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THE NANOSATC-BR, CUBESATS DEVELOPMENT PROGRAM - CAPACITY BUILDING WITH THE NANOSATC-BR2'S LAUNCH, FIRST OPERATIONS AND EXPECTED RESULTS THROUGH INPE'S GROUND STATION AT SANTA MARIA

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Abstract. The INPE-UFSM's NANOSATC-BR CubeSats Development Program started in early 2008. Nowadays, the program has two CubeSats in space: the NANOSATC-BR1 (1U), launched in 2014 and currently in standby mode, and the NANOSATC-BR2 (2U), which was recently launched on March 22, 2021, from the Baikonur Cosmodrome, Kazakhstan. In this article, the launch of NANOSATC-BR2 is presented alongside with its final tests, initial operations and expected scientific results. Regarding the Capacity Building, the main objective of the program, this work focuses on the involvement of the undergraduate students and professionals from the Federal University of Santa Maria (UFSM) in the tracking and control of CubeSats through the INPE's Ground Station at Santa Maria, which works as an excellent tool for supporting CubeSat scientific missions from all around the world, and also on qualifying students to work on the Ground Segment of space missions. The program was supported by the Brazilian Space Agency (AEB) and the Ministry of Science, Technology and Innovation (MCTI).

Keywords: CubeSats, capacity building, ground station, nanosatellites, space mission

INTRODUCTION

The NANOSATC-BR CubeSat Development Program consists of a Brazilian INPE-UFSM (National Institute for Space Research - Federal University of Santa Maria) Capacity Building program on space science, engineering and computer sciences for the development of space technologies based on the CubeSat standard, which had the first Brazilian CubeSat, the NANOSATC-BR1, launched in June 2014. This CubeSat has successfully completed its mission in space, not only obtaining measurements of the SAMA (South Atlantic Magnetic Anomaly) through the usage of the XEN – 1210 magnetometer, developed by Santa Maria Design House (SMDH), but also validating the resistance of electronic circuits tolerant to space radiation. In this article, it is exposed the final tests, the launch and first operations of the brand-new CubeSat of the project, the NANOSATC-BR2 satellite, launched on March 22, 2021. The expected scientific results using the data from the payloads are also discussed as well as the challenges that its operation is currently facing in space. The Capacity Building Program focuses on the usage of INPE's Ground Station at Santa Maria (positioned at longitude 53.7083º W and latitude 29.7292º S), State of Rio Grande do Sul (RS), where students and professionals from several Engineering courses (Aerospace, Electrical, Mechanical) learn how to track and control CubeSats in space, obtaining important data from space missions, and also how to carry out ground station maintenance, automation, staff training and documentation. It is also discussed the support of INPE's Ground Station at Santa Maria for other CubeSat missions as well as possibilities for expanding the functionalities of the Ground Station's antennae in the near future. The program has support from the Brazilian Space Agency (AEB) and from the Ministry of Science, Technology and Innovation (MCTI).

The paper is organized as follows: Section 1 is dedicated to describing the NANOSATC-BR2's launch, institutions involved and other relevant information about its development. Section 2 describes the NANOSATC-BR2's operation, frames received, problems in space and scientific results obtained by the NANOSATC-BR program. Section 3 describes the Capacity Building through INPE's Ground Station at Santa Maria, with the involvement of students in the program. Section 4 eventually describes the support that the NANOSATC-BR Program may offer to other CubeSat missions as well as future work related to improving the INPE's Ground Station at Santa Maria.

NANOSATC-BR2: institutions involved, final technical tests and launch on March 22, 2021

The NANOSATC-BR2 is a 2U CubeSat, (10x10x22.6 cm), with three major objectives: academic and capacity building; scientific mission; and technological mission development. The scientific mission is to monitor the Earth's Ionosphere and Magnetic Field. The Ionosphere composition disturbances in the SAMA region over Brazil have severe effects on satellite telecommunications as well as on the precise location with services such as the Global Positioning Systems (GPS) (Schuch et al., 2019a). The payload equipments for the scientific mission are a Langmuir probe that measures plasma temperature, density, and electric potential and a XEN-1210 magnetic field sensor based on the Hall effect.

A list of institutions involved with the NANOSATC-BR2 Project, as well as the stakeholders of the mission are described by Figure 1:

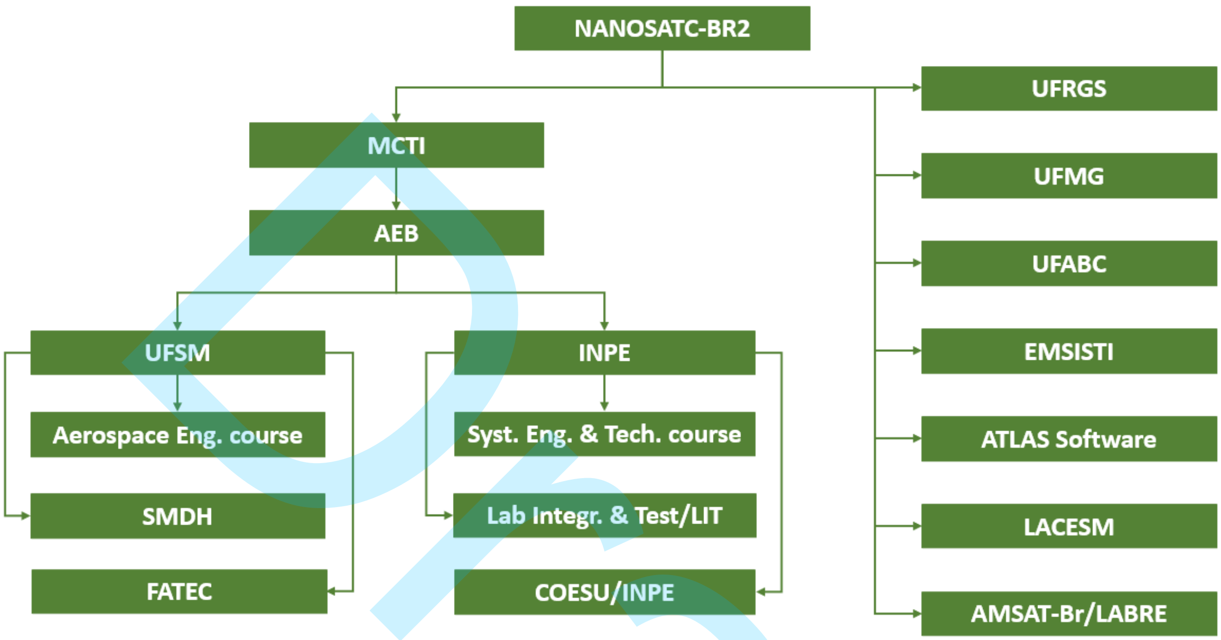

Figure 1: List of the Brazilian institutions and stakeholders of the NANOSATC-BR2's Project.

Acronyms of the Brazilian institutions involved in the Project are: MCTI (Ministry of Science, Technology and Innovation); AEB (Brazilian Space Agency); UFSM (Federal University of Santa Maria); INPE (National Institute for Space Research); SMDH (Santa Maria Design House); FATEC (Science and Technology Support Foundation); COESU/INPE (Southern Space Coordination of INPE); UFRGS (Federal University of Rio Grande do Sul); UFMG (Federal University of Minas Gerais); UFABC (Federal University of ABC); EMSISTI (Brazilian Startup); ATLAS Software (Brazilian Startup); LACESM (Space Science Laboratory of Santa Maria); AMSAT-Br/LABRE (Brazilian Satellite Radio Amateur community).

Space missions involve complex systems; hence, it is vital to test if the satellite meets its system requirements and is operating according to the designed parameters before the launch. Thus, a complete test campaign was performed. The NANOSATC-BR2 test plan followed the protoflight model philosophy: the tests occur with the satellite flight model using the qualification test levels and the flight test duration (ESA, 2012).

The environmental tests were planned in accordance with the methodology presented by Bürger (2014), and comprise Dynamic Tests, Thermal Vacuum Tests, in addition to required procedures such as Bakeout (to remove undesired gas in the materials), mass and center of mass measurements, and functional tests (NANOSATC-BR Program, 2020). Unlike larger satellites, CubeSats are not required to take electromagnetic compatibility tests since they have a mechanism to prevent their activation while inside the launch vehicle before orbit insertion (Cal Poly, 2014). Figure 2 illustrates the general Assembly, Integration and Test (AIT) sequence adopted; the yellow boxes indicate environmental tests and mass propriety measurements, the blue boxes the assembly phases, and the green ones the functional tests. CDS means CubeSat Design Specification (The CubeSat Program, 2014).

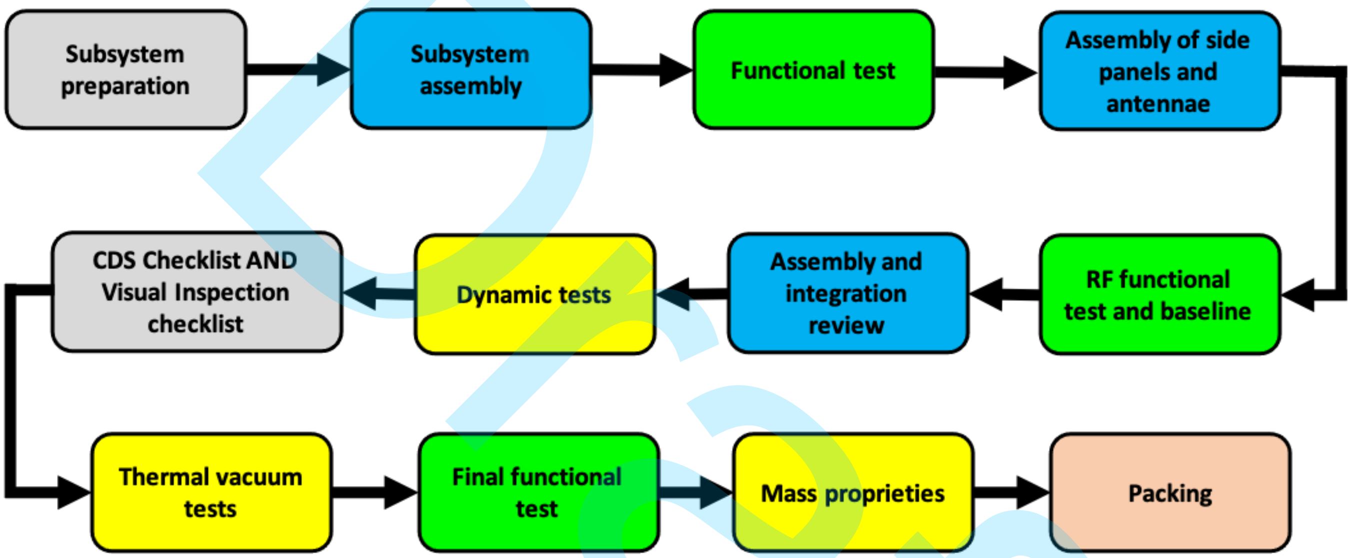

Figure 2: Checklist and general Assembly, Integration and Test sequence employed by the NANOSATC-BR2 mission (NANOSATC-BR Program, 2020).

While dynamic tests emulate the launch vehicle environment and ensure the satellite will resist the launch phase, thermal vacuum tests verify if the satellite will manage its temperature correctly once in space, maintaining its subsystems inside the designed temperature range. Functional checks between each test ensure the satellite is operating as expected and, eventually, exposing test failures. Figure 3 presents the environmental tests' general sequence with the specific dynamic tests: resonance, sinusoidal test, random vibration test, quasi-static test and shock test; functional tests and inspections are in green squares, while the Packing item describes the preparation for transportation.

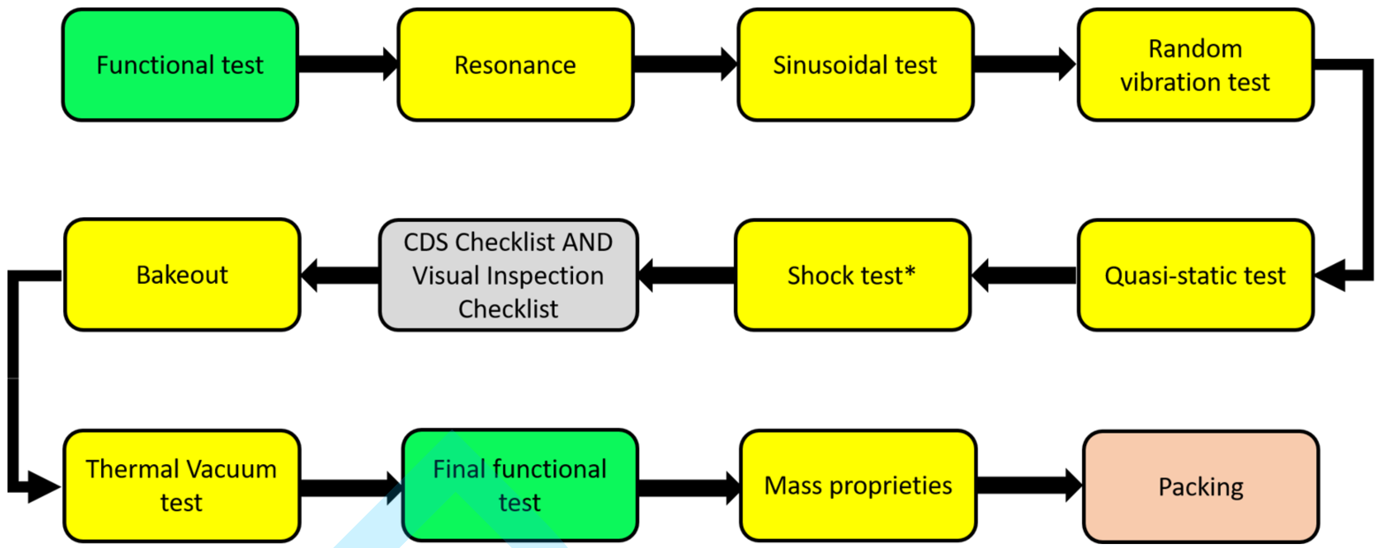

Figure 3: Environmental tests' general sequence; each yellow square comprises a specific detailed test sequence. The asterisk symbol indicates that the test was planned but not performed (NANOSATC-BR Program, 2020).

By the end of 2020, the AIT campaign finished at the Integration and Testing Laboratory (LIT/INPE – MCTI), located at INPE's Headquarters in São José dos Campos (SP), Brazil. The CubeSat passed through several tests (Figure 4) during the beginning of December 2020 (dynamic, thermal, mass properties, etc.), without any non-compliance being detected. This campaign had the active participation of students and professors from the postgraduate course at INPE in Space Systems Engineering and Technology (PG-ETE), and also the technical support and expertise of the LIT/INPE team. The assembling and functional testing were performed to meet the operation scenarios in compliance with the mission concept of operation (Almeida, 2021). The integrated and tested Flight Model (Figure 5) was then ready to be packed and sent for the launch site, in Baikonur - Kazakhstan.

Figure 4: The NANOSATC-BR2 mounted with several internal and external thermocouples inside the Thermal Vacuum Chamber (left), and the CubeSat placed inside a Test-POD on a shaker at the Integration and Testing Laboratory (right) (Asencio, 2021).

Figure 5: The integrated and tested NANOSATC-BR2's Flight Model ready to be packed and transported, at the Integration and Testing Laboratory in December 2020.

On March 22, 2021, the NANOSATC-BR2 was ready to be launched by a Soyuz-2.1a/Fregat vehicle (Figure 6), operated by the company GK Launch Services, from Baikonur Cosmodrome, Kazakhstan. In this specific launch event, 38 satellites from 18 countries were sent to space, being the NANOSATC-BR2 one of the CubeSats launched as a piggyback payload.

Figure 6: The Soyuz-2.1a/Fregat launch vehicle, carrying the NANOSATC-BR2 satellite and lifting off from the Baikonur Cosmodrome, Kazakhstan on March 22, 2021 (GK Launch Services, 2021).

The NANOSATC-BR2: first operations, frames received and current problems in space

Since the NANOSATC-BR2's launch, several radio amateurs from all around the world have been collecting and forwarding frames from the satellite, confirming its initial operation in space. The INPE's Ground Station at Santa Maria also received several beacons and frames during NANOSATC-BR2's passages over the South of Brazil (Figure 7), contributing to the LEOP (Launch and Early Orbit Phase), one of the most critical phases of a space mission.

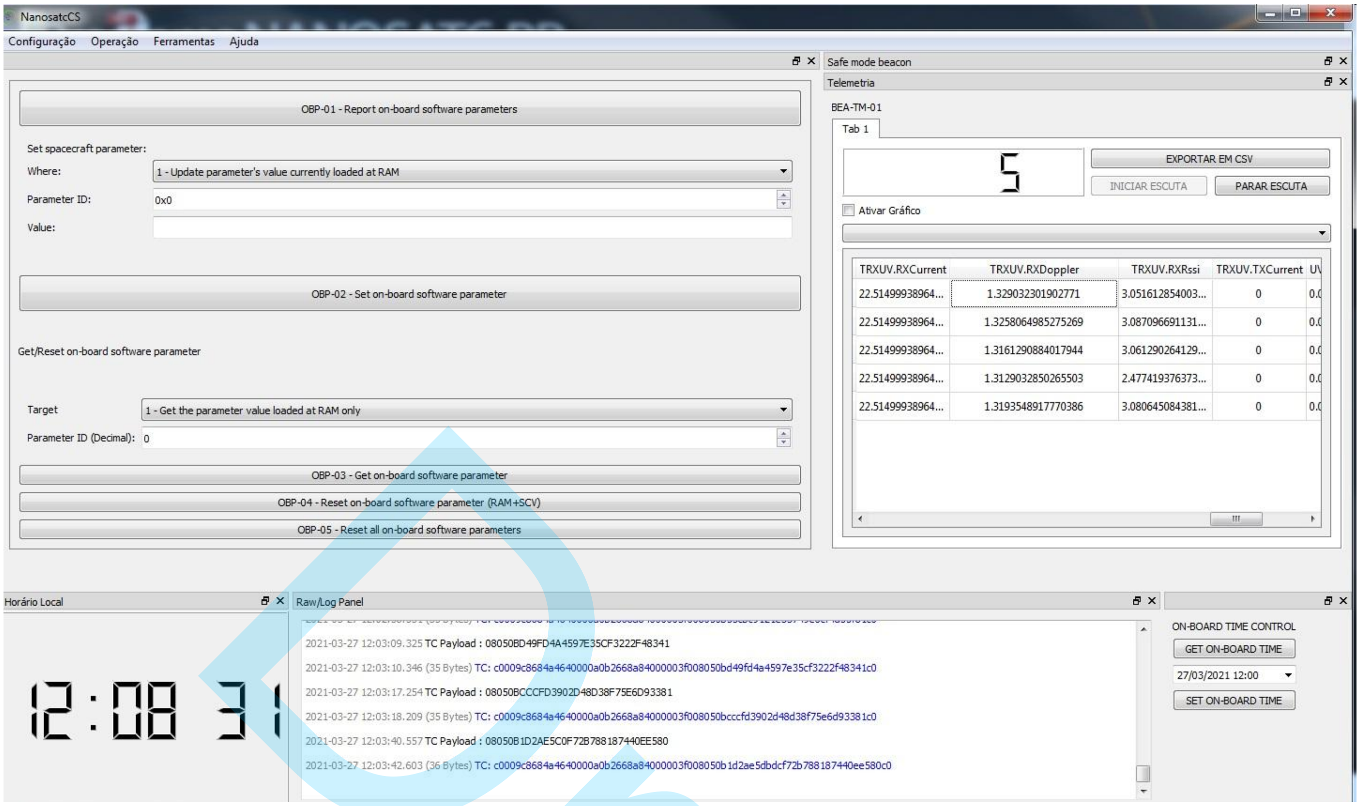

Figure 7: Safe Mode Beacon (5 Frames) received during a passage over the city of Santa Maria (RS), throughout the very first week of the NANOSATC-BR2's flight.

Regarding the expected scientific results, the NANOSATC-BR2 may expand the measurements of the terrestrial magnetic field made by its predecessor, the NANOSATC-BR1, throughout its entire orbit at 600km altitude, using the XEN-1210 magnetometer. By doing so, the NANOSATC-BR2 will complement and confirm the studies made with the Brazilian data of the magnetic field at the SAMA region, such as the one made by Heirtzler (2002).

The NANOSATC-BR2 may also use data from two different instruments that work simultaneously in space, identifying Ultra-Low Frequency (ULF) pulses in the geomagnetic field and also making the magnetometer work in conjunction with the measurements obtained by the Langmuir Probe.

In the first mission of the program, the NANOSATC-BR1 data were collected by the Scientific Mission Payload, which was a XEN-1210 magnetometer. The observations showed an excellent correlation with the theoretical figures for the geomagnetic field intensity, given by the International Geomagnetic Reference Field model (IGRF-IAGA/IUGG) at the same altitude (Schuch et al., 2019a). The same good correlation is also expected in this new NANOSATC-BR2 mission. A map of the total intensity of the geomagnetic field for an altitude at 614 km over South America, in the domain of SAMA (Heirtzler, 2002), is presented in Figure 8. The intensity of the geomagnetic field changes from 24.000 nT outside the SAMA to 17.000 around the center of this anomaly, signalized by a black star in Figure 8. The INPE's Ground

Station at Santa Maria, GS (INPE-COESU), is inside the region of SAMA with larger decrease. The colored line in Figure 8 indicates the approximate orbit of the NANOSATC-BR1 on August 17, 2014, from 10:57 a.m. to 11:07 a.m. During this period, the NANOSATC-BR1 moved from the South Pole towards to the geographic North Pole.

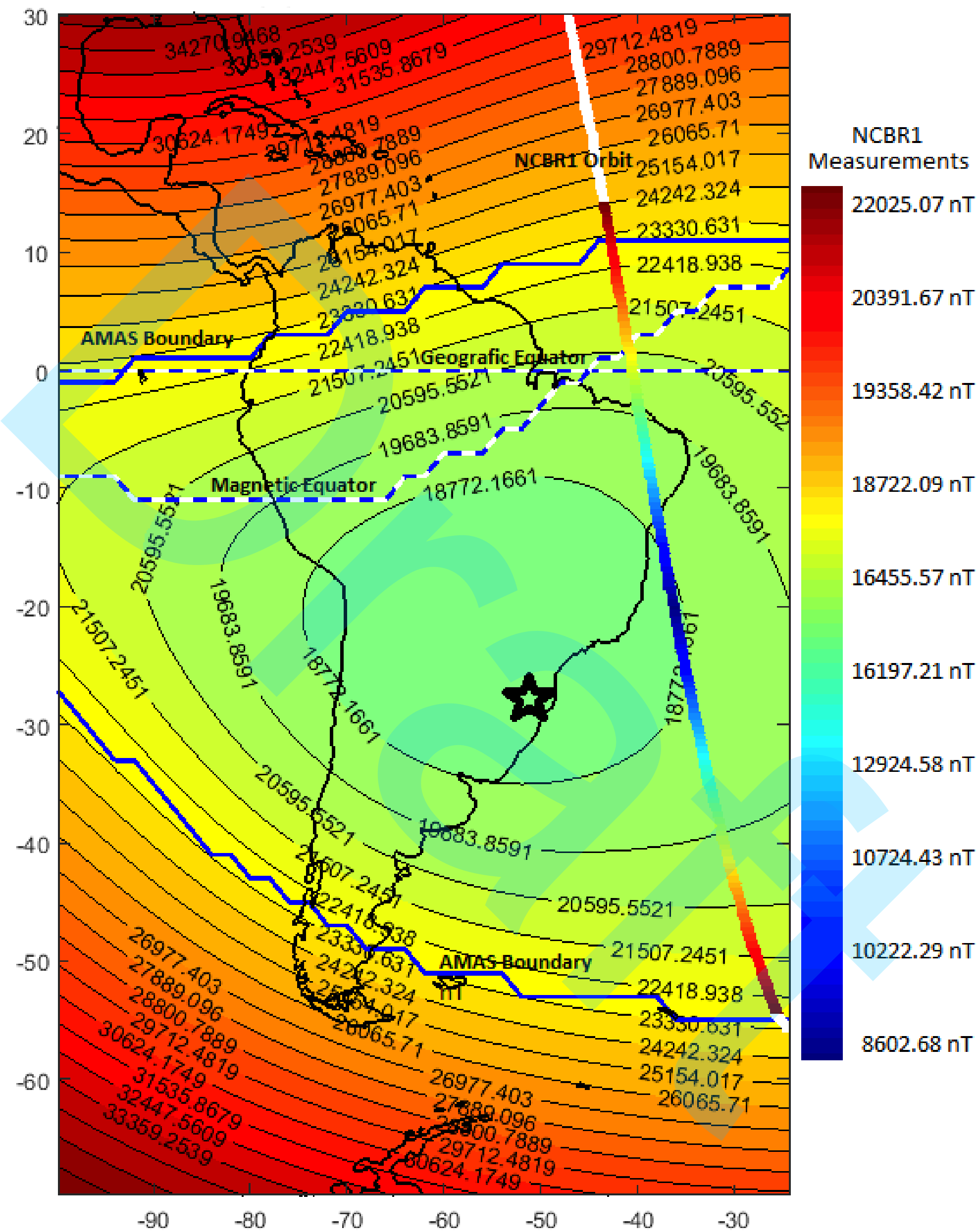

Figure 8: Geomagnetic field total intensity, according to the IGRF, showing the SAMA and NANOSATC-BR1 Scientific mission payload measurements at 614 km altitude in 2014 for the Geomagnetic Field. The black star indicates the location of the INPE's Ground Station at Santa Maria (INPE-COESU), which is located near the center of the SAMA (Schuch et al., 2019a).

When it comes to technological results, the first mission of the program had electronic circuits for space applications developed by SMDH, with the objective of technology demonstration of connecting payloads and the satellite's service module in an environment subjected to Single Event Effects (SEE) (INPE, 2018; Schuch et al., 2019a). Also, the first mission had a Field Programmable Gate Array (FPGA) developed by UFRGS to test the fault tolerant software against radiation (Schuch et al., 2019b). For the second mission of the program, a new electronic circuit was developed by SMDH as well, with greater resistance to space events, such as the SEE.

An Application Specific Integrated Circuit (ASIC) was developed as one of the technological payloads of the NANOSATC-BR1 Project. The radiation hardened digital cells designed by SMDH proved a tolerance to solar energetic particles with energies of up to 100 MeV (Schuch et al., 2019a).

The SEE tolerance of two shift registers, with 256 stages and 8 inverters between each chain, is shown in Figure 9. The blue bars correspond to the shift registers designed using the conventional digital cells provided by the foundry. The red bars represent the radiation hardened digital cells designed by SMDH. It should be mentioned that radiation hardened cells designed by the Brazilian Design House proved tolerance to SEE with X-rays events of severity R1 and R2 (Noval et al., 2016). In relation to the R3 event, the designed cells reported some errors by SEE (Noval et al., 2016). The number of errors in the shift registers designed using the standard cell library is comparatively larger than the shift registers using rad-hard cell library.

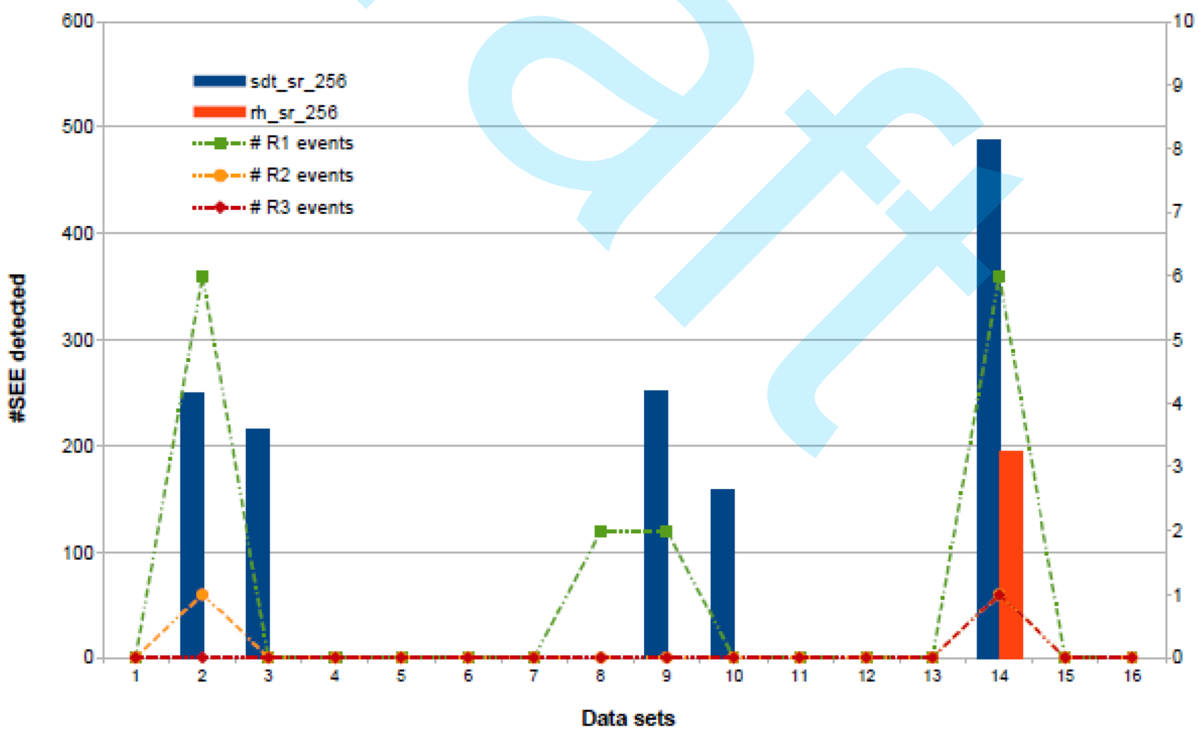

Figure 9: The NANOSATC-BR1 SEE tolerance comparison of two shift registers (256 stages, 8 inverters) (Medeiros et al., 2014; Noval et al., 2016).

Since the rad-hard cells developed by SMDH were able to be properly tested in space environment, successfully withstanding the space radiation during events R1 and R2 in the beginning of September (the first peaks shown in Figure 10), the next step to characterize the cells was to identify when exactly the rad-hard cells started to demonstrate errors and malfunctions during the R3 event. The solar energetic protons detected by GOES-15 satellite during September 2014 were used in order to analyze and quantify the energy levels measured during the specific R3 occurrence which generated cell errors; therefore, the tolerance of the customized cells was properly estimated. This means that, in the higher peak observed in the graph of Figure 10, the cells developed by SMDH were properly tested in a R3 event environment, demonstrating some tolerance to space weather radiation effects. However, some errors and malfunctions started to occur right after such peak, observed on September 12 th. The fluency of Solar Energetic Protons (SEPs) (Medeiros et al., 2014) during September 2014 at different levels of energy is also demonstrated in Figure 11. During the first two weeks of the month, SEPs with energies above 100 MeV were reported.

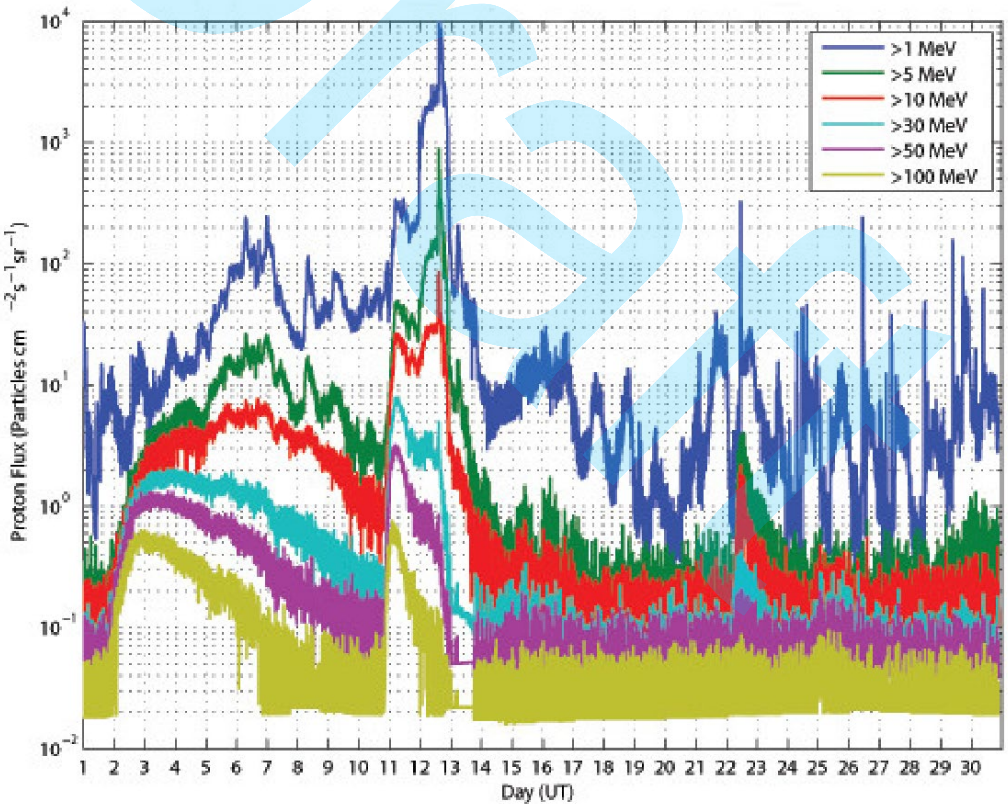

Figure 10: The Solar Energetic Protons - SEPs detected by GOES-15 satellite during September 2014 (Medeiros et al., 2014).

From ten months after launch and since then, the NANOSATC-BR2 have been facing a very challenging situation: it is locked in safe mode, sending the same frame repeatedly. This situation begun when the CubeSat was right on the border of the South Atlantic Magnetic Anomaly, in the same weekend that other small satellites presented malfunctions, indicating a possible radiation effect. One example of this is the JY1Sat that stopped transmitting on the same day that the NANOSATC-BR2 became locked in its current situation. The JY1Sat failure was detected with the support of an amateur radio network, which notified the NANOSATC-BR Program's members about the severe impacts that the space weather's conditions may have caused to small satellites during the beginning of May 2021. The Ground Station at Santa Maria receives the same data after every one minute, indicating that the OBC (On-Board Computer) was probably affected by an intense emission of X-Rays, occurred between late April 2021 and early May 2021. The frozen frames received are illustrated by Figure 11:

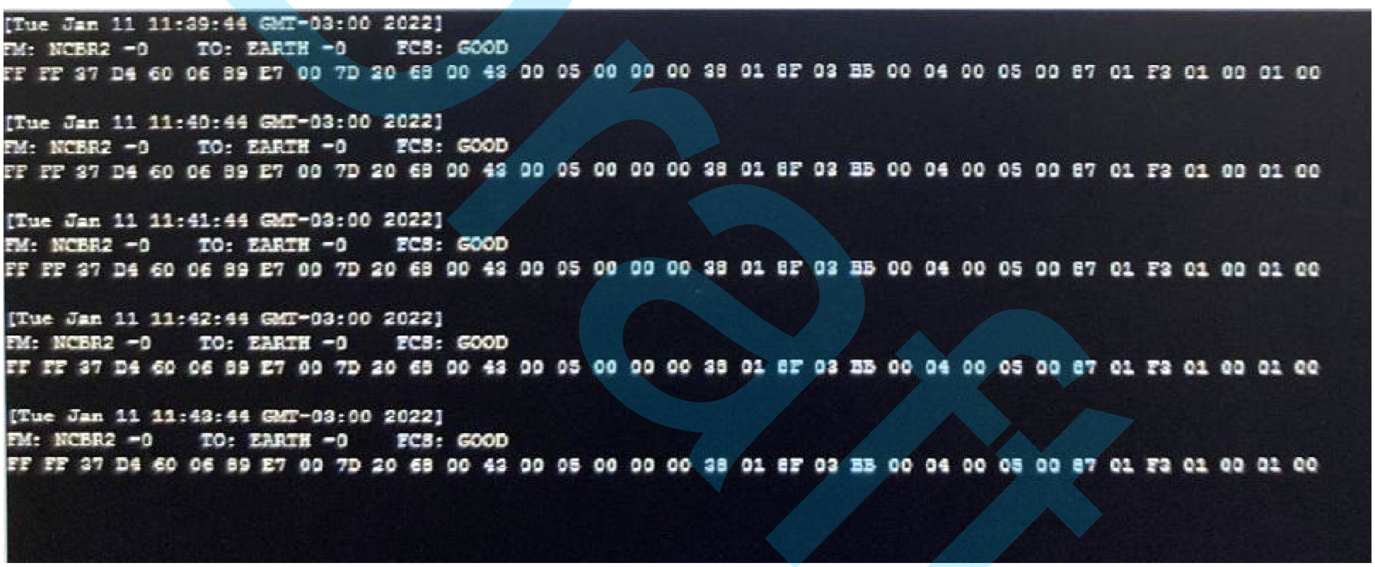

Figure 11: Frozen Frames (5) received on January 11, 2022. The data locked are sent every minute.

Several corrective measures have been taken throughout the last months with the objective of changing this situation, such as debugging the on-board software, sending telecommands for resetting the power cycle of the satellite, engineering model testing in various scenarios, as well as continuous contact with the amateur radio network in order to monitor the satellite's telemetry in different locations worldwide.

Such situation is common in CubeSat-based Science missions using COTS (Commercial off-the-shelf components), since there are not many redundancies designed for space applications in these products. Since the NANOSATC-BR2 passed successfully through all the rigorous tests conducted at LIT, the authors strongly believe that its failure occurred due to severe space weather's conditions. It is also relevant to mention that the study and solution analysis of this problem also contribute to capacity building development, the main objective of the NANOSAT-BR CubeSat program.

NANOSATC-BR Program: Capacity Building through INPE's Ground Station at Santa Maria

The main goal of the INPE-UFSM's NANOSATC-BR CubeSats Development Program is to perform a specialized human resource capacity building program based on the training of UFSM's undergraduate students and professionals, through science, technological and innovation initiation at INPE/MCTI, in the main areas of Engineering, Computer Sciences and Physics. The program also performs the training of INPE's graduate students through master and doctorate programs in Engineering and Technology of Space Systems and in Space Geophysics.

Currently, one of the main tools for accomplishing this task is the INPE's Ground Station at Santa Maria, which contains UHF/VHF antennas for both receiving telemetry and sending telecommands, as well as a S – Band dish antenna for downlink in this specific band. The antennas are positioned on the roof of the building of the Southern Space Coordination of the National Institute for Space Research - MCTI (Figure 12):

Figure 12: VHF and UHF Antennas positioned on the Roof of the building of the Southern Space Coordination of the National Institute for Space Research - MCTI, in Santa Maria, RS.

Students track satellites, control the antennas pointing and perform uplink and downlink communications through several and interrelated software installed in the computers located at the Ground Station Control Room of LITN (Nanosatellites Integration and Testing Laboratory) (Figure 13):

Figure 13: Computers of the Santa Maria Ground Station Control Room (GS), located at the Nanosatellites Integration and Testing Laboratory, integrated at COESU/INPE - MCTI, in Santa Maria, RS.

Initially, students use the Orbitron Freeware, a free tool for obtaining the exact position of a given satellite in space, with the objective of predicting the orbit of a spacecraft and the exact time in which the tracking process will be successful over the city of Santa Maria, RS. The software also provides important information regarding the tracking process, such as the exact Azimuth/Elevation degree values of the passage, the possibility of settling the uplink/downlink frequencies manually, and also simulations for future passages of a specific CubeSat over Santa Maria, RS. The Orbitron interface, showing the NANOSATC-BR2 about to fly over Brazil, is in Figure 14:

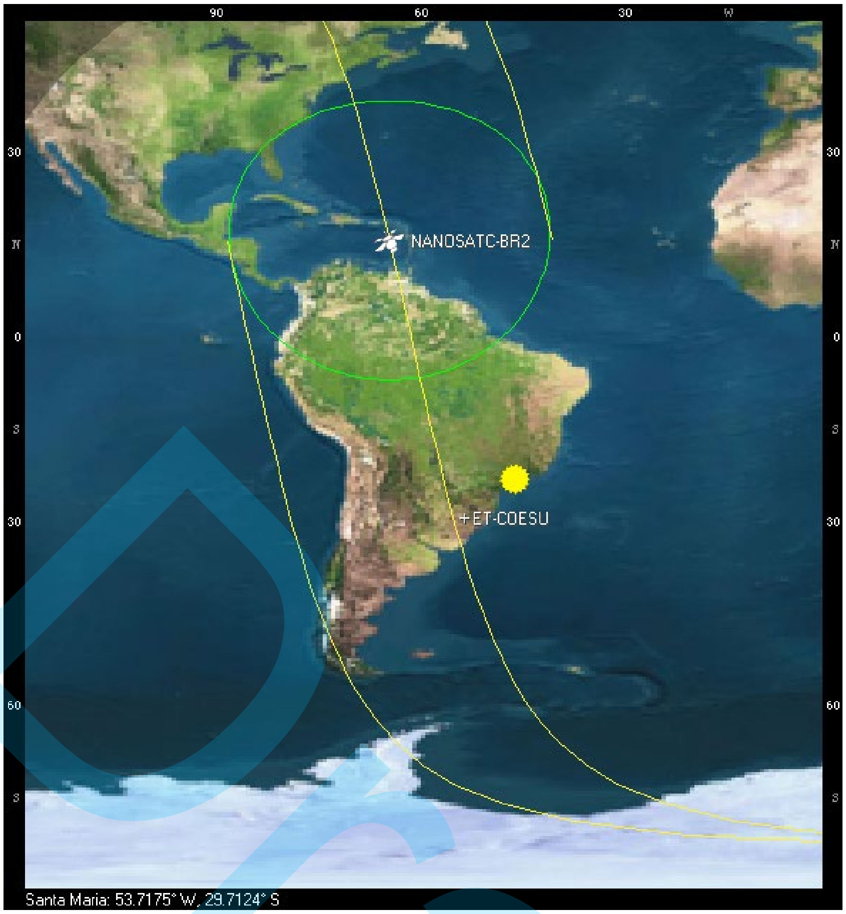

Figure 14: NANOSATC-BR2 CubeSat about to fly over Brazil, as shown in the interface of the Orbitron software.

Once the satellite is correctly tracked and its position can be predicted in real time, the green circle around the spacecraft, also exposed by Figure 14, indicates the area in which the satellite signal can be reached. Then, the Ground Station transceiver unit is settled in the correct uplink/downlink frequencies and modes for both receiving telemetry and sending telecommands, whereas the fine adjustment of the radio is manually performed by rotating the dial knob. A description of the whole process of NANOSATC-BR2's tracking, from the satellite to the mission's stakeholders, is described by a block diagram, represented by Figure 15:

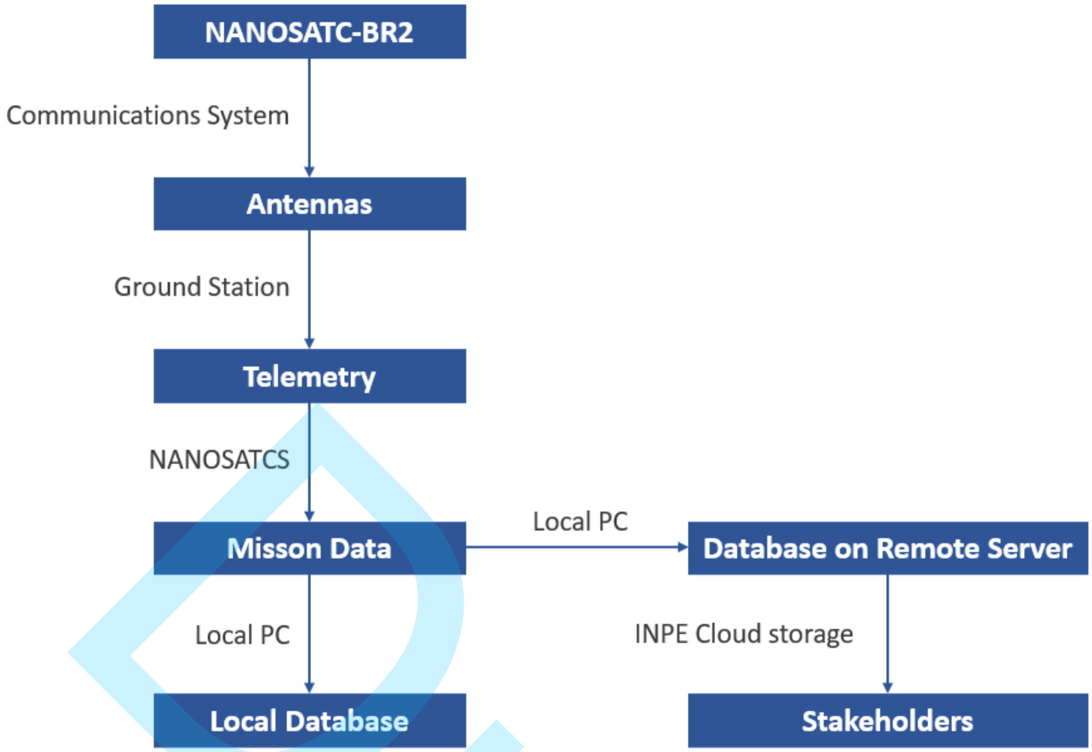

Figure 15: Block Diagram of NANOSATC-BR2's Data Acquisition.

NANOSATC-BR program: support to other CubeSat scientific missions through INPE's Ground Station at Santa Maria and future work

Students have important weight on the Project technical and scientific branches, since their tasks in the tracking process will provide important scientific and technological data for space missions, such as temperature values of CubeSats in space, battery voltage, parameters of magnetometers, etc. The NANOSATC-BR Program has offered support for several CubeSat Missions worldwide since its beginning, being the most recent case, the ITASAT-1 Mission, a 6U CubeSat launched in December 2018 which was successfully tracked by the NANOSATC-BR Program's members throughout its whole mission. In December 2021, the satellite completed three years operating in orbit, with the NANOSATC-BR program members completing the anniversary Flight Plan from this CubeSat in space successfully.

For the near future, it is expected an increase in the number of Brazilian nanosatellites as well as of operators of the INPE's Ground Station at Santa Maria, expanding this way the tracking possibility of space missions. These operators may contribute to improving the tracking operations and perform hardware and software upgrades. An example of a near future development is the tracking and telemetry process automation, which are currently dependent on on-site staff to operate satellites. Future work regarding the tracking of satellites in the S-Band is also expected, increasing this way the number of space missions which the NANOSATC-BR Program will contribute to.

CONCLUSION

Since it provides to young people the possibility of working and contributing to space missions from all around the world, the Brazilian INPE-UFSM NANOSATC-BR CubeSat Development Program proved to be an excellent tool for developing a new generation of Scientists, Engineers and Researchers in Aerospace Technologies in Brazil.

Being exposed to Ground Station's technology, students coming from several Engineering courses (Aerospace, Electrical, Mechanical, among others) are nowadays contributing to the success of scientific space missions.

It is expected an increase in the Brazilian Government Agencies support with more investments for the development of Space Technology and new university initiatives. Examples such as the Brazilian INPE-UFSM NANOSATC-BR, CubeSats Development Program, with its two nanosatellites (the NANOSATC-BR1 & NANOSATC-BR2 Projects) should be taken into account in this sense.

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