In-orbit validation of satellite attitude control system through VCUB1 mission

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***Abstract*—The VCUB1 mission is the first Earth observation and data collection satellite developed by a private company in Brazil, Visiona Space Technology. VCUB1 is a 6U Cubesat with the primary mission of validating the attitude control software. This paper presents the methodology applied for performing in-orbit validation tests and the results obtained. Initially, dynamics and operation simulations are executed on ground to validate the test procedure and setup, followed by in-orbit testing and telemetry downlink. From the in-orbit results, the VCUB1 attitude control software was successfully validated, with the performance meeting the requirements.**

***Index Terms*—VCUB1, control, attitude, validation, performance.**

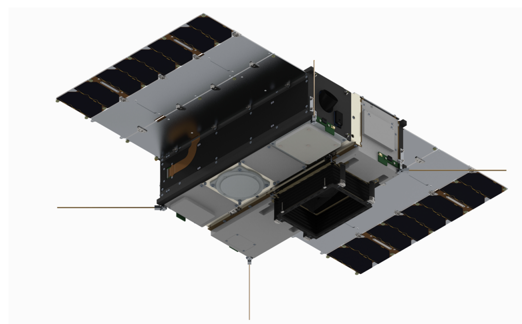

Fig. 1. VCUB1 cubesat.

I. Introduction

Founded in 2012, Visiona Tecnologia Espacial is a joint venture between Embraer Defense & Security and Telebras (Telecomunicações Brasileiras SA). Focused on the integration of space systems and the provision of satellite-based services, the company meets the objectives of the Brazilian Space Program and market demands.

Visiona was responsible for the Geostationary Defense and Strategic Communications Satellite Program, SGDC-1, launched in 2017 in partnership with Thales Alenia Space. In 2023, the company launched VCUB1, the first Earth observation and data collection nanosatellite designed by a company in Brazil.

VCUB1, shown in Fig. 1, is a 6U satellite with a 3U primary optical payload. The camera is capable of performing TDI images with a swath width of 14 km. The optical payload provides four spectral bands, green, red, red edge, and near infrared. As a secondary payload, VCUB1 carries a software-defined radio for ground data collection.

The satellite's onboard data handling and attitude control software was fully developed by Visiona and was first tested in orbit with VCUB1. The mission objective is to validate the payloads and the newly developed software.

VCUB1 was launched in April 2023 and went through a period of software validation and camera calibration. After commissioning and the start of the imaging operation, approximately 500,000 km² of images were successfully acquired. In January 2025 VCUB1 reentered after completing its mission successfully.

This paper focuses on the in-orbit validation of the VCUB1 Attitude and Orbit Control Subsystem (AOCS). The components of the subsystem, the in-orbit validation methodology, and the obtained results are presented in the following sections.

II. VCUB1 AOCS

The VCUB1 AOCS has the responsibility of initially stabilizing the satellite and providing the correct pointing to power generation and payload operation. The AOCS can be divided into hardware and software. The hardware is composed of the equipment listed in Table I. The selected hardware represents standard equipment commonly used in most space missions. These components were chosen to test and validate a diverse range of algorithms.

The Visiona-developed AOCS software was based on the PROBA-2 attitude control software. In [1], the main modules of the PROBA-2 software are presented and the development philosophy is detailed, including the software validation tests performed in the simulations. The same approach and design were applied to VCUB1.

TABLE I
VCUB1 AOCS HARDWARE.

Equipment	Quantity
Magnetorquer	3
Reaction wheel	3
Star Tracker	2
Magnetometer	3
Gyroscope	3
Sun sensor	2
GPS	1

In terms of software, navigation, guidance, and control algorithms were developed in MATLAB/Simulink language [2] and coded in C to be embedded in the onboard software, as described in [1]. The software has the ability to easily change its configuration. Is it possible to define which pointing mode will be used, the commanded attitude profile, and the enabling of specific functions.

Some algorithms implemented in VCUB1 have been published in previous papers. The star tracker Earth exclusion angle prediction for Earth avoidance is presented in [4]. Furthermore, [5] describes the strategy for angular momentum management of the reaction wheels to avoid zero crossing. Both of these algorithms were validated in orbit by the VCUB1 mission.

The software was developed to have ten different pointing modes, each has a specific objective and pointing profile defined by the user. The modes are as follows: BDOT, Magnetic Safe, Earth Target, Flight, Sun, Inertial, Imaging, Geodetic, and Orbital. Some of these modes were also used in PROBA-2 and are described in [1]. Here, all the modes implemented in VCUB1 are explained.

A. BDOT mode

The BDOT mode objective is to detumble the satellite. In this mode, the satellite angular velocity is reduced and the stabilization in one axis is achieved. For this mode the AOCS only uses the reaction wheels at constant speed, the magnetorquers, and the magnetometers. The attitude control in one axis is performed based on the magnetic field measurements.

B. Magnetic Safe mode

Stabilization in three axis using the magnetic field is the objective of the Magnetic Safe mode. The reaction wheels are used at constant speed, and the magnetorquers perform the three-axis stabilization. This mode requires orbit knowledge to compare the magnetic measurements with the Earth magnetic model.

C. Earth Target

The Earth Target mode is the first mode in which a fine pointing is performed using the reaction wheels. In this mode, the satellite performs the necessary maneuver to point toward a fixed coordinate on-ground.

D. Flight mode

In Flight mode, fine pointing is performed to align a selected axis with the satellite's velocity vector. This operational mode is implemented for future missions where orbital maneuvers are necessary.

E. Sun mode

The Sun mode executes the necessary maneuver to align the solar panels with the Sun vector. The maneuver can be simple or with optimization to avoid Star Tracker blinding by the Earth.

F. Inertial mode

The objective of the Inertial mode is to achieve an attitude relative to the inertial frame. In addition, a relative angular velocity can be commanded.

G. Imaging mode

The Imaging mode performs the pointing to a commanded target on-ground, followed by the push-broom maneuver during image acquisition. In this mode, yaw steering can be commanded. The yaw steering maneuver consists in a rotation around the Z axis, where the velocity of the target point (at the local vertical) relative to the Earth surface is perpendicular to the intersection of the Y Z plane.

H. Geodetic mode

In the Geodetic mode, fine pointing to nadir is performed with respect to the WGS84 model of the Earth. In this mode, the yaw steering can also be commanded.

I. Orbital mode

The Orbital mode performs fine pointing of the satellite in relation to the Orbital frame. This reference frame has the X-axis along the radial position of the satellite, the Y-axis along the orbit normal, and the Z-axis completes the right-handed frame. This mode was used for nadir pointing in the VCUB1 mission.

III. IN-ORBIT VALIDATION

Inherited from the SGDC-1 program, VCUB1 requirements are based on premises from the ECSS standars. The Space Engineering Verification Document (ECSS-E-ST-10-02C) [3] presents the verification process to be applied to a space product and the documents to be generated at each of the following steps:

- Verification planning: Before launch and even before Assembly, Integration and Testing (AIT), Visiona implemented, for the AOCS subsystem, the Verification Plan (VP), Verification Control Document (VCD), and Test Procedures documents.
- Verification execution and reporting: In this step, every test procedure for AOCS validation in orbit is executed. The results are translated into official reports to ensure that the requirements are met.
- Verification control and close-out: To conclude the mission, Visiona arranged a Mission Close-Out Review,

presenting to a board how each VCUB1 subsystem performed.

The first step to perform an in-orbit test of the AOCS software is to define the operational mode that will be tested. From this, the software parameters are defined to achieve the expected pointing condition. However, before uploading these parameters to the satellite, a verification is performed using the Dynamic Satellite Simulator (DSS) on ground, detailed in III-A.

After verification, the given parameters are allowed to be uploaded to the satellite. The test is executed and the telemetry is downloaded so that the in-orbit behavior can be compared to the simulation results.

These steps compose the methodology applied to validate the VCUB1 AOCS software in orbit. In the sections below, the DSS and the process to setup the test in orbit are detailed.

A. *Dynamic Satellite Simulator*

The Dynamic Satellite Simulator consists of software where the AOCS application runs alongside a "real-world" simulator, which generates data for attitude and orbit dynamics, sensors readings, and actuators commands.

The AOCS software on the DSS is the same as the one running on the VCUB1 onboard computer. Therefore, the simulator can be used to verify the satellite's behavior given the AOCS parameters that will be used for an in-orbit test, such as enabling some software functions and commanding different attitude profiles. With this, the test is performed first in the simulator, ensuring that it does not damage the satellite.

B. *In-orbit test setup*

Once the test is fully verified on-ground, the satellite operator can execute the procedure. To change satellite parameters, configuration tables (binary files) are sent to VCUB1. When loaded, these tables set a new operational mode for the AOCS software. Possible configurations are, for example:

- To automatically point to the Sun when in sunlight
- To use attitude and orbit Kalman Filters
- To overwrite a sensor reading (in case of hardware error)
- To select the attitude control philosophy

During all tests, telemetry packets are collected and downloaded. This data is then compared with simulations to ensure that the obtained results are as expected.

IV. In-orbit results

During the validation process, all the AOCS operational modes performed as expected in-orbit. In this section, the main results are presented. Each test is related to one AOCS operational mode, which is described, and its pointing requirements are detailed. The results are shown and evaluated against the requirement.

A. *Sun mode*

In VCUB1 mission, the Sun mode has the Absolute Pointing Error (APE) requirement of 1° and a Relative Pointing Error (RPE) of 0.2° over a 60 s window. To validate this mode in-orbit, an attitude was commanded to align the satellite's solar panels with the Sun direction vector.

The telemetry collected from this test is presented in Fig. 2 and Fig. 3, where the resultant APE and RPE are shown, respectively. The APE achieved is in the order of 0.2°, below the requirement, and the RPE was maintained below 0.2° for more than 60 seconds, also within the requirement.

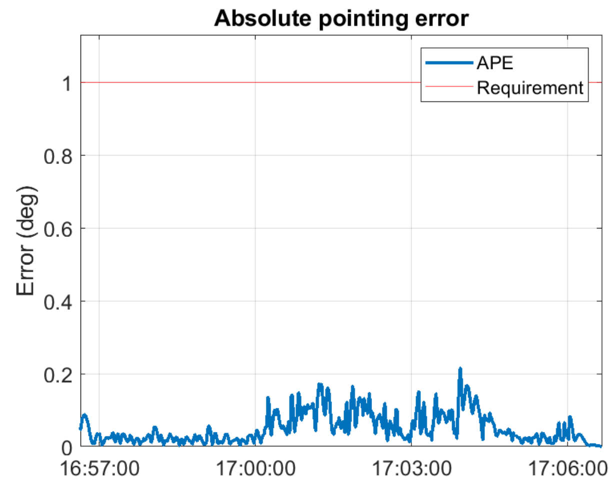

Fig. 2. Absolute pointing error achieved with Sun mode.

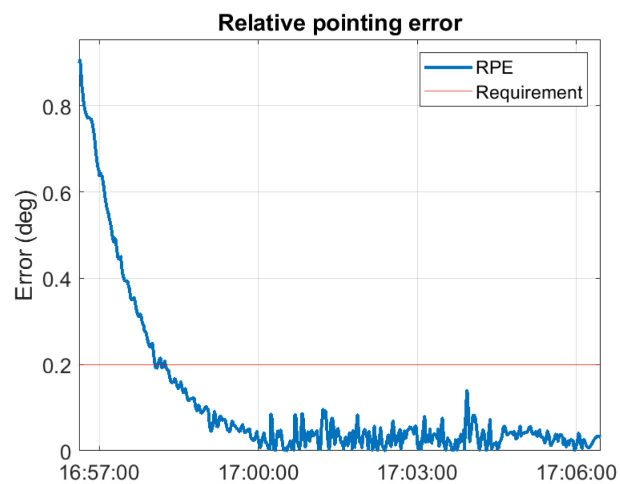

Fig. 3. Relative pointing error achieved with Sun mode.

To visualize the satellite attitude, the VCUB1 data was fed into Ansys STK (System Tool Kit) [6]. Fig. 4 shows the satellite's body frame axis along with the Sun direction vector. It can be seen that the satellite's -Z body-axis (red), is aligned with the Sun vector (yellow). This confirms that the commanded attitude was achieved successfully.

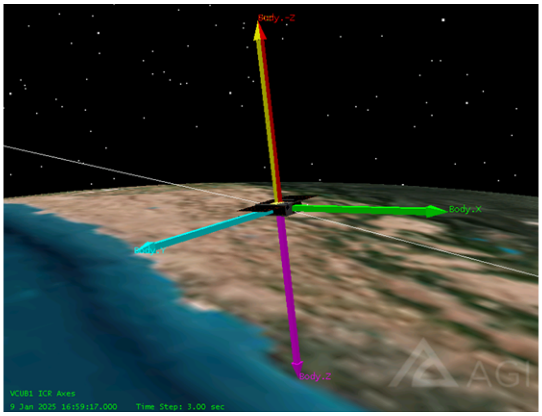

Fig. 4. STK illustration of pointing achieved with Sun mode.

B. *Orbital mode*

As detailed in Section II-I, in the Orbital mode, the reaction wheels are used for fine-pointing control in the orbital reference frame. For VCUB1, this mode has the APE requirement of 1° and RPE of 0.2° over a 60 seconds window.

This mode was used several times during the VCUB1 mission, mainly to perform a fine-pointing to nadir. Fig. 5 presents the APE during a maneuver commanded by using the orbital mode. Starting with an error of 27°, it took approximately 2 minutes for the satellite attitude to converge.

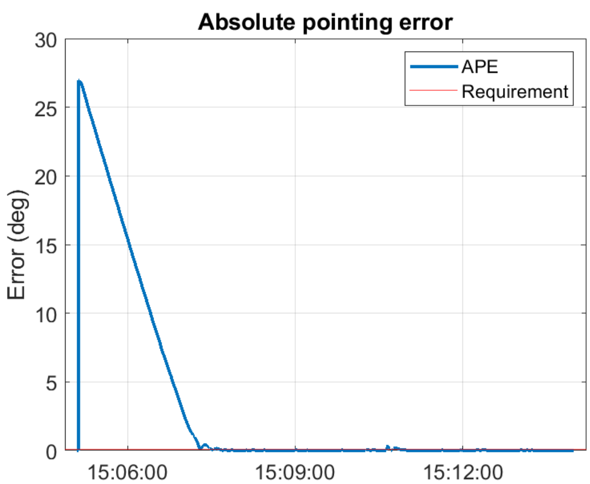

Fig. 5. Orbital mode maneuver absolute pointing error.

A closer look at the data in Fig. 6 shows that, after convergence, the APE is kept below the requirement. The RPE obtained is presented in Fig. 7, it remains below the required value for more than 60 seconds, thus being compliant with the mode requirement.

C. *Imaging mode performance*

For Imaging mode the pointing requirements are an APE of 0.06° and an angular velocity error of 0.0036°/s. Fig. 8 shows the APE during an imaging operation, with the pointing

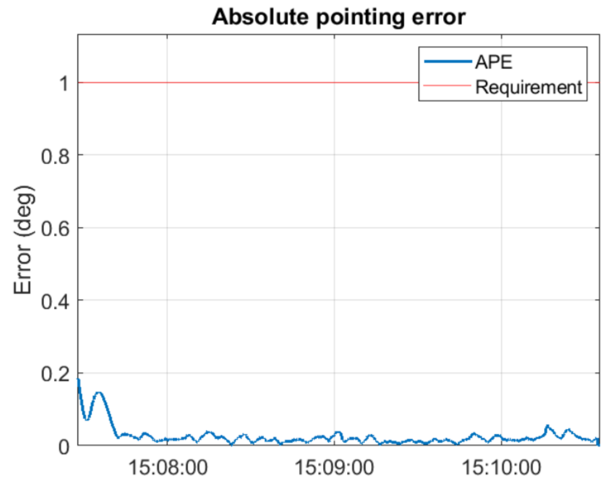

Fig. 6. Absolute pointing error achieved with orbital mode.

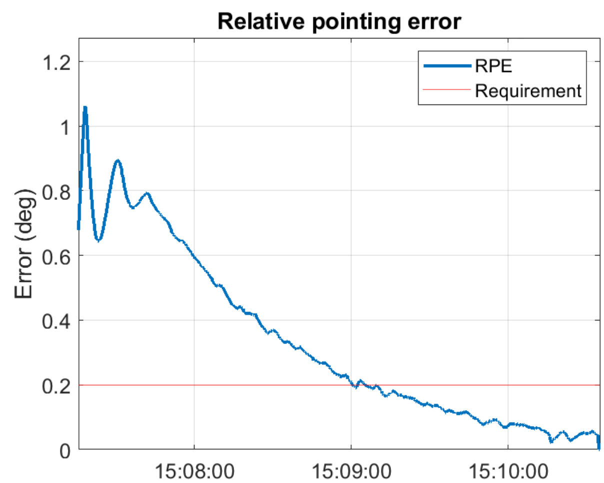

Fig. 7. Relative pointing error achieved with orbital mode.

requirement being met for the duration of the imaging, 15 seconds.

The angular velocity error is shown in Fig. 9. The error achieved is above the requirement; however, this behavior was expected. Simulations performed on ground predicted the same angular velocity error seen in-orbit. Because our system considered margins in other requirements, the angular velocity error was accommodated within the acceptable margins and did not affect the image quality.

Figures 10 and 11 present two images captured by VCUB1, after grounding processing, demonstrating the pointing performance of the imaging mode.

D. *Inertial mode performance*

The pointing requirement for the Inertial mode is an APE of 1°. To validate the AOCS Inertial mode in orbit, the satellite captured a picture of the Moon. This test was challenging, since the VCUB1 mission was not planned to perform this kind of maneuver and imaging.

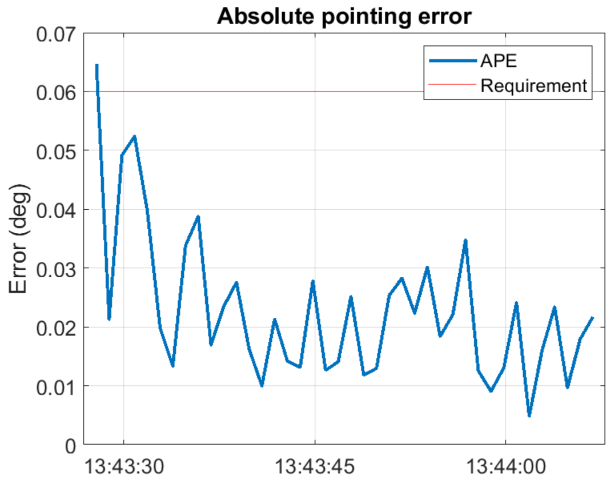

Fig. 8. Absolute pointing error achieved during imaging.

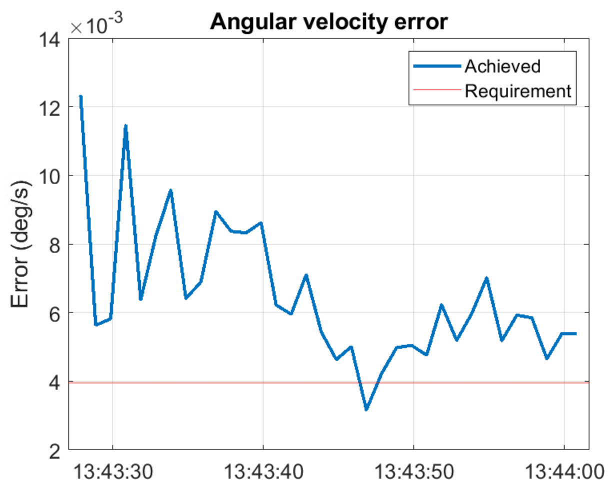

Fig. 9. Angular velocity error achieved during imaging.

Due to VCUB1's TDI camera, a push broom maneuver is needed for correct imaging. To achieve this maneuver with the Inertial mode, first an attitude with a pitch offset relative to the Moon position was commanded, and once the imaging started, a relative angular velocity in pitch was applied. Fig. 12 shows an STK scenario with the attitude telemetry from the maneuver moment. The top image shows the commanded offset in relation to the Moon, while the second image shows the Moon being imaged during the commanded angular velocity.

Fig. 13 presents the APE obtained since the first commanded attitude, with an offset from the Moon's position. A large maneuver was performed, and convergence was achieved. The plot shows the APE with a zero value during the maneuver: This is due to the loss of GPS measurements, which is compensated for by the use of a TLE for orbit estimation, so the maneuver continues to be performed.

Fig. 14 shows the APE a few minutes before the image and during the imaging. Although the error is maintained below the requirement, an increase in the error occurs when the relative

Fig. 10. Satellite view of Brasília, capital of Brazil - Captured by VCUB1.

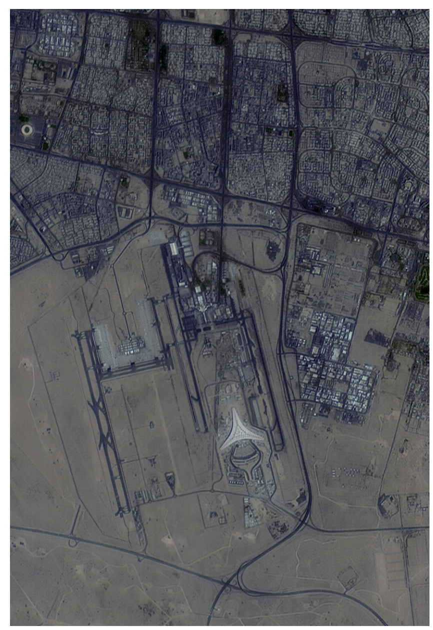

Fig. 11. Satellite view of Kuwait - Captured by VCUB1.

angular velocity is commanded for the push broom maneuver, Fig. 15 shows the moment where the angular velocity of 0.01 rad/s in pitch is commanded.

For push-broom imaging of the Moon, given the geometry of the problem, the commanded angular velocity should be related to the camera linerate according to Eq. 1.

$$\omega = \frac{2l_{var}}{n} atan(L/d_{E,M}) \approx \frac{l_{var} L_{pixel}}{d_{E,M}}, \tag{1}$$

In Eq. 1, ω is the angular velocity, l_{var} is the camera linerate,

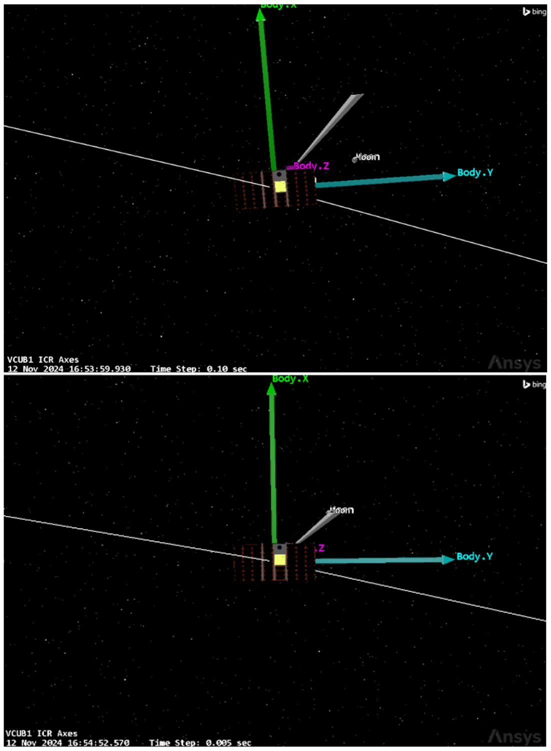

Fig. 12. Pointing profile for moon imaging, first commanded offset (above) and the pushbroom (below).

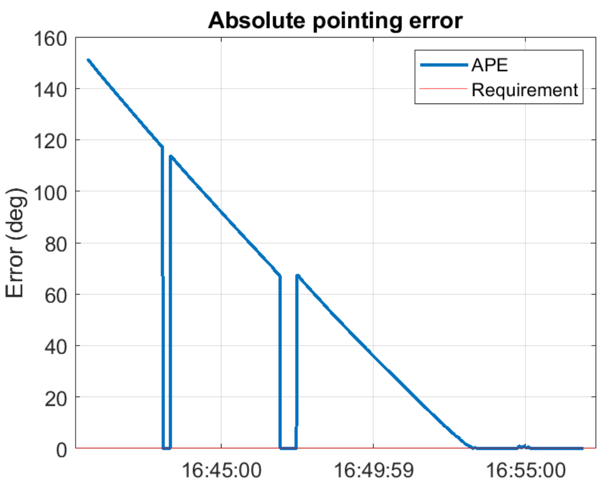

Fig. 13. Maneuver performed for Moon imaging.

n is the number of lines in the image, $2L$ is the image size, proportional to n, $d_{E,M}$ is the distance between Earth and the Moon, and L_{pixel} is the Moon projected length of the pixel. In our case, the satellite had a maximum angular velocity and a minimum linerate limitation. With the lowest linerate, a commanded velocity of 0.018 rad/s would be required, which exceeded the spacecraft's limits.

Knowing this, the angular velocity commanded for the pushbroom was chosen to be in accordance with the maximum value VCUB1 can achieve. This is the main cause of the

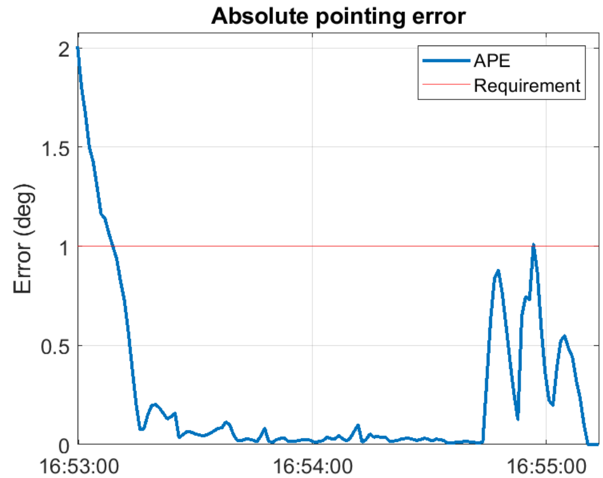

Fig. 14. Absolute pointing error achieved during Moon imaging.

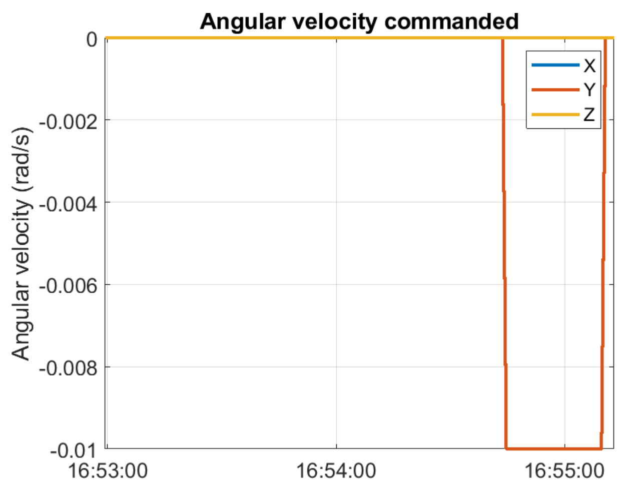

Fig. 15. Angular velocity commanded during Moon imaging.

flattening in the final image of the Moon, presented in Fig. 16 in raw and processed formats. However, with this test, the Inertial mode was successfully validated, meeting the pointing requirement.

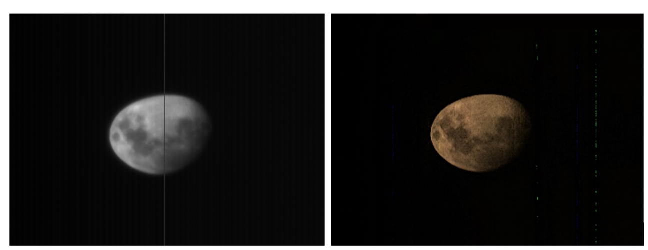

Fig. 16. Moon image Raw (left) and post-processed (right) - Captured by VCUB1.

V. Conclusions

This paper presents the validation process of the VCUB1 attitude control software in-orbit. The validation methodology is discussed, including the initial simulation on ground to evaluate the test setup and procedure, the in-orbit test, and the telemetry analysis.

All AOCS operational modes were successfully tested in-orbit, and the main results are presented and discussed in this paper. The performance of the operational modes met the mission requirements. From these results, the VCUB1 AOCS software was successfully validated in-orbit.

Having validated the software during the VCUB1 mission, minor modifications allow portability for Visiona's future satellites, with a larger structure and a different hardware architecture. This demonstrates that Brazil, through Visiona, has achieved autonomy in attitude control software development and is ready for the next missions in the upcoming years.

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