Journal of Systems Engineering and Electronics
Vol. 31, No. 6, December 2020, pp.1230 – 1244

Qualification and validation test methodology of the open-source CubeSat FloripaSat-I

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Abstract: The FloripaSat-I project consists of an initiative from the Federal University of Santa Catarina (UFSC), in Brazil, to train students to design, test and integrate innovative space systems. The group just developed its first open-source CubeSat, the FloripaSat-I, which aims to empower students to develop space systems through a practical approach, where they have full control of the design and test of a real spacecraft. The project has already gone through all the stages of a CubeSat mission prior to the launching and operation stages. A prototype of the satellite, as well the engineering models 1 and 2 (EM-I and EM-II) were built. The expertise provided by the engineering models allows the development of a functional flight model (FM). This paper presents the validation and qualification tests that pass various FloripaSat-I models, from the engineering model to the flight model. All stages of the project are described, the tests performed in each phase, as well as the lessons learned. Thus, this paper serves as a guidance for other university teams that want to test their own CubeSats, as well as teams that want to use the open-source hardware and software left as heritage by this project.

Keywords: embedded system, nanosatellite, cubesats, test methodology.

DOI: 10.23919/JSEE.2020.000103

1. Introduction

FloripaSat-I is a space technology demonstration mission created by the Federal University of Santa Catarina (UFSC, in Portuguese) and run entirely by students of the institution. The main goal was to launch a core-satellite developed by the students, which is composed of three main modules: the electric power system (EPS), the on-board data handling (OBDH), and the telemetry, tracking and command (TT&C). The launch occurred in December 20, 2019 as a secondary payload together with the Brazilian Space Agency 's satellite CBERS-04A in a Chinese Long March 4B rocket.

The mission is testing key technologies that enable faster and cheaper development of future satellites using the same core structure. As an educational mission, it also serves to train engineering students in conception, design, implementation, integration and operation of a complete space mission. It is based on an experimental platform for space technologies research, providing empirical data for diverse experiments before, during, and after the launch in orbit.

In this paper, FloripaSat 's service platform was developed and available as an open-source project. Software and hardware for the EPS, OBDH, and TT&C modules are available from a public repository and may be used by other groups in future missions.

Following a system engineering approach, the project went through the prototype model (PM) to engineering models (EMs) EM-I and EM-II, as well as to the final flight model (FM), with tests occurring in all phases to validate the systems. The FloripaSat-I team had adopted diverse processes of verification and validation for different CubeSat models. In this paper, the qualification stages of prototype, engineering, and FMs of FloripaSat-I are described. The results obtained in the tests were decisive to correct failures, validate the sub-systems, update PM for EM-I, then for EM-II and from EM-II to FM.

In addition, this paper aims to show the evolution of the open-source platform throughout the project stages. By presenting the validation and qualification steps, this

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Manuscript received February 01, 2020.

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This work was supported by the Brazilian Space Agency , the National Council for Scientific and Technological Development, and the Coordination for the Improvement of Higher Education Personnel.

article serves as a guide for other groups that will make use of the platform or will develop their own CubeSats.

This paper is organized as follows. Section 2 presents the methodology used during the project phases. Section 3 presents the tests to which the EM is submitted. Section 4 presents the validation/qualification of the FM. Finally, Section 5 presents conclusions drawn during the entire project.

2. Methodology

Regarding the development of CubeSats, especially in the university environment, the systems engineering approach should consider the academic needs, include the factor that the team is composed of students and manage the constraints of the available resources. The documentation and information transmitted among the students actuating in different phases of the project shall also be considered. During the FloripaSat-I, several students cooperated in the mission, leading academic research and testing different techniques. Therefore, keeping the documentation consistency and traceability, as well as controlling the implications in the main satellite subsystems were a challenge. Attention should be taken to organize all the different results and inputs, and the people involved must have the same focus, which needs to be in compliance with the mission requirements and objectives.

FloripaSat-I is a nanosatellite, standard CubeSat 1U, with the main external dimensions of 100 mm×100 mm× 113.5 mm. It weighs less than 1.3 kg and meets a set of other requirements that will be presented in the following section. In the orbit, this small spacecraft faces the hostile space environment, where typical temperatures measured by CubeSats in low earth orbit range from −30°C when eclipsed by the Earth to 60°C in direct sunlight. The satellite is not only exposed to a cyclic thermal variation, but also to high levels of radiation, low pressure, and many other issues with great potential to permanently damage the satellite hardware, compromising the mission. Moreover, even before placed in the orbit, the satellite has to support the rocket launching, a very critical phase in terms of mechanical stress.

It is important to mention that in space, the satellite will have contact with high levels of radiation. If it is not properly handled, it may cause multiple problems in its electronic systems. Those problems may vary from a simple "bit-flip", that is a change in a logic level of a memory, i.e., single event upset (SEU), to an irrecoverable damage in the hardware, caused by current peaks or permanent "bit-flip", i.e., single event latchup (SEL), single event burnout (SEB) [1].

Every aspect cited above has to be anticipated when designing the satellite hardware and firmware to ensure that the spacecraft will properly operate along its mission. There are still functional and non-functional requirements, for example data transform rates, energy consumption, and other parameters that impact the final model, but they are not discussed in this paper since the main goal is to give a general idea regarding the development of FloripaSat-I.

2.1 Project phases

In order to have an operational satellite ready for launch for the first time, the first activity that the team initiated was the definition of a project management strategy, with the participation of all students. As an initial task, a literature review on CubeSat projects [2−4], and on project management was carried out. Adapted from the "system engineering general requirements" [5], a document from European Space Agency (ESA), the project was divided into the following phases, simplified as follows:

Phase 0 Mission analysis: definition of the general system requirements; table of general requirements; design of the subsystems; product tree and block diagram; reference document; model documentation and registration; mapping processes.

Phase 1 Feasibility analysis: document of possible solutions with the used references; development of a first concept; initial proposal solution; block diagram of the subsystems; prototype model.

Phase 2 Definition of preliminary design: preliminary technical details (electrical, mechanical, etc.); definition of the preliminary list of materials; definition of the preliminary design for manufacturing; design and definition of support equipment and testing.

Phase 3 Development of EM: manufacturing and testing of the satellite engineering models.

Phase 4 Detailed definition design: system concept and operating procedures, including development, tests and pre-qualification of critical components.

Phase 5 Development of an FM: manufacturing and testing of the satellite flight model.

Phase 6 Qualification and integration: validation of equipment; integration of subsystems; testing and verification.

Phase 7 Launch and mission control.

The systems engineering approach adopted since the early stage made an organized and structured workflow possible , allowing clear objectives and major deliveries for each phase and improving the development process. Furthermore, during major design definitions and project reviews, this approach acts as a subsidy for how the critical decisions should be carried and offers useful tools to accurately measures the compliance of this decision with the mission requirements. In particular, Phases 3−5 are the most affected ones, since they represent the major project schedule, activities, and development decisions. The outputs generated at the end of these phases determine the key factors that influence the mission success, then it is essential to analyze the preliminary and critical design review documents to ensure the proper development and next challenges.

Throughout the project, the aforementioned phases enabled the team to gradually improve the design of the modules by including clear delimitation of the expected readiness in each stage and demanding design reviews. These periodic assessments brought important design changes from PM until FM that will be described in detail along the next sections. Despite these critical changes, by following incremental steps, the transitions became a natural project iteration, and problems were detected before turning infeasible to be solved. These reviews result from major testing campaigns between the models, as organized in Fig. 1, where LIT means Laboratory of Integration and Testing and INPE means National Institute for Space Research.

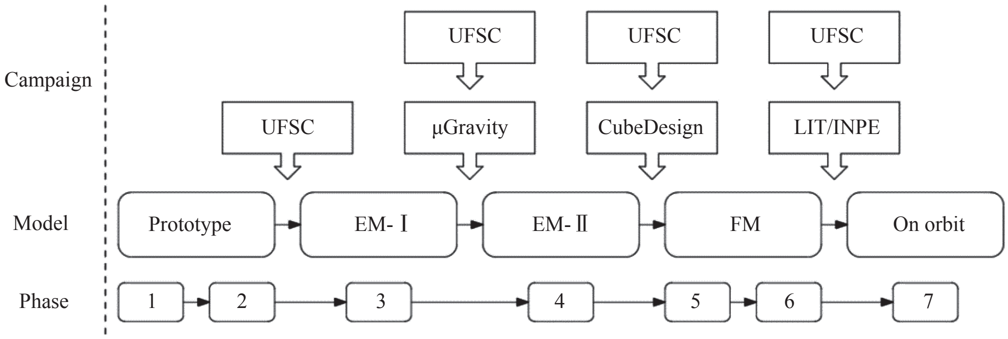


Fig. 1 Flow chart of the development and tests of FloripaSat-I

2.2 Milestones

During the development of the FloripaSat-I mission, two remarkable milestones were achieved regarding the design maturity: the preliminary design review (PDR), which occurs between Phase 2 and Phase 3; and the critical design review (CDR), before the progress to Phase 5. In the PDR, significant design changes were considered, and, with the external support of experts in the field, new strategies were defined to meet the mission requirements. This transition was essential to review the architecture and implementation for both hardware and software early in the development chain and made it possible to trace the key elements of later designs.

Also, equally important, the CDR brought the confidence that the EM-II design had enough maturity to be used as start point for the flight model and created another opportunity for external support and analysis. Throughout the elaboration of the review document, not only important discussions and minor changes were fulfilled, but also design and documentation flaws were found. Then, even before the review by the external reviewers, the team could find problems by themselves, that otherwise could cause critical failure in the satellite subsystems and operation. Moreover, by having to fulfill several topics and settle dependencies of this phase to complete the review document, the team had to propose measurements to accelerate the process of the satellite and ground station regulations, define how to approach mandatory tests required for the qualification campaign, elaborate an operation plan and finish all development activities.

2.3 Project evolution

In the preliminary design phase, teams of students were defined for the development of each subsystem, and to develop different prototypes for demonstration of concepts that helped to define the design of the engineering models. In this phase, different models were developed for each subsystem. For example, for the energy power system, four different prototypes models were studied, produced and tested in the laboratory that supported the maturity of the project. The tests applied to the prototypes will not be detailed throughout this paper for their relative simplicity. However, the knowledge gained from its execution made it possible to create an EM.

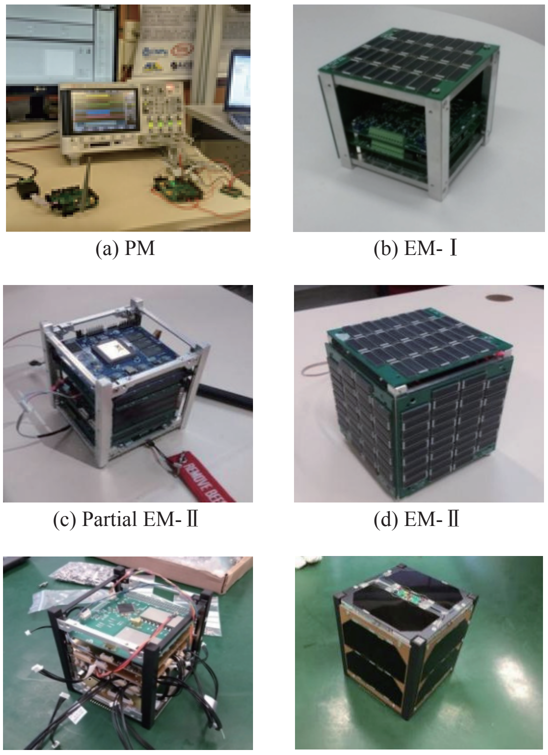
During the EM phase, two models were built, namely EM-I and EM-II. Only one of the EM was expected to be built, but the team had the opportunity to test them in two different scenarios that arose from specific opportunities during the development. As a result, the findings and also failures observed in the first and second tests were transformed in improvements of the EM, here referred to EM-I and EM-II as they were two important milestones of the project. The first is the μGravity project, a project aimed to test various experiments in a micro-gravity environment [6]. Towards this end, the satellite was subjected to a sub-orbital test flight and had its first field experience. The second is the CubeSats competition offered by the INPE, which aims to foster Brazilian aerospace research. In the competition, several universities submit their prototypes to semi-optimal tests that do not guarantee validation/qualification, but provide useful guidance to the participating teams [7].

In Table 1, there are the main activities used to test the PM, EM and FM. This table reunites the phase regarding the level of development, the model associated with the corresponding phase, the tests, the opportunity/facility to perform the test, a brief description of the test, and finally the electrical status of the satellite during the test, where "On" means it is working and "Off" means it is electrically disabled. Following the status "Off", it is also indicated the way to shutdown the satellite: pressed kill switch (KS) or inserted remove before flight (RBF). Each test in Table 1 will be further discussed in the next section.

Table 1 Timeline of FloripaSat-I: main tests from PM to FM

Phase	Model	Campaign	Test	Status
3	EM-I	μGravity	Communication	On
3	EM-I	μGravity	Sensor measurement	On
3	EM-I	μGravity	Hardware functionality	On
4	EM-II	CubeDesign	Thermal cycling	On
4	EM-II	CubeDesign	Random vibration	Off (KS)
4	EM-II	CubeDesign	Fit check	Off (KS)
4	EM-II	UFSC	Sun emulator	On
4	EM-II	UFSC	Communication test	On
5	FM	UFSC	Mass	Off (KS)
5	FM	UFSC	Center of gravity (CG)	Off (RBF)
6	FM	LIT/INPE	Dimension	Off (RBF)
6	FM	LIT/INPE	Fit check	Off (KS)
6	FM	LIT/INPE	Vibration	Off (KS)
6	FM	LIT/INPE	Thermal cycling	On
6	FM	LIT/INPE	Bake out	On

To have a general idea about the different models of FloripaSat-I, in Fig. 2 there are pictures showing the evolution of the hardware.


(a) PM (b) EM-Ⅰ

(c) Partial EM-Ⅱ (d) EM-Ⅱ

(e) Partial FM (f) FM

Fig. 2 FloripaSat-I evolution through different phases

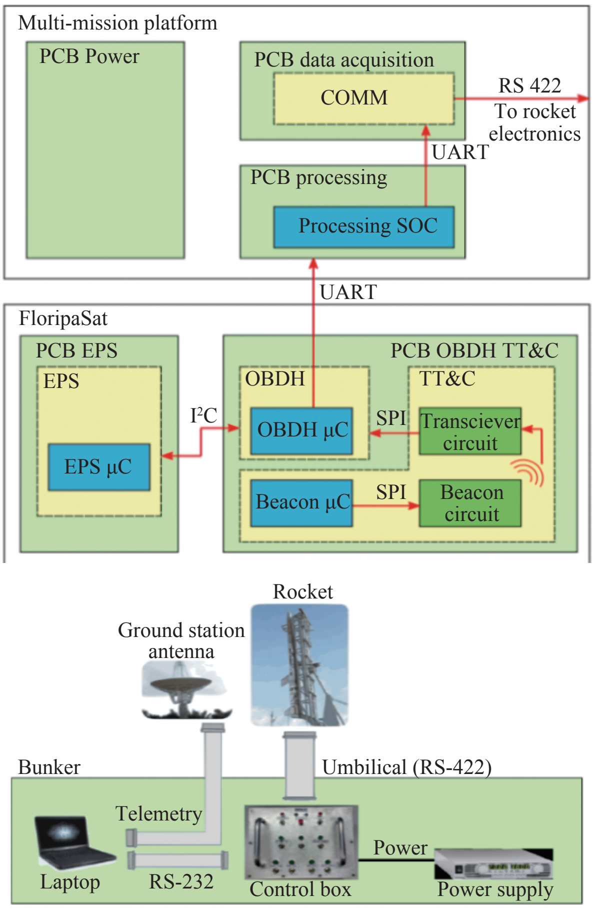
3. EMs

In this section, two test campaigns of EMs of FloripaSat-I are described, namely, the μGravity and CubeDesign, as well as their main results, lessons learned, and consequent modifications. The scenarios that FloripaSat-I was exposed to include hardware integration, robustness to launch, radio communication, telemetry decoding, battery charge management, measurements with inertial measurement unit (IMU), temperature sensors, thermal cycling, and vibration. The purpose of them was to ensure that the FloripaSat-I EMs present the necessary functionalities expected from the mission as well as demonstrating robustness in relevant environments.

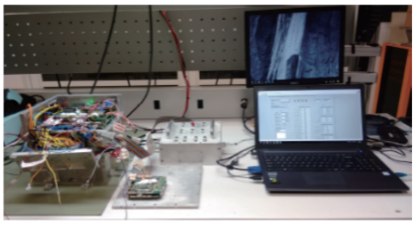
3.1 EM-I: μGravity

The subsystems of EM-I of FloripaSat-I have been tested on board of the sounding rocket VSB-30 launched from the Alcântara Launching Center, Brazil in December 2016 in order to validate their design in a relevant environment. A dedicated embedded system has been proposed to operate as an electronic interface between the nanosatellite subsystems and the rocket electronics. This embedded system was designed with minimum change in the hardware of the satellite because modification in the nanosatellite design would imply in testing a different setup from the final model version [8].

Fig. 3 shows the FloripaSat-I architecture diagram for the suborbital test. In this version of the FloripaSat, OBDH and TT&C were on the same board and EPS in another. When the satellite was at a high altitude, OBDH shall buildup the data frame and send it to the TT&C subsystem (via serial peripheral interface (SPI)). TT&C was responsible for sending and receiving data from the ground station. However, it is not possible to add an antenna for the EM-I on the VSB-30 rocket flight as the payloads would not be deployed. Therefore, to test TT&C, it is configured to transmit data internally from the beacon radio to the transceiver radio. Even without the antennas, the radio frequency circuits should be able to send and receive data to each other, due to their proximity.



Suborbital experiment setup



Experiment integration

Fig. 3 FloripaSat-I architecture diagram for the suborbital test

After the integration process, carried out at UFSC, the EM-I boards were sent to the Department of Aerospace Science and Technology (DCTA, in Portuguese), with support of the Brazilian Air Force, to be submitted to the flight acceptance tests. Three FloripaSat-I subsystems had been tested in the μGravity campaign: EPS, TT&C, and OBDH. Examples of measurements conducted during the flight include the acceleration, angular velocity, and charge of the battery, shown in Fig. 4, Fig. 5 and Fig. 6. Results indicate that the acceleration is up to 16 *g* and concentrated in the longitudinal axes during the launch. The result for the batteries remaining electrical charge shows that during the flight, the batteries discharging rate is the same as before the flight since the subsystem’s power consumption has remained the same. The angular speed in the longitudinal axis saturated the range of the sensor, which was set to 250°/s. This worst condition of rotation happened in the beginning of the launch and decreased with the rising of the rocket.

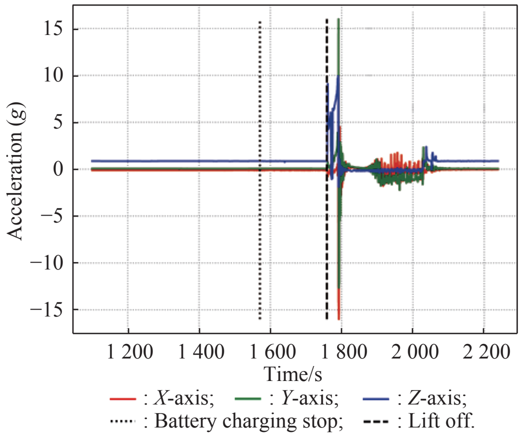


Fig. 4 Acceleration from the OBDH accelerometer during the μGravity experiment

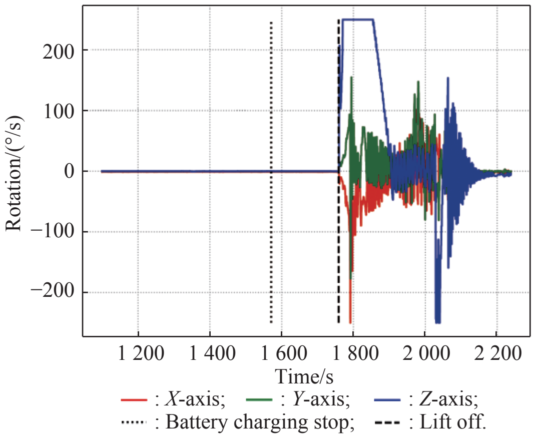


Fig. 5 Rotation from the OBDH gyroscope during the μGravity experiment

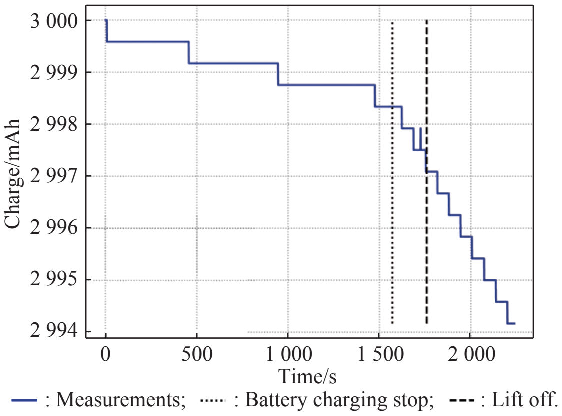


Fig. 6 Battery charge during the μGravity experiment

During the tests an unstable metal-oxide-semiconductor field effect transistor (MOSFET) of the kill-switch circuit was noticed as well as the absence of an external circuit to charge the batteries safely. The problem related to the KS concerns the activation of the MOSFET-N used to power off the satellite. When the switches were activated, they put the MOSFET's gate in a high impedance state. The modification made later caused the KS to be connected to battery voltage when activated. During the flight, another anomaly was that the radios did not work properly. Therefore, the team decided to change the topology of communication and opted for commercial radios made in China. It was noticed that the radio under development by the team was not reaching the desired power, and in addition, it was proving to be a very complex circuit and difficult to assemble. In this context, due to the available time and human resources, employing a commercial radio was considered to be the best alternative. Finally, a significant modification was the decision to split the printed circuit board (PCB) in three parts, each one dedicated to EPS, OBDH, and TT&C, exclusively. Before that, the OBDH and TT&C modules were both on the same board. While this layout allowed a compact architecture, this proved to be a complicated approach for testing by a team without much maturity with space systems. Thus, to ease the testing and development of the different subsystems, the OBDH and TT&C were separated into two boards in the following model.

From this time on, in addition to focus on the operational functionalities of the satellite, the design was also driven by constraints that could make it easier to fabricate the boards, weld components and test the main parts by different members working simultaneously.

These findings have allowed important modifications to be made on the design EM-II of the FloripaSat-I, as follows: revision on the TT&C radio circuit; on-flight dynamic modification of the measurement range in the OBDH IMU and implementation of an external battery charger circuit for the EPS.

3.2 EM-II: CubeDesign

The EM-II is an improved version of EM-I with EPS, OBDH, and TT&C in different PCBs, a mechanical structure similar to the FM, an interface board for external communication, EMs of solar panels, electrical heaters for batteries, an EM of KS and circuit for RBF.

The 1st CubeDesign [9] was a Brazilian competition for students involved in projects of small satellites, including graduate, undergraduate, and high schools from all around the country [7]. To promote a healthy environment among the teams, integrate the students, share experiences and provide technical assessment of the projects, the event was held in São José dos Campos-SP, at facilities of the INPE on July 25−28, 2018. In the same category of FloripaSat-I was the 2U CubeSat Zenith from Federal University of São Paulo (USP), 1U OrbitaSat from Pontifical Catholic University of Minas Gerais (PUC Minas) and 1U Facens from Sorocaba Faculty of Engineering (FACENS).

The requirements for the projects were the same as "CubeSat Design Specification rev13" [10], but, in addition to that, the examiners (technicians of INPE) elaborated a battery of tests based on an imaging mission. FloripaSat-I does not have any camera, and for this reason some criteria of the competition did not apply for it, however, the team registered in the event because of the relevance of the initiative for Brazilian CubeSats, opportunity to expose the project to other people as well as to test some subsystems in the LIT of INPE (LIT/INPE). After the tests, the satellite should send telemetry to demonstrate that it was still functional and in the last day each team presented the project for the public.

During the competition, the EM-II of FloripaSat-I had to send telecommand (TC) and receive telemetry (TM), manage the energy of battery at the illuminated and shadowed portions of the orbit, support environment tests like thermal cycles of −10°C to 50°C and random vibration based on parameters of launcher Falcon 9 (SpaceX) [11]. One functional test consisted of reading the battery current when the satellite was exposed to sun and shadow, checking how the battery was charged and discharged, respectively. The battery current data was sent by radio communication to the ground station (GS), where the data was unpacked and showed on a computer. This test was successful and validated the current reading of the battery, communication between different subsystems of the satellite, data handling, telecommunication with the GS, and data unpacking/decoding. The other functional test was the determination of the sun position in one of the axis. In the test, sunlight hit the satellite at an angle of −135°, but the satellite measured −130°, determining the sun position with a margin of 5°.

Thermal cycling and vibration tests were both realized in a laboratory environment, class International Organization Standard 8 (ISO 8), together with all the CubeSats in the category of FloripaSat-I. The thermal cycling at ambient pressure took 5 h and the temperature was monitored in one edge of each satellite. Fig. 7 shows the curve of temperature that EM-II was exposed to, and Fig. 8 shows the EM-II of FloripaSat-I inside the chamber for the thermal test. During the test, a shift of the radio frequency was observed due to temperature raise, which required the adjust of GS software to mitigate communication deviation. The heaters were not turned on due to problems in the interface cables, which caused unstable connection. In order to solve this problem, new cables were assembled, and the resin was added to better attach the connector to the cables. The report of the test written by LIT/INPE stated that neither occurrence nor non-conformity was observed in FloripaSat-I. After the test, all subsystems worked correctly.

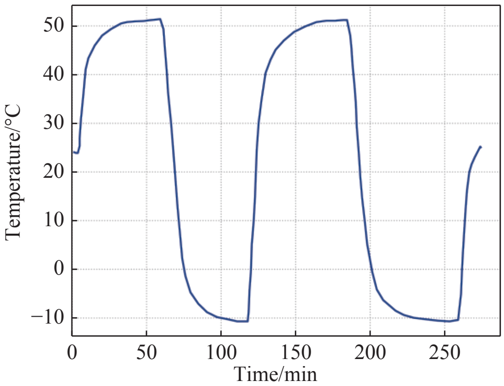


Fig. 7 Temperature during the thermal cycling in CubeDesign

Fig. 8 EM-II of FloripaSat-I prepared for thermal cycling (center)

After this test, the EM-II of FloripaSat-I faced the vibrational campaign, which used parameters of the rocket Falcon 9 to mimic the launch scenario. In this test FloripaSat-I did not lose any component, while two of the other satellites that were tested along FloripaSat-I did. However, the vibrational test produced a malfunction in the batteries circuit. It is understood that this was due to lack of proper fixation of the batteries, which changed from on to off and vice-versa at a high rate due to the vibration of connectors at the poles. Fig. 9 shows the EM-II and deployer used for vibration tests.

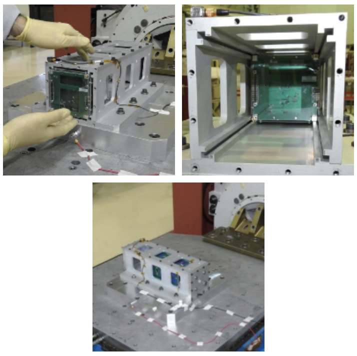


Fig. 9 EM-II of FloripaSat-I in the vibration test

3.3 EM-II: UFSC

3.3.1 Sun emulator

To demonstrate the operation of the satellite power system, the EM was subjected to an orbit simulation test. The simulator, shown in Fig. 10, consists of four high power LEDs (100 W each) used to illuminate the solar panels.

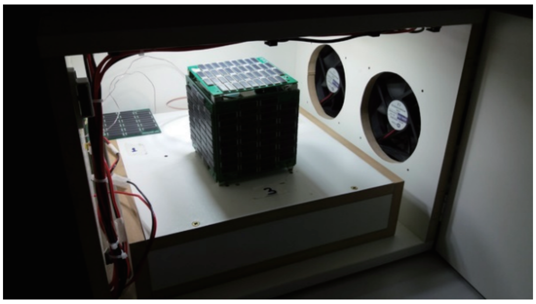


Fig. 10 EM-II in the sun emulator

Solar irradiance behavior was emulated by controlling high power LEDs through a current source. In space, solar irradiance can be considered approximately constant, and changes in input power are caused by the flight dynamics of the satellite in orbit. The system with the LEDs is connected to a LabVIEW controlled source, which changes the light intensity according to predefined orbit data. With those considerations, a long duration test can be performed, where several orbit cycles are emulated. A photo of the satellite during the functional testing process is presented in Fig. 10 and a sample of the curves generated during the test in Fig. 11.

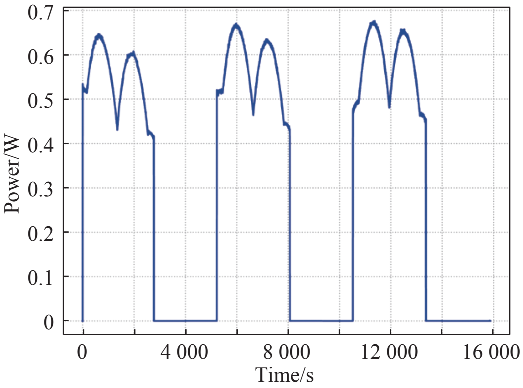
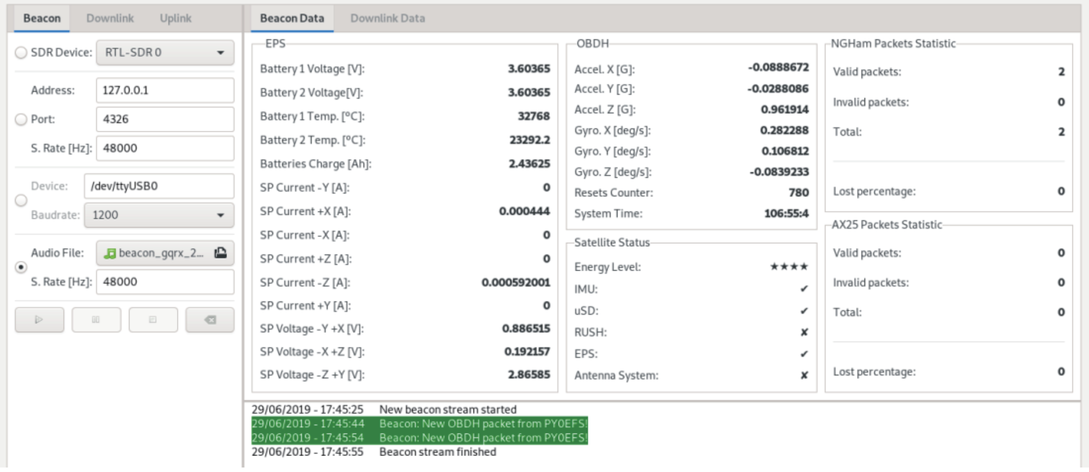


Fig. 11 Solar panel power

It is important to mention that the emulator used does not have the ability to emulate the same level of irradiance found in space, nor even emulate the exact same light spectrum. However, the purpose of the test is not to validate solar panels in flight conditions, but rather to preliminary test the operation of the satellite subsystems acting together, also considering the energy capture.

To perform CubeSat mission control, a software called “FloripaSat-GRS” was developed, which has the ability to decode the received data (in real-time or previously captured) and to send remote controls for satellite operation. It was developed based on the GNU Radio environment. Fig. 12 presents a screenshot of the main screen of the program. It was initially used during experiments in the sun emulator in order to test the telemetry functionality in long-term testing.



SDR Device: RTL-SDR 0
Address: 127.0.0.1
Port: 4326
S. Rate [Hz]: 48000
Device: /dev/ttyUSB0
Baudrate: 1200
● Audio File: beacon_gqrx_2...
S. Rate [Hz]: 48000

EPS

Battery 1 Voltage [V]:	3.60365
Battery 2 Voltage[V]:	3.60365
Battery 1 Temp. [°C]:	32768
Battery 2 Temp. [°C]:	23292.2
Batteries Charge [Ah]:	2.43625
SP Current -Y [A]:	0
SP Current +X [A]:	0.000444
SP Current -X [A]:	0
SP Current +Z [A]:	0
SP Current -Z [A]:	0.000592001
SP Current +Y [A]:	0
SP Voltage -Y +X [V]:	0.886515
SP Voltage -X +Z [V]:	0.192157
SP Voltage -Z +Y [V]:	2.86585

OBDH

Accel. X [G]:	-0.0888672
Accel. Y [G]:	-0.0288086
Accel. Z [G]:	0.961914
Gyro. X [deg/s]:	0.282288
Gyro. Y [deg/s]:	0.106812
Gyro. Z [deg/s]:	-0.0839233
Resets Counter:	780
System Time:	106:55:4

Satellite Status

Energy Level:	★★★★
IMU:	✓
uSD:	✓
RUSH:	✗
EPS:	✓
Antenna System:	✗

NGHam Packets Statistic

Valid packets:	2
Invalid packets:	0
Total:	2
Lost percentage:	0

AX25 Packets Statistic

Valid packets:	0
Invalid packets:	0
Total:	0
Lost percentage:	0

```
29/06/2019 - 17:45:25    New beacon stream started
29/06/2019 - 17:45:44    Beacon: New OBDH packet from PY0EFS!
29/06/2019 - 17:45:54    Beacon: New OBDH packet from PY0EFS!
29/06/2019 - 17:45:55    Beacon stream finished
```

Fig. 12 GS software

3.3.2 General tests

In order to partially test the TC and TM module functionality, the satellite was subjected to spectrum analysis. The fast Fourier transform (FFT) of the signals transmitted by the beacon and the downlink can be seen, respectively, in Fig. 13 and Fig. 14.

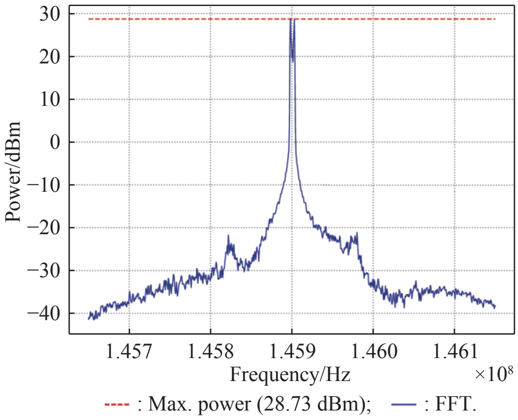


Fig. 13 Output power of the beacon radio

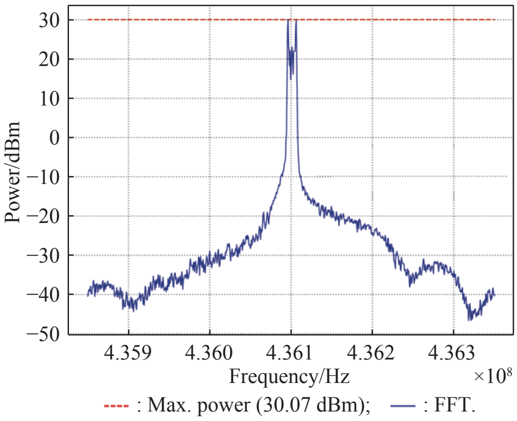


Fig. 14 Output power of the downlink radio

The signal’s central frequency is very close to 145.9 MHz. Considering the losses in the connections and adapters used for the measurements, the real power can be considered to be close to the expected value (30 dBm).

From Fig. 13 it is possible to verify that the output power of the beacon radio module is approximately 28.73 dBm (≈746.4 mW).

The graph in Fig. 14 shows the output power of the downlink radio module. From the maximum value of the curve, it is possible to observe that the output power is 30.07 dBm (≈1 016 mW). Considering the losses in the connections, the desired power was achieved. The central frequency of the signal is approximately 436.101 MHz, very close to the specified frequency of 436.1 MHz. Regarding the bandwidth of both signals, the measured values are approximately 7 kHz and 12 kHz.

3.4 Lessons learned

The tests described above were important so that the team could finally move to the FM. Among the most significant lessons learned from the beginning of the project till the latest development of EM-II are the necessity to simplify, organize, integrate, and document. At first, even due to inexperience of the team, OBDH and TT&C modules were on the same board, in a very compact and complex architecture for testing by a team without much maturity with space systems. It hindered and slowed the progress of the project because the failure in the board and subsequent attempts to remedy the problem delayed the teams. To facilitate the testing and development of the different subsystems, the OBDH and TT&C were separated into two boards in the next model.

Another lesson learned is the realization of simplification. The difficulties found with hardware and software were mainly caused by the complex design of the subsystems. The problems noticed in the μGravity push the team for simpler schemes and for the utilization of commercial radios. In the software, there were problems with integration of subsystems in the I^2C communication bus, which in the occasion had a multi-master strategy. From the results of μGravity tests, the team decided that OBDH would become the master.

The last improvement obtained from μGravity was the recognition for integrated work. The preparation period for that test was short, where the group had not yet an assertive integration methodology and triggered some of the major software and hardware problems. For example, there was no instruction even to stack up the boards and short circuits were caused by this simple issue.

The participation in the CubeDesign highlighted even more the necessity for documentation because, for the first time, there were people from outside to evaluate the project. Another fact that contributed to this was the distance of hundreds of kilometers from the city holding the competition and the laboratory of the team, as well as the absence of some leaders of the subsystems. As one question raised and required a fast response, for some cases there was no one to answer or none information in the documents. Since then, the group has been trained to document parallel to the development.

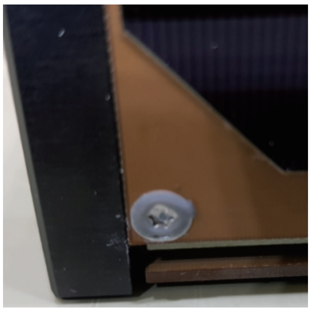
Finally, tests on the solar emulator helped the team to improve the knowledge and control of solar panels. This learning has been implemented in FM to enhance the energy harvesting and reduce the risks associated with energy management.

4. FM

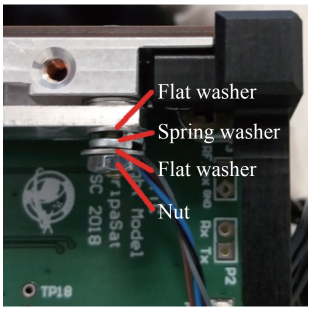
To proceed with FloripaSat-I, the activities of assembly, integration, and testing (AIT) were deeply developed at Phase 6, an opportunity where the team followed in some sort the methodology presented in [12]. The main objective with the AIT campaign is a well defined and efficient procedure of AIT dedicated to minimize the time and costs, keep the reliability consistent with the mission, as well as be appropriate for proper integration with the launch vehicle.

4.1 Main changes in FM

Considering the problems listed in the EM-II, from a mechanical point of view, the main changes dedicated to keeping all the parts fastened during the vibration test and launch are shown in Fig. 15. For this reason, during the integration campaign, epoxy was applied in every bolt and nut to paste them in the structure. Whenever it was possible, every bolt was fastened with nut and a sandwich of flat, spring, and flat washer, a configuration that avoids damage in the surfaces of the satellite caused by the spring washer and keeps bolts and nuts tight.



(a) Epoxy on a bolt of a solar panel



(b) Sandwich of washers to support dynamic loads (not fastened yet)

Fig. 15 Detail on the bolts

Finally, as one of the lessons learned during the CubeDesign tests, silicone was added to the batteries connectors and cable connectors, as shown in Fig. 16. The main objective was to reinforce a permanent contact between them and avoid electrical failure.

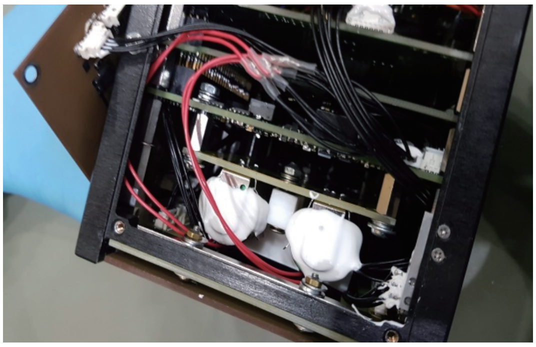


Fig. 16 Silicone in the connectors of batteries

4.2 Testing facilities

The AIT campaign of FM of FloripaSat-I was conducted in two different places: the simpler tests were at UFSC and more complex at the system qualification area from LIT, in the INPE, São José dos Campos, Brazil.

At UFSC, most of the electrical tests used an oscilloscope, function generators, and multimeter, while the mechanical ones used caliper, mass balance, an apparatus to test the center of gravity and a thermal vacuum chamber as shown in Fig. 17. All of these tests were executed in laboratory ambient, without too restrictive environmental control.

Fig. 17 Thermal vacuum chamber for preliminary out-gassing tests

On the other hand, at LIT/INPE, the test room had a cleanliness condition ISO 8 [13], temperature (23±2)°C, relative humidity of (50±10) %. The facilities used to test FloripaSat-I at LIT/INPE were as follows:

(i) Thermal-vacuum chamber, dimensions 1 m × 1 m from LIT;

(ii) Thermal cycling chamber, Thermotron model SE-1000-3-3;

(iii) Vibration testing system, model V804 & V964LS, manufacturer LDS.

From the tests in the campaign at LIT/INPE, vibration is mandatory by the launch vehicle while the remaining are not, but they are important to have proper integration with the deployer and to assess the behavior of the satellite in similar conditions that it will face since the launch through the operation in orbit. The vibration tests require the integration of FloripaSat-I with the deployer container, whose option for FM or identical structure is dictated by the launcher office. In the case of FloripaSat-I, the tests were conducted with a commercial deployer innovative solutions in space's (ISIS's) 1U test picosatellite orbit deployer (POD). Once the components of FloripaSat-I were commercial off-the-shelf (COTS), with the exception of solar panels and antenna in the FM, it was assumed that the electromagnetic compatibility (EMC) was not necessary in the FM.

4.3 Test specifications

Before any test, the external surfaces of FloripaSat-I were cleaned with isopropyl alcohol. For all dynamic and environment tests, FloripaSat-I was fully integrated. Mass property tests were done in the FM. However, the epoxy and resin were not yet applied. As shown in Table 1, the thermal-cycling and bakeout were the only occasions in this campaign where FloripaSat-I was operational (closed antennas), but the team received the TM only in the thermal-cycling, through its umbilical cables as shown in Fig. 18. To avoid an unexpected and dangerous operation during the remaining tests, the KS RBF were acting, as indicated in Table 1.

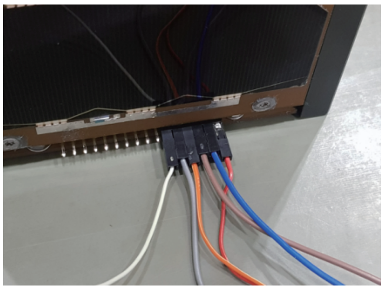


Fig. 18 Umbilical pins for communication, software programming and recharge of batteries

4.3.1 Mass

This test checks the total mass of the satellite (without RBF), which must be less than 1.33 kg [10]. The verification is made with a balance of precision. Fig. 19 shows FloripaSat-I total mass (yet without epoxy and resin).

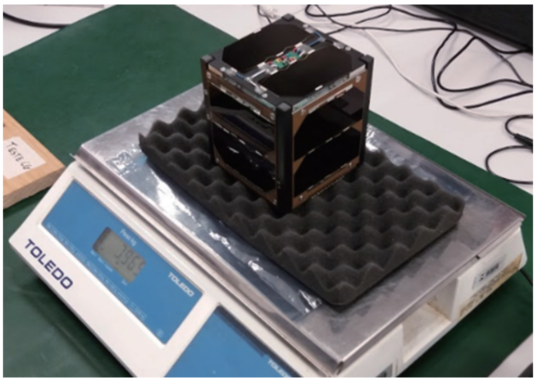
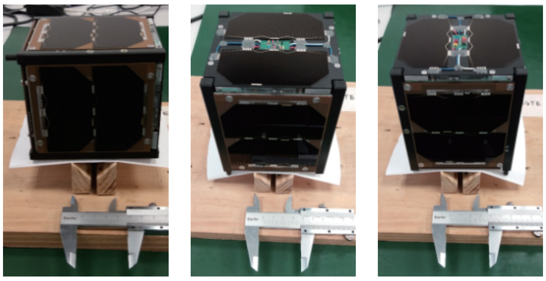


Fig. 19 Mass of FloripaSat-I: 965 g

4.3.2 CG

This test checks the CG of the satellite, which must be less than 2 cm from the geometric center (see Fig. 20) [10]. The team developed a simple test-bench based on two parallel bars fixed on a plate, 4 cm from each other. The geometric center of the satellite is put in the middle of the bars and, if the satellite does not fall, the CG is within the radius of 2 cm. This strategy does not measure the location of CG, however, it does prove if the satellite follows the requirement.



(a) *X* axis (b) *Y* axis (c) *Z* axis

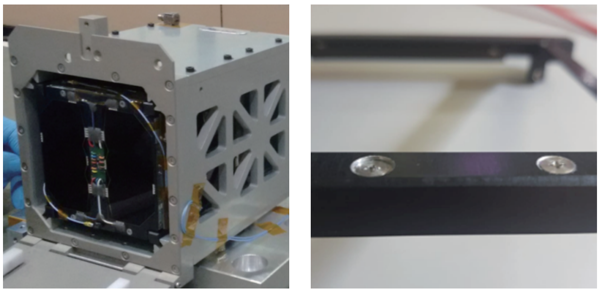
Fig. 20 CG within 2 cm from the geometric center

4.3.3 Dimension

This test checks the main external dimensions of FloripaSat-I, which must be (100±0.1)mm × (100±0.1)mm × (113.5±0.1)mm in the *X*, *Y* and *Z* axis, respectively, for proper integration in the standard 1U CubeSat deployer [10]. This verification is performed by measuring, with a caliper or micrometer, the main external dimensions of FloripaSat-I.

4.3.4 Fit check

This test assesses the proper integration of the satellite inside of the deployer. The satellite must slide smoothly and without too much clearance. Even though the structure of FloripaSat-I is a commercial model with flight heritage, this test is important because the team drilled four holes on the rails of the structure to house bolts of the attitude determination and control system (ADCS). Fig. 21(a) shows the fit check test, and Fig. 21(b) shows the modifications in the structure of FloripaSat-I, absent in other structures.

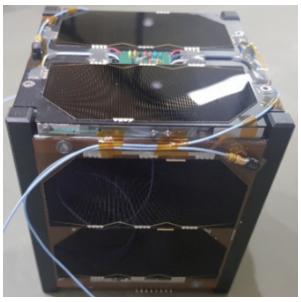


(a) Fit check in ISIS's 1U test POD (b) Housed bolts on the rail

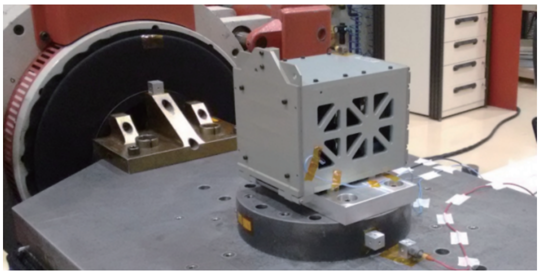
Fig. 21 Fit check in ISIS's 1U test POD and detail of housed bolts on the rail

4.3.5 Vibration tests

To measure and control the acceleration profile during the dynamic tests, accelerometers were positioned on three external surfaces of the satellite, one on each axis, over areas without solar cells. The satellite was then inserted into a commercial deployer, similar to the FM, and fixed on a shaker. No functional evaluation was performed during the test, but only a visual inspection. Fig. 22(a) shows some of the accelerometers and Fig. 22(b) shows the satellite during a vibration test.



(a) Position of the accelerometers



(b) Shaker

Fig. 22 FloripaSat-I in the dynamic test

The CubeSat was tested entirely off, with RBF pin removed but with pressed KS, in a genuine 1U Test POD supplied by INPE, simulating the normal launching condition. The tests were conducted along the three main axes of the satellite, and all of them were successful. Following the visual inspection done during, and just after these tests, there was no indication of external damages, cracks, or loose parts in the test unit. The set of vibration tests follows Fig. 23.

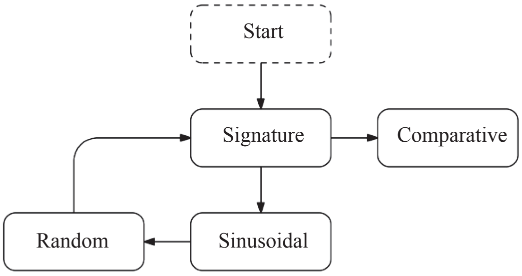


Fig. 23 Sequence of dynamic tests

A signature testing is conducted before and after the tests that really stress the satellite (sinusoidal and random vibration) in order to identify the presence of significant variations in the dynamic response, a condition that may represent mechanical failures. For the signature task, Table 2 presents the specifications.

Table 2 Resonance survey test (signature)

Name	Parameter
Frequency range/Hz	5–2 000
Vibration level	0.25 g
Sweep rate/octaves per minute	2
Number of sweeps (5–2 000 Hz)	1
Test axes	3 (X, Y, Z)

The resonance survey vibration level was changed to 0.25 g instead of 0.5 g, as suggested by the laboratory experts because it was too close to the maximum level (0.6 g) set for the acceptance level sine vibration test.

Regarding the sinusoidal sweeping vibration, Table 3 brings the envelope of the test, and so does Fig. 24 in a graphic format.

Table 3 Sinusoidal vibration test

Name	Parameter
Frequency range/Hz	5–2 000
Vibration level	5–8 Hz // 4.66 mm DA
	8–100 Hz // 0.6 g
Sweep rate/octaves per minute	4
Number of sweeps(5–100 Hz)	1
Test axes	3 (X, Y, Z)

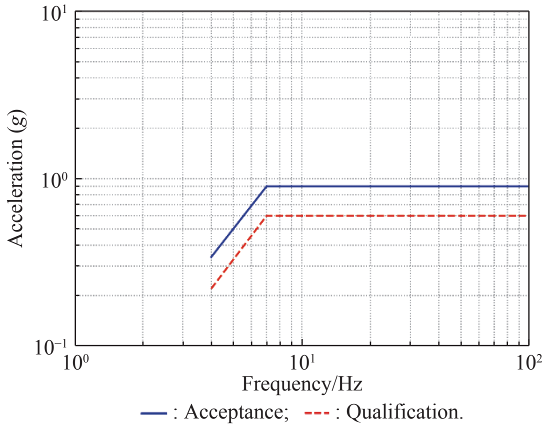


Fig. 24 Sinusoidal sweeping vibration

The random vibration test conditions are listed in Table 4 and presented in Fig. 25.

Table 4 Random vibration test

Name	Parameter
Frequency range/Hz	20–2 000
Vibration level (ASD)	20–140 Hz // +4.5 dB/oct ave
	140–600 Hz // 0.04 g^2/Hz
	600–2 000 Hz // −6 dB/oct ave
Overall acceleration level	6.12 gRMS
Test duration	One minute per axis
Test axes	3 (X, Y, Z)

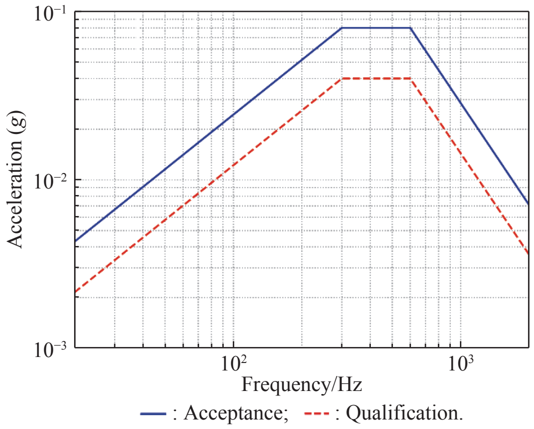


Fig. 25 Random vibration

After the sinusoidal and random vibration, the signature test was repeated. A summary of the initial and final signatures are presented in Table 5, with the corresponding deviation (if any).

Table 5 Comparative of resonance survey test (signature)

Axis	Signature 1/Hz // *g*	Signature 2/Hz // *g*	Δf/Hz // %
X	195.2 // 0.8	203.5 // 0.9	8.3 // +4.2
	–	248.1 // 0.5	–
	370.8 // 1.8	345.0 // 2.2	25.8 // −6.9
	–	468.5 // 1.5	–
Y	240.8 // 0.7	233.6 // 0.6	7.2 // −3.0
	274.7 // 0.6	288.2 // 0.7	13.5 // +4.9
	368.6 // 0.5	351.3 // 0.7	17.3 // −4.7
	599.1 // 1.0	610.0 // 0.9	10.9 // +1.8
	721.5 // 0.5	–	–
	780.0 // 0.6	818.3 // 1.7	38.3 // +4.9
	–	884.7 // 1.6	–
	1 275.0 // 1.5	1 245.0 // 1.2	30.0 // −2.3
Z	271.4 // 0.6	255.6 // 0.5	15.8 // −5.8
	–	325.0 // 0.5	–
	410.6 // 1.0	433.4 // 2.0	22.8 // +5.5
	441.1 // –	–	–
	477.0 // –	–	–
	521.9 // –	–	–
	–	708.6 // 0.8	–
	–	985.6 // 2.9	–
	1 028.0 // 3.8	1 053.0 // 2.5	25.0 // +2.4
	1 573.0 // 6.8	1 536.0 // 4.9	37.0 // −2.3
	1 722.0 // 6.5	1 641.0 // 5.5	81.0 // −4.7

Table 5 indicates a maximum difference of 6.9 % in the frequency variation, which means that the mechanical structure has supported the loads. The peak responses change from one to another test, but this does not mean that structural degradation occurs. Such type of behavior is mainly caused by the configuration that the CubeSat is “fastened” in the test POD through a helicoidal spring, and therefore does not characterize a rigid-type fixation.

4.3.6 Thermal tests

For the following thermal tests, thermocouples were attached on nine different points on the surface of the satellite, including over the solar panels and structure. Two of them, on the structure, were used to designate the temperature status of the test and as input for the progress of the tests. Fig. 26 shows FloripaSat-I ready for both thermal tests. The parameters of the tests are indicated in Table 6.

The thermal-cycling test was executed in the thermal cycling chamber, equipment with a metallic grill inside where the satellite was placed upon to allow the condition of released KS and operational satellite. In this case, the telemetry was received through the umbilical interface of the satellite. The temperature profile during the test is shown in Fig. 27.

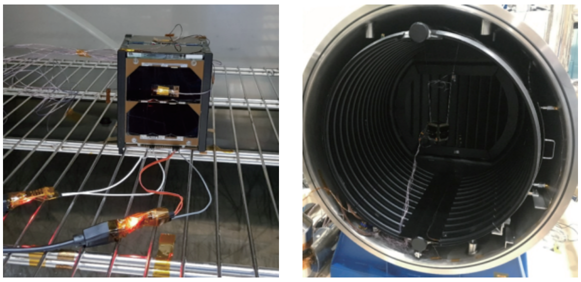

(a) Thermal cycling (b) Bake out

Fig. 26 FloripaSat-I in the thermal tests

Table 6 Parameters for the bake and thermal cycling

Thermal cycle		Bake out	
Parameter	Value	Parameter	Value
Number of cycles	2	Part 1	
Min. temp. ($T_{\min}$)/°C	−15	Pressure/mbar	$<1\times10^{-4}$
Max. temp. ($T_{\max}$)/°C	+50	Temperature/°C	23
Duration in $T_{\min}$/min	30	Duration/h	12
Duration in $T_{\max}$/min	60	Part 2	
Heating rate/(°C/min)	5.5	Pressure/mbar	$<1\times10^{-4}$
Cooling rate/(°C/min)	3.5	Temperature/°C	60
Stabilization criteria/(°C/10 min)	1	Duration/h	6

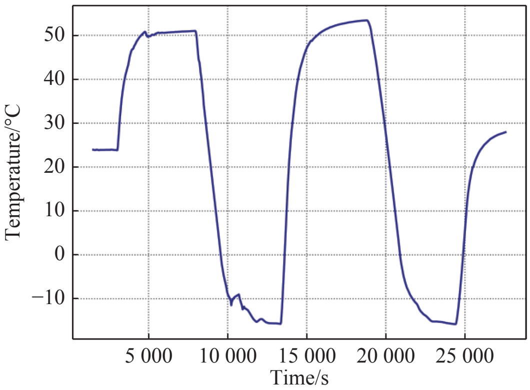


Fig. 27 Temperature profile during the thermal cycling test

On the other hand, for the bake out the satellite was suspended inside a thermal-vacuum chamber by rows. During all this test, it remained operational, although the TM was not monitored. During the first 12 hours, the satellite was exposed to a vacuum environment around 21°C, as shown in Fig. 28. In the following 2 h, the temperature inside the chamber was raised until it achieved 60°C, and the test lasted for 6 more hours at this constant temperature (Fig. 29). The bake out test, at high vacuum and temperature, aims to allow the degassing of moisture and volute materials of the specimen. According to the results of the chemical contamination analysis of the sensor included in the camera after the bake out test, no chemical contamination was detected in the infrared spectral range by the method used in the samples. Fig. 30 shows data of the pressure during the bake out.

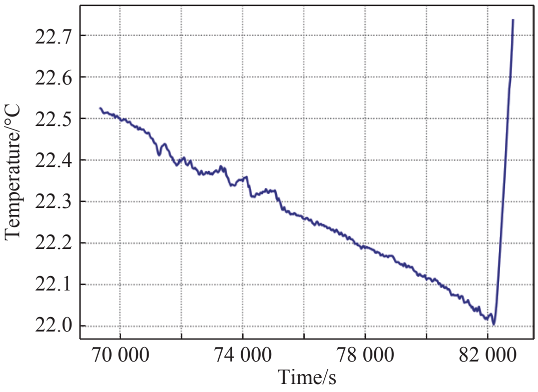


Fig. 28 Temperature during the first part of the bake out test

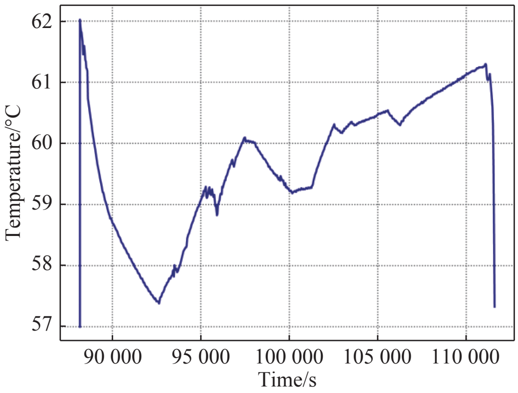


Fig. 29 Temperature during the second part of the bake out test

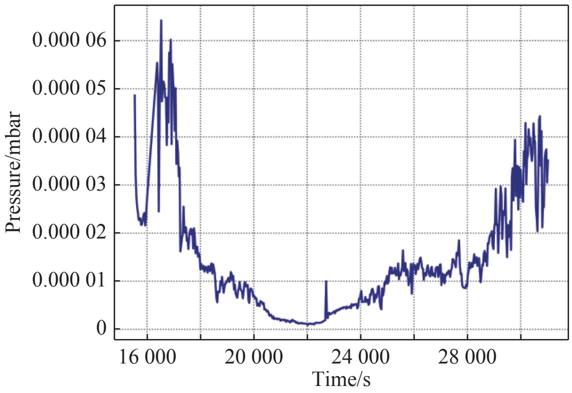


Fig. 30 Pressure during the bake out test

5. Conclusions

The participation of EMs of FloripaSat-I in those two important events held in Brazil proved to be important for the development of the project, as well as the testing performed at the university. The sounding rocket put the subsystems in the harsh condition of stress, usually presented in rockets that use solid propellant. Using the TM of the tests, modifications were proposed to the next model of FloripaSat-I. The second and most advanced model of the CubeSat was tested in the most important facility related to a satellite in Brazil, called INPE, where the team was able to experience how a qualification test looks like. This stage also gave useful information to implement new modifications in the project.

The sounding rocket and the CubeDesign exposed the EM in similar conditions that operational CubeSats face. As expected, problems urged from tests, and it requested some correction of the project. Part of the design defined in the beginning of the project showed appropriate response during the tests, and modifications were implemented for those who failed during the tests. As a consequence of the tests in the laboratory and relevant environment, the FloripaSat-I achieved TRL 6 for several of its subsystems [14].

The tests conducted during the μGravity program and CubeDesign competition are difficult to reproduce in laboratories of Brazilian faculties and should be encouraged. They are important to explore the failures and malfunctioning of the subsystems before the real mission. The know-how of the team increased after each testing procedure, putting the project closer to the specifications required for the launch of FloripaSat-I and its operation around the Earth.

The campaigns that the EMs went through allow a more robust FM to be built. The operation and robustness of the FM could be proven by testing, also performed at INPE.

Based on the aspects presented in this paper, it can be seen that the process of manufacturing a CubeSat is gradual. Improvement is achieved through a variety of tests, which can validate the choices made by system engineers during the development phases, or even indicate the failure of the system.

Thus, in addition to presenting the validation of an open-source CubeSat, which can be used by other teams as a service module for their payloads, this paper shows a realistic view of the difficulties encountered along the way.

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