# Findings from the ESA Education Fly a Rocket Campaign - Sensor Experiments Team

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## Abstract

The paper summarises the endeavour of 24 students during a Fly a Rocket campaign in October 2021. The programme is an educational week-long activity aimed at university students with limited hands-on experience. The campaign took place at Andøya Space Center and was possible by the collaboration of ESA Education, Andøya Space, and the Norwegian Space Agency. The participants learnt about the fundamental aspects of a rocket launch campaign, from deciding the scientific case, rocket assembly, safety briefings and countdown procedures. The students came from diverse backgrounds, such as aerospace engineering, electrical engineering, physics, mathematics and astronomy. They were divided into three groups for the campaign: payload, telemetry and sensor experiments. The paper mainly focuses on the findings of the sensor experiments group. It first introduces the launch campaign details and the online course. Then, all the steps that went into the scientific cases, which students had to prepare, are summarised. The cases they decided to work on included a comparison of the trajectory simulation done in OpenRocket and the real-life measurements, cloud detection using optical and humidity sensors, the measurement of the spin of the rocket and the collection of data from the atmosphere that was compared to the international standard atmosphere. This paper aims to share the learning outcomes from this campaign with the wider public and students. The collaboration and responsibilities of the students taught them many important lessons, most notably the importance of diversity and the significance of cross-communication between teams.

## Keywords

Andøya Space Center, ESA Education, Fly a Rocket, OpenRocket, Sensor experiments

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## Acronyms

| | |
|---|---|
| DOF | Degrees of freedom |
| IMU | Inertial measurement unit |
| ISA | International standard atmosphere |

## 1. Introduction

This paper is the result of ESA's Fly a Rocket campaign 2020-2021, and its main goal is to provide an inside look at the program as well as details on one of the main scientific cases. At the beginning of the paper, the focus will be primarily on the campaign's prerequisites, such as the online course, the launch campaign, and the completed study cases. Moving forward, the emphasis will shift to the paper's main study case, the comparison of real-world sensor data and OpenRocket predictions for the calculated trajectory of the Rocket. The main result would be the OpenRocket simulation's accuracy compared to real-world scenarios.

## 2. Fly a Rocket

The Fly a Rocket Program is an interactive hands-on program by the ESA Education Office in partnership with Andøya Space Education and the Norwegian Space Agency designed for university students studying STEM subjects. The campaign itself provides an opportunity for the students to get experience with an actual sounding rocket and gain knowledge about rocketry, sensor electronics, balloon meteorological data experiments, and a rocket launch. It also enables students to perform scientific experiments and collaborate in an international environment. Firstly, in the theoretical sense through an online course, and subsequently in practice by flying to Andøya, Norway, an island above the Arctic circle, and working side-by-side with field experts.

### *2.1. Online Course*

One of the prerequisites for attending the launch campaign was to complete an online course provided by Andøya Space Education. The online course covered the basics of rocket propulsion, rocket dynamics and foundations of orbital mechanics. Additionally, it covered the details of the student rocket, which was to be launched during the campaign. The pre-study material also contained a section focusing on atmospheric physics and the northern lights, which are characteristic of Andøya.

The knowledge gained from the pre-study material concluded in a three-part assignment given over a period of six months. The first tested the understanding of basic orbital dynamics by calculating a satellite's trajectory orbiting Earth. In the second part, the students performed increasingly more accurate calculations on the student rocket. It started from handwritten calculations and progressed to a 2D numerical solution written in Python. The last, optional part expanded on the previous solutions aiming to deliver a 3D numerical solution to the rocket's trajectory.

### *2.2. Launch Campaign*

The rocket for the launch campaign was a $2.7\ \mathrm{m}$ sounding rocket called the Mongoose 98, slightly modified for student launch campaigns. The rocket body was made of carbon fibre, except the nose cone, which was made of fibreglass to not interfere with the GPS tracking. The rocket was fitted with a Pro98 engine from Cesaroni, which used solid propellant to raise the rocket to an apogee of about $8\ \mathrm{km}$ and a maximum speed of $\mathrm{Mach}\ 2.2$. To introduce scientific objectives to the campaign, a series of study cases were analysed based on the available sensors on the rocket.

There were seven different sensors mounted on the aluminium avionics plate of the rocket. There was an accelerometer, magnetic field sensor, pressure sensor, GPS, IMU, a temperature array and an optical sensor.

After assembling and testing, the rocket was delivered to the professionals at Andøya Space for final testing and adjusting the centre of mass. Before it was launched, the students participated in the safety briefings and the countdown procedure. Multiple students had specific roles during the countdown. These mainly included telemetry, launchpad operations, science objective monitoring and mission operations. They took part in the go/no go sequence before launch, which gave them a unique experience of launching a sounding rocket. In the end, the rocket was successfully launched on the 14th of October 2021 from Andøya Space Centre, reaching an apogee of $8.6\ \mathrm{km}$.

### *2.3. Study Cases Overview*

One of the critical parts of the launch campaign were the study cases, that aimed at utilizing the pre-determined sensors on the rocket. Students had to come up with reasoning for why these sensors would be interesting for data analysis.

A brainstorming session concluded in four study cases.

The first scientific case compared the weather balloon and rocket temperature and pressure readings with the ISA model [1] up to $20\ \mathrm{km}$.

The second case focused on determining the spin of the rocket using the angular velocity derived from the accelerometer, magnetometer and optical sensor converted into frequency.

The third case focused on cloud detection using optical, temperature and humidity sensors. The aim was to confirm the assumption that once the rocket goes through the clouds, the light intensity lowers, humidity increases, and the temperature gradient will change.

The fourth study case, the principal discussed in this paper, concerned the comparison between the sensor measurements and OpenRocket simulation to determine the rocket's trajectory.

## 3. Trajectory of the Rocket

### *3.1. Python Simulation Trajectory*

As part of the second assignment, the students were tasked with writing a two-dimensional simulation of the rocket's flight trajectory using Python, treating this as an initial value problem. To achieve this, the equations of the rocket's motion were derived with the following major assumptions and simplifications:

- Constant drag coefficient $C_d$.
- The rocket is non-rotational.
- The rocket is a point mass.

The rocket's equations of motion are established under these assumptions using Newton's second law (Eq. 1).

$$\vec{T}(t) + \vec{D} + m(t)\vec{g} = m(t)\vec{a} \tag{1}$$

Where $\vec{g}$ is the gravitational acceleration vector, $\vec{a}$ is the rocket's acceleration vector, and $m$ is the rocket's mass. Both $\vec{T}$ and $m$ were functions of time. $\vec{T}$ was assumed to be equal to the average thrust of the rocket's motor during the burn time (up to $6.09\ \mathrm{s}$) and then set to 0, while $m$ was approximated as a linear decrease from wet mass to dry mass of the rocket during the burn. By expanding this equation into two dimensions and applying the drag equation, the final system of equations was obtained (Eq. 2).

$$\begin{bmatrix} T\cos\theta \\ T\sin\theta \end{bmatrix} + \begin{bmatrix} -\frac{1}{2}\rho\left(\frac{dx}{dt}\right)^2 AC_d\cos\theta \\ -\frac{1}{2}\rho\left(\frac{dy}{dt}\right)^2 AC_d\sin\theta \end{bmatrix} + \begin{bmatrix} 0 \\ -mg \end{bmatrix} = \begin{bmatrix} \frac{d^2x}{dt^2} \\ \frac{d^2y}{dt^2} \end{bmatrix} \tag{2}$$

Where $\theta$ is the rocket's angle relative to the horizontal, $A$ is the rocket's frontal area, $x$ and $y$ are displacements in the horizontal and vertical directions, and $\rho$ is air density dependent on $y$ as given in Equation 3.

$$\rho(h) = \rho_0 e^{-\frac{y}{H}} \tag{3}$$

Where $\rho_0$ is the density at sea level, and $H$ is the scale height [1]. The system of equations in Equation 2 was then solved numerically using the Runge-Kutta method. The results of this simulation for $\theta = 75°$ and other initial parameters given in the assignment can be seen in Figure 1.

The rocket simulation can be extended to three dimensions, introducing a 6-DOF system. The dynamics of this system are then fully described by four state vectors, namely the position vector $\vec{X}$, a quaternion $\vec{Q}$ which describes its orientation, the linear momentum $\vec{P}$, and the angular momentum $\vec{H}$. Knowing these vectors at any given point in time allows for determining the state of the rocket at any subsequent point in time. This is accomplished by solving a set of ordinary differential equations describing the dynamics of the rocket, given in Equation 4, using the Runge-Kutta method [2].

$$\begin{gathered} \dot{\vec{X}} = \frac{\vec{P}}{m(t)} \\ \dot{\vec{Q}} = f(\vec{Q}, \vec{H}) \\ \dot{\vec{P}} = \vec{F}(t) \\ \dot{\vec{H}} = \vec{M}(t) \end{gathered} \tag{4}$$

$f(\vec{Q}, \vec{H})$ represents the quaternion derivative [3]. $\vec{F}(t)$ and $\vec{M}(t)$ represent the resultant force and moment acting at the centre of gravity of the rocket as a function of time. $m(t)$ represents the rocket's mass, which changes in time. For this simulation, the following forces and moments were considered for modelling the trajectory of the rocket: axial drag, normal drag, force due to gravity, thrust and the moment due to drag force acting through the centre of pressure.

The standard drag equation is used with a constant drag coefficient obtained from an OpenRocket model for modelling the drag forces. The density is adjusted according to the rocket's altitude based on the ISA. The gravitational force is calculated using a constant gravitational acceleration of $g = 9.81\ \mathrm{m/s^2}$. Thrust is obtained from the thrust curve of the rocket engine, the Cesaroni 15227N2501-P [4]. The normal drag force causes a moment, with the moment arm being the distance between the centre of pressure and gravity. In the modelling of this moment, a shifting centre of gravity due to changing mass is considered.

The complete rocket trajectory is obtained by numerically solving the set of ordinary differential equations given in Equation 4. Doing so renders the trajectories shown in Figure 1.

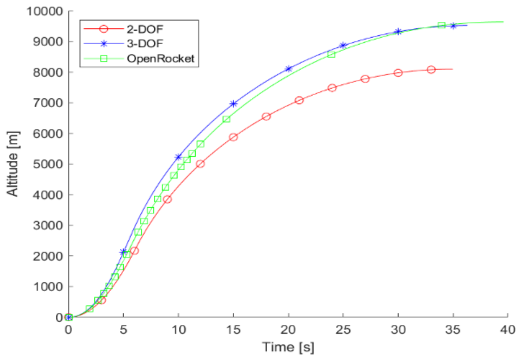


**Figure 1. Python and OpenRocket trajectory simulations**

The apogee on the 6-DOF case was 17% higher than it was for the two-dimensional case.

### *3.2. OpenRocket Trajectory*

The OpenRocket simulation software was developed as a master's thesis project by Sampo Niskanen in 2009. This open-source program was created to support amateur rocketry. The OpenRocket 6-DOF simulation software has vast educational benefits since it allows anyone from middle school students to even rocketry teams in universities to run calculations, design their rocket, and test it.

The software allows users to define the rocket model and launch conditions to generate the expected behaviour including altitude, roll rate and recovery deployment events. The calculation process is detailed in the software documentation [5]. However, as with any simulation, the software cannot take all effects into account and must use assumptions to achieve the most accurate result. The biggest challenge, as with any aerospace simulation, occurs during the transonic and supersonic parts of the flight. This is due to the effects that shock waves and expansion fans can have on the aerodynamic forces acting on the rocket. Furthermore, atmospheric conditions such as wind in different heights affect the overall trajectory. The assumptions identified as having a major contribution to the data generation can be listed as follows [5]:

- The angle of attack is close to zero.
- The flow around the body is steady and non-rotational.
- The fins are flat plates.
- Pressure drag for supersonic velocities uses certain assumed hypersonic and supersonic conditions.

Ultimately the intention was to analyse the error in the rocket simulation for the transonic speeds and above by comparing it with flight data from the campaign. Transonic flows are difficult to model as high-fidelity computational fluid dynamics analysis is required due to the non-linearity of the governing equations [1].

To model the rocket, the structure given in Figure 2 was adopted. To represent a correct mass distribution, the rocket mass and centre of gravity were overwritten to the measured values of the physical rocket. The main properties used to model the rocket are given in Table 1. Both the centre of gravity and the centre of pressure are measured from the nose tip.

A simulation of its flight was obtained using an average windspeed of $5\ \mathrm{m/s}$ with standard deviation of $1\ \mathrm{m/s}$ and a wind direction of $90°$. For the atmospheric conditions, the ISA was specified. The launch rod was set to a length of $300\ \mathrm{cm}$ at an angle of $16.3°$. The resulting trajectory of this simulation is given in Figure 1.

**Table 1. Properties used in OpenRocket model**

| Properties | Values |
|---|---|
| Mass with motor [g] | 19500 |
| Length [cm] | 271 |
| Diameter [cm] | 10.3 |
| Center of gravity [cm] | 194 |
| Center of pressure [cm] | 205 |

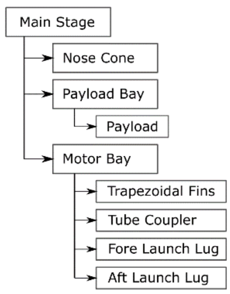


**Figure 2. Schematic of OpenRocket components used to model the rocket**

### *3.3. IMU Data and Qualitative Analysis*

The IMU provides inertial data in 9-DOF. It is composed of three individual sensors, each measuring orthogonally, given in Table 2.

**Table 2. IMU sensors**

| Sensor type | Range |
|---|---|
| Magnetometer | -16 to 16 Gauss |
| Accelerometer | -16 to 16 g |
| Gyroscope (angular velocity) | -2000 to 2000 deg/s |

The encoder of the telemetry station transmitted the data from the IMU sensors in 16-bit integers, where the integer value corresponded linearly to the scale of each sensor.

The intention was to integrate this inertial data using a Kalman filter to obtain the rocket's trajectory. However, this method would have certain trade offs:

- The trajectory would most likely be subject to significant drifts as the error would accumulate over time.
- Some of the sensors either saturated (gyroscope) or provided faulty data (magnetometer), and filtering their influences out is very challenging.
- Most open-source IMU orientation filters are not tuned to work with significant accelerations; a substantial amount of work would have to be put into implementing the algorithm.

For future work it is recommended to implement a Kalman filter to obtain the trajectory from IMU.

## 4. Discussion and Results

This section compares the methods used to determine the rocket's trajectory. It was decided that simulation data from OpenRocket would be used for its higher accuracy than the Python script. The main data sources were the following sensors: GPS, IMU, accelerometer and barometer. The sensor data was compared with OpenRocket data to establish its precision for a rocket of this type empirically. The presented plots focus on the flight up to the point of apogee.

Figure 3 shows the altitude over time for each source of data: OpenRocket, GPS and barometer. All three sources present the same characteristic curve, although they predict different apogees. The barometer follows the OpenRocket curve closely for $M < 2.0$ but under-predicts the apogee, likely due to a lag in pressure equalisation between the interior and exterior of the rocket at supersonic speeds. The GPS apogee, $8627\ \mathrm{m}$, is likely to be the most accurate as it would not have been affected by pressure changes, however its low sampling rate reduces its accuracy during ascent.

Figure 4 shows the local Mach number over time. The derivative of the altitude data obtained from the barometer only gave the vertical velocity, hence the barometer curve differs greatly from the OpenRocket simulation. The accelerometer, on the other hand, follows the OpenRocket curve closely, varying slightly at higher Mach numbers. All three sources predict that the maximum speed was reached at a similar time, approximately $6\ s$ after ignition.

The data obtained from the Python simulations before the campaign explained what the trajectory should look like and what the altitude would be. The more accurate approach of OpenRocket simulation then provided a more detailed approximation.

Figure 5 presents the rocket's acceleration against time and it was expected that the onboard sensors would closely follow the OpenRocket prediction here as both the IMU and the accelerometer directly measure the acceleration. The curve from the accelerometer generally follows the OpenRocket simulation, giving a very similar characteristic shape, although the maximum acceleration differs by about $2\ \mathrm{G}$. This acceleration occurs during launch and therefore the discrepancy is likely caused by OpenRocket omitting the effect of friction between the rocket and the launch rail.

Unfortunately, the IMU data was not usable. Although it follows the same shape, the huge difference in magnitude compared to the other two sources indicates an error with the sensor and/or data retrieval.

Overall, it was found that the barometer provided the most accurate readings for altitude, whilst the accelerometer was the optimal choice for velocity and acceleration. It is expected that the GPS will have provided similar results, however its low sampling rate reduced the accuracy of its derivatives.

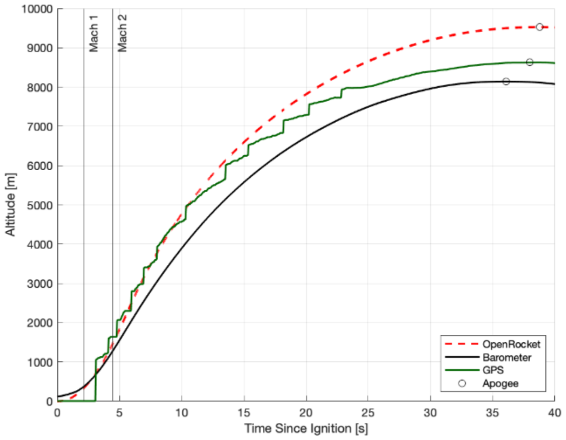


**Figure 3. Comparison of Altitude Data**

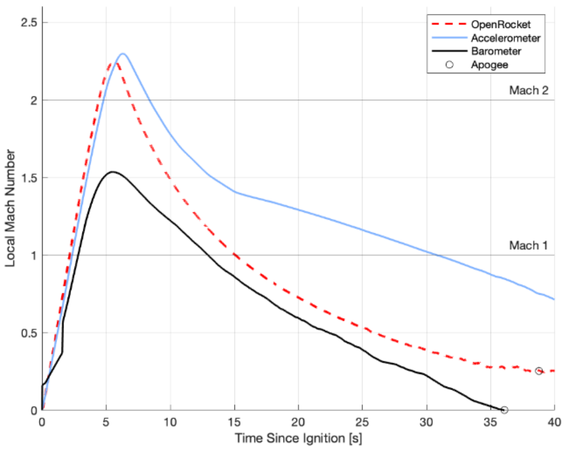


**Figure 4. Comparison of Mach Number Data**

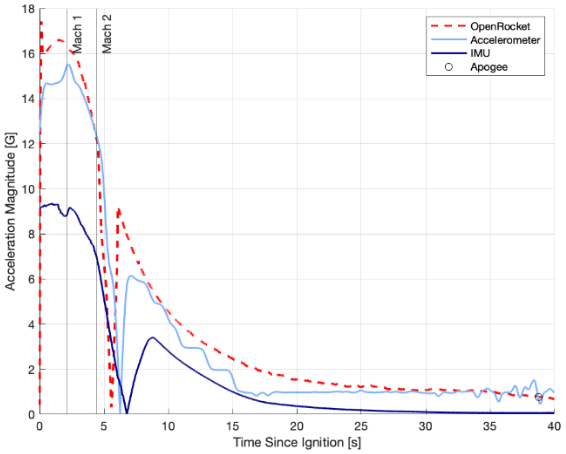


**Figure 5. Comparison of Acceleration Data**

## 5. Conclusion

The paper summarised students' work as part of ESA Academy Fly a Rocket Programme and the consequent work on data analysis to determine the accuracy of OpenRocket simulation software for rockets of this type. Full detail of the programme's specifics was given, and simulation software basics were explained, starting from simple Python estimations to the advanced simulations using OpenRocket. Furthermore, the data readings from the other sensors on the rocket were discussed. In the end, the data obtained from the sensors which could be used to predict rocket trajectory was compared in detail with OpenRocket. The OpenRocket was concluded to offer good precision for low Mach number speeds and slowly decreasing precision at higher Mach numbers. However, the rocket trajectory estimation precision up to Mach 2.5 is still very relevant to amateur rocketry as it provides a good idea about the rocket's behaviour.

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