motor broke from spinning aggressively for a long period of time. It also could have been broken during the faster landing from the first flight, which dislodged several wires in the flight computers.

Pre-and Post-Launch Procedures Assessment

Our pre/post launch procedures were effective at streamlining the preparation of the rocket. Although our checklists and task-delegation made it easy for us to quickly assemble the rocket for launch, in both cases (preparation before the first launch and preparation between launches), we had trouble with our flight computers. As we worked to prepare the avionics bay, we kept losing continuity with our RRC3 altimeters. We didn't want to launch without a backup and sacrifice safety for time, so our assembly process was delayed by a few minutes over the 1 hour limit. This was because we had to reconnect several wires and change both flight computer batteries. If the wire had not been disconnected, we would have launched within the hour time limit. However, we didn't feel comfortable only launching with one flight computer, so we prioritized safety over speed. In future launches, it would be smart to tape over the terminal blocks of the altimeters to ensure that the wires don't get disconnected as we move the sled around in the avionics bay during preparation.

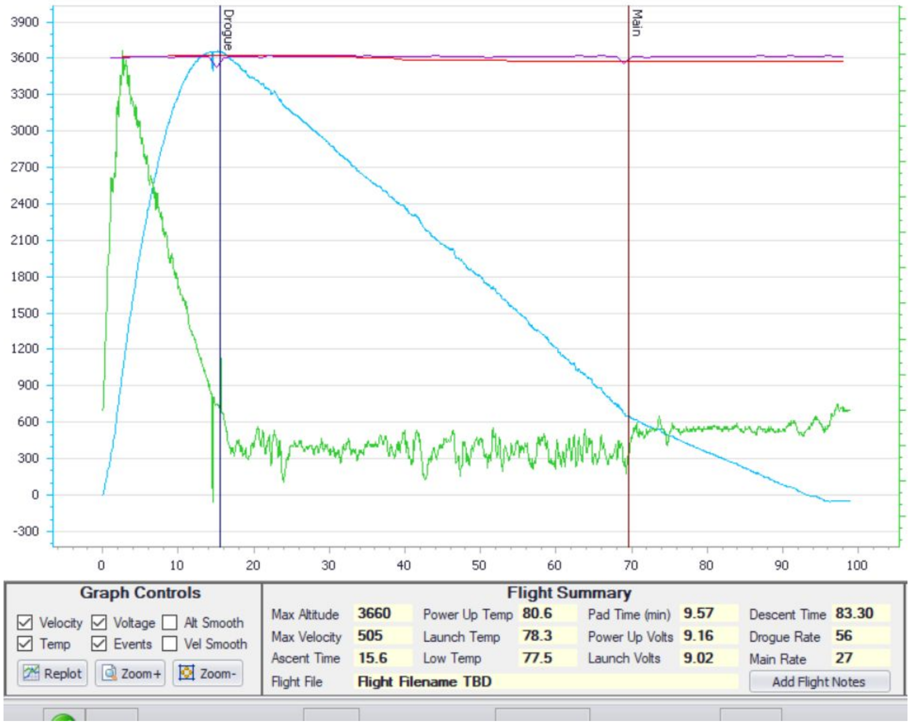
Our post launch procedures were designed mostly to keep students safe. Thus, the first things that we did were check to make sure that all of the ejection charges exploded during descent, then to disarm the flight computers by disconnecting the switch wires. After the judges deemed the rocket was in one piece and in safe condition, the rocket was disassembled and cleaned after both flights. In between launches the parachutes and shock cords were inspected for holes and burns. The parachutes were refolded and the shock cord was rebundled. In addition, the motor casing was cleaned after both flights. The main focus of both the pre and post launch procedures was to assemble the rocket as quickly as possible as safely as possible.

Other Sensor Data

The other sensor data that was collected during the flight was the longitude and latitude of the rocket. The longitude of the rocket during flight was centered around -92.9269 degrees and the latitude was centered around 45.5459 degrees. The negative longitude indicates that the longitude was West and the positive latitude indicates that the latitude was North. These values are consistent with the actual latitude and longitude of North Branch, MN which was 45.5102 degrees North and 92.9931 degrees West respectively.

Appendix

<u>Flight Computer Data: Flight 1</u>



<u>Flight Computer Data: Flight 2</u>