Lessons Learned During Testing Through Commissioning of the joint Brazil-US SPORT Mission

Lidia Shibuya Sato, Luís Loures, Victor Costa, Rodolfo Wottrich, Ana Carolina Jeronymo, Herbi Júnior, Pedro Lyra Cabral, Renan Menezes, Mateus Oliveira, Thadeu Carvalho, Emerson Oliveira, Denis Vieira
Instituto Tecnológico de Aeronáutica
Praça Marechal Eduardo Gomes, 50 - Vila das Acácias, São José dos Campos - SP, 12228-900; +55 (12) 3305-8565
shibuya@ita.br

Charles Swenson
Utah State University
Logan, UT 84322; +1 (435) 797-1000
charles.swenson@usu.edu

Joseph Casas, Linda Krause
NASA Marshall Space Flight Center
320 Sparkman Drive, Huntsville, AL 35805; +1 (256) 544-8477
joseph.casas@nasa.gov

ABSTRACT

SPORT is an international partnership mission between Brazil and the United States to study ionospheric space weather processes that occur at low latitudes. Operating a CubeSat on orbit is certainly one of the most exciting milestones of a CubeSat project, but it is only a part of the mission. To be able to achieve this milestone the efforts of the engineering team were focused late in the project on the integration, testing, and delivery followed by the on-orbit commissioning of the observatory. This paper details the major events and lessons learned by the SPORT team during these phases of the project. SPORT experienced a failure of the battery subsystem during environmental testing followed by physical damage during shipping from Brazil to the United States for Launch. However, more than pointing out these problems, solutions, and lessons learned, this paper explains how the international team worked to overcome the issues and finalize the observatory for delivery and launch. After release from the ISS the SPORT team looked forward to the on-orbit observatory operations, first contacts, and the commissioning phase of the observatory, that is also described on this paper.

SPORT MISSION OVERVIEW

The SPORT (Scintillation Prediction Observations Research Task) observatory consists of a 6U CubeSat bus developed in Brazil by Instituto Tecnológico de Aeronáutica (ITA) that hosted a suite of science instruments provided by the United States [1]. Stakeholders in the project included the FAPESP, Brazilian Space Agency, NASA, and the US Department of Defense. The project was developed at ITA Space Center "*Centro Espacial ITA*" [2].

In this joint mission, Brazil and United States partners decided for a science mission to study Space Weather. Space weather refers to the conditions and disturbances that occur in the space environment, primarily driven by the dynamic behavior of the Sun. It encompasses a range of phenomena, including solar flares, coronal mass ejections, solar wind, and geomagnetic storms. These events can have various impacts on technological systems, satellites, power grids, and even human activities. The SPORT CubeSat aims to contribute to the understanding of ionospheric disturbances, once space weather events can perturb the ionosphere, a region of the Earth's upper atmosphere where ions and free electrons are abundant. These disturbances can affect radio wave propagation, causing signal degradation or loss in communication systems that rely on ionospheric reflection, such as long-distance radio communications and global navigation satellite systems like GPS.

The SPORT CubeSat is equipped with instruments and sensors to measure various parameters of the ionosphere, including electron density, temperature, and ion composition, for instance. These measurements help in characterizing the ionospheric conditions and studying the causes and effects of scintillation and they were provided by the American partners of the project, such as Utah State University, University of Texas in Dallas, Aerospace Corporation and NASA Goddard Space Flight Center. The science that can be achieved by SPORT can be seen in [3] and [4].

Understanding and predicting space weather is crucial for mitigating its potential impacts on technological systems, satellite operations, communication networks, power grids, and human activities. By monitoring and studying space weather phenomena, scientists and organizations strive to improve forecasts and develop strategies to protect critical infrastructure and ensure the safety and reliability of space-based and terrestrial systems. Space weather monitoring involves the continuous observation of solar activity, solar wind, and geomagnetic conditions using a network of ground-based and space-based instruments. Scientists and organizations, such as the National Oceanic and Atmospheric Administration (NOAA) and the Space Weather Prediction Center (SWPC), analyze these data to provide forecasts, alerts, and warnings about potential space weather events, allowing for mitigation and preparation measures to be taken.

Launch and Orbit injection.

SPORT was launched as part of the CRS-26 resupply mission to the International Space Station (ISS) from Kennedy Space Center on November 26th, 2022. The docking of the Dragon Capsule occurred on the next day on the ISS, November 27th and then SPORT waited on ISS until December 29th, when it was inserted into its final orbit and operations started.

Figure 1: SPORT Jettison from ISS.

MISSION TIMELINE

The start of the mission was in 2015 with some initial meetings and workshops to define the mission and the science that would be interesting for both countries. The first proposal was sent in 2016 and got funding by NASA Head Quarters for the payloads and in 2017 the spacecraft development was funded by FAPESP. The project followed the NASA System Engineering process in terms of system Reviews, and the timeline of project can be seen in Figure 2. SPORT observatory is composed of the spacecraft (or bus) and the payload, and details of the observatory design can be seen in [5].

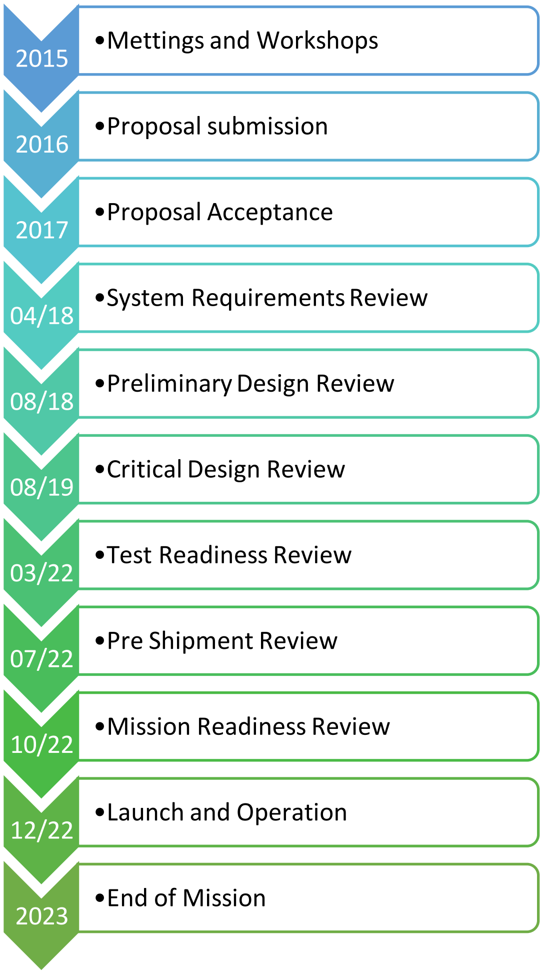

Figure 2: SPORT Mission Timeline.

During the Assembly, Integration and Testing phase the team had to deal with challenges of going to a critical phase of the project concurrently with COVID-19 pandemic. The COVID-19 pandemic has had a significant impact on work across the globe, and some of the key effects on the project were:

a) Remote work and telecommuting: To mitigate the spread of the virus, the team implemented remote work policies, allowing employees to work from home in the activities that allowed it, making use of video conferencing tools, collaboration platforms, and remote work technologies.
    - The pandemic introduced new challenges to mental health and well-being in the workplace. Isolation, uncertainty, and increased workloads could contribute to stress, anxiety, and burnout.
    - Flexible work arrangements had to be made.

b) Health and safety protocols: To ensure workplace safety, health and safety protocols were implemented, such as social distancing, mask-wearing, and increased sanitation measures.
    - Reduced number of people inside the laboratories at ITA and at INPE. Only essential personnel at each AIT activity were allowed to be in person at the laboratories.
    - Activities that could be done in parallel were serialized. Activities took longer to be accomplished.
    - Positive cases of COVID required quarantine of the team and replacement whenever possible.

Nevertheless, besides all the challenges, the observatory and the ground segment were ready for the deployment of the observatory in July 2022. This paper describes the activities performed during this phase in more detail in the next section.

THE ASSEMBLY, INTEGRATION AND TEST PROCESS

Satellite Assembly, Integration, and Test (AIT) is a critical phase in the development and deployment of a satellite. It involves the physical construction, integration, and comprehensive testing of all the subsystems and components to ensure the satellite's proper functionality and readiness for launch. Figure 3 describes the simplified AIT process for SPORT Proto Flight Unit.

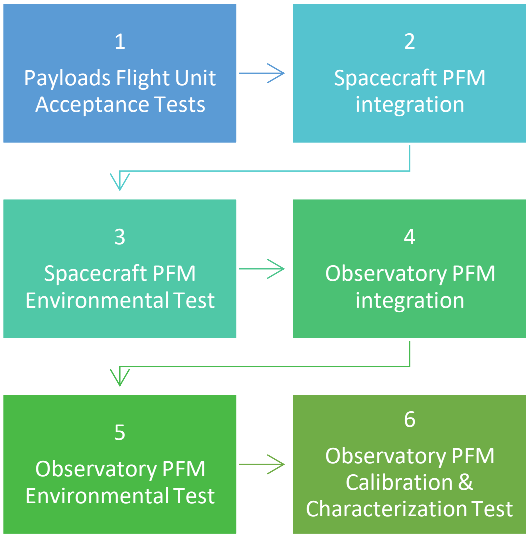

Figure 3: SPORT PFM simplified AIT block diagram.

Mechanical Integration: The satellite's structure is assembled by integrating various structural elements, such as panels, brackets, and frames. Mechanical integration ensures that all components are securely connected, aligned, and can withstand the mechanical stresses during launch and in space. Figure 4 shows the team performing pre-integration tests of the structure to be sure all parts could be integrated as designed. This pre-integration test was performed in all structural units upon acceptance, so at least four structural integrations were performed by the team.

Figure 4: SPORT structure pre-integration tests. Mechanicals parts only.

Lessons Learned:

- The quantity of fastening screws for the SPORT's tabs was not sufficient to withstand the vibration levels. We increased the number of fastenings, and the problem could be solved.
- The selection of the base material for the structure manufacturing reduced the complexity of the assembly, since some materials do not need helicoil. The number and types of screws shall be reduced to facilitate the procedures and quality control.
- The development of two specific MSGEs, one to handle the spacecraft and one to be used during integration aided the AIT process and improved the project safety.
- In the next project the team is studying a way to easily access the internal elements of the spacecraft, especially in a complex system such as SPORT.
- The fishing lines used to hold the probes were not suitable and continuously failed during vibration tests. A non-conformity was identified in the parts that guided the lines and adjusted the supplier's design and we specified a different line.

Electrical Integration: The electrical subsystems, including power systems, avionics, data handling units, and communication systems, are integrated into the satellite's structure. This involves connecting cables, harnesses, and electrical interfaces, ensuring proper electrical continuity and compatibility between different components. Figure 5 presents the integrated stack with the core components of the spacecraft. This stack was the denser in terms of components and harness to be connected on the other subsystems.

Lessons Learned:

- The cables routing was very well exercised on the engineering unit, and it could be reproduced on the flight unit, but the connection philosophy can be improved in next missions. Cables soldered on the PCBs can be a good solution, in some cases connectors could facilitate assembly and disassembly.
- Debugging connectors and interfaces can be improved. The team faced some limitations in the use of the JTAG interface, especially related to the bus velocity.
- Due to ADCS and CDH on board computer sharing, less tests were performed. After ADCS reached its orbit, it was noted a proper test interface and easy to use TM/TC access was needed for better firmware development, verification, and validation. A lack of interfaces for operation and real-time analysis is shown to be a must for enhanced tests prior to launch.

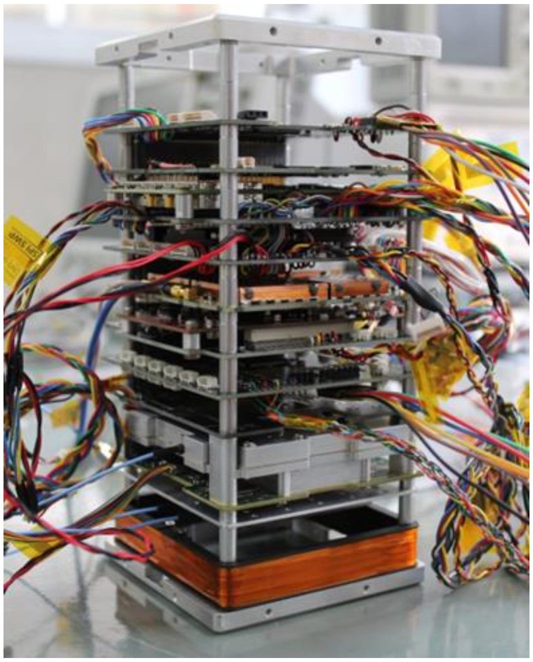

Figure 5: SPORT Main Core integration (On Board Computers, radios, interface boards, GPS Receiver and one magnetic coil).

Functional Testing: Each subsystem is individually tested to verify its proper functioning and compatibility with other subsystems. This includes tests such as power-on tests, communication tests, sensor calibration, and performance verification of various instruments and equipment. At this level, several functional tests were carried out at the subsystem level, such as Attitude Determination and Control Subsystem (ADCS) sensors calibration, reactions wheels characterization, RF mockup tests. Figure 6 shows the setup used to characterize the gyros integrated to the onboard computer.

Lessons Learned:

- The model philosophy implemented on the project was very helpful. The use of the FLATSAT to anticipate tests in and some functionalities helped to accelerate the development. The development model, a stage prior to the Engineering Unit, with all flight-like components on the table also gave the team more time for development and tests of the software.

- Unitary functional tests are mandatory but not sufficient to guarantee the correct integration of the system. It is necessary to provide more time to the team for logical and testing integration.

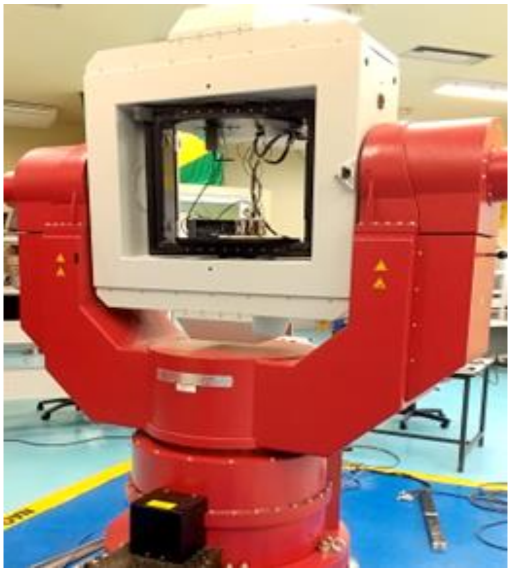

Figure 6: Gyrometers characterization in a 3-axis setup.

System Integration: Once individual subsystems are tested and verified, they are integrated into the overall satellite system. This includes integrating the payload with the bus and verifying their interaction and performance as a unified system. After each step of the assembly and integration process, intermediary functional tests were carried out to be sure that the system was still working as designed. Figure 7 shows the team testing the integration of the Electrical Power Subsystem (EPS) and the main core of the spacecraft.

Lessons Learned:

- The incremental approach aided the AIT process since the intermediary functional tests could provide a stage of verification prior to the next step and the detection of failures in this case could be anticipated.
- The existence of a defined test procedure and test report at each stage helped the team to reproduce the same type of test several times.

Figure 7: PFM Integration and intermediary functional tests.

Environmental Testing: Satellites undergo a series of environmental tests to simulate the harsh conditions they will experience during launch and in space. These tests include vibration testing, which exposes the satellite to simulated launch vibrations; thermal vacuum testing, which recreates the extreme temperatures and vacuum environment of space (Figure 8); thermal cycling testing, which cycles between hot and cold cases to simulate the dynamic behavior of expected temperature conditions; and radiation testing, which exposes electronic parts to sources of ionizing radiation to test sensibilities to Single-Event Effects and Total Ionizing Dose. In the SPORT project the thermal vacuum tests were performed at the spacecraft level, aiming the acceptance of in-house developed boards and to characterize the behavior of the spacecraft. The vibration tests were performed according to the launcher provider requirements at the observatory level. Due to the time constraints, the team decided to perform thermal cycling tests only at the observatory level, and radiation tests focused on specific circuit boards.

Lessons Learned:

- The time and procedures preparation must not be underestimated for the thermal and vacuum tests. Those tests were the most expensive in terms of cost, schedule, and team allocation.
- The thermal vacuum test is the most expensive part of the development process, so it is crucial to have a clear understanding of what we want to test. This test involves multiple teams and requires round-the-

clock dedication as it cannot be interrupted. It is essential that the person responsible for the testing has the necessary expertise, as without it, the results will not be meaningful for analysis.

- It is uncommon to perform Thermal Balance Tests on CubeSats, but in this project the test was performed to validate the thermal model and it proved worthful.
- After the vibration test one of the payloads stopped responding at the functional tests. No other choice besides disassembling the spacecraft and checking further the problem. A minimal disassemble was performed and a new vibration test was required. A waiver was discussed with the launcher provider to run this second vibration test at lower load. All procedures were recorded in a report, and it is part of the project archive.
- In future projects it is recommended to design the spacecraft and the assembly process in such a way that facilitates the assembly and disassembly of the observatory.

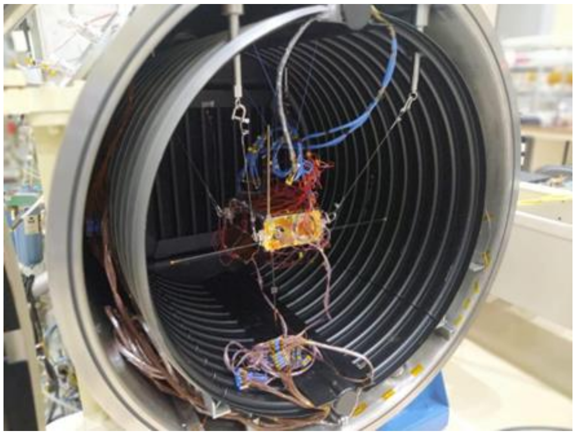

Figure 8: Spacecraft Thermal-vacuum test setup.

Performance Testing: Once the satellite has successfully passed the environmental tests, a comprehensive set of performance tests was conducted. These tests evaluate the satellite's ability to meet specific mission requirements, such as data transmission rates, power consumption, and attitude control accuracy. In this sense, power consumption tests to define the power consumption in each mode were carried out. RF communication tests were also performed to test the telemetry and telecommand channel, the data download and radio receiver input and transmitter output. Performance tests were also done during thermal cycling and thermal vacuum tests, that included long duration tests. At this stage, several End-to-End tests were performed. Some of the performance tests were carried out into thermal cycling conditions, as presented on Figure 9.

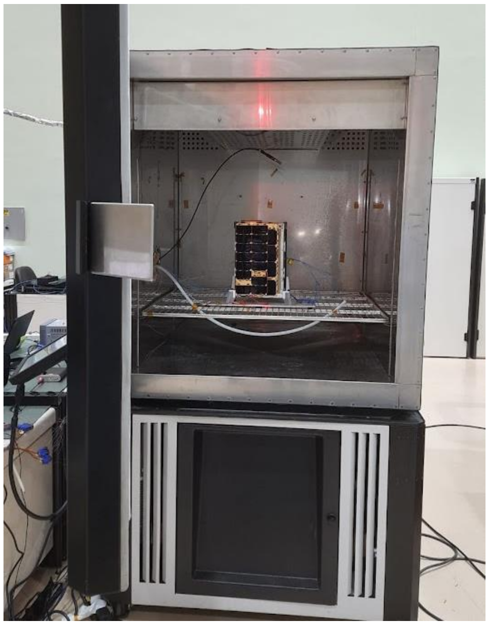

Figure 9: SPORT Proto-flight unit during the thermal cycling tests.

Lessons Learned:

- For End-to-End Tests, it is preferable to utilize the closest equipment configuration that will be deployed on the satellite and the ground station used during in-orbit operations. This approach enhances the assurance of configuration and performance, in addition to facilitating the identification of any issues that may arise.
- To ensure accurate representation of satellite components under development it is recommended to set aside identical reserve equipment that matches the Flight Models to be eventually deployed. This practice allows for better replication of the components and facilitates seamless integration during the production phase of the Flight model.
- When feasible, assign a dedicated individual to document the outcomes of test procedures, equipment integration campaigns, and model qualification campaigns in a designated Logbook. It

is crucial to record these notes while the activities are being carried out to prevent the loss or forgetting of valuable information.

- Maintaining a photographic record of Integration and Testing activities is crucial for easy identification of configurations, analysis, and presentation of results at a later stage.
- The climate chamber test (Thermal cycling test) is less complex as it does not involve cryogenic systems and high vacuum. We only control the humidity and temperature of the chamber. It requires a smaller number of teams, making it a quicker and less complex test and it can be used as an alternative test for thermal vacuum tests in case of schedule constraints and mission risk level.

Final Checks and Preparations: Before the satellite is prepared for launch, a final set of checks is performed to ensure all systems are functioning correctly. These checks include system-level functional tests, electromagnetic compatibility testing, and final verification of all mechanical and electrical connections. At this phase the misalignment between the Ion Velocity Meter (IVM) and the spacecraft star tracker was measured to assure the correct attitude pointing knowledge to the payload. As required for the launch provider's Safety Review documentation, physical properties of the observatory such as mass, center of mass and momentum of inertia were measured. Figure 10 External measurements and weight were also recorded as part of the project verification database.

Figure 10: SPORT PFM During Mass Properties Tests.

Lessons Learned:

- During AIT process, and more precisely sensor/actuator orientation verification, it was noted the Sun Sensor was mounted upside down. Since it was noted before final satellite packing, it could be fixed by software.
- During final checks the sensor mapping of SPORT was updated based on the test results. Tests showed it is mandatory to give confidence to the team on the orientation of the sensors.
- Some final checks will require specific MGSEs. In the case of the SPORT a specific MGSE had to be developed for the mass properties and other one to IVM and star tracker misalignment measurement.
- Some final checks had to be performed with the flight unit in the field. The transport box developed by the team provided a secure and controlled environment to perform such tests.

Battery Issue during AIT

During the AIT process, one of the major issues that occurred was the failure of the battery during the spacecraft proto flight model environmental test. The purpose of this test was to aid the acceptance of internal development (such as interface boards, mechanisms control board and other in-house development) and determine the spacecraft performance in space-like conditions, prior to the integration of the payloads. The test focused on functional tests during thermo-vacuum conditions. During this test it was planned to execute the hot and cold start of the spacecraft to evaluate the performance of each of the subsystems.

The issue during this test was that the spacecraft did not respond to the commands from the beginning. After several tries, the team decided to interrupt the test and investigate the issue. The spacecraft was removed from the thermal chamber and during the investigation it was noticed that the problem was with the battery pack.

The main issue was that the pouch cells of the battery swelled during the thermal vacuum test, and this caused a deflection on the PCB consequently the malfunction of the EPS system. Figure 11 shows the battery during visual inspection at battery acceptance tests and Figure 12 shows the same battery pack after the environmental test. The test was performed inside the operation temperature and pressure ranges of the equipment.

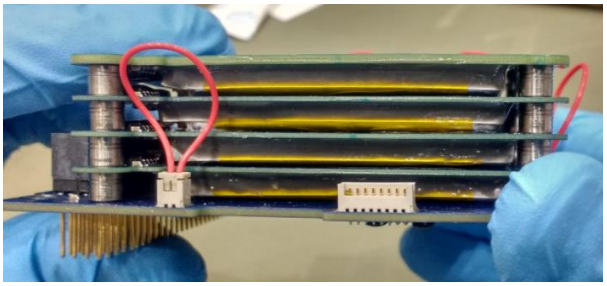

Figure 11: Battery pack visual inspection before test.

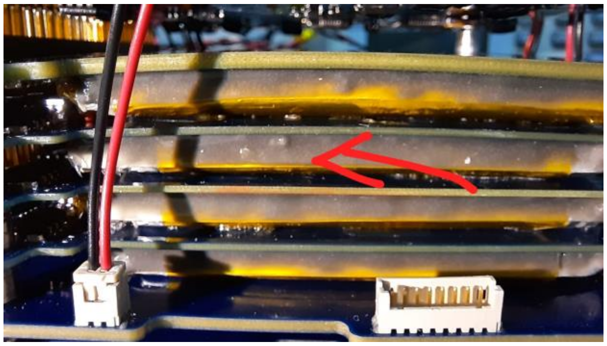

Figure 12: Battery pack visual inspection after test (deflection and bubbles formation on the resin).

As a project philosophy, the engineering unit of the EPS of the spacecraft was a spare unit, so the team decided to run an environmental test on the spare units of the battery. Unfortunately, the same problem occurred in this spare unit at a lower temperature and in a short period of time. After some time in ambient conditions, the battery was still functional but not reliable for flight or for handling on ground, so it was stored in a safe condition but discarded for use. Reference [6] provides some more details about these phenomena that can occur on pouch cells under harsh environments. The cause of the defect on the battery pack cannot be surely determined, but a batch of low reliability is one of the probable causes.

At this late stage of the development, changing the battery configuration was not an easy task. The supplier was contacted but, unfortunately, they could not provide us with the same set of battery packs in terms of capacity, since the cells themselves were not available on the market anymore. The solution could be a greater battery pack, that requires destructive tests as part of the tests for the launcher provider and longer delivery time, or a smaller battery pack, that could not fit in our mission requirements.

The challenge at this point was to find a new battery pack with a short delivery time that meets que mission requirements in terms of interfaces, performance, and delivery time. Several discussions took place, and the problem was identified as the higher risk for the mission for that moment. The team searched for solutions that minimize rework or changes in this late stage and we could find a battery pack that could replace the damaged one, and the delivery time could be accommodated by the project schedule.

The most important aspect of this issue and how the team overcame the problem was the frequent updates to the management about the status of the problem, the possible solutions and the support of the entire team to solve and quickly take decisions during the process. This issue shifted our schedule in about 3 months, considering that the issue occurred at the end of 2021 and many vendors and partner laboratories closed for Christmas and New Year. This also required the team to update some analysis and impacts of the change, where it was determined by the analysis that the impacts on power were minimum.

After the acceptance tests of the new battery pack, the spacecraft was integrated, and environmental and performance tests took place as designed for the mission. Once the team finished the Assembly, Integration and Test phase, the next project milestone was the Pre-Shipment Review. The PSR was a quality control process conducted before goods or products are shipped to the customer or end-user, where these main activities were accomplished:

- Compliance with Specifications: SPORT observatory was evaluated to ensure that it meets the specified requirements, such as dimensions, materials, finishes, and functionality.
- Quantity Verification: The pre-shipment review includes verifying the quantity of products to ensure that it matches the ordered quantity. In our case, photos, videos, and the PI of the project was on-site to assure the item before shipment.
- Packaging and Labeling Check: The review examines the packaging and labeling of the products to ensure that they are properly labeled, appropriately packaged for safe transport.

- Documentation Review: The pre-shipment review involves a comprehensive review of the accompanying documentation, such as invoices, packing lists, certificates of compliance, and quality control records.
- Non-Conformance Resolution: If any non-conformances or discrepancies are identified during the review, they are documented, and appropriate corrective actions are taken to rectify the issues before shipment. At this project any non-conformance was presented at the pre-shipment review.
- Final Approval for Shipment: Once SPORT passed the pre-shipment review and any necessary corrective actions have been taken, it received the final approval for shipment.

SPORT TRANSPORT AND HANDOVER

The handover process involves transferring the CubeSat from the development and testing phase to the entity responsible for its deployment in space, which may also involve operation. The summary of SPORT handover activities is presented in Figure 13. Approximately a year prior to the anticipated launch date, regular bi-weekly meetings commenced with the launch provider. These meetings aimed to share technical documentation about SPORT, facilitate mandatory Safety Reviews for launch, and provide updates on the development progress and readiness status of the observatory.

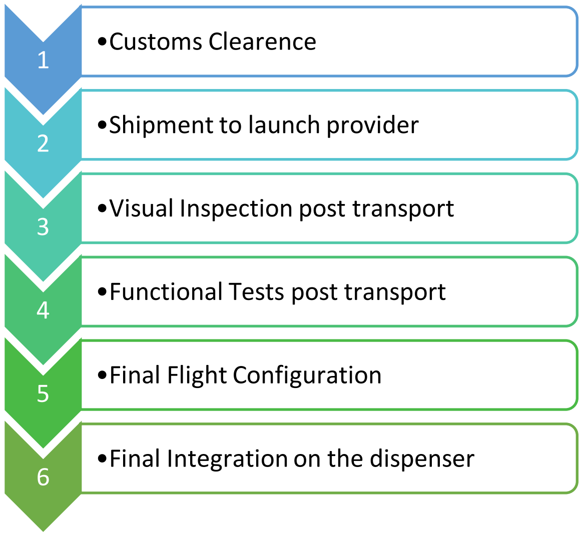

Figure 13: Transport and Handover short timeline.

Transport issue

Regrettably, SPORT encountered an issue during transportation, and determining the exact cause or location of the problem has proven challenging. However, the team had to address the consequences, which manifested as a damaged spacecraft that could not be deployed into orbit in its current condition. “Going a step back” in the transport process, the team developed a box to transport SPORT, as shown in Figure 14. This case was wrapped in bubble plastic and placed in a hard case, where all the spaces were filled with anti-static foam. Shock sensors were placed in the transport case and in the hard case. (Figure 15)

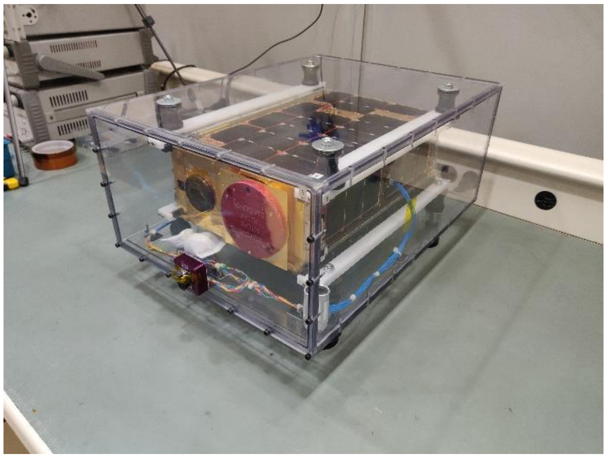

Figure 14: SPORT inside the transport box.

Figure 15: SPORT final transport configuration in the hard case.

The hard case was provided to the transport agent and then shipped to United States. Prior experience of the Brazilian partners in transporting the goods using a transport agent as the most recommended way to have the insurance for the CubeSat was the key factor for selecting this way of transport. The team, composed of a mechanical engineer, electrical engineer, software engineer and technical coordination, travelled later to the US to execute the activities according to Figure 13. Once at the launch provider facility, the team noticed that the external shock sensors were activated, but not the internal ones. It was registered and the unpacking process started. Then the first visual inspection showed that the spacecraft had moved from its fixed position, and it was damaged (Figure 16).

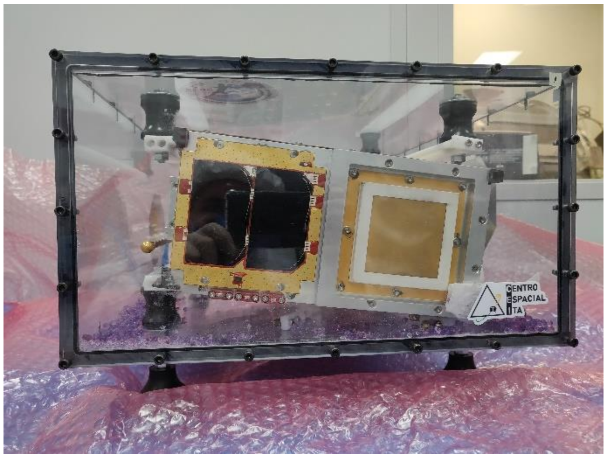

Figure 16: SPORT PFM after first step of unpacking.

Looking closer, but without touching any part, the team could see that a probe was damaged (Figure 17). No further damage could be seen at this first inspection. One of the possibilities for the sensor shock activation and seen damaged on the Observatory is that the hard case was dropped from a certain altitude to the ground.

At this point activities stopped, and an emergency meeting was called with the project manager, our procurement sector, and the project PI. The instrument that we could see as damaged was the E-field probe, part of the Space Weather Probe instrument from Utah State University.

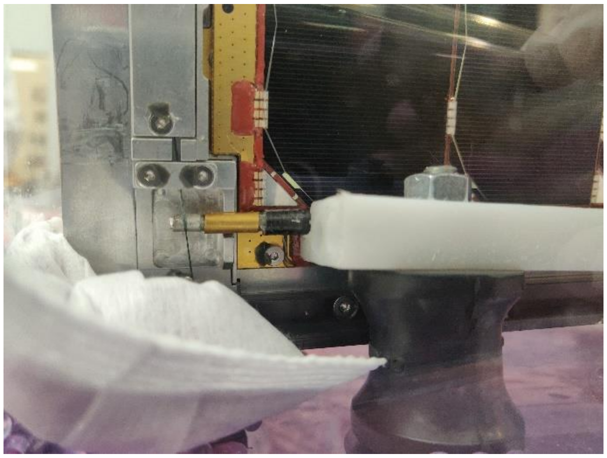

Figure 17: E-field probe broken, missing sensor element.

Several pictures were sent, and the instrument PI decided to include in the team from USU, to be at the launcher provider facility, a former collaborator who was responsible for the probe assembly to help in the refurbishment of the sensor. The insurance company was notified, but as the activity was performed on a Friday, no other activities could be done until the next Monday. Meanwhile the ITA team prepared a report to provide to the insurance company and to discuss with the project team to define the next steps. On Sunday the USU team arrived and, in a briefing, meeting the situation was explained, and a course of action was defined.

No tests or further inspections could be done without the approval of the insurance company, but on the Monday morning a SPORT team meeting was called, the situation was explained and all the parties agreed that at that point, without performing functional tests and other inspections, the real damage could not be measured and as a team it was decided that the team at the launcher facility was allowed to finalize the unpacking and perform further inspections and functional test to understand the extension of the damage.

Finalized the unpacking, the team could see the broken piece of the probe, as shown in Figure 18. Further inspection showed that no damage occurred to the solar panels. The springs of the hinges of the booms were damaged but spare parts were available for exchange. Functional tests, as far as they could be tested, showed expected behavior, so it was determined that only the E-field probe was broken.

Figure 18: E-field broken sensor.

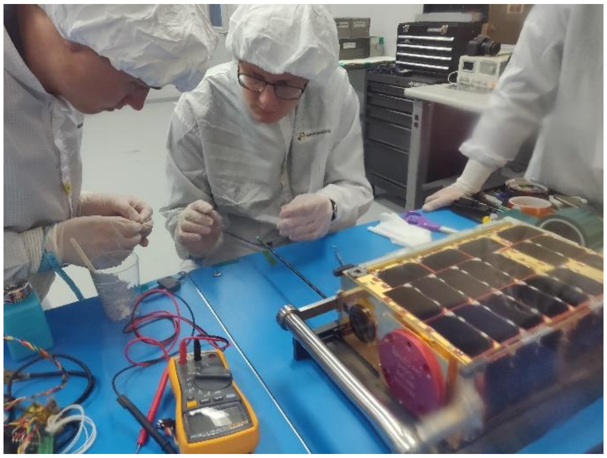

Figure 19: USU team during probe repair.

The USU team analyzed, and the repair could be easier than the first plan, so they started while ITA team was helping in the procedure. After the repair the probe should stay for as long as possible curing, so the ITA team performed other activities in the flight unit, such as more functional tests and final software configuration of the observatory.

The next day calibration tests were performed on the repaired probe. At this point the ITA software engineer had to come up with a creative solution and extracted the payload information using the UHF channel, given that in regular operation the payload data comes from the X-band channel. The positive aspect was that it was possible and calibration data showed that the performance of the repaired probe was not significantly different from the previous calibration data, performed in Brazil. In the meanwhile, a representative of the insurance company arrived to inspect the observatory to be aware of the situation. He understood that without functional tests and probe repair, no conclusion could be stated by the team regarding the damage after transport.

With the good results of the calibration tests and the functional tests it was agreed that the SPORT Observatory was ready for launch. An observation to the insurance company was made that perhaps further damage could be seen only in orbit. The team was informed and the project manager from NASA MSFC was at the launcher provider facility following very closely all last activities.

All the ties of the fishing lines that held the probes were replaced and damaged springs were exchanged for new ones. Thermal optical tape was applied, and final functional test performed. University of Texas at Dallas representative performed the final visual inspection and flight screws placement on their instrument, removing the RBF cover of the instrument and SPORT Proto Flight Unit was ready for visual inspection (Figure 20), external measurement, and fit checks prior to the final integration on the deployer together with PetitSat [7], the CubeSat that shared the same deployer.

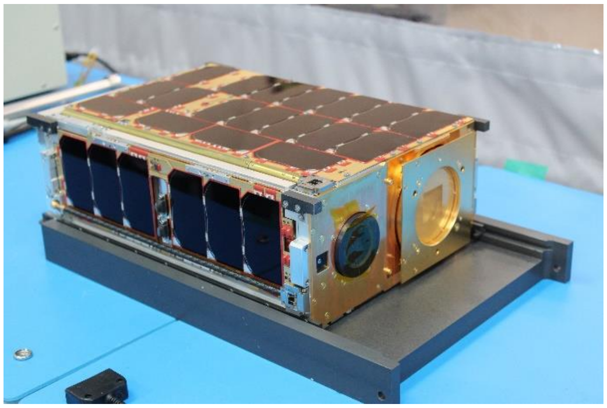

Figure 20: SPORT final flight configuration.

During the whole process, the launch provider team showed total support to the SPORT team, working extra hours, and allowing the team to finish the planned activities and running against the clock. All the impacts of an unsuccessful action on the handover activities were put in place throughout the process, informing all parties.

Not only schedule was considered, but logistics, further impacts on political aspects of the partnerships and concurrence with other ongoing projects and human resources availability were important players in the decisions made as a team.

After the final integration to the deployer the team came back to Brazil and waited for the next step, the Mission Readiness Review, where all science objectives and readiness of the teams were checked a couple of weeks before the spacecraft launch as part of the CRS-26 resupply mission to ISS.

LAUNCH AND EARLY ORBIT OPERATION PHASE & COMMISSIONING STATUS

Again, this phase did not occur as planned and we describe here the challenges of getting the first signals after SPORT's placement in orbit, ground station problems, and spacecraft anomalies. In this section we present the status of the spacecraft and discuss changes to the baseline operational plan along with initial and expected scientific results from the SPORT mission.

The simplified ConOps of SPORT Observatory is presented in Figure 21.

Launch and Early Orbit Operation Phase (LEOP)

After its injection into orbit from the ISS, SPORT had an orbital period of about 92 minutes. On December 29, 2022, within less than ten orbits, the SPORT team saw the first window of opportunity to communicate with the satellite over Brazilian territory. In that opportunity, INPE's ground station in Cuiabá received the first beacons from the spacecraft.

With the first data samples from orbit, the team observed the spacecraft in a satisfactory general state. The spacecraft was in its SAFE operating mode and with the expected energy consumption. The battery was fully charged, and all temperature sensors were in the nominal ranges.

Communications in the next few days became a challenge because of uncertainties in satellite tracking. The first orbits fit well into the initial pass predictions, which were based on the nominal state vectors provided by the launch provider. However, for the next days the team did not have access to SPORT's precise Two-Line Element (TLE) sets. Therefore, for several days the team struggled to track the satellite correctly and did not get much, or even any, telemetry.

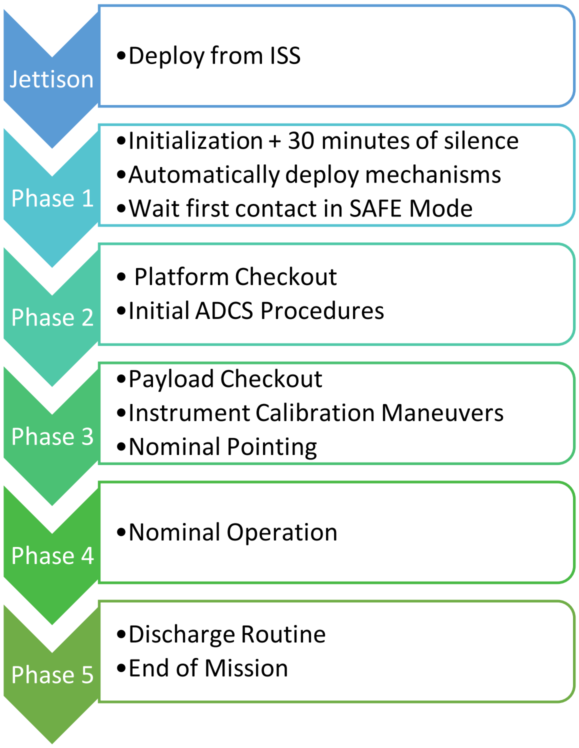

Figure 21: Planned Concept of Operation.

Not only during the period of TLE problems, but also afterwards, the SPORT team received invaluable assistance from the amateur radio community. Whereas INPE's ground stations were more specialized, and therefore had narrower line-of-sight, radio amateurs were able to receive and demodulate beacons, with which the SPORT team was able to determine that the spacecraft continued to be generally healthy.

Although the spacecraft was generally healthy, an issue arose that continues to the day this text is written. The EPS has a watchdog mechanism that reacts to the lack of communication from the onboard computer (OBC) if it is over a certain time threshold - four minutes by default. This watchdog mechanism is triggered frequently, resetting the spacecraft at an average of about 26 hours. Much longer and shorter periods have been observed (from one orbit to five days). The SPORT team was not able to determine the cause of the problem, although some possibilities have been identified. Those include a software defect or malfunction in any of the nodes connected to the I2C bus. An analysis of the moments of reboots over approximately 100 occurrences (in three months) suggest there is no relation between the reboots and positions on the globe.

One of the possible culprits may be the VHF/UHF radio, which presents an anomalous behavior. During LEOP, when the SPORT team unsuccessfully tried communication with the satellite as stated above, the assistance from radio amateurs helped determine that sometimes the radio was configured to transmit at 9600 bps instead of the default 1200 bps. Programmatically, the OBC sets 1200 bps at boot, so whenever the spacecraft reboots the radio goes back to the expected rate. However, the radio's hardware falls back to 9600 bps when it reboots, suggesting the radio reboots in moments different than the spacecraft. The onboard software allows for setting the default transmission rate, which at first glance solved the problem. However, the radio continues this erratic reboot behavior, that may or may not be related to the more general spacecraft reboots.

In the following days, the SPORT team proceeded with the previously written nominal LEOP procedures, which included the status check of the deployable elements. SPORT has eight mechanically deployable elements, including two antennas, four probes (also known as booms), and two solar panel arrays. In particular, two booms were stowed on top of the solar panel arrays, which in turn should only be deployed when the corresponding probe was successfully deployed. All elements but one probe should be deployed autonomously by the initialization routine in software. The remaining probe would be deployed later during commissioning. The status check revealed that five out of the seven elements that should have been deployed were successfully deployed. One boom was not, and therefore also its respective array. This demanded manual deployment tries over the course of some days, with different parameters, including the deployment of the array to force the deployment of the boom above it. The tries were unsuccessful, and the elements remain stowed.

The stowed solar panel array results in reduced power availability, which however has not caused problems or concerns during the mission so far. Eventually the decision was made to leave the booms stowed and proceed with the commissioning phase. At this point, the LEOP phase was considered over.

Commissioning and Status

During the following months, the SPORT team proceeded with operating the spacecraft daily, within the limitations of personnel and hours.

The EPS meets expectations, with adequate power conditioning and distribution. All power buses and switchable lines operate within their nominal operating ranges. Energy consumption levels are very close to what has been characterized during AIT. The only situations in which the battery was not fully charged or close to that were in tests involving the payloads, with a significant energy consumption. To this date, the battery has not undergone a significant depth of discharge, except in a handful of situations.

During AIT and based on the detailed thermal analysis conducted by the team, the thermal behavior of the spacecraft has been characterized in several scenarios. This led to the necessity of incorporating thermal solutions into the design. One of them was a heat sink, along with thermal pads, for the Data Storage Unit (DSU, one of the OBCs), which was a hot spot. Another one was the application of a thermal tape to the outer faces of the mechanical structure, to allow for better heat dissipation. Also, the battery included an autonomous heater, which activates when battery temperature drops below 4 ºC. The results observed during commissioning are that no temperature readings ever surpassed their nominal ranges. In particular, DSU's temperature was observed to be within 5 ºC of the predicted temperature in the hot case, which indicates that the thermal analysis models behave closely to what has been observed on orbit.

After orbit injection, the initial ADCS commissioning procedures showed that the absolute angular rate of the spacecraft was about 1.0 °/s based on gyroscope and magnetometer readings. This rate indicated that reaction wheels alone could be able to exchange the residual angular momentum and bring the rotational speed close to a halt, directly in the Attitude Acquisition Mode (AAM) or even in the Nominal Mode (NM). However, in the first attempts to acquire attitude, we observed reaction wheels saturation and angular rates increasing, which led to the procedure to always command the spacecraft into the Detumbling Mode (DM) after NM or AAM attempts. Evaluation of the spacecraft housekeeping data, along with simulations on ground, led to the conclusion that there was a mismatch between the actual orientation axes of reaction wheels and the reference matrix embedded in the ADCS onboard software. Fortunately, we could change the elements of the reference matrix via telecommand (TC) and validate the correction through an open-loop flight test procedure.

The respective procedures to perform AAM and NM presented challenges because they rely on precise attitude determination by ADCS sensors, and it has been difficult to obtain valid attitude readings from the star tracker - the most precise sensor. Even when the star tracker achieves a valid attitude and despite control modes stabilizing the spacecraft in the inertial reference frame a few times, in most of the attempted cases the control system does not converge, and we do not observe a station-keep behavior. For that reason, obtaining nominal pointing for the science payloads is still an ongoing challenge.

Communications with the satellite continue to present challenges as well. Tracking is not an issue anymore, given the frequently updated TLEs, but still other issues remain. First, due to an undetermined reason, the uplink is intermittent even in good passes, causing the operators to sometimes need to resend TCs multiple times until the spacecraft receives and executes them. Sometimes the spacecraft does receive TCs, but the downlink fails, causing the response to a TC to be lost and sacrificing precious pass time. There are also infrastructure issues that happen sporadically that cause passes to be lost, such as network connectivity problems between the control room and the ground station antennas. Also, some procedures such as scheduling an X-band downlink pass take several TCs that could have been synthesized into fewer during software development, by means of an automated procedure.

Lesson learned:

- It is imperative to simplify and optimize operations as much as possible. Suggested measures include:
    - A mechanism to send multiple TCs as one (script). This is not trivial because the spacecraft must know what to do if a TC fails.
    - Automate complex tasks into as few TCs as possible, although the more verbose methods must also be available for debugging.

In SPORT, the superset of all data generated by the bus and by the payloads is downloaded via X-band. The downlink has been successfully demonstrated several times, which validates the end-to-end chain (data collection to data analysis on the ground by the science teams). However, the X-band downlink also presents a difficulty, which is the fact that the onboard X-band antenna is directional. Coupled to the lack of nominal pointing, and with a low (but not null) angular momentum, it makes the success of any given X-band transmission an uncertainty.

The aforementioned spacecraft resets are in fact a complication in operations, but their impact is handled through a few TCs that recover the state of the spacecraft, so mission goals are not affected. All payloads operate nominally, and all science teams have been successful in decoding the resulting science data. The payloads require nominal attitude to yield the best-quality data, and as mentioned, this is an ongoing challenge.

The boom that was not deployed by the automated procedure is a Langmuir probe that pertains to the payload SWP and which also carries the sensor element of the payload MSM. Its deployment was deferred in order to have MSM on during deployment so that the magnetic field was characterized before, during, and after deployment. It has been successfully deployed.

During integration and testing, it was determined that SPORT would run into power restrictions that would need to be managed by software. In order to maximize science data collections in regions of greater interest, the SPORT team implemented a mechanism called SCIENCE scheduler. It selectively navigates among spacecraft operating modes, effectively powering components on and off, to turn the payloads on in regions of interest and off outside of them. It works by analyzing information regarding ascending/descending orbit nodes (provided by ADCS' orbit propagation algorithms) and then scheduling data collection periods when the nodes fall within a window of local times of interest. The commissioning of the SCIENCE scheduler algorithm demonstrated that it operates as expected.

FINAL REMARKS

The SPORT CubeSat increased the level of knowledge and expertise of the team at ITA Space Center, and it is much more complex than the former CubeSat of the Center, ITASAT [8]. The pre-launch anomalies were not only technical in nature but included aspects such as schedule, cost, partnerships, and team motivation which had to be considered when making decisions on how to proceed. The examples where these decisions had to be made were during the problem with the flight hardware on environmental tests and during the handover at the launcher facility after the transport issue. In all these situations the key factor was the transparency of the team to report the problems, the possible solution and the decision made as a team.

Some other lessons learned during the project are listed below.

- *Schedule:* Some activities had a longer duration than initially expected. This can be due to several factors such as technical complexity, workload, multi-tasking, and of course the COVID-19 pandemic. To reduce the risk of increased duration and delays a few options may be to breakdown technically complex activities, establish intermediate milestones, improve workload planning, and reduce multi-tasking. Also, including in some activities a buffer or a margin would be helpful. The close control of the primary, secondary, and tertiary critical path is important to keep the speed and the schedule. And some good practices used during the project that helped the management and are highly recommended are:
  - Deliverables and milestones definition.
  - Definition of predecessor and successor relations.
  - Critical Path follow-up and alignment with stakeholders.
  - Routine update with team (weekly) and stakeholders (bi-weekly).
- *Risk Management:* Most of the failures were identified since the beginning of the project and the impacts were mapped in a Failure Mode Effects and Critical Analysis table, but the severity and the impact on the schedule needs to be revisited. Another aspect is that the project developed a process to monitor and mitigate the risk, and as a result two Master Thesis were defended using SPORT as a case of study [9], [10]. In terms of risks, some can be pointed out:
  - Products and Services purchased from suppliers may be subject to risk such as: price variation; lack of availability; delivery delays; or present defects (non-conformities). To reduce this type of risk, it is important to invest in supply chain risk management. In addition, it is important to invest in a quality assurance process so that defects are identified as soon as possible.
  - Institutional partnerships may present specific risks, such as: partner leaving the project; uncertainty and lack of alignment with partner expectations; International partners may have export restrictions (such as ITAR and EAR for the US). To reduce this type of risk, it is important to: seek to formalize agreements (framework agreement); technological safeguards agreement if necessary; and understand and comply with partner nation export regulations.
  - For a space system such as a small satellite, one source of uncertainty and risk is the definition of orbit. It is necessary to define how the satellite will be placed in orbit (launch and deployment). To reduce this type of risk, the main action is to invest in analyses and simulations as soon as possible, so that a feasible solution can be defined.
  - Risks external to the organization may impact the small satellite project. External risks can be economic, social, political, health, environmental, natural hazard. As an example of the impact of external risk, we have the pandemic, especially in 2020 and 2021. One recommendation is to create means to monitor the possibility of external risks and have contingency and emergency plans in case they occur.
  - There are organizational risks such as: people management; operations and processes; facilities, equipment, resources; data, information, cyber security; management (governance, finance, legal compliance); strategy; reputation. These may impact the project. Therefore, alignment and monitoring with the organization's management is recommended to reduce these risks.
- *Highly integrated tests:* in general ground segment development and testing with the platform. It presents a challenge, as it is a complex system, includes several locations and involves integrated development with a partner. Involving the ground team in the early stages of the project is mandatory to reduce rework or inconsistencies between the ground system and the space system. The quantity of tests and rehearsals can improve the knowledge and the iteration among the teams.
- *Assembly, Integration and Test:* More time for testing showed necessary to the project and especially more test setups, such as a Hardware-in-the loop setup for ADCS System.
  - *Simulator:* After SPORT reached its orbit, the ADCS commissioning process began. During this time, some problems came in place that may be avoided if proper simulation was performed. During AIT process, due to

    simulator limitations, the operating modes were tested mostly as individual modes rather than ADCS operation as a whole. That means few mode transitions were performed. Also, provided the poor simulator interface, as soon as a simulation went wrong, the only option was to perform a reset and start over. This led to few abnormal/emergency operation tests, which were experienced in real operation.
    - *Sensor and Actuator characterization:* In-orbit operation has shown that sensors and actuators have a different behavior than in Earth conditions. Reaction wheels did not reach the maximum speed as described in ICD. Other sensors such as MEMS also had variations in its correction coefficients for biases and gains. A better sensor/actuator characterization is a must for a reliable control operation, either as a quality sensor/actuator correction or control gain adjustments.
- *Operation:*
    - Due to the multidisciplinary nature of the team, the utilization of straightforward diagrams to depict the sequences of events in the satellite's life cycle proves beneficial in enhancing comprehension during planning discussions concerning commissioning activities.
    - In a nominal scenario, the procedures defined prior to the operation in orbit were good to define the number of commands that could be sent during a pass and for planning purposes, but in the case of issues during commissioning, as happened to SPORT CubeSat, it is necessary to define the procedures in daily base, so a certain level of flexibility is required on the telemetry and telecommand planning.
- *Training human resources:*
    - One of the main purposes at ITA Space Center is to train human resources for space related projects. This purpose is being achieved as 9 collaborators was hired by aerospace industry in Brazil and abroad.
    - The high rate of collaborators exchange is one of the challenges of running consecutive projects, as it has been done at the ITA Space Center, once new collaborators require a knowledge curve to be able to produce the expected results on the project.
- *ADCS commissioning phase:* The ADCS of SPORT has been a challenge and some improvements can be done in the future missions.
    - Implement autonomous routines to perform device auto-tests and auto-check to save ground resources and time passes.
    - Design a control system able to transit in different modes according to state measurements, requirements, or failures without ground interference during the entire orbit trajectory.
    - Autonomous attitude determination mode with housekeeping data generation for state estimation, as well as system redundancy to save attitude and orbit states after failure or onboard computer reset.
    - The standardization of attitude data housekeeping packages for different flight modes would simplify ground analyses and data management.
    - Methods and tools to perform statistical treatment and parametrization of ADCS housekeeping packets would facilitate the ground evaluation of attitude data states.

The lessons learned during the SPORT project have been a valuable source of knowledge for the team and for the ongoing projects of ITA Space Center, such as ITASAT-2 [11] and SelenITA [12]. The lessons learned are being applied to these two missions in early phases and decisions are based on previous experiences.

SPORT Team

Instituto Tecnológico de Aeronáutica: *Linélcio dos Santos Paula, Jéssica Garcia de Azevedo, Edward Hsiao, Jonas Fulindi, Douglas Casale, Valdemir Carrara, Luiz Henrique, Breno Crucioli* / **Utah State University:** *Joel Mork, Jason Powell* / **University of Texas at Dalla:** *Roderick Heelis, Mark Mankey, Michael Perdue, Matthew Depew* / **Goddard Space Flight Center:** *Guan Le, Todd Bonalsky, Kenneth Bromund* / **Aerospace Corporation:** *Rebecca Bishop, Pablo Settecase, Faraz Zaerpoor* / **Instituto Nacional de Pesquisas Espaciais:** *Elias Salome Sobrinho , Manoel Fellipe Costa, Mauricio Ferreira, Walter Abrhaão, Joaquim Costa, Marcelo Banik, Glauber Miranda, Luciano da Silva, Francisco Chagas, Manoel Jozeane Mafra de Carvalho, Antonio Carlos Pereira, Luciana Cardoso, Paulo Cardoso*

Acknowledgments

The SPORT project is supported by the Brazilian Space Agency and sponsored by FAPESP under the process 2016/24970-7. The authors would like to thank NASA Science Directorate and SOUTHCOM for funding the SPORT Mission.

References

1. Spann, J., C. Swenson, et al. "The Scintillation Prediction Observations Research Task (SPORT): An International Science Mission using a CubeSat". Proceeding of the 31st Annual AIAA/USU Conference on Small Satellites, August 2017.
2. Loures da Costa, L., et al. "The ITA Space Center and its role in space education in Brazil". Proceeding of the 34th Annual AIAA/USU Conference on Small Satellites, August 2020.
3. Habash Krause, L., et al. "Science ConOps for Application of SPORT Mission Data to Study large (~1000 km) Ionosphere Plasma Depletions". Proceeding of the 36th Annual AIAA/USU Conference on Small Satellites, August 2022.
4. Habash Krause, L. et al. "On the Role of Ground-based Assets to Maximize Science Return of Small Satellites in Low Earth Orbit: The SPORT CubeSat Mission as a Case Study" Proceeding of the 37th Annual AIAA/USU Conference on Small Satellites, August 2023.
5. Loures da Costa, L., et al "The Scintillation Prediction Observations Research Task (SPORT): A Spacecraft Development for an International Mission". Proceeding of the 32nd Annual AIAA/USU Conference on Small Satellites, August 2018.
6. Masatoshi, U., et al. "Development and on-orbit operation of lithium-ion pouch battery for small scientific satellite "REIMEI"". Journal of Power Sources, Volume 196, Issue 20, 2011, Pages 8755-8763, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2011.06.051.
7. Klenzing, J. & Davidson, R.L. & Jones, S.L. & Martinis, C. & Zawdie, K.A. & Earle, Gregory & Smith, J.M. & Halford, Alexa & Noel, S. & Paschalidis, N. & Pfaff, R.F. & Robertson, E.. (2019). The petitSat Mission – Science Goals and Instrumentation. Advances in Space Research. 66. 10.1016/j.asr.2019.12.013.
8. Shibuya Sato, L., et al. "The ITASAT – The Lessons Learned from the Mission Concept to the Operation". Proceedings of the 33rd Annual AIAA/USU Conference on Small Satellites, August 2019
9. Paula, L. S. "Uma abordagem para análise e gerenciamento de riscos aplicada a missões de nanosatélites (CubeSats)". Master Thesis, Instituto Tecnológico de Aeronáutica, São José dos Campos, 2023
10. Cabral, P. L., "Processo para gestão de riscos aplicado em projetos de satélites". Master Thesis, Instituto Tecnológico de Aeronáutica, São José dos Campos, 2022
11. Loures da Costa, L., et al "ITASAT-2 Mission Overview". Proceedings of the 36th Annual AIAA/USU Conference on Small Satellites, August 2022.
12. Matos, T., et al. "Engineering Challenges of a CubeSat Mission Around the Moon: First Steps on the Path to SelenITA" Proceedings of the 37th Annual AIAA/USU Conference on Small Satellites, August 2023.