Exploring Low-Cost DIY Rockets with Flight Recording using 3D Printing and Low-Cost Sensors

Design, Launch, Data Analysis, and Lessons Learned

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2024-10-30

Contents

```
## Warning: Paket 'ggplot2' wurde unter R Version 4.2.3 erstellt

## Warning: Paket 'pracma' wurde unter R Version 4.2.3 erstellt

##
## Attache Paket: 'dplyr'

## Die folgenden Objekte sind maskiert von 'package:stats':
##
##     filter, lag

## Die folgenden Objekte sind maskiert von 'package:base':
##
##     intersect, setdiff, setequal, union

## Warning: Paket 'plotly' wurde unter R Version 4.2.3 erstellt

##
## Attache Paket: 'plotly'

## Das folgende Objekt ist maskiert 'package:ggplot2':
##
##     last_plot

## Das folgende Objekt ist maskiert 'package:stats':
##
##     filter

## Das folgende Objekt ist maskiert 'package:graphics':
##
##     layout

## Warning: Paket 'webshot2' wurde unter R Version 4.2.3 erstellt

## Warning: Paket 'geosphere' wurde unter R Version 4.2.3 erstellt

##
## Attache Paket: 'geosphere'

## Das folgende Objekt ist maskiert 'package:pracma':
##
##     geomean
```

1 Goals

3D printed Fit multiple motors Record as much flight data as possible for "cheap"

2 Design

The design section is divided into three parts. The first covers the rocket's overall design, detailing its structure and components. The second explains the simulations conducted to evaluate the rocket's expected performance and stability. The final part outlines the features of the flight recorder and the key decisions made during its development.

2.1 Rocket Structure

The rocket follows a traditional hobbyist design, featuring a single motor located at the base with no active guidance system (Center, 2024). To ensure stability during flight, fins are positioned at the bottom. Additionally, since the rocket is intended for recovery, the nosecone must be detachable, triggered by the ejection charge from the motor. This requires the ejection blast to travel the full length of the rocket to the nosecone without damaging the on-board electronics responsible for recording flight data. Based on these goals, the following decisions were made regarding the design and manufacturing of the rocket:

2.1.1 The Case for 3D Printing

Due to the goals of affordability and easy of manufacturing the decision to use 3D printing to manufacture as many pieces of the rockets as possible was made. 3D printing allows anybody with access to the 3D model of the rocket to produce it nearly identical. The widespread adoption of 3D printing for hobby projects made printers as well as filament widely available, cheap to obtain and easy use. Therefore the rocket can not only be replicated with low complexity for the builder but also at a minimal cost or effort involved (Pearce & Qian, 2022). Additionally the process of 3D printing allows to easily build geometries that would usually be hard or expensive to machine or produce at small production volumes and scales (Berman, 2012, 2020). Specifically FDM 3D printing was used to build the complete Rocket structure.

2.1.2 Selected Materials

Different 3D printing filaments offer different strength or density properties that might be more beneficial to use on different parts of the rocket (Bambu Lab, 2024). The most used hobbyist Filament, PLA, is an all rounder, offering good toughness, strength, stiffness, layer adhesion and ease of printing for a low price per kilogram. For this reason, PLA was chosen as the default material for most parts of the rocket that aren't subjected to high forces or extreme temperatures.

The option of printing certain components in more expensive, ultra-lightweight filaments like ASA Aero (ASA infused with a temperature-activated foaming agent) was considered. However, this approach was ultimately set aside due to the reduced strength and increased printing complexity, which limits the ability to create intricate designs to some extent.

There are 2 parts on the rocket that required further consideration before selecting the filament:

1. The fins of a rocket are often quite thin and stick out of the rocket body often making contact first when impacting during soft landings or transportation. Therefore the

2. asdf asdfasd fasdfas d.asdf asdfa dafsdfasdfa sdfa.sdf asdfasd fasdfasdfas df.asdf asdfas df adsfasdfasd. adsfasdf asdf asdf asdf asdfa.afsdf asdfas dfasdf asdf asd f.

2.2 Performance & Stability Simulations

2.3 Flight Recording System

3 Launch

In this chapter I will first analyse the launch based on the data the various sensors recorded. Following that I will compare the actual measurements with the result of the simulation. This chapter concludes with a failure analysis that summarizes all encountered issues and investigates their root causes, aiming to prevent similar and related failures in the future.

3.1 Data Analysis

The data analysis will first take a look at each sensors individual measurement. At the end the data of multiple sensors will be combined to get a more comprehensive understanding of the flight and to compare performance as well as accuracy of sensors.

3.1.1 Pressure Sensor

The primary function of the barometric pressure sensor is to measure the rocket's altitude throughout its flight. With an accuracy of approximately ±8 Pa, it can determine altitude to within ±0.5 m (Gravity, 2020). Since each point in the following figure represents the difference between the initial ground measurement and the reading at that specific moment, the cumulative accuracy adjusts to about ±1m — still providing a very reliable measurement. Additionally locally weighted scatterplot smoothing (LOWESS) has been used to plot an additional curve that is less susceptible to the minor variations in the sensors measurements.

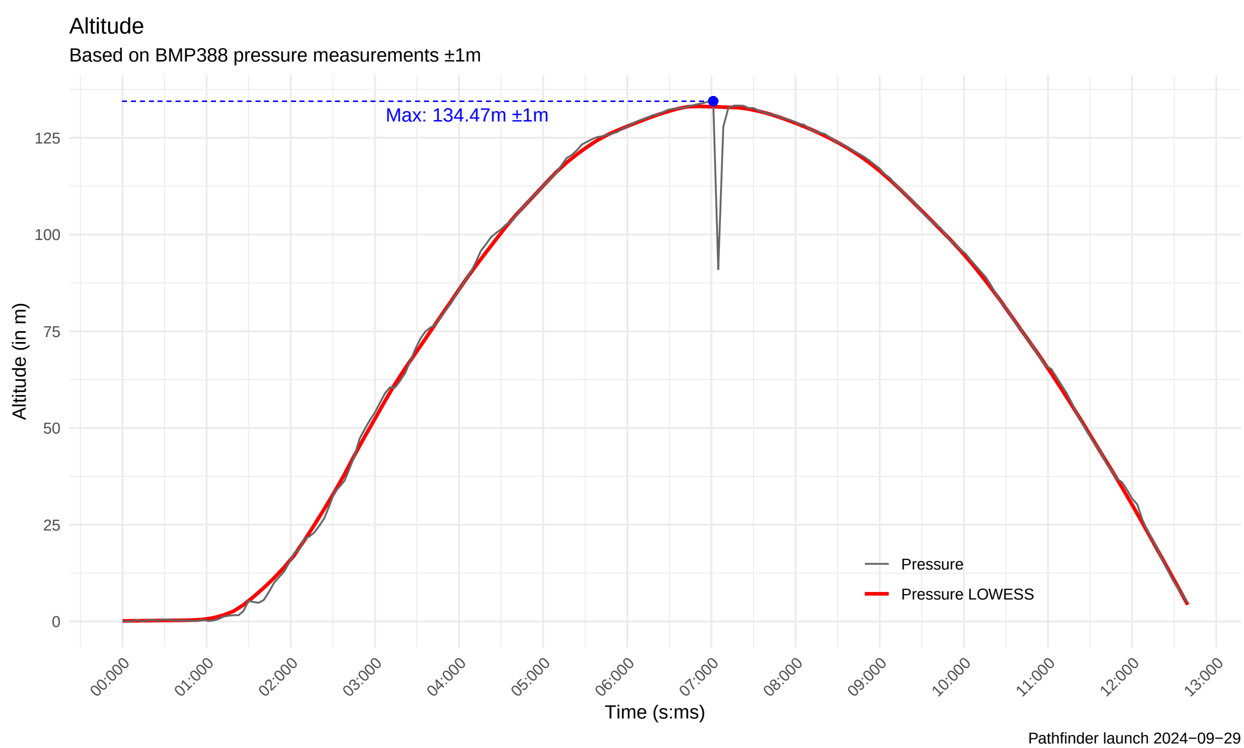

Figure 1: Altitude as measured by the barometric pressure sensor

The data shows a steep ascent between 1:00 and 2:00 followed by a slow increase until the peak of 134.47m is reached at 7:00. At this point all upwards velocity is lost due to gravity and friction. Gravity now continues to accelerate the rocket towards the ground again. Since the rocket moves faster and faster towards the ground it becomes apparent that the parachute system failed. The ejection charge was supposed to release the parachute at roughly 8:00 but the nose did not manage to seperate causing the rocket to impact the ground without slowing down.

The sudden drop shortly after the peak is reached (or perhaps covering the timeframe where the peak was really reached) is quite interesting to see. It's difficult to determine whether this dip is due to measurement error occurring coincidentally at this time, or if the rocket encountered a unique pressure phenomenon at its peak Additional flights might bring more insight if this is merely a correlation or if this is actually caused be the rocket reaching its peak. Perhaps future flights might also profit from redundant sensors.

Using the altitude data, the gradient of altitude can be calculated to determine the rocket's vertical speed. While the barometric pressure recorded by the sensor might look smooth at a first glance it becomes apparent that the minimal variations in the sensors measurements result in huge spikes when calculating the gradient. Calculating the gradient of the altitiude LOWESS yields a lot better and cleaner results that should still be very accurate since it only reduces the variation and doesnt alter the curves trajectory. This graph shows that the maximum vertical speed was around 40 m/s.

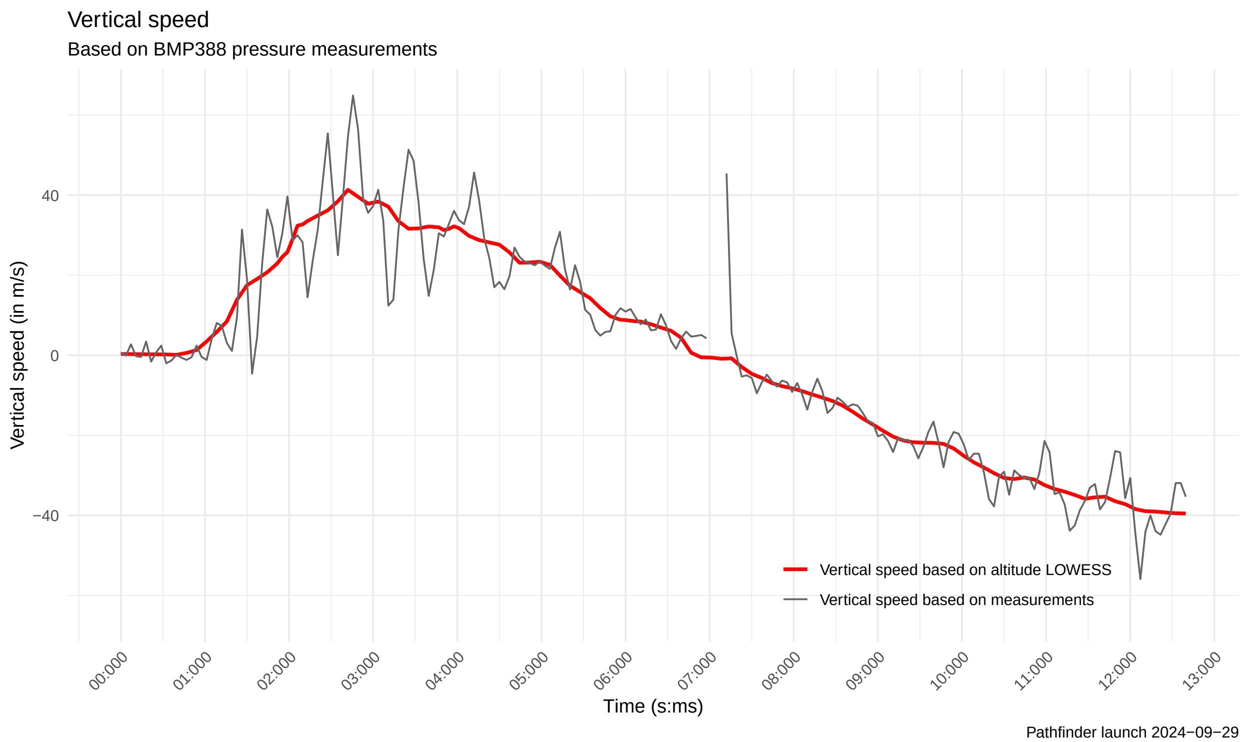

Figure 2: Vertical Speed as measured by the barometric pressure sensor

Trying to calculate a gradient from either of the calculated vertical speeds yielded no usable results. In this case even the variations of the LOWESS are to significant to produce usable data. Perhaps calculating another LOWESS based on the Vertical speed LOWESS might produce nicer looking results but it is questionable how accurate those would still be.

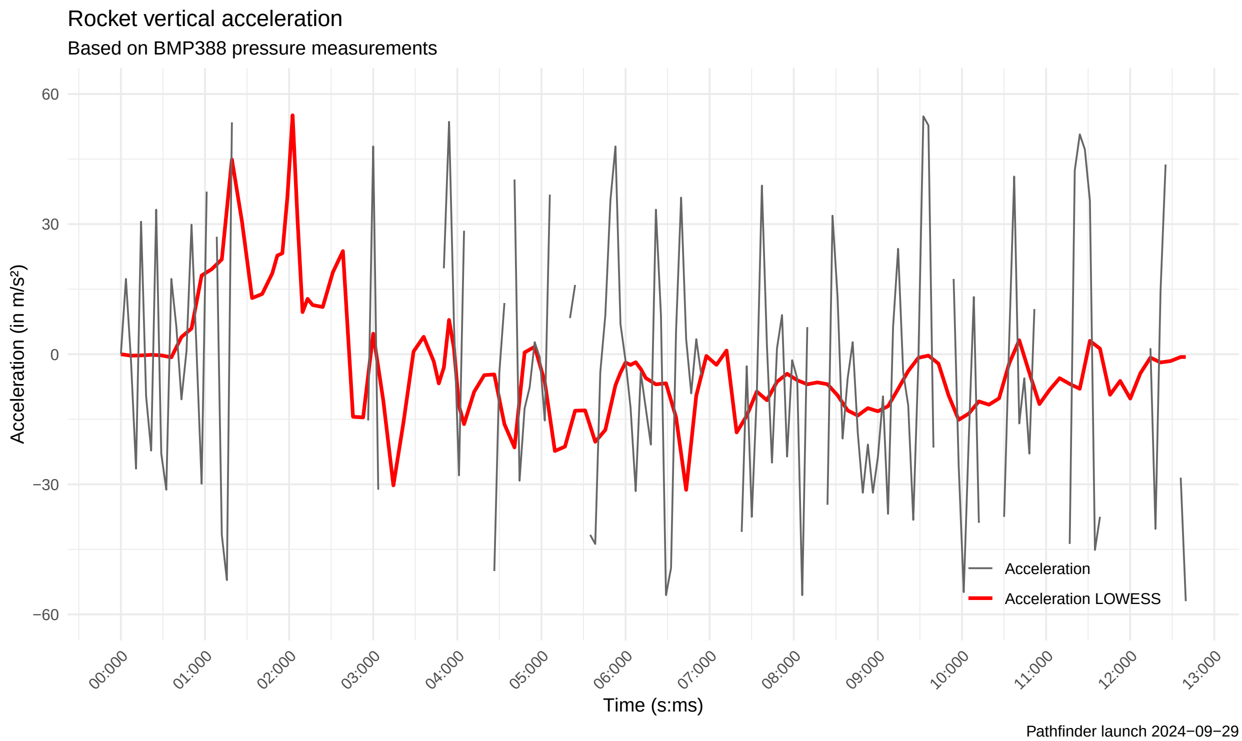

Figure 3: Vertical Acceleration as measured by the barometric pressure sensor

The barometric pressure sensor is the perfect sensor for determining the altitude during the flight accurately. The high velocity of the rocket does not seem to have decreased the quality of measurements except perhaps the sudden decrease and increase shortly after or during the peak of the rocket. Variations in the individual measurements make it hard to calculate a gradient but using local regression it is possible to still determine the speed of the rocket during the launch. The variations seem to be to high to calculate the acceleration of the rocket though which is a bummer since it would have been interesting to compare the vertical acceleration measured by the pressure sensor and the accelerometer.

3.1.2 Accelerometer

The accelerometer recorded the acceleration of the rocket in 3 axis during the launch. The most interesting axis is the vertical axis labeled with Y in the graphic below.Looking at the data it becomes apparent though that there. As expected the vertical acceleration matches the thrust curve of a D12-5 engine in shape and duration (Estes, 2023) confirming the validity of measurements to some degree.

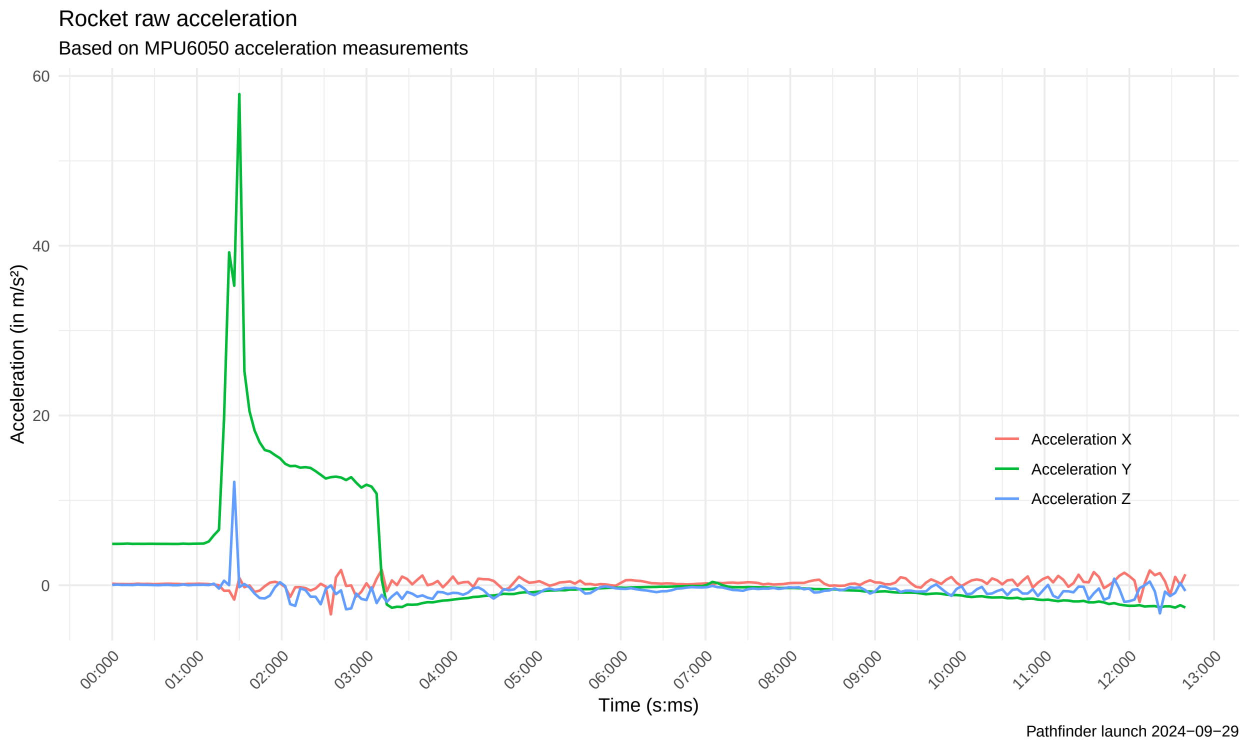

Figure 4: Raw Acceleration as measured by the Accelerometer

While the general shape of the thrust might look okay and follow expectations a closer inspection shows that the accelerometer data is actually flawed. During the period on the ground before lift-off there should have been a force of roughly 9.81 m/s² representing gravity. Instead the total acceleration on all axis before liftoff was only 4.87-4.91m/s². This seems to be pretty exactly half of the expected acceleration hinting at a scaling issue in either the library or the accelerometers scale factor that is calibrated at the factory. Simply multiplying measured values by two yielded unsatisfactory results and it is very likely that poor understanding and integration of this sensor ahead of flight made the data unusable.

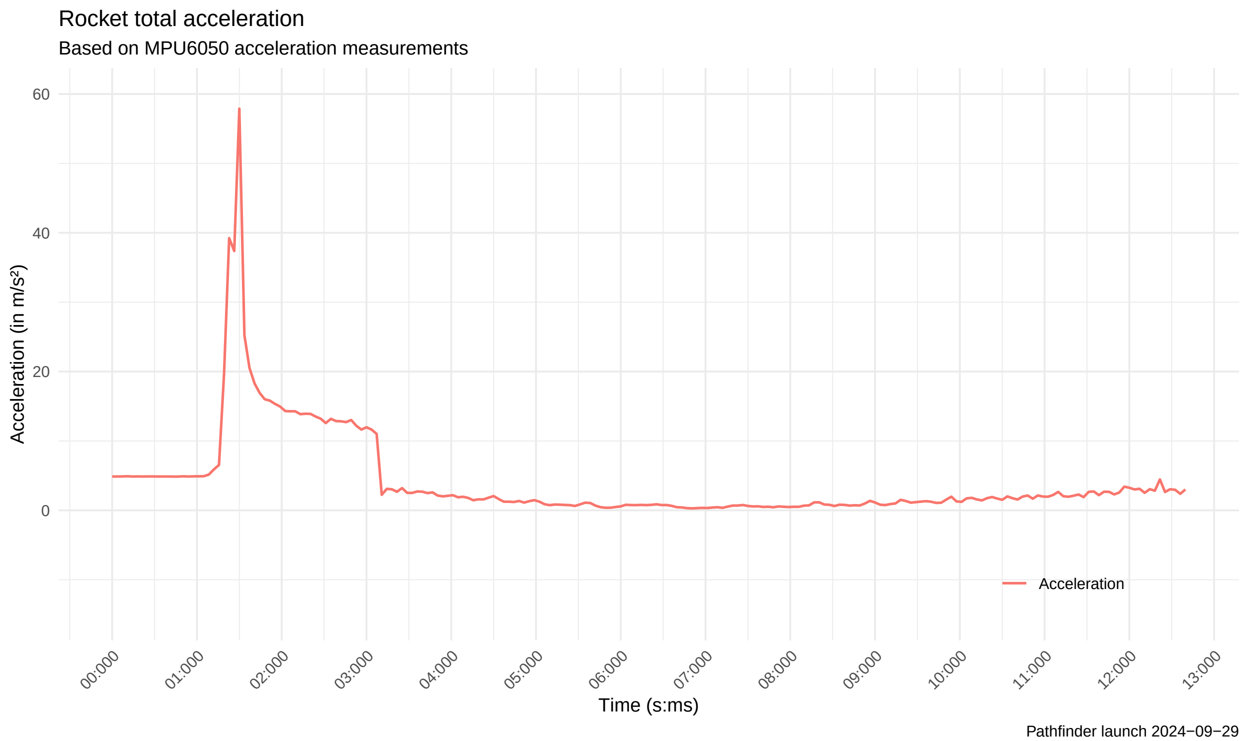

Figure 5: Total Acceleration as measured by the Accelerometer

Further flights must take a closer look at the accelerometer before launching, particularly ensuring that the expected acceleration of gravity is present before launch for the collected data to be trustworthy.

3.1.3 Gyro

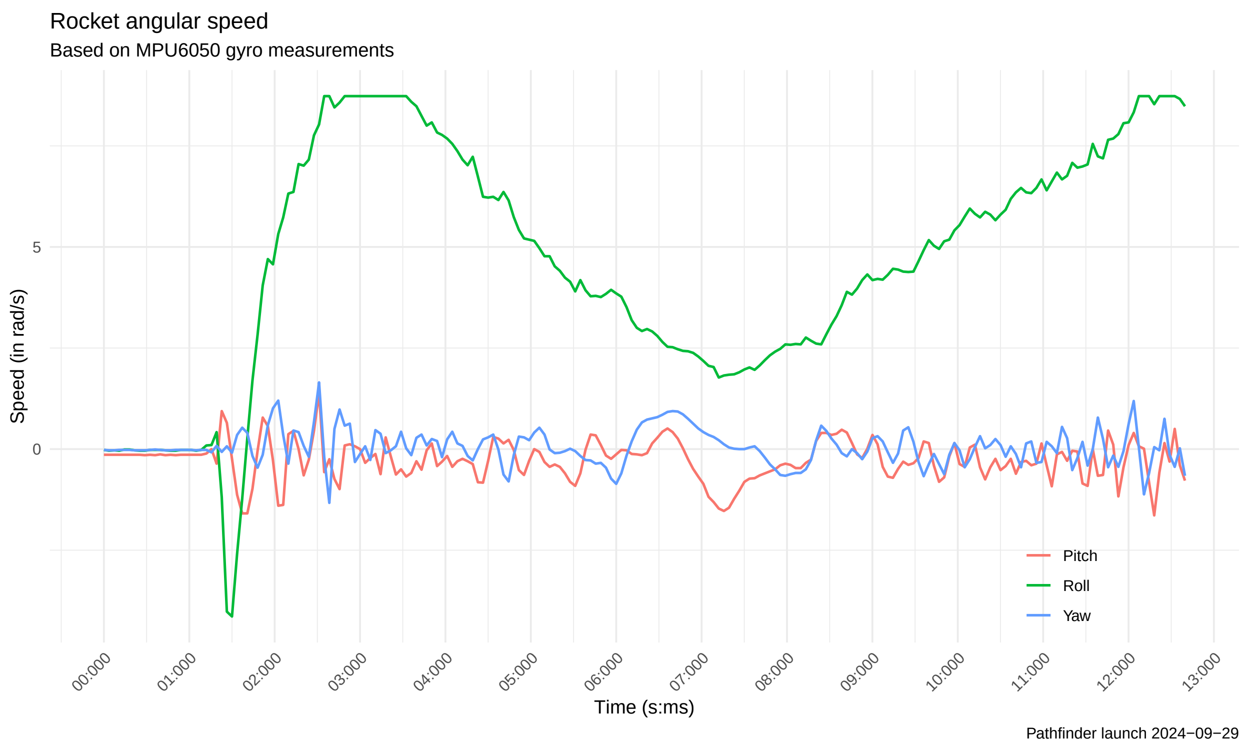

Figure 6: Rocket rotation during flight

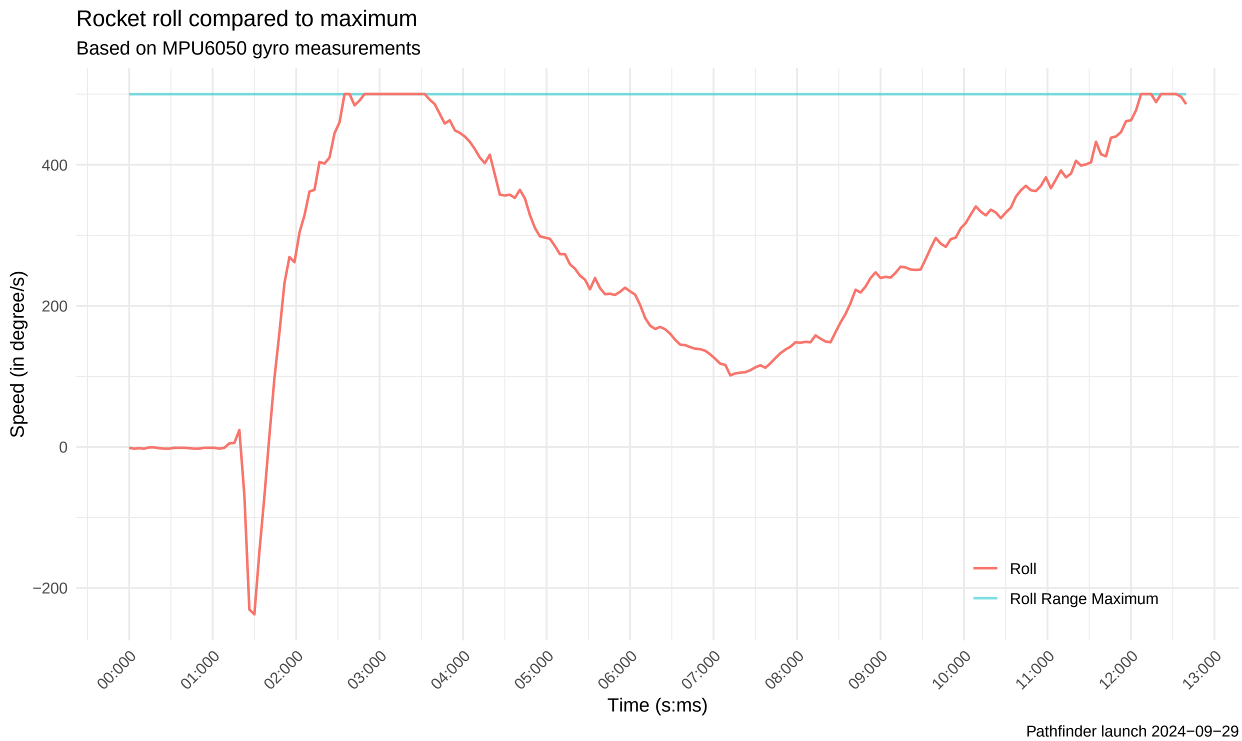

Figure 7: Measured roll compared to maximum range

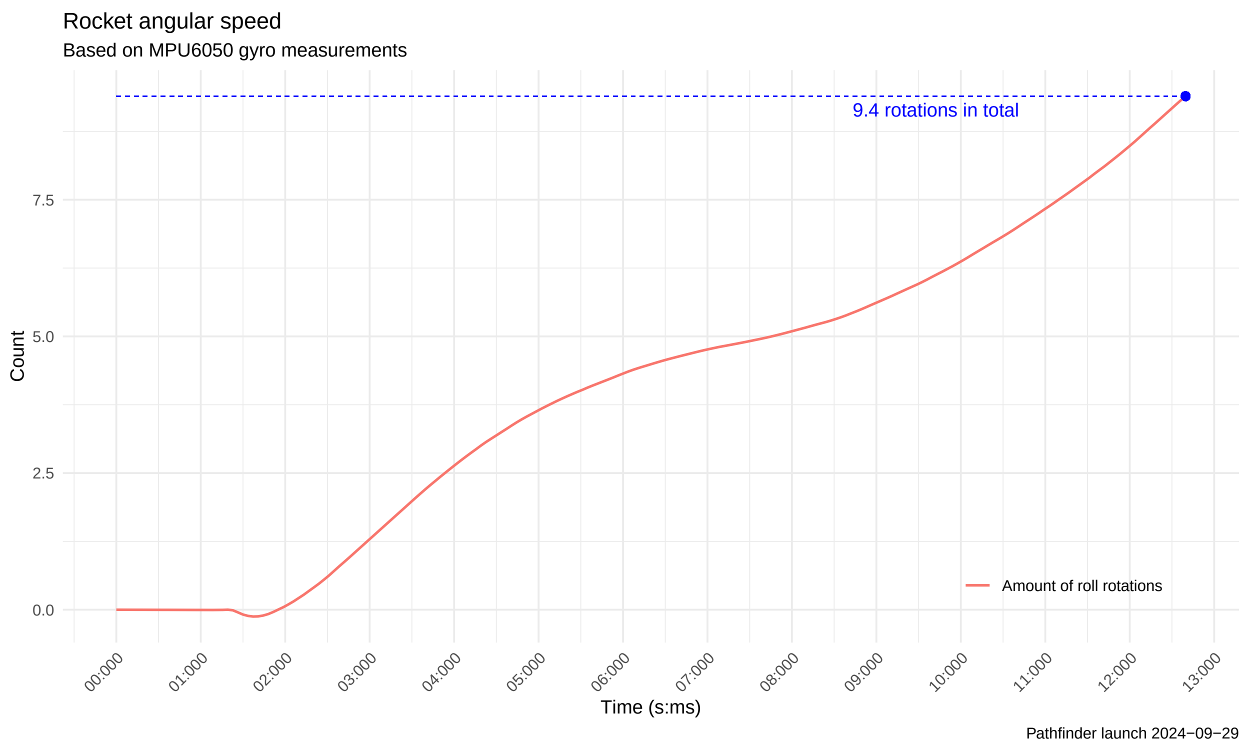

Figure 8: Amount of rotations around roll axis

3.1.4 GPS

https://github.com/mikalhart/TinyGPSPlus/blob/0a205759da22a1c54c5f5285480fe6132592a4e2/examples/UsingCustomFields/UsingCustomFields.ino#L27 No VDOP, interesting for altitude and most of the speed

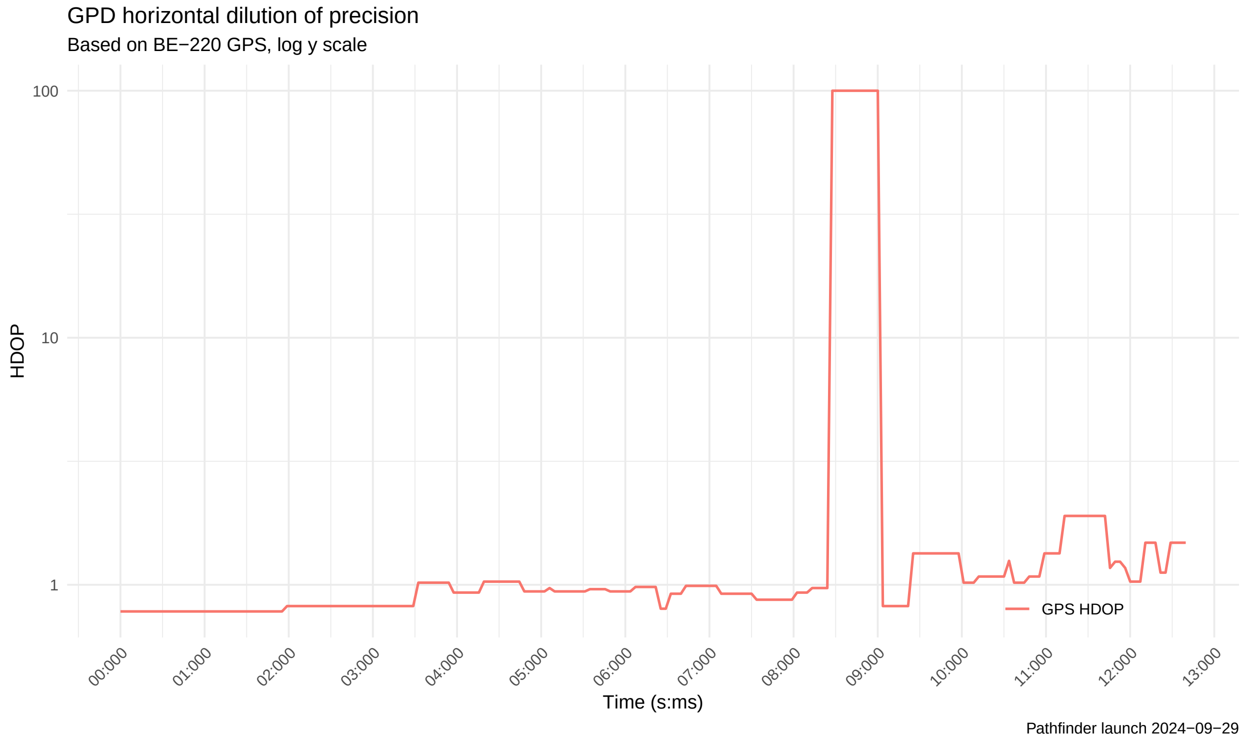

Figure 9: GPD horizontal dilution of precision

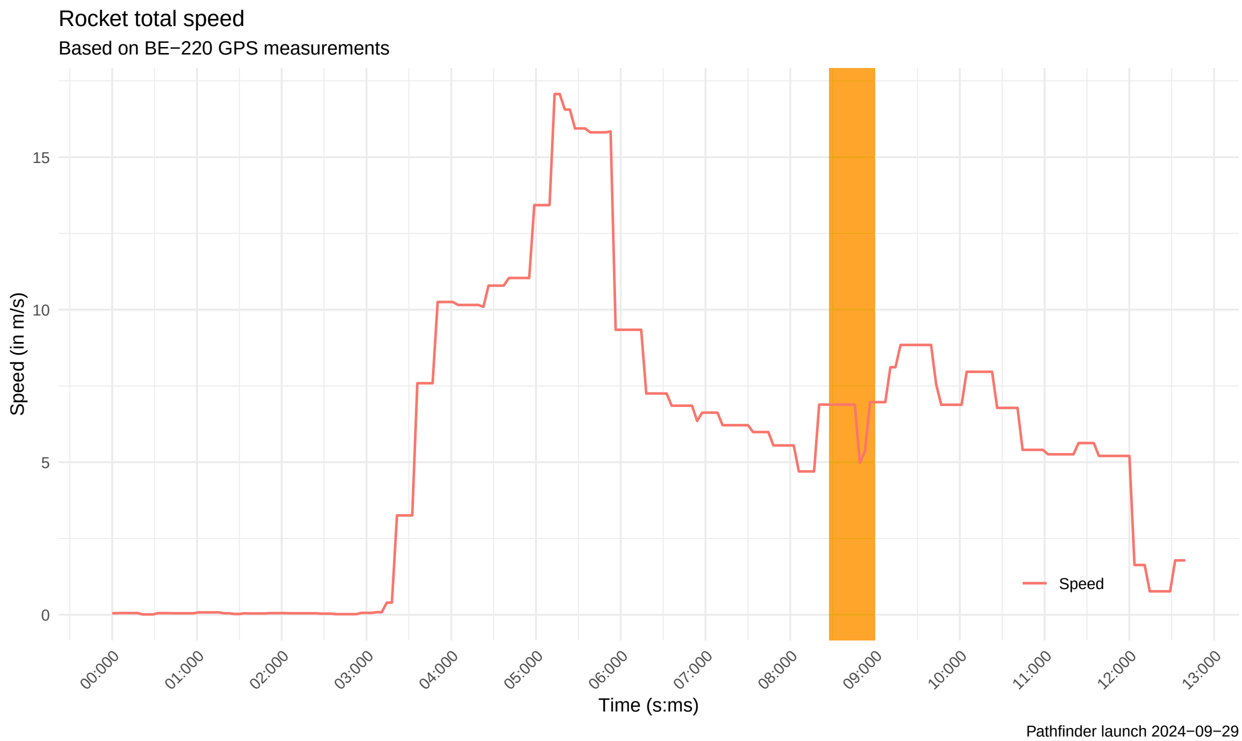

Figure 10: Total speed measured by GPS

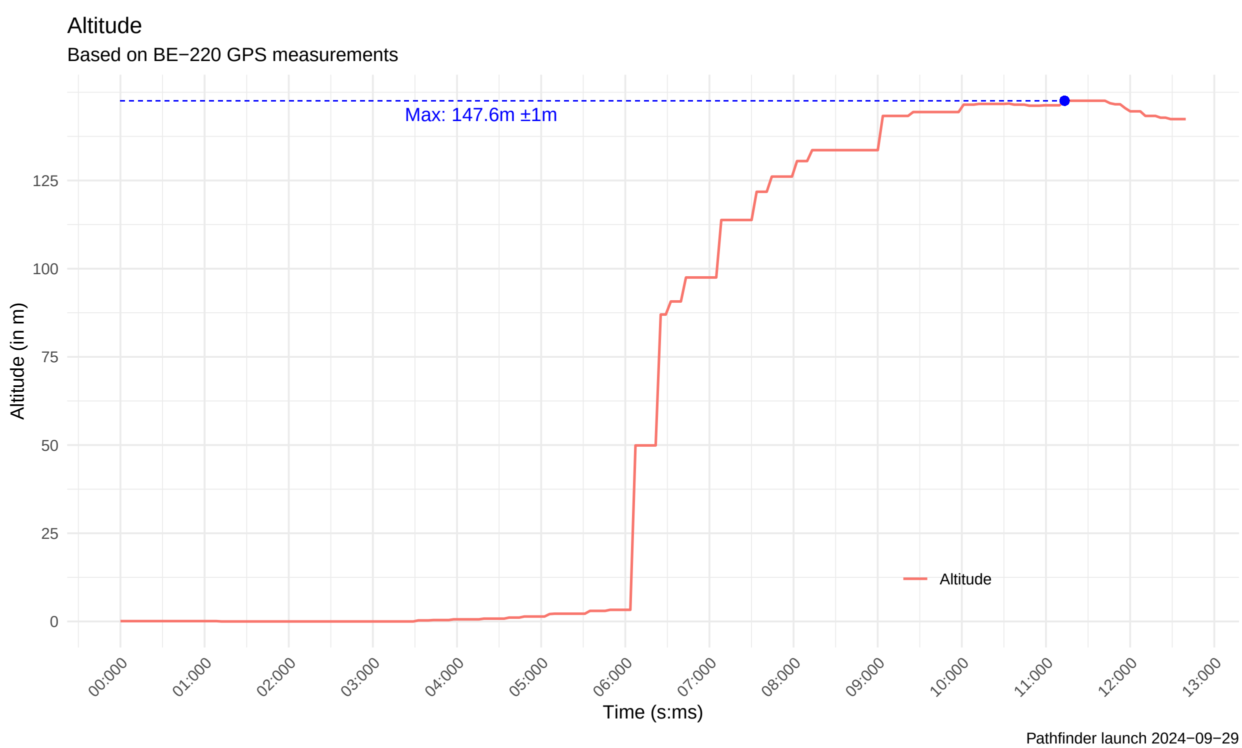

Figure 11: Altitude measured by GPS

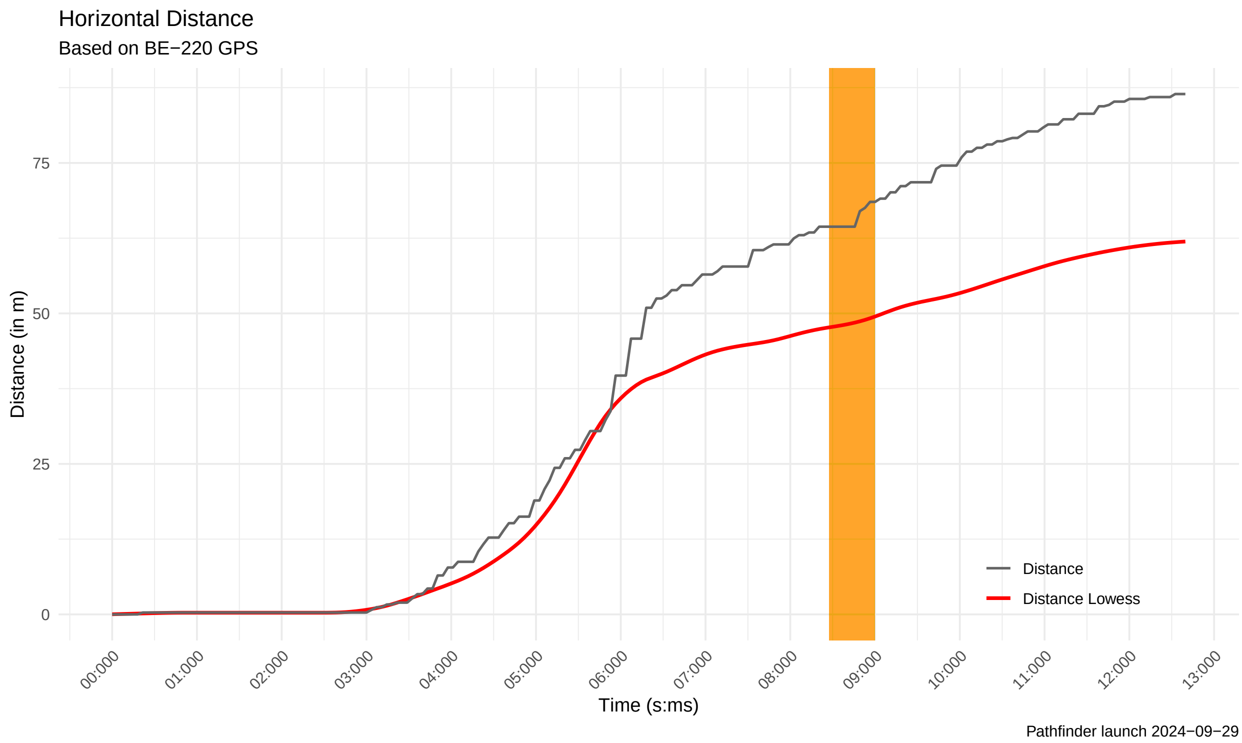

Figure 12: Horizontal distance of rocket based on GPS

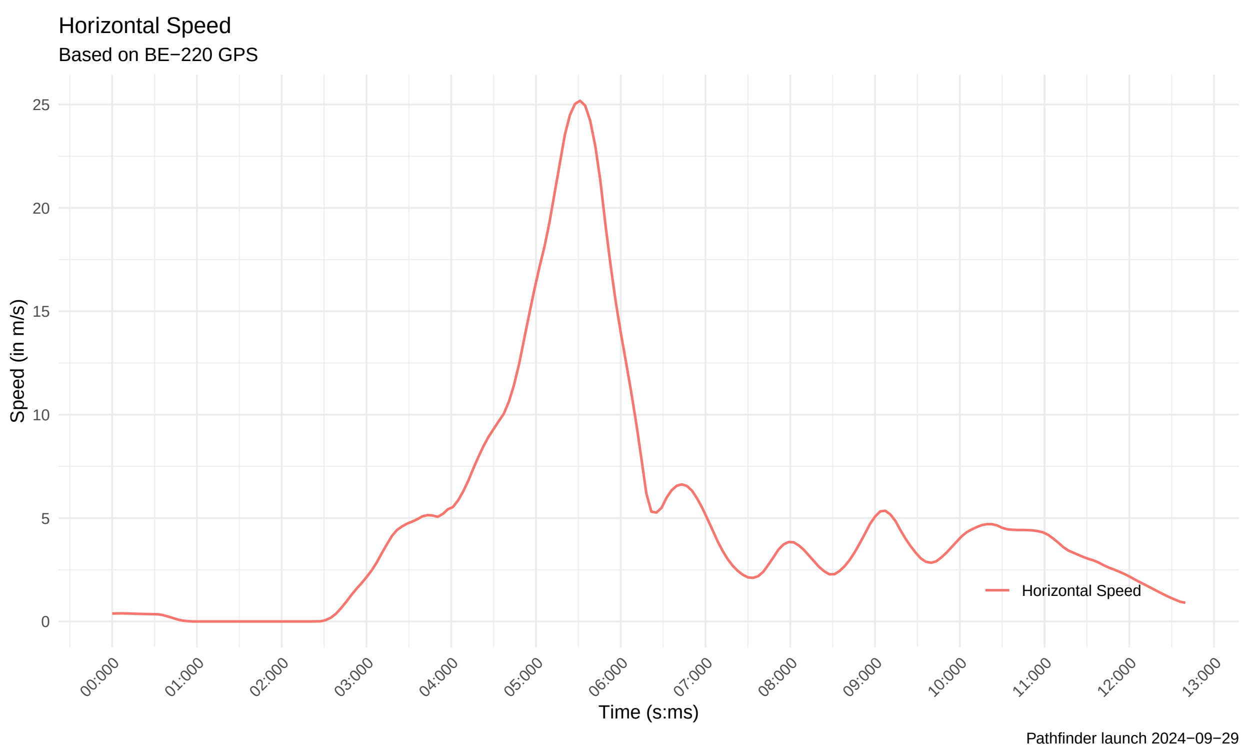

Figure 13: Horizontal speed of rocket based on GPS

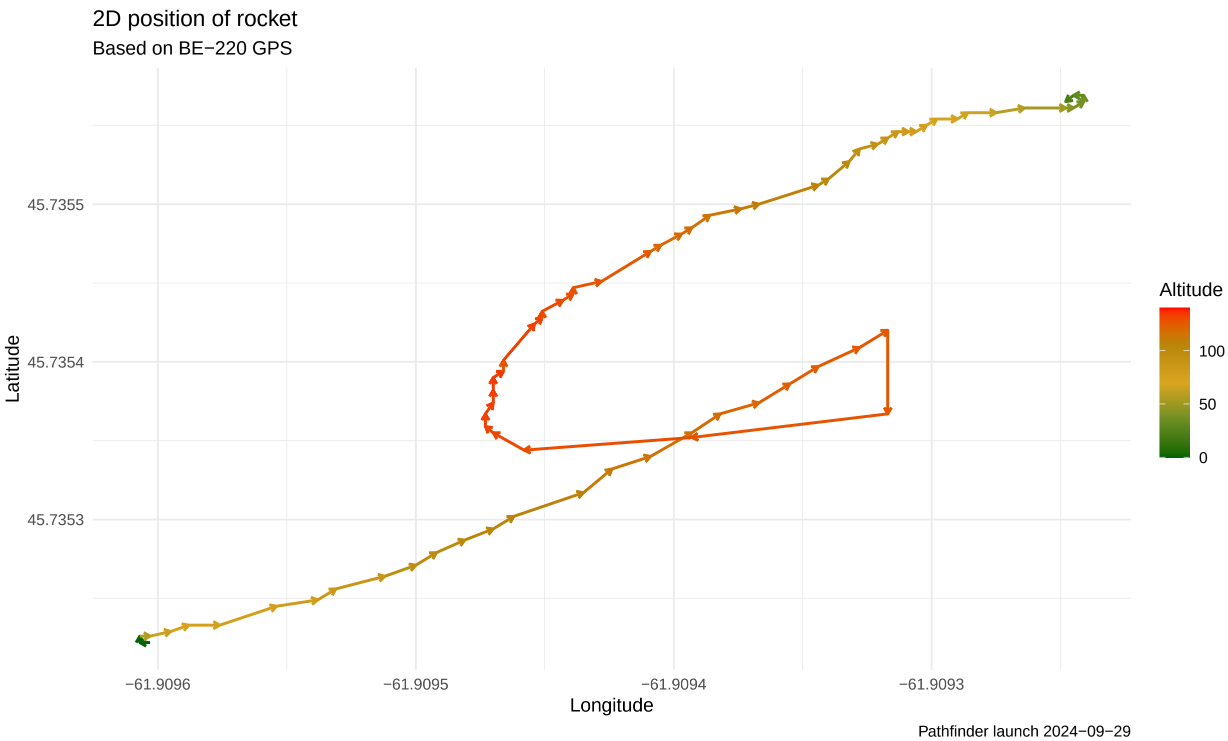

Figure 14: 2D position of rocket based on GPS

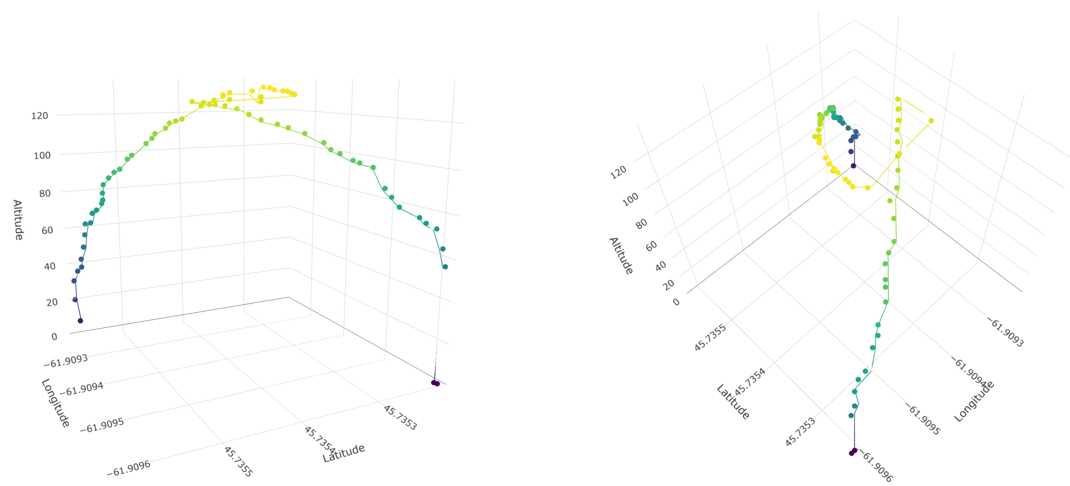

Figure 15: 3D position of rocket based on GPS and Barometer data

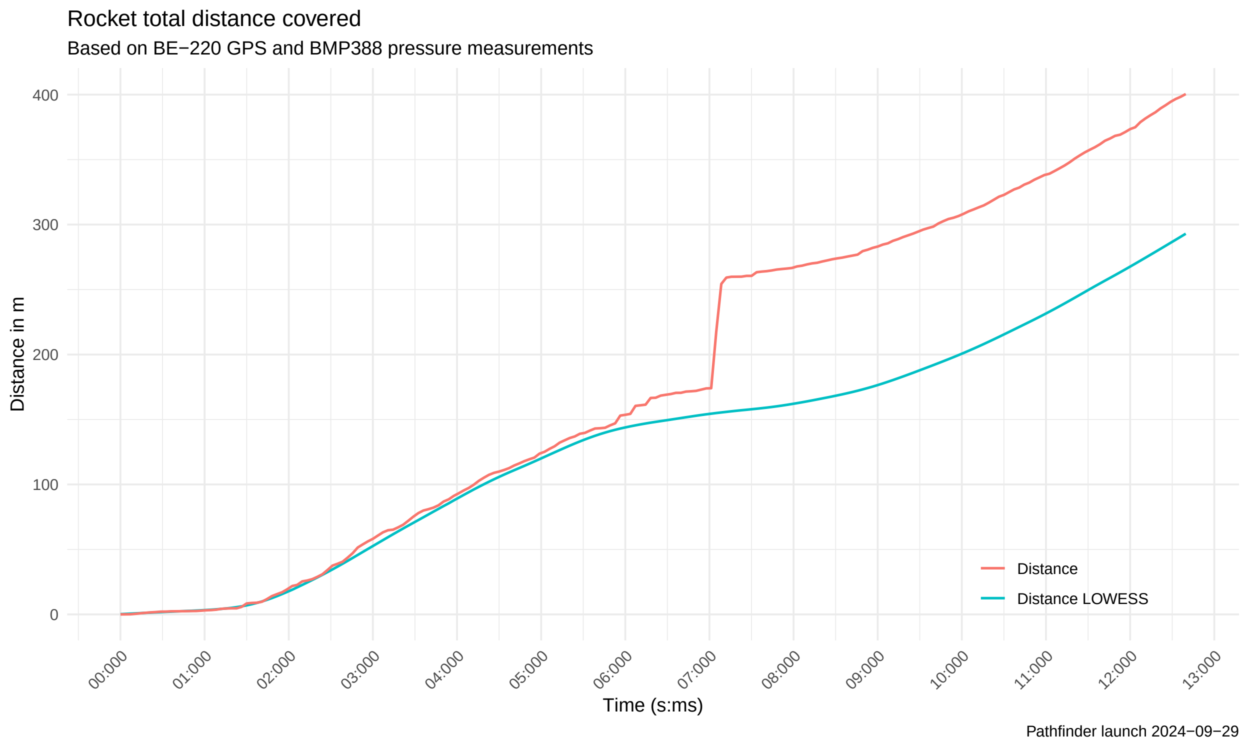

Figure 16: Total distance covered by rocket based on GPS and Barometer

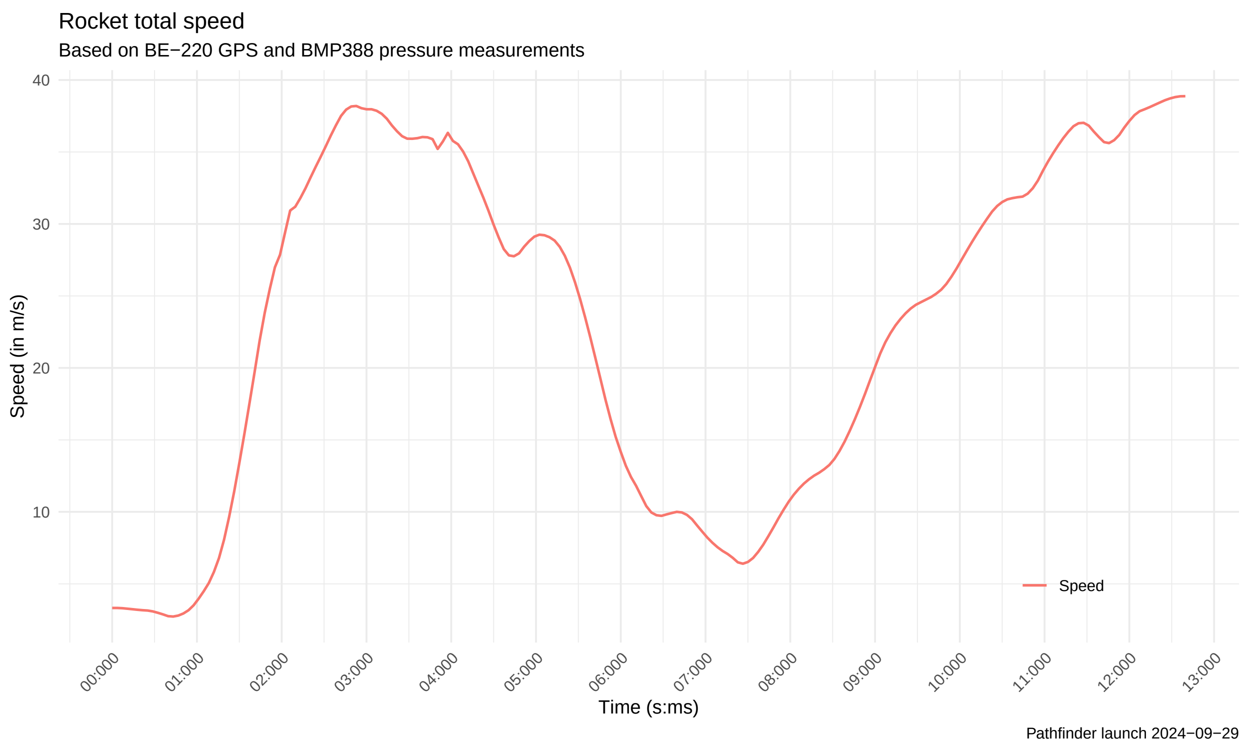

Figure 17: Total speed of rocket based on GPS and Barometer

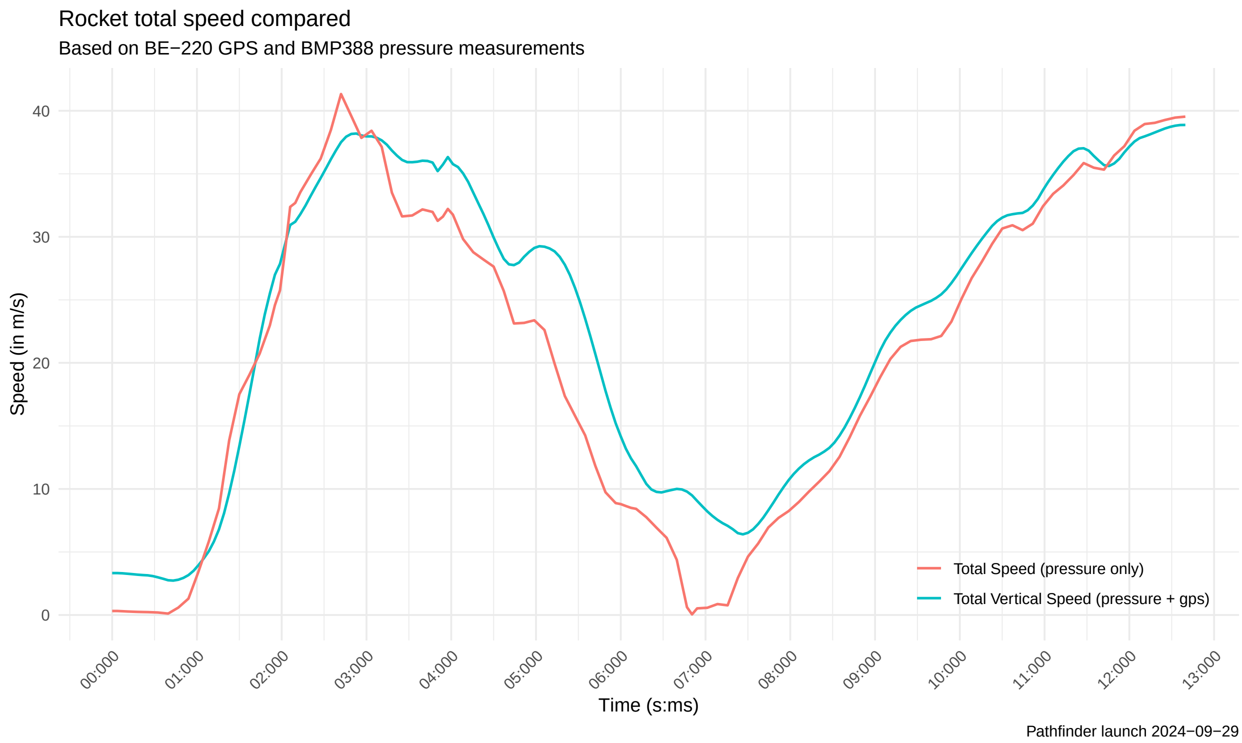

Figure 18: Total speed of rocket compared to vertical speed

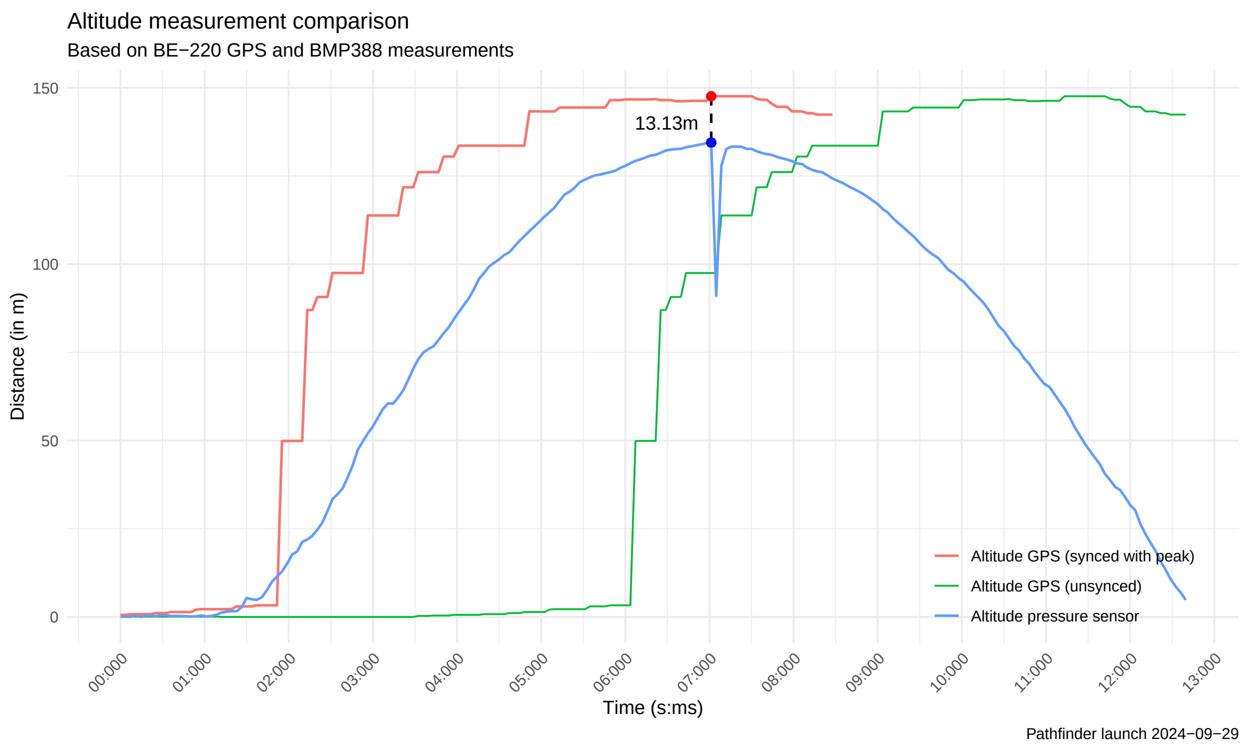

Figure 19: Comparison of GPS and barometer altitude measurements

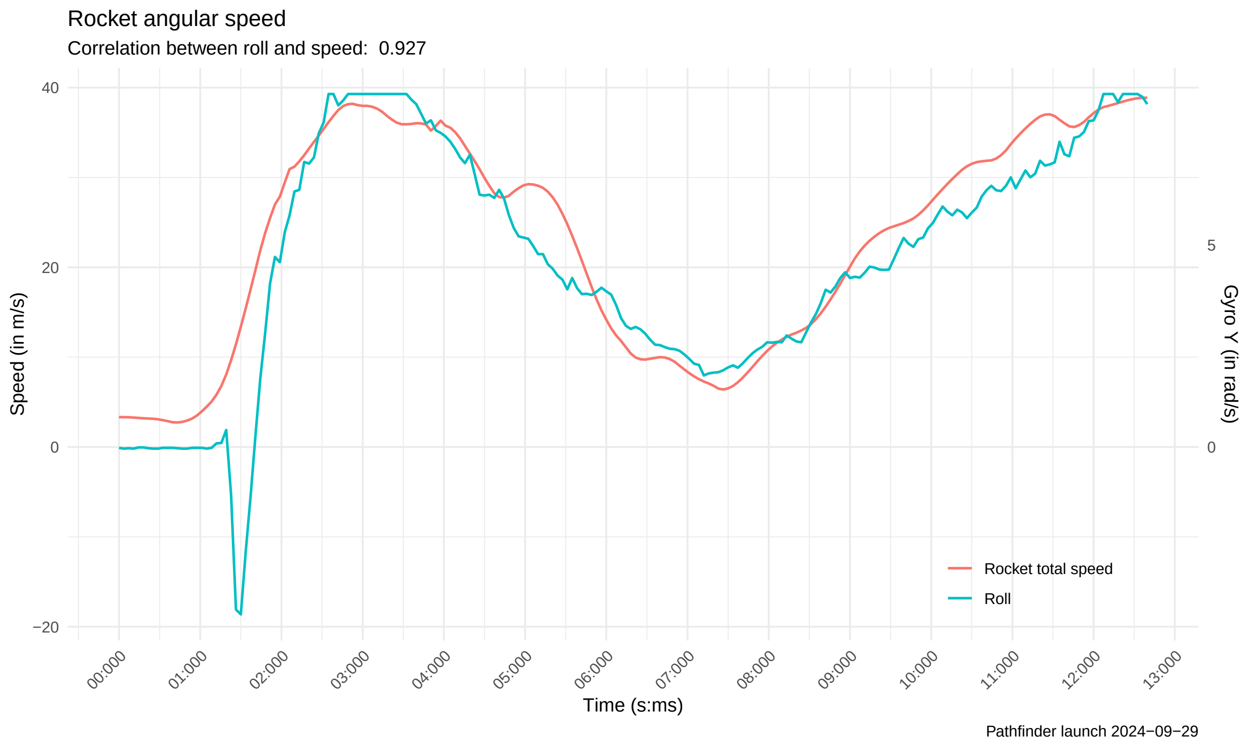

Figure 20: Correlation between speed and roll

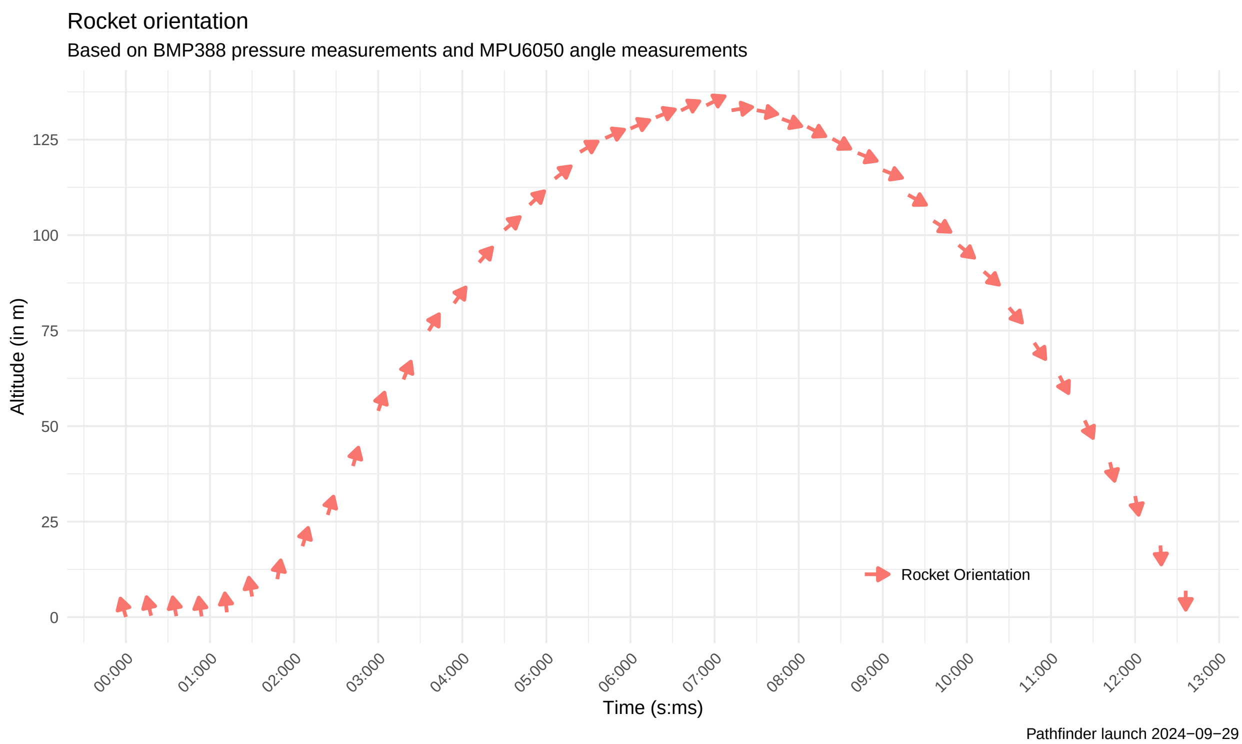

Figure 21: Rocket rotation during flight

3.2 Comparison with simulation

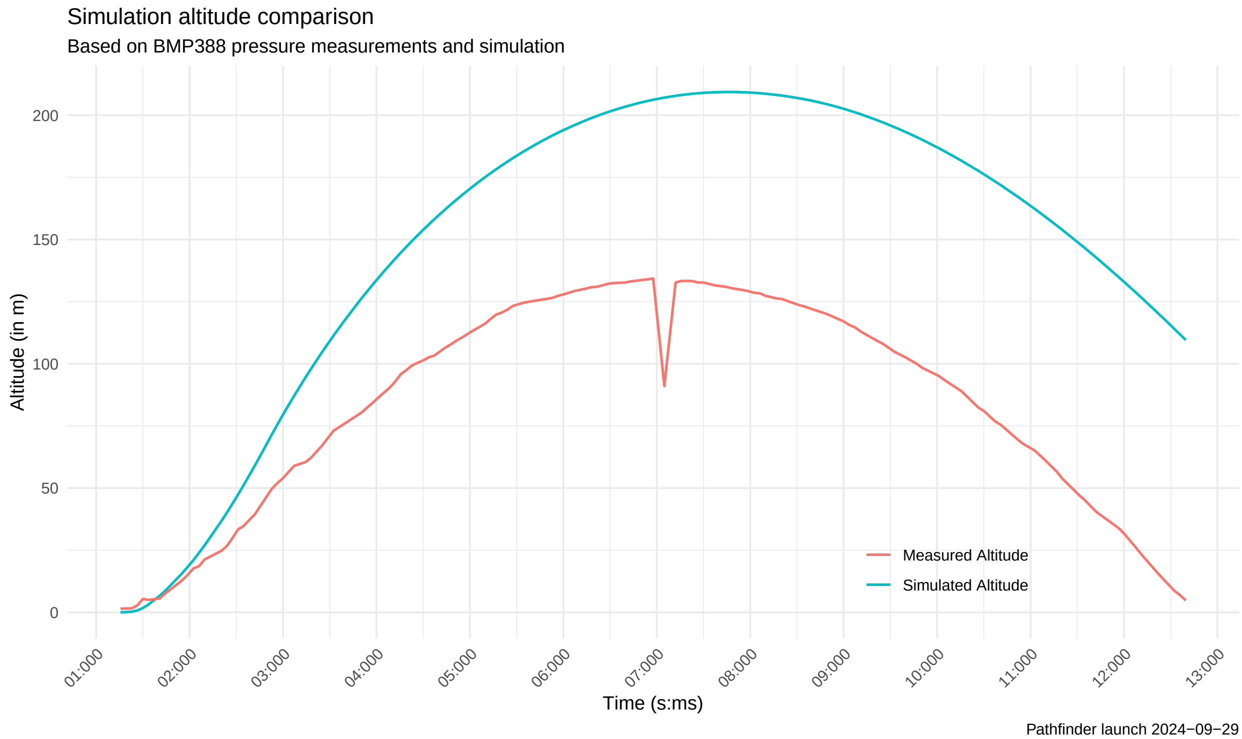

Figure 22: Simulated altitude compared with measured altitude

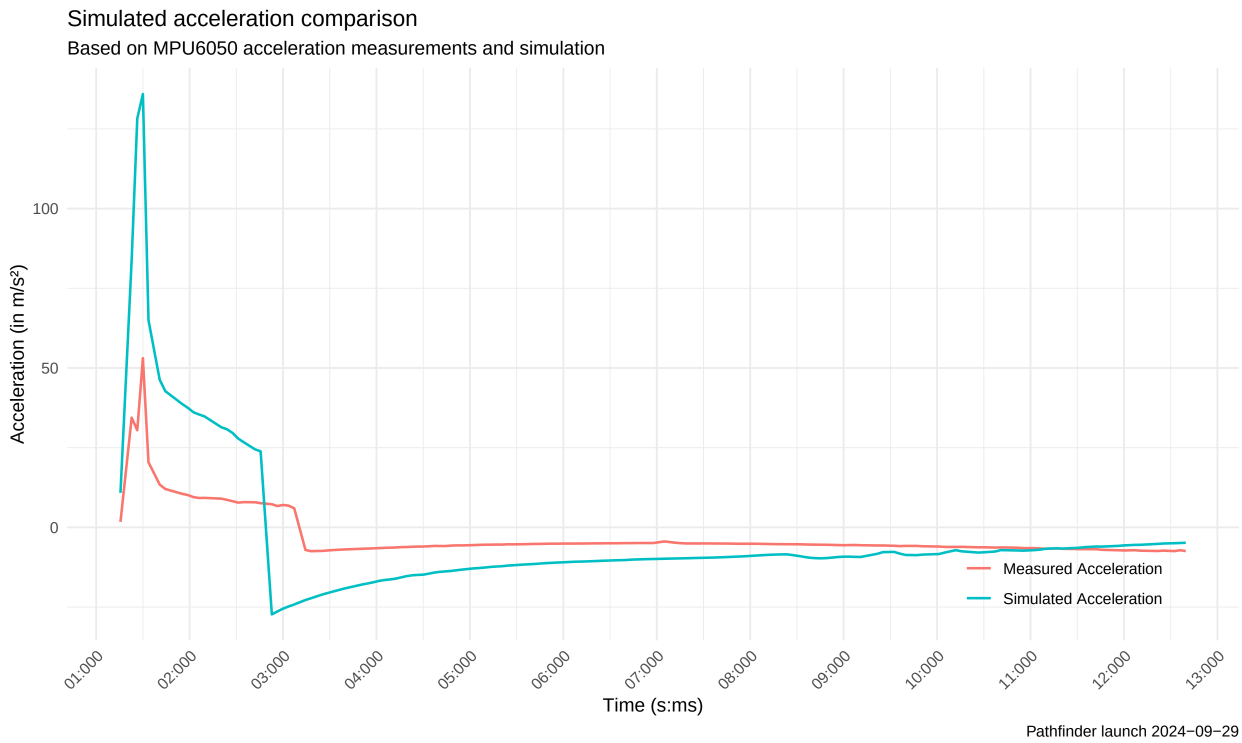

Figure 23: Simulated vertical acceleration compared with measured acceleration

3.3 Failure Analysis - Parachute, SD-Card, GPS VDOP and satellites

4 Conclusion

4.1 Critical Reflection

4.2 Next steps

This is an R Markdown document. Markdown is a simple formatting syntax for authoring HTML, PDF, and MS Word documents. For more details on using R Markdown see http://rmarkdown.rstudio.com.

When you click the **Knit** button a document will be generated that includes both content as well as the output of any embedded R code chunks within the document. You can embed an R code chunk like this:

```
summary(cars)
```

```
##      speed           dist       
##  Min.   : 4.0   Min.   :  2.00  
##  1st Qu.:12.0   1st Qu.: 26.00  
##  Median :15.0   Median : 36.00  
##  Mean   :15.4   Mean   : 42.98  
##  3rd Qu.:19.0   3rd Qu.: 56.00  
##  Max.   :25.0   Max.   :120.00
```

4.3 Including Plots

You can also embed plots, for example:

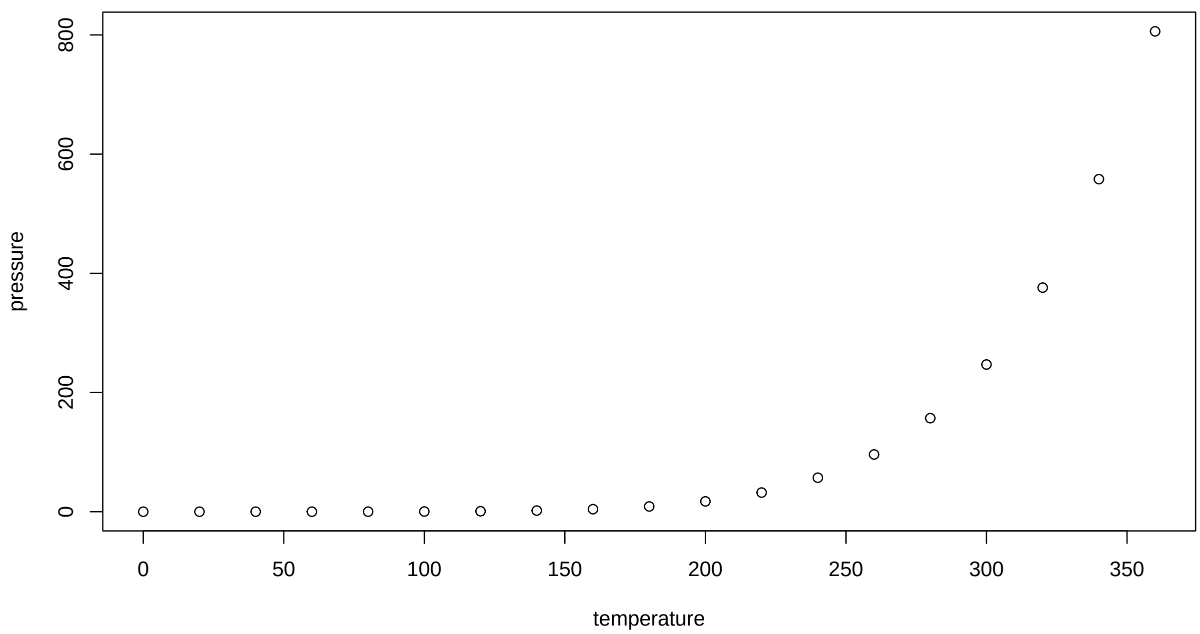

Figure 24: This is my plot

Note that the `echo = FALSE` parameter was added to the code chunk to prevent printing of the R code that generated the plot

References

Bambu Lab. (2024). Choose the right filament - 3d filaments guide for bambu lab printers [Accessed: 2024-10-03]. https://bambulab.com/en/filament-guide

Berman, B. (2012). 3-d printing: The new industrial revolution. *Business horizons*, *55*(2), 155–162.

Berman, B. (2020). Managing the disruptive effects of 3d printing. *Rutgers Business Review*, *5*(3), 294–309.

Center, N. R. (2024). Model rockets [Accessed: 2024-10-04]. https://www1.grc.nasa.gov/beginners-guide-to-aeronautics/model-rockets/

Estes. (2023). D12-5 technical specifications [Accessed 30-10-2024]. https://estesrockets.com/products/d12-5-engines#spec

Gravity. (2020). Bmp388 barometric pressure sensors [Accessed 30-10-2024]. https://www.dfrobot.com/product-1792.html

Pearce, J., & Qian, J.-Y. (2022). Economic impact of diy home manufacturing of consumer products with low-cost 3d printing from free and open source designs. *European Journal of Social Impact and Circular Economy*, *3*(2), 1–24.