E178 Final Report

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Contents

List of Figures

E178 Final Report

I. Introduction

The final project rocket brings together all of the theory learned throughout E178: Advanced Rocketry for a successful high-powered rocket flight to collect experimental data. The final project rocket is a fiberglass frame with thermistors, a GPS, an accelerometer, a magnetometer, and a gyroscope. The rocket was designed to collect altitude, acceleration, velocity, temperature, and rotation durign the flight. The rocket was flown twice on April 8 and twice on April 14 to collect four sets of experimental flight results.

The rocket is constructed from a Madcow 54mm Adventurer body and uses a custom internal avionics bay. The rocket uses a Featherweight Raven 3 as the main flight computer, an Eggtimer Quark as the back-up flight computer, and the Teensy Data Logger to save sensor data on an SD card.

Flight 1 and Flight 2 used J425 motors, Flight 3 used a J453 motor, and Flight 4 used a J530 motor.

Fig. 1. Picture of the rocket set up for Flight 3

II. Flight 1

A. Acceleration, Velocity, and Altitude

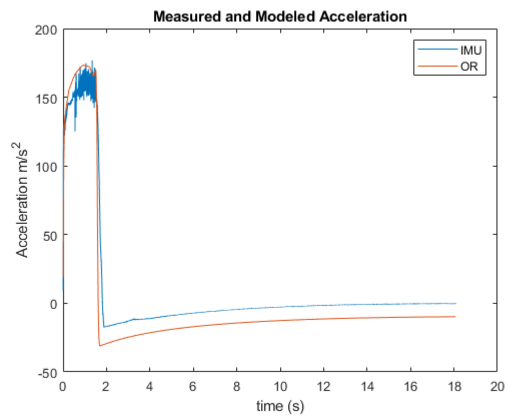

Fig. 2. Flight 1 measured and modeled acceleration.

For the acceleration graph, there is a peak acceleration around 175 m/s^2 for both the IMU and OpenRocket measurements with burnout ending at 1.8 s. After burnout, there is some disagreement between the IMU measurement and Open Rocket possibly caused by rocket modeling errors or environmental factors.

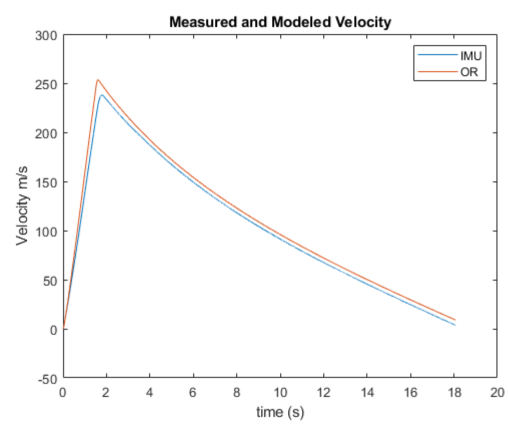

Fig. 3. Flight 1 measured and modeled velocity.

The IMU flight measurements match the expected OpenRocket Velocity fairly closely for velocity. The Open Rocket expected a slightly higher peak velocity at 255 m/s compared to the IMU measurement of 235 m/s.

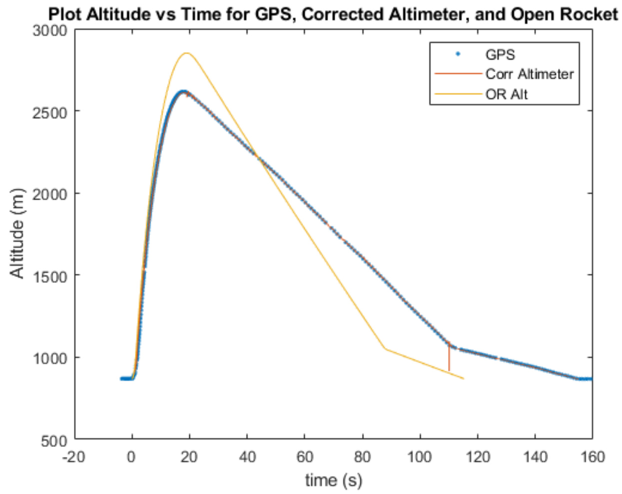

Fig. 4. Flight 1 altitude versus time.

For the plot of altitude versus time, there are some interesting observations. The peak altitude measured by the GPS at 2600 m is significantly lower than the expected Open Rocket peak altitude at 2800 m. This agrees with the difference shown in the velocity plot. These differences could be caused by launch angle, temperature, and wind conditions that were not ideal.

For parachute deployment, the OpenRocket model expected the main chute to deploy at 84 s but the main chute didn't deploy until 117 s during the flight.

B. Axial Rotation

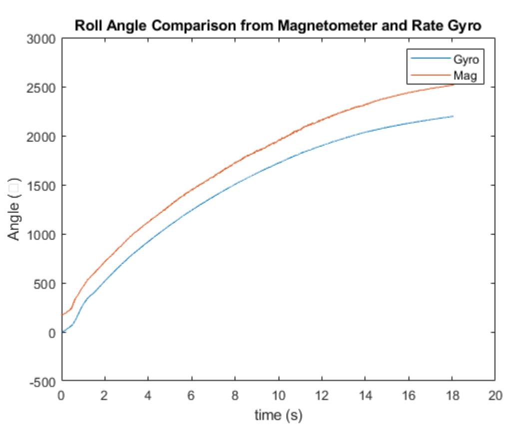

Fig. 5. Flight 1 average roll angle.

There is an offset in the roll angle from the magnetometer and rate gyroscope and then the angles measured by each diverge over time.

C. Average C_d

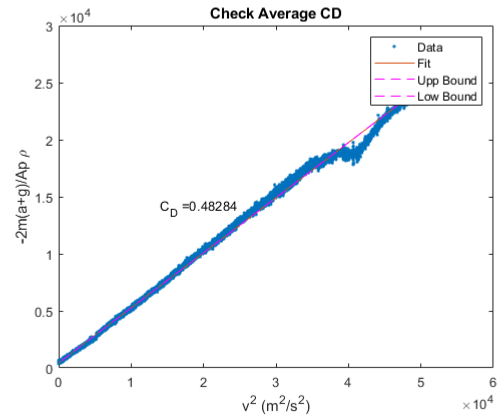

Fig. 6. Flight 1 average drag coefficient.

The drag coefficient is calculated by comparing velocity squared with $-2m(a+g)/A\rho$.

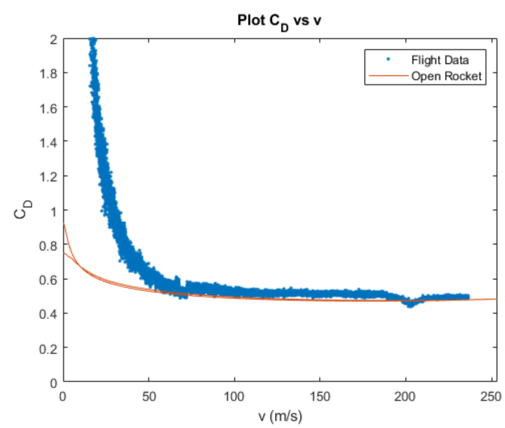

Fig. 7. Flight 1 coefficient of drag versus velocity.

The plot of C_D versus velocity do not match up very well between the flight data and OpenRocket.

Looking at the plots of average C_d as well as C_d versus velocity, there are several interesting graph artifacts. The plot of C_d versus velocity is from burnout to apogee, and when the motor burns out the rocket is at its highest speed. We derive the velocity by integrating the acceleration, however, there is the assumption that the rocket is purely vertical. If the rocket is horizontal or has a horizontal velocity component, then subtracting 1g in the model to get velocity decreases the agreement from the model. Therefore, at low velocities under 50 m/s there is poor agreement because the model assumptions breakdown.

D. Thrust Curve Comparison

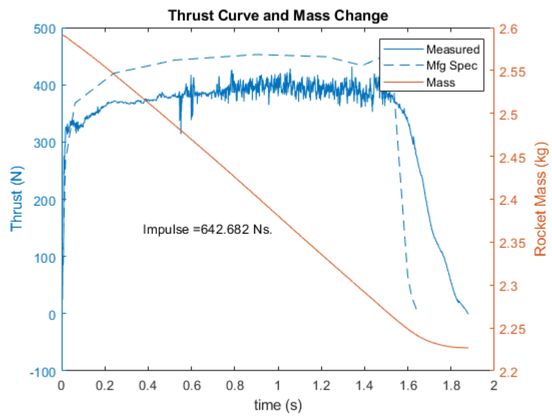

Fig. 8. Flight 1 thrust curve and mass change.

The thrust curve has a similar shape to the provided model; however, it is a bit lower. Thrust curves are calculated from acceleration data, so the measured thrust curve may be lower as a result of the rocket not being completely vertical during flight.

E. Temperature vs Altitude

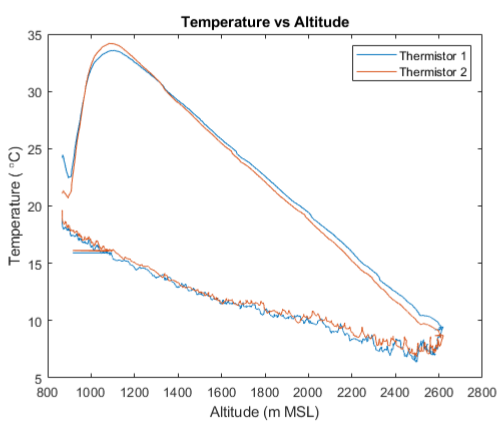

Fig. 9. Flight 1 temperature versus altitude.

The temperature measured from the two thermistors agree with each other. The temperature starts at 23°C and increases to 34°C during motor burnout. Then the temperature decreases as the rocket increases altitude to 10°C at the peak of the rocket's ascent. The temperature then slowly decreases down to 18°C as the rocket descends after parachute deployment.

III. Flight 2

Flight 2 happened during launch day 1 and used the same J425 motor as Flight 1. The rocket performed the flight smoothly and landed with every part undamaged. The rocket still went up at an angle both due to inaccurate placement and the strong wind that took place during that launch. To avoid a great deviation from the launch site to the landing position of the rocket, the main chute is changed from one of size 45 inches to one of size 36 inches due to a wind speed higher than 7 m/s.

A. Acceleration, Velocity, and Altitude

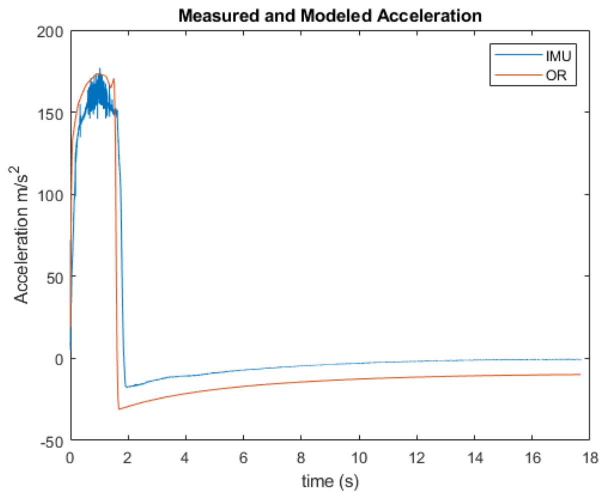

Fig. 10. Flight 2 measured and modeled acceleration.

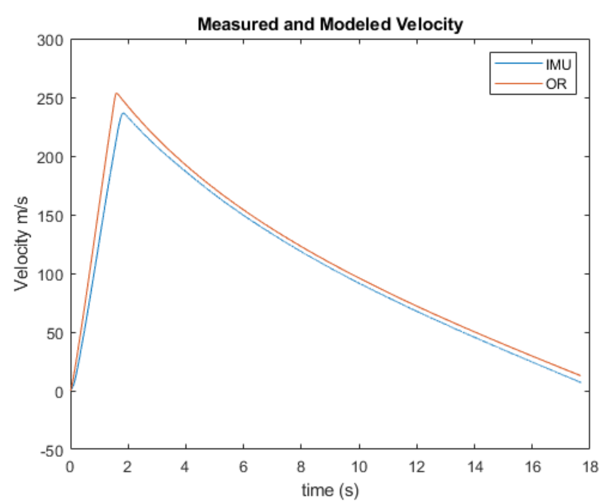

Fig. 11. Flight 2 measured and modeled velocity.

The first two figures, figure 10 and figure 11, focus on the part of the flight before apogee. Similar to flight 1, flight 2 is also quite successful and the general kinematics of the flight follows what was modeled by the open rocket simulation. The small discrepancy comes from the sloped orientation the rocket went instead of the ideal vertical situation in the simulation. This results in smaller acceleration values in the vertical direction both before and after burnout; thus, a generally lower velocity throughout the flight.

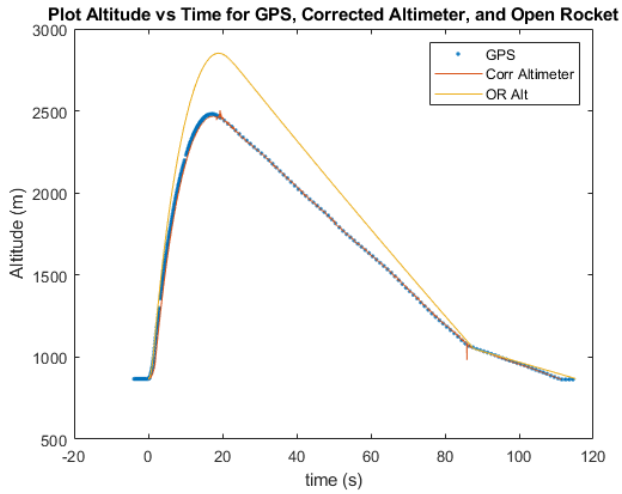

Fig. 12. Flight 2 altitude versus time.

The resulting altitude map for the flight is plotted in figure 12, containing the comparison among corrected results from altimeter, GPS altitude log and the open rocket altitude simulation results. As expected, the GPS and altimeter both show the correct pattern with a steep climb before apogee, a smooth turn around apogee, and another turn when the main chute deploys. The time of the turning points align with those from the simulation and the general height is lower than the ideal situation mainly due to angled orientation of the flight.

B. Axial Rotation

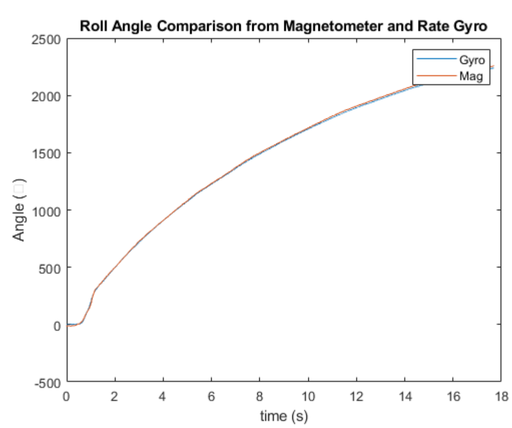

Fig. 13. Flight 2 average roll angle.

In figure 13, there is a great agreement between magnetometer and gyroscope results in the rolling angles of the rocket. Thus, no further processing of the data is needed.

C. Average C_d

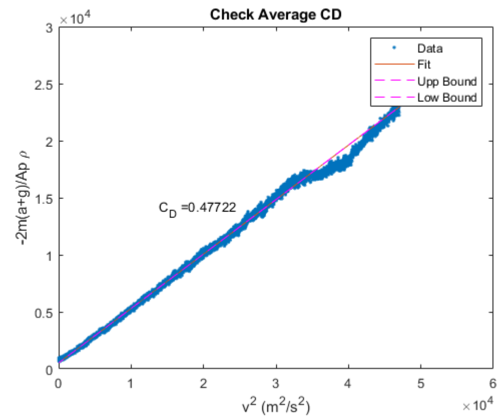

Fig. 14. Flight 2 average drag coefficient.

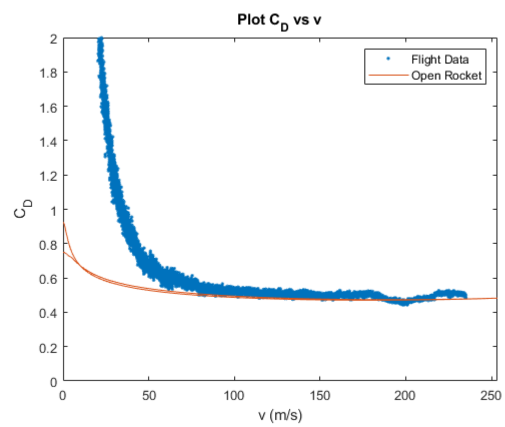

Fig. 15. Flight 2 coefficient of drag versus velocity.

Figure 14 and 15 examines the post boost drag coefficient. Average drag coefficient C_d can be calculated from the slope of a linear regression of performed in figure 13, it aligns with the simulation quite well. The plot of C_d versus velocity in figure 6 exhibits some interesting agreements and discrepancies. As explained earlier, the rocket did not perform a perfect vertical flight, thus the velocity from burnout to apogee failed to align with the model perfectly. Thus, with the assumption that all drag and thrust forces act in the vertical direction, the calculation performed poorly in the lower velocity conditions due the larger effect gravitational acceleration has on rocket performance under lower velocity conditions. The rocket did not go super sonic, thus in higher velocities, the results did align with the model quite well.

D. Thrust Curve Comparison

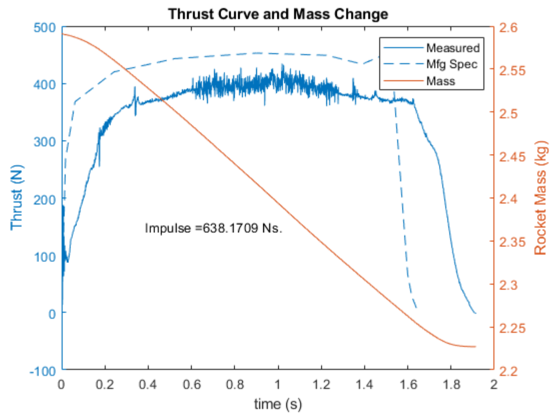

Fig. 16. Flight 2 thrust curve and mass change.

The thrust curve and impulse in figure 16 does align with the provided model quite well. The recorded thrust curve is a bit longer than the provided model could be results from non-ideal combustion and also inaccurate selection of lift-off time and burnout time since the motor burns in quite a short and delicate time period.

E. Temperature vs Altitude

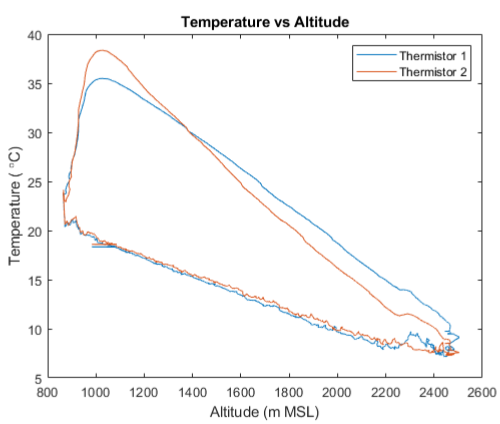

Fig. 17. Flight 2 temperature versus altitude.

The thermistor outputs in figure 17 also align with the expectations. The temperature lapse rate is estimated to be -0.0090984 K/m. This is not far from the standard condition of -0.0065 K/m and the difference can be resolved into factors containing the weather conditions, electronic errors etc.

IV. Flight 3

For flight 3 a J453 motor was used in comparison to the J425 motors used in flights 1 and 2 of launch day 1. Since wind speeds were low, roughly zero meters per second, the 45" parachute was sufficient and the temperature measured was an even 60° F.

A. Acceleration, Velocity, and Altitude

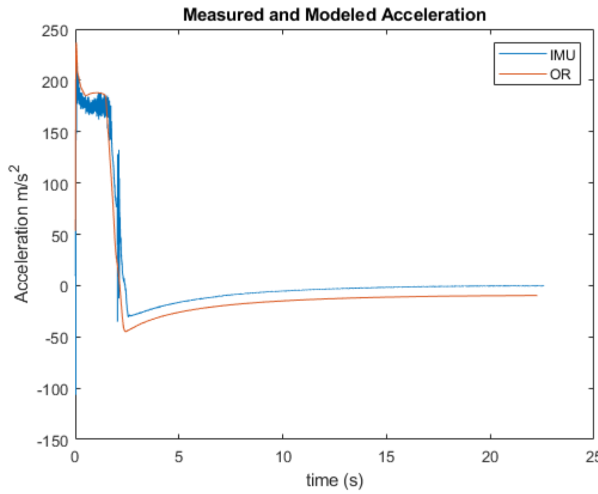

Fig. 18. Flight 3 measured and modeled acceleration.

The measured and modeled acceleration examines the assent, specifically zooming in on the burnout. There is an initial spike at about 200 m per second squared in both the OpenRocket simulation and the IMU. This spike starts to decline around the 2-second mark which represents the time to burnout. The OpenRocket simulation has a higher initial acceleration than our measured acceleration which is also seen in our measured and modeled velocity, altitude, and thrust curve; possible causes will be spoken of later. Also observable is that our upper plateau lasts longer than the modeled section which we will see also plays into our other graphs. After this sharp decline the acceleration plateaus and remains positive which shows the rocket continuing its assent, however, we see that the measured acceleration is higher than the modeled acceleration which might be due to the 1g subtraction in extracting the acceleration, but it is not shown before 5 seconds which may indicate that another factor caused this difference.

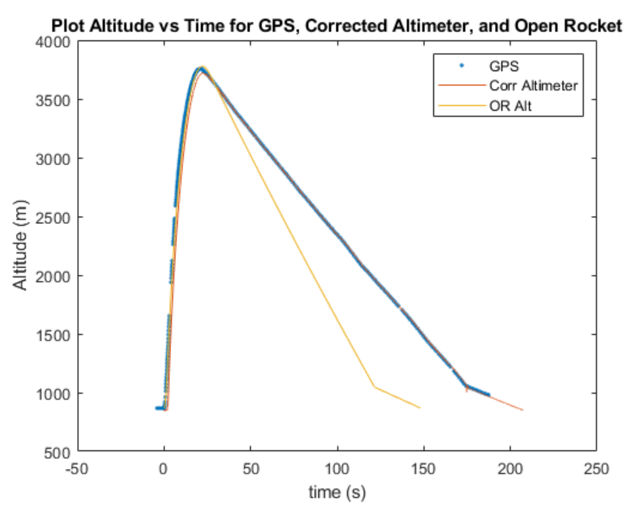

Fig. 19. Flight 3 measured and modeled velocity.

In the measured and modeled velocities, there is a difference in the max velocity speeds and time between the measured and modeled velocities. The measured velocity comes from integrating our measured acceleration which causes the same disparity in velocity as our measured and modeled acceleration. The difference in the peak velocity time is a result of the acceleration's peak lasting longer meaning it will take longer to reach the peak velocity. Unlike the acceleration graphs, our velocity has great agreement after the burnout period for the rest of the assent.

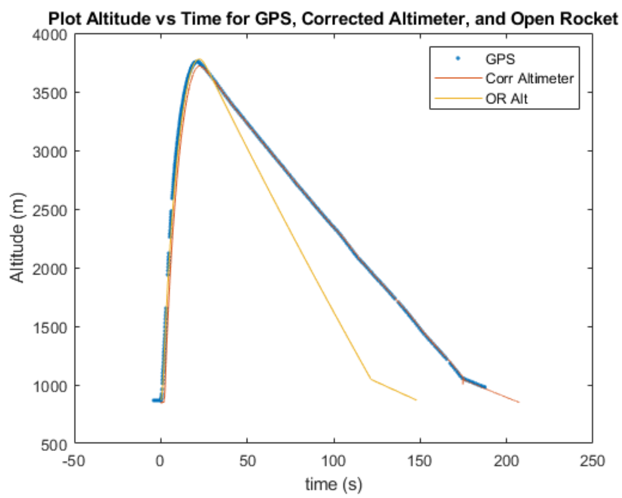

Fig. 20. Flight 3 altitude versus time.

In the altitude graph the GPS, corrected altimeter, and OpenRocket simulations are plotted against one another. The OpenRocket has a higher apogee height which agrees with the acceleration and velocity graphs; because the initial acceleration and velocity are different in our measured and modeled versions and the burn of the motor is what dictates the flight it is expected a lower initial acceleration will cause a lower peak apogee assuming similar. We see that the OpenRocket also does not align past apogee. This is due to the modeling system that OpenRocket uses as the software assumes that most of the drag is due to the parachute. In our application, we used a 12" drogue parachute which is contributing a smaller percentage of the drag compared to the rest of the body of our rocket, a length of 169cm with a 54 mm diameter. The software assumes a negligible amount of drag from the body which would mean less drag overall is being provided so the rocket will descend faster. After that section, there is a less steep descending period, which starts slightly above 100m for both measured and modeled, which represents the main parachute deploying. Because the main parachute is so large we see that the simulation and measured descend rate are the same which further explains the disparity for the drudge shoot section. When looking at the GPS and the corrected altimeter the descent occurs at a lower rate. Another point of note is when looking at the GPS the assent there are not many data points which mean few satellites are locked on. Due to government regulations precise GPS lock can not happen as GPS at those altitudes with the speeds of a rocket would be classified as a guided missile which would raise alarm and since there is an agreement before and after it is unnecessary to have GPS lock at those points. Agreement between the GPS, corrected altimeter and OpenRocket look good for the ascent and the agreement between the GPS and corrected altimeter on the descent.

B. Axial Rotation

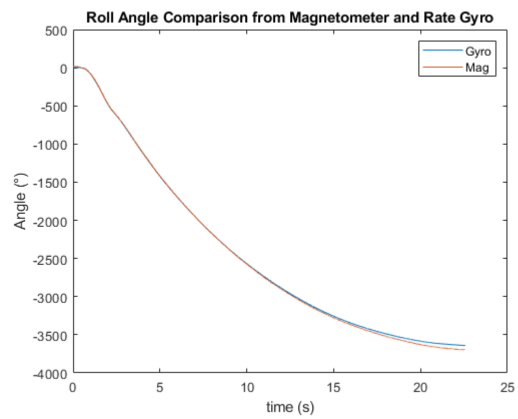

Fig. 21. Flight 3 average roll angle.

There is a great agreement in the roll angle from the magnetometer and rate gyroscope, so a filter such as a Kalman filter is not necessary.

C. Average C_d

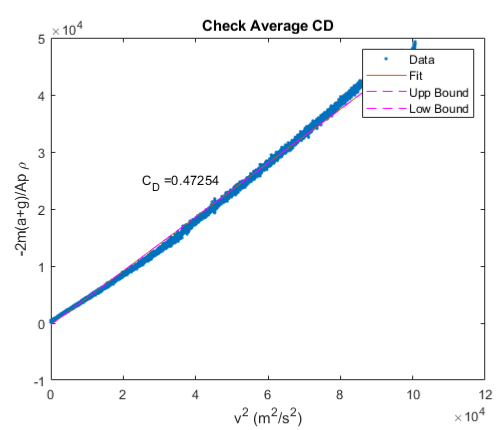

Fig. 22. Flight 3 average drag coefficient.

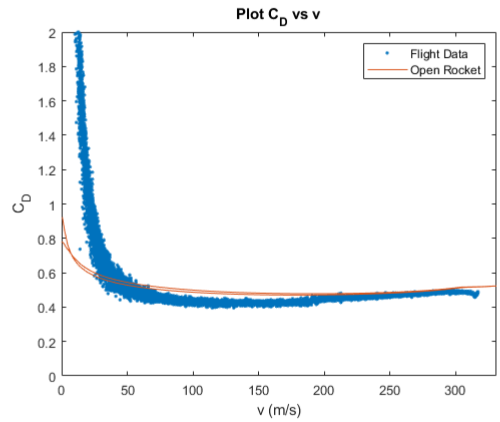

Fig. 23. Flight 3 coefficient of drag versus velocity.

The coefficient of drag graphs examine the assent specifically from burnout to apogee, with the rocket's highest speeds at burnout and lowest at apogee Looking at the average coefficient of drag versus velocity squared there is generally great agreement. When looking at the coefficient of drag versus velocity we see similar agreement and the same dip except at velocities lower than 50 meters per second. This is due to OpenRocket simulating the entirety of the flight as purely straight upwards but in reality, as the rocket slows to apogee the rocket will approach a horizontal position which increases surface area thus greatly increasing the drag. This issue is solved in the average coefficient of drag graph due to the squaring process making smaller values significant.

D. Thrust Curve Comparison

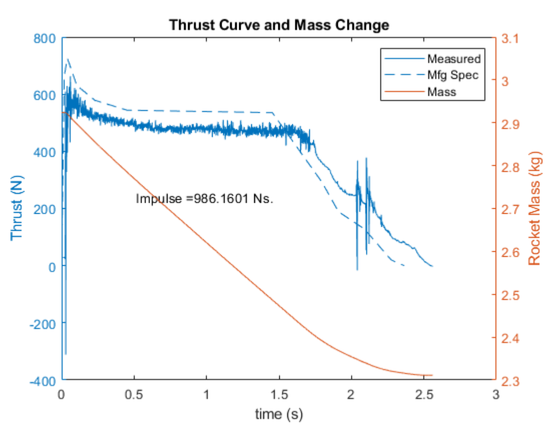

Fig. 24. Flight 3 thrust curve and mass change.

The thrust curve and mass change graph look at the burn time, thrust, and mass of the motor that is modeled from ThrustCurve.org versus our measured values which are derived from the acceleration and coefficient of drag calculated. The dotted line represents the thrust curve that the motor should have followed. The measured motor lasted longer, both in the upper plateau and overall burn time, than the thrust curve of the motor showed which validates the time difference in the accelerations and velocity graphs. There is also a difference in the total impulse since the impulse from ThrustCurve.org for the motor used is 1012.6 newtons but when actually used it only reached 986.2 newtons. This explains the difference between the measured and modeled peak altitude, acceleration, and velocities .

E. Temperature vs Altitude

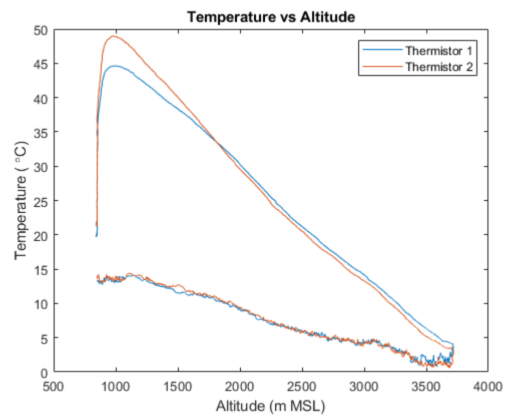

Fig. 25. Flight 3 temperature versus altitude.

The temperature versus altitude graphs shows the temperature taken from two external thermistors throughout the flight. The temperature at launch was 60° F which is about 16° C however the data is cropped to 1000 m for clarity of the graph. The top section represents the assent with the peak corresponding to the launch to burnout and the steady decrease in temperature to the burnout to apogee. Once the rocket reaches burnout at around 1000m the temperature which had been rising fast due to the motor burning begins to slow down due to being at such high cold altitudes. Then the rocket reaches apogee and slowly descends which is represented by the lower section. Here we get an agreement of the point of apogee with our altitude versus time plot. This area gives us the true temperature with altitude which allows us to extract the lapse rate and compare it to the standard lapse rate. A best-of-fit line of the descent provides a lapse rate of -0.049016 ° C per meter or 4.9 ° C per kilometer. This flight provides a lapse rate that is noticeably lower than the standard lapse rate of 6.5 ° C per kilometer and also compared to the lapse rates of flights 1, which was a similar time and starting temperature on a different day, and flight 4, which was the same day just later with a starting temp of 70° F or about 21° C. As seen in the first assignment various conditions such as humidity, pressure, and temperature differences will influence the flight and might be the cause of this large difference front the standard.

V. FLIGHT 4

A. Acceleration, Velocity, and Altitude

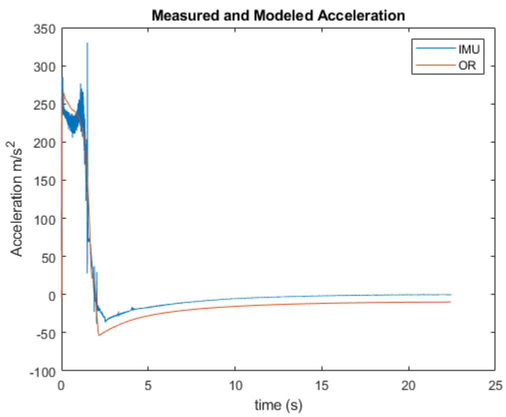

Fig. 26. Flight 4 measured and modeled acceleration.

For acceleration, note the difference between measured acceleration (IMU) and the Open Rocket modeled acceleration. There is agreement during burnout, which corresponds to later measured and modeled C_d agreement, but after the burnout period when the rocket is slowing down there is a noticeable difference. This difference may be related to the 1g subtraction in extracting the acceleration, but it is not shown before 5 seconds which may indicate that another factor caused this difference.

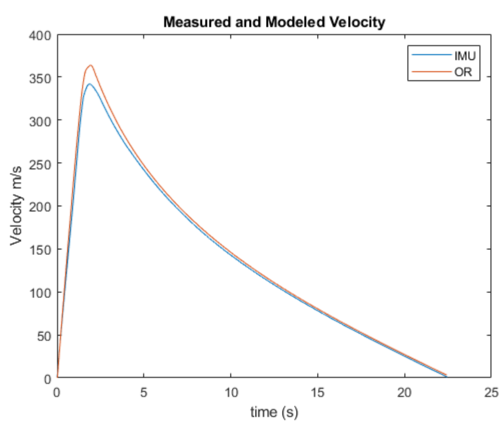

Fig. 27. Flight 4 measured and modeled velocity.

For velocity, there is not the same lack of agreement after 5 seconds. There are differences in peak velocity, which we can attribute to the differences in impulse of the motor and the OpenRocket simulated impulse. Additionally, the tilt of the rocket during launch could have caused a lower peak velocity.

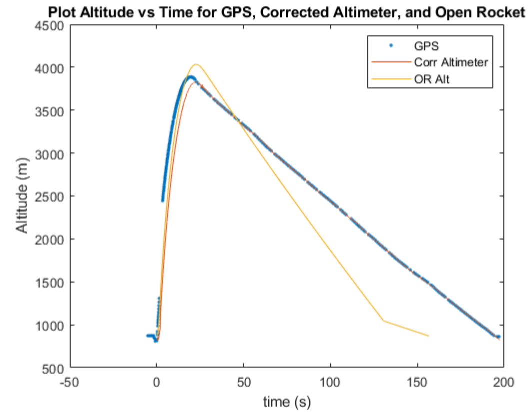

Fig. 28. Flight 4 altitude versus time.

For the plot of altitude versus time, there are a few key elements to investigate. First, like in the plot of velocity versus time, the difference in peak altitude can be partially attributed to a difference in conditions which cause the rocket to not have purely vertical motion. OpenRocket simulates launch with ideal weather conditions, but the launch angle, temperature, and wind conditions were different during flight 4. Additionally, the GPS is losing lock during ascent, which can be observed from the lack of thick blue line and only a few dispersed dots at 0 seconds. Before 0 seconds the GPS has lost its lock completely, with only 3 satellites.

The main chute's lack of deployment can also be clearly observed from this plot, as the OpenRocket model has a bent yellow line around 125 seconds and the rocket altimeter does not exhibit this same bend. The model and the true altitude differ greatly during descent, and this can be attributed to a difference in descent rate. Ideally, the descent rates should be the same. Drag in Open Rocket is calculated from the point mass coming from the shroud lines and the parachute, and the OpenRocket modeled drouge chute size was not the same as the true chute size.

B. Axial Rotation

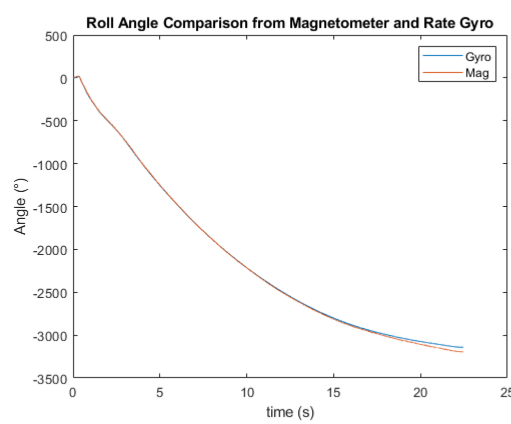

Fig. 29. Flight 4 average roll angle.

There is great agreement in the roll angle from the magnetometer and rate gyroscope, so a filter such as a Kalman filter is not necessary.

C. Average C_d

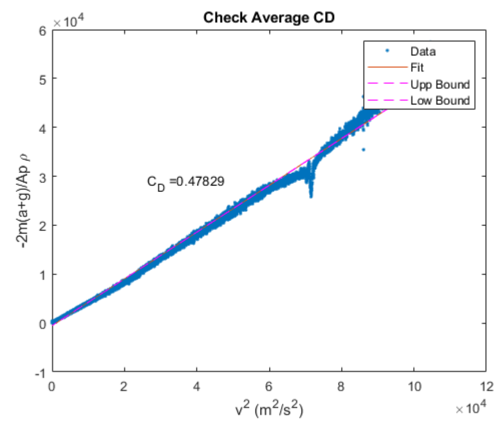

Fig. 30. Flight 4 average drag coefficient.

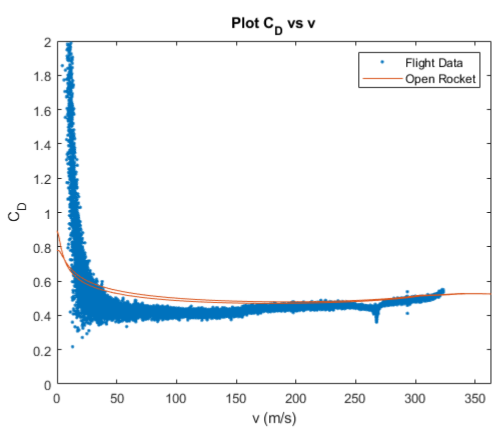

Fig. 31. Flight 4 coefficient of drag versus velocity.

At low velocities under 50 m/s there is poor agreement because the model assumptions breakdown. Additionally, there is a large spike at 331m/s. This is when the rocket hits sonic velocity, which OpenRocket does not handle well. In the average C_d plot, there is also the negative and positive dip observed, but not the agreement issue as the velocity is squared such that it gets small enough to go to 0. The negative dip in the drag profile is not unusual, but all other dots are fake artifacts.

D. Thrust Curve Comparison

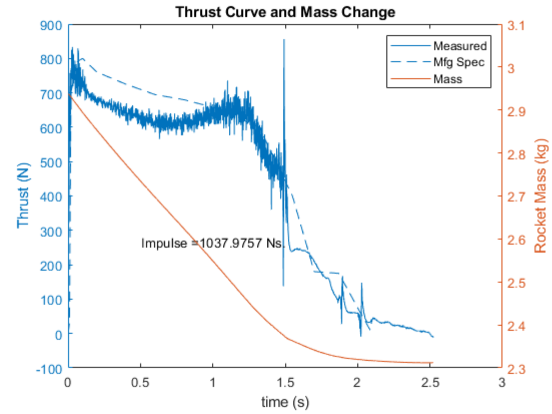

Fig. 32. Flight 4 thrust curve and mass change.

The thrust curve aligns well with the provided model, however it is a bit lower. There is also a difference in the total impulse since the expected impulse from ThrustCurve.org for the motor used is 1115.5 Ns when the calculated impulse was 1037.9757 Ns.This explains the difference between the measured and modeled peak altitude, acceleration, and velocities, as thrust curves are calculated from acceleration data.

E. Temperature vs Altitude

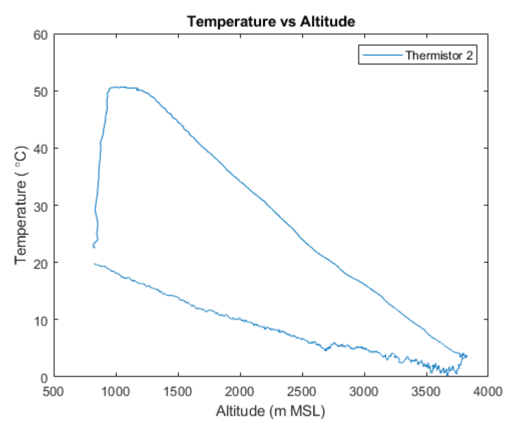

Fig. 33. Flight 4 temperature versus altitude.

For flight 4, only the data from thermistor 2 could be recovered. Upon landing and inspection, the data from flight 4's thermistor 1 looked like noise with square waves, making it impossible to create a meaningful story of temperature during flight from. As a result, only the temperature from thermistor 2 is included above. While we are unsure of the reason that thermistor 1 was destroyed, one plausible conclusion is that either it was damaged during landing or the circuit was damaged when installing it for the final flight. The temperature lapse rate from a line of best fit for the second thermistor is -0.0061002 K/m. This is not far from the standard condition of -0.0065 K/m, and the remaining difference in lapse rate can be attributed to different weather conditions.

VI. Conclusion

Overall, the rocket performed 4 successful flights over 2 launch days. The only errors were from equipment failures in the fourth flight. Most of recorded data from multiple sensors agree with each other and the post-processing meets the expectations from the OpenRocket model based on pre-recorded metrics. The impulse and kinematics values are all lower than expected due to non-ideal combustion and flight conditions including a launch angle that was not straight.

Our largest failure in the flights comes from the fourth flight when the main chute failed to deploy and one of the two thermistors failed to record accurate data. The rocket remained undamaged despite the lack of chute deployment. Both Raven and Quark failed to deploy the injection charge on the side with the main chute. The electronics and both injection charges were functional when tested after the flight. Based on this, we can only surmise that the failure is due to some loose connection or other electronics problems mid-flight, including possible brief shorting, due to extreme temperature, pressure, vibration or tumbling experienced during the flight since the charges are functional and so are the main parts of electronics. The inaccurate recording from one of the thermistors is likely the results of an ungraceful landing and possible dragging against the ground from flight three damaging the thermistor on the side.

Aside from the main difficulties in flight 4, the project could benefit from several modifications to the rocket. The customized avionics bay fits all electronics well, however, a cleaner wiring and allocation of space inside will significantly reduce the difficulties on site assembling avionics before each flight. Better and more even fillets at the tail can reduce the trajectory angle from vertical, leaning closer to the ideal situations. Last but not least, the addition of more sensors and hardware will provide more insights into the flight and help with mapping the flight with more details in analysis.

The team learned a lot about rocketry and experimental flight design from the final project. The rocket design, construction, testing, flights, and data post-processing taught the team about all aspects of high powered rocketry. The lessons learned will be valuable for future projects involving rocketry and for experimental engineering in general.