Final testing, pre-launch activities, launch and post-launch analysis of a sounding rocket made by students in Spain

Alba Badia Rifà[1], *Daniel Cantos Gálvez*[2], *Adam El Ghaib Bougrine*[2], *Javier Hidalgo Marí*[2], *Marc Martí Arasa*[2], *Arnau Pena Sapena*[2]

Abstract

This paper summarizes the final launch preparation tests, the operations before, during, and after the launch, and the results of the launch of a supersonic sounding rocket developed by university students in Spain with the collaboration of INTA (National Institute of Aerospace Technology). The students are part of the Cosmic Research association, based at the Polytechnic University of Catalonia ESEIAAT, and the rocket is called Bondar. INTA is a Public Research Organization under the Spanish Ministry of Defense dedicated to scientific research and development of systems and prototypes in the fields of aeronautics, space, hydrodynamics, security, and defense. The staff of the El Arenosillo Experimentation Center (CEDEA) collaborated in the Bondar mission with their knowledge and launch capabilities. The launch of the rocket took place on the 30th of November of 2021. Two students from BiSky, a rocketry team from the University of the Basque Country, also participated in this project, specifically in the development of the on-board and ground-based avionics subsystems. The paper presents information on the mission systems, the operations before, during, and after the countdown to the launch, the documentation required by INTA-CEDEA for the launch, and the results of said launch. In short, the systems developed by Cosmic Research for the launch are: the rocket, the launch pad, the rocket transport box, the flight simulator, and the ground-based rocket tracking station. The documentation required by INTA includes: a detailed description of the systems, a ground risk assessment, a flight risk assessment, structural analysis, aerodynamic analysis, and a list of countdown operations. Launch post-analysis activities evaluate the performance of systems and operations during the most critical phase of the mission. The Bondar Mission, due to its technical and operational complexity, was the most ambitious project ever developed by students in Spain in the field of rocketry. After a successful launch, Bondar became the highest-flying Spanish student-made rocket, with its apogee around 8 km AGL (Above Ground Level).

Keywords

INTA, launch operations, sounding rocket, Spain, students.

[1] Cosmic Research, Spain, alba.badia@cosmicresearch.org
[2] Cosmic Research, Spain

Acronyms/Abbreviations

CEDEA *Centro de Experimentación De El Arenosillo*

CR *Cosmic Research*

ESEIAAT *Escola Superior d'Enginyeria Industrial, Aeronàutica i Audiovisual de Terrassa*

INTA *Instituto Nacional de Técnica Aeroespacial*

1. Introduction

CR (Cosmic Research) is a student association founded in 2016 with the mission of launching suborbital rockets for the benefit of society. Since its foundation, the CR's team has launched 37 rockets and more than 100 CanSats. With the launch of Resnik in 2017, the association set the Spanish altitude record at student level, achieving an apogee of 2 km.

Following its trail, the Bondar mission was started in 2020, whose goal was to develop all the technologies necessary to launch a stratospheric rocket. This paper aims to give an overview of the steps followed up to the end of the launch campaign.

2. Mission Systems

2.1. Rocket

Bondar is a 2.6 m long, passively stabilized, supersonic, aluminum rocket. It is fitted with custom avionics for apogee detection and separation, and data downlink. It is a sounding rocket with payload capabilities up to 0.5 kg.

Figure 1. Bondar rocket

2.2. Launchpad

Horizontally-stabilized structure with variable elevation angle. It is formed by a six meters tall tower and rail to provide mechanical guidance for the rocket during lift off.

Figure 2. Launchpad

2.3. Rocket transport box

A 2895 x 580 x 690 mm wooden box filled with custom antistatic and antivibration foams fitting the rocket shape that prevents it from sliding to ensure safe transportation during operations.

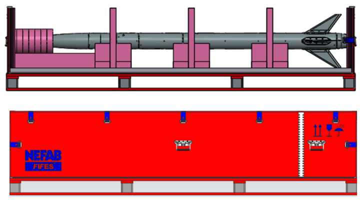

Figure 3. Rocket transport box

2.4. Flight Simulator

CR's own simulator is a 6-Degrees of Freedom stochastic simulator based on MATLAB, which uses semi-empirical aerodynamic models to predict the rocket trajectory.

2.5. Ground-based rocket tracking station

Two antennas were installed on CEDEA's optronic systems to process the in-flight telemetry data by a custom made ground tracking station and send this information to the control center.

3. Operations

In this section, the operations before, during, and after the countdown will be presented. These operations start with the review after transport of all the systems of the mission and end once the team arrives at the headquarters after the launch.

3.1. Pre-launch operations

This group is the most extensive. It comprises activities before arriving at CEDEA and also operations in the spaceport.

First of all, there is a review of all the mission systems. When all the systems are checked, the launch campaign officially starts. This is followed by the sorting and packing of all the components. Then the team proceeds to the transportation. Once in the spaceport, there is the assembly of all the systems, with the exception of the motor, the electronics bay and the recovery bay of the rocket, which are reserved for the launch operations.

During this phase, 3 tests were conducted. The verification of the data reception regarding the avionics and the ground stations, the data injection verification and a launch operations simulation. When all the tests were passed, the last step was the flight trajectory simulations.

3.2. Launch operations

The launch operations start with the motor assembly and end when the motor is ignited. The most critical operations are reserved for this period. In short, these activities are, in chronological order: the assembly of the motor, the final assembly of the recovery bay and electronic bay with the rocket structure, the introduction of the motor inside the rocket, the transportation and placement of the rocket in the launchpad, the final avionics tests and simulations, the introduction of the ignitor, the final security checks regarding the drop area security footprint of the spaceport, and the ignition of the motor.

Since this group includes the most critical operations, it was necessary to detail also the holding operations, the GO/NO-GO criteria and the emergency procedures.

The holding operations comprise all the procedures that solve a possible problem during the countdown. Their importance derives from the necessity of knowing in each moment how to solve a problem, given the tension of the countdown period. Also, it is extremely important to know how much time it can take to solve a problem in order to decide whether the launch operations should be postponed until the next launch window or not.

The GO/NO-GO criteria includes all the conditions that must be met in order to authorize the start of the launch operations. Some examples are: to not surpass the wind limits defined by the simulations, to have favorable weather conditions, to have all the systems ready and all the flight permissions.

The emergency procedures include the instructions to follow if one or more of the potential risks of the launch operations occur. All the team members must be familiarized with these protocols and must have a copy with them.

3.3. Post-launch operations

These operations start once the motor is ignited and finish when the team arrives at the headquarters. They are divided into two groups: the post-launch operations at the spaceport and the post-launch operations outside of it.

The post-launch operations at the spaceport start with the lift off of the rocket. It leaves the launchpad at an approximate velocity of 40 m/s. The powered flight lasts 6 seconds, in which the motor burns all its propellant. Then, the motor runs out of propellant and it continues its ascent for approximately 30 seconds. Once the rocket reaches the apogee, the avionics command the separation of the recovery bay from the avionics bay and the drogue parachute is released. At the same time, the motor bay and the recovery bay are discarded into the sea. The upper stage descends at an approximate velocity of 17 m/s for 8 minutes and then it is recovered from the sea.

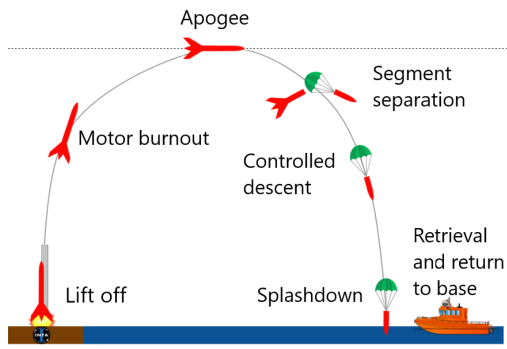

Figure 4. Post-launch operations

Once the avionics bay is recovered, the electronics team proceeds to recover all the electronic components and the SD card. They return to the spaceport and the team starts sorting and packing all the systems. Finally, the team proceeds to the transportation of all the material to the headquarters.

4. Documentation

The safety requirements set by the launch site demanded the production of various documents to ensure system integrity and operational safety before, during and after the launch.

4.1. System description

To better understand the Bondar rocket and serve as reference, a detailed description of all the components of each system was provided, including dimensions, materials, and other complementary information.

4.2. Ground Risk Assessment

For security reasons all risks that might interfere with the mission were identified, assessed, and classified. The risks were evaluated taking into account severity and frequency, following a method proposed by INTA [1][2], to ascertain their criticality. These values were used to determine if mitigation strategies were necessary to reduce their criticality to an acceptable level.

The estimations were based on CR's previous work and other reliable documents. To ensure quality the document was reviewed by both INTA and ASPY, a risk prevention company.

4.3. Flight Risk Assessment

Following the same line of work as the ground risk assessment, this document compiles all the risks associated with the flight of the rocket.

It includes, but is not limited to: motor explosion, premature separation of recovery devices, structural failure (specially the fins and their supports), pitch-roll coupling, high roll rates, and aeroelastic phenomena.

CR's simulator was used to study some of these risks and propose adequate mitigation measures, but literature was also consulted for certain cases.

4.4. Structural Analysis

For both the rocket and the launchpad a FMEA (Failure Mode and Effect Analysis) study was carried out, identifying the most critical failure modes and how to prevent them. For those failure modes related to mechanical overload, a FEA (Finite Element Analysis) was performed. The position and magnitude of the loads experienced in-flight for specific structural parts were determined with simulator data, and CAD models for those parts were designed. With these models, the NX Nastran Design solver was used, alongside Siemens NX software, to obtain the strain and stress profiles for all parts. These results were compared with the maximum yield values of the material, thus providing a theoretical Safety Factor, ensuring that the systems could withstand their expected loads. Other studied failure modes, making use of the Hyperworks suite, included: vibrational modes, local and global buckling, and fin and ogive overheating.

4.5. Aerodynamic Analysis

The aerodynamic analysis of the rocket comprised many aspects. First, it offered a detailed description of the flight simulator, followed by the input parameters. The stability of the rocket was verified under nominal flight conditions, and the expectable values of certain parameters were studied throughout the flight, to serve as inputs for the structural analysis. Risks associated with aerodynamic phenomena were also studied. Finally, the trajectory of the rocket under variable weather conditions was studied for both nominal and adverse conditions (motor explosion, loss of fins, premature separation), to ensure the spaceport footprint was respected.

5. Results and discussion

The data used to perform the analysis of the flight comes from three different sources:

a. CR's simulator: used during launch operations to predict the rocket trajectory and ensure safety.
b. On-board avionics: developed by BiSky Team, transmitted data every 0.3 s to the ground stations.
c. INTA's tracking devices: offer trajectory data at a 50 Hz rate, starting at 1.16 s into the flight due to a tracking error during lift-off.

5.1. Acceleration

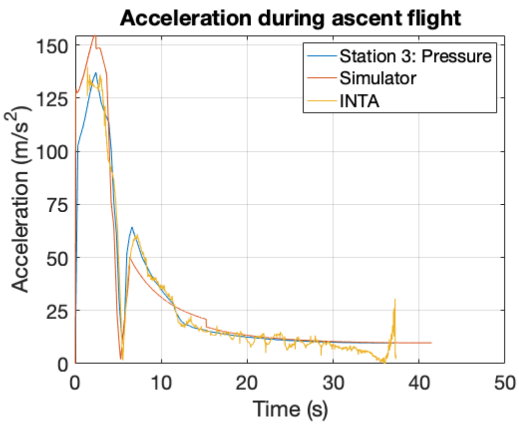

Figure 5. Acceleration during ascent flight

Figure 5 shows the absolute value of the acceleration during ascent flight. The acceleration phase lasts approximately 6 s, and the rest is deceleration.

The readings obtained from the avionics and INTA are almost identical, except from the noise present in the latter due to the higher sampling rate. The divergence at the end is not significant and is attributed to the distance between the rocket and the tracking device.

The simulator predicted a higher acceleration rate during the powered flight, which might not have been achieved due to subpar motor performance and higher drag forces.

The latter can be also observed in the deceleration phase. A higher peak after motor burnout indicates a higher supersonic drag, which quickly decelerates the rocket to the subsonic region (around 12 s after lift-off). The simulator predicted a longer supersonic phase, lasting until around 15 s.

Acceleration rates in the subsonic region are almost identical, which leads to the conclusion that drag discrepancies must be associated with supersonic drag (associated mostly to shock waves). The numerous bolts and rivets in the fuselage, as well as the voluminous fin supports are believed to be the origin of this increased drag. Efforts in the simulator have to be made to adequately characterize the rocket drag (updating current models based on [3]), and constructive improvements are needed for future rockets.

5.2. Velocity

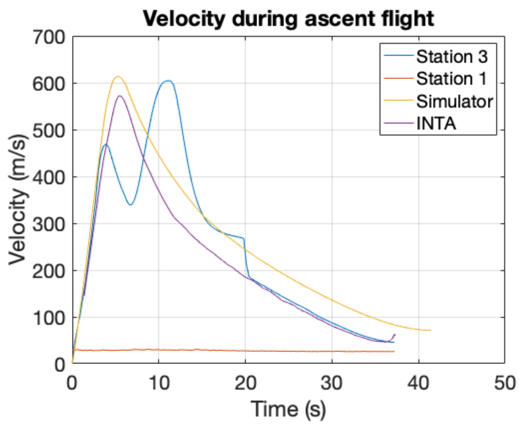

Figure 6. Velocity during ascent flight. Raw data

Figure 6 presents the velocity readings from the two ground stations. Station 1 did not receive consistent data at any point, while station 3 is not accurate during the majority of the flight, since it offers a velocity profile characteristic of a two-staged rocket. The root of the problem has not been identified, and can be associated either with data reading, transmission or reception. Since acceleration readings are correct, the velocity will be obtained through integration (using an explicit scheme), taking into account the Euler angles (which define the orientation of the rocket).

After manipulating the avionics data, the results in figure 7 show a better correlation with reality. The slight difference can arise from the acceleration discrepancies, inaccuracy of the Euler angles measured, or due to the numerical integration scheme.

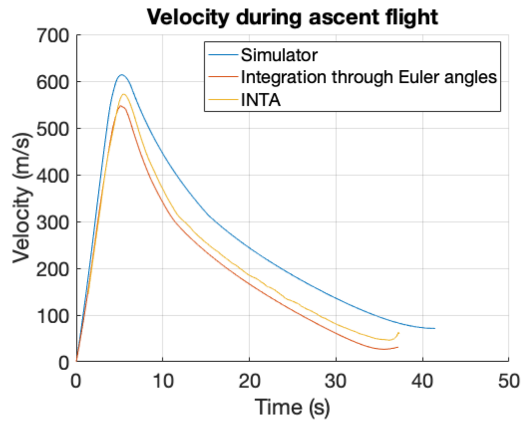

Figure 7. Velocity during ascent flight. Manipulated data

The effects of increased supersonic drag can be seen also in this figure, since the change in slope becomes significant after around 300 m/s (in the transonic region). This strengthens the hypothesis presented from the acceleration data.

The deceleration rates after going below Mach 1 are similar and the model for predicting subsonic drag (also extracted from [3]) is assumed to be accurate.

5.3. Trajectory

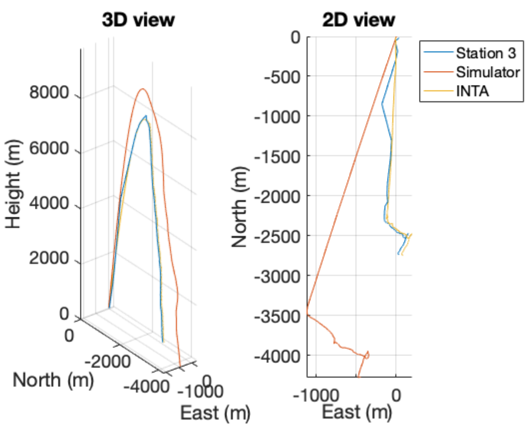

Figure 8. Rocket trajectory

Figure 8 shows the trajectory of the rocket according to the three sources.

Once again, the level of accuracy of the avionics, as received by ground station 3, is high. However, Global Positioning System (GPS) data is not completely accurate during the higher speed segment of the flight. This causes the divergence towards the west during the ascent. If the time is taken into account, it could also be observed that the GPS information is lagging behind during this part, and recovers precision once the rocket moves slowly.

The information from INTA was given in Universal Transverse Mercator (UTM) coordinates defined over the EUROPEAN DATUM 1950 ellipsoid, while the GPS offered geographical coordinates. The discrepancies between both can be appreciated in the descent segment when plotted over a flat surface.

On the other hand, the discrepancy in terms of apogee is clearly observed on the left plot. The expected apogee of around 10 km was approximately 2 km above what the rocket actually achieved. This is the effect of the higher drag force and lower motor thrust explained previously.

In terms of operation, launch platform orientation can be extracted from figure 8. The right subfigure clearly shows how the platform was not adequately oriented at 190º azimuth. This was detected during pre-launch operations after the platform was fixed to the ground. The large safety margins used in terms of wind tolerance and the high variability accepted in the MonteCarlo analysis eliminated the need to correct it, which would have been very time-consuming.

As for the elevation, an angle of 8º was measured with respect to the vertical, only 2º shy of the desired 10º. Since the result fell within the MonteCarlo variability, it was deemed acceptable. The difference cannot be observed on the graph.

6. Conclusions

This mission served as a means to grasp the sheer amount of systems involved even in a stratospherical launch such as Bondar's. Extensive testing, documentation, and careful operations, among other things, were key to carry the mission to successful completion under INTA's stringent requirements. Nevertheless, such an environment was enriching and a viewing window to what a commercial launch might entail.

Well defined operations specially, and carefully prepared protocols, allowed for a fast reaction to unforeseen circumstances and thus contributed to the success of the launch campaign.

Bondar's launch served as a valuable validation of CR's simulator, shedding light on the areas requiring further refinement. A bigger focus on the aerodynamics of the rocket fuselage is necessary for future rockets, as it plays an important role on the performance of the supersonic flight. If those aspects can not be tackled, better models for the characterisation of the rocket should be explored in order to increase the accuracy of the predictions.

Increased drag, coupled with alleged subpar motor performance, limited the apogee of the rocket to 7.8 km, 2.2 km shy of the expected 10 km. With a maximum speed of 572 m/s (according to INTA), the rocket reached Mach 1.7, and withstood accelerations up to 14 g. However, it did not prevent the rocket from becoming the most powerful ever launched by Spanish students.

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Finally, a heartfelt thanks to all the former members that contributed significantly to the success of the Bondar mission.

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