Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2019-58
Manuscript under review for journal Ann. Geophys.
Discussion started: 23 May 2019

Annales Geophysicae
Discussions
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The Present & Future of the Brazilian INPE-UFSM NANOSATC-BR, CubeSats Development Program

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Abstract. The Brazilian INPE-UFSM NANOSATC-BR CubeSats Development Program, the related Capacity Building Program (CBP), the results of the NANOSATC-BR1, the first Brazilian CubeSat launched from Russia in June 2014, and the Program's future and present are discussed. The NANOSATC-BR Program consists of two CubeSats, NANOSATC-BR1 (1U) & NANOSATC-BR2 (2U). NANOSATC-BR2 is expected to operate in orbit for at least 12 months, while NANOSATC-BR1 this year has completed more than four years in orbit operation. The CBP is concerned with activities in space science, engineering and computer sciences for the development of space technologies using CubeSats satellites. The INPE-UFSM's CBP has the involvement of UFSM's undergraduate students, graduate students from MG/II/UFRGS, ITA/DCTA/CA-MD, and the participation of INPE's graduate students in the Onboard Data Handling (OBDH) subsystem development, verification and validation for the NANOSATC-BR2. The NANOSATC-BR1 & NANOSATC-BR2 Projects Ground Stations (GS) can operate with VHF/UHF band and S-band antennas. This paper also focuses on the future development of NANOSATC-BR3 & NANOSATC-BR4, in a partnership with the UFSM's Aerospace Engineering Course and on the launching of NANOSATC-BR2. The Program's concepts were developed (i) monitor the Geospace in real time and determine the effects concerning the very close environment (by measuring the Earth's Magnetic field, the Ionosphere, and the energetic particle precipitation) and (ii) study the disturbances at the Earth's Magnetosphere-ionosphere system over the Brazilian Territory. The Program has received financial support from the Brazilian Space Agency (AEB) and the Ministry of Science, Technology, Innovation and Communications (MCTIC).

1 Introduction

The NANOSATC-BR, CubeSats Development Program, consists of a Brazilian INPE-UFSM Capacity Building Program on space science, engineering and computer sciences for the development of space technologies based in the CubeSats standard, which started with the first Brazilian Scientific Nanosatellite: the NANOSATC-BR1. The Capacity Building Program was conceived at the Southern Regional Space Research Center (CRS), from the Brazilian National Institute for Space Research -

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INPE/MCTIC, where acts the Program's General Coordinator and Manager, with technical collaboration and management of the Mission's General Coordinator for Engineering and Space Technology at INPE's Headquarter (HQ), in São José dos Campos, São Paulo. The Program has the involvement of undergraduate students from the Federal University of Santa Maria – UFSM and graduate students from INPE/MCTIC, ITA/DCTA/CA-MD and UFRGS.

This article explains the Program institutional arrangement and the technical characteristics of the satellites and their missions. The Program has support from the Brazilian Space Agency (AEB) and the Ministry of Science, Technology, Innovation and Communications (MCTIC).

1.1 The Brazilian NANOSATC-BR Team

The NANOSATC-BR Team, has the contribution from seventy five persons from several Brazilian Institutions such as: INPE/MCTIC, UFSM, SMDH, UFRGS, UFABC, UFMG, EMSISTI, ITA/DCTA-MD.

It is the NANOSATC-BR, Cubesats Development Program policy, not to delete any name of person who is participating or did collaborate, directly or indirectly, with its Projects and even after someone left the Program.

The work is composed by the efforts of:

1 - Nelson Jorge Schuch, 2 - Otávio Santos Cupertino Durão, 3 - Alexandre Álvares Pimenta, 4 - Polinaya Muralikrishna, 5 - Adriano Petry, 6 - Marlos Rockenbach da Silva, 7 - José Valentin Bageston, 8 - Odim Mendes Jr, 8 - Nalin Babulau Trivedi, 9 - Severino Luiz Guimarães Dutra, 10 - Alisson Dal Lago, 11 - Clezio Marcos Denardini, 12 - Ezequiel Echer, 13 - Luis Eduardo Antunes Viera, 14 - Geilson Loureiro, 15 - Maria de Fátima Mattiello Francisco, 16 - Mario Celso de Almeida, 17 - Valdemir Carrara, 18 - José Sergio de Almeida, 19 - Helio Kuga, 20 - Rafael Lopes Costa, 21 - Lucas Lopes Costa, 22 - Natanael Rodrigues Gomes, 23 - Renato Machado, 24 - Andrei Piccinini Legg, 25 - João Baptista dos Santos Mar-tins, 26 - Ricardo Reis, 27 - Fernanda Gusmão de Lima Kastensmidt, 28 - Rubens Zolar Gehlen Bohrer, 29 - Eduardo Escobar Bürger, 30 - Cassio Espindola Antunes, 31 - Tardelli Ronan Coelho Stekel, 32 - Carlos Roberto Braga, 33 - Juliano Moro, 34 - William do Nascimento Guareschi, 35 - Claudio Machado Paulo, 36 - Fernando Landerdahl Alves, 37 - Lucas Lourencena Caldas Franke, 38 - Mauricio Ricardo Balestrin, 39 - Guilherme Paul Jaenisch, 40 - Iago Camargo da Silveira, 41 - Rodrigo Passo Marques, 42 - Tális Piovesan, 43 - Jose Paulo Marchezi, 44 - Tiago Bremm, 45 - Vinicius Deggeroni, 46 - Leonardo Zavareze da Costa, 47 - Pietro Fernando Moro, 48 - Thales Ramos Mânica, 49 - Anderson Vestena Bili-bio, 50 - Andreos Vestena Bilibio, 51 - Tiago Travi Farias, 52 - Marcos Antonio Laurindo Dal Piaz, 53 - Lauro Barbosa Alves, 54 - Pablo Ilha Vaz, 55 - Elói Fonseca, 56 - Lidia Hissae Shibuya Sato, 57 - Mar-celo Henrique Essado de Morais, 58 - Cristiano Strieder, 59 - Fernando Sobroza Pedroso, 60 - Alex Mül-ler, 61 - Artur Gustavo Slongo, 62 - Lorenzzo Quevedo Mantovani, 63 - Alan Pitthan Couto; 64 - Pedro Camargo Kemmerich; 65 - Mauricio Beux Dos Santos, 66 - Ricardo Duarte, 67 - Luiz Siqueira Filho, 68 - Gabriel Henrique da Rosa Vizcarra, 69 - André Luís da Silva, 70 - Danilo Almeida, 71 - Lázaro Camargo, 72 - Sinval Domingos, 74 - Andres Horna, 75 - Wendell Silva.

2 NANOSATC-BR: Capacity Building

The principal objective of the INPE-UFSM's NANOSATC-BR, CubeSats Development Program, through the NANOSATC-BR1 & NANOSATC-BR2 CubeSats Projects, is to perform a Specialized Human Resource Capacity Building Program through the training of UFSM's undergraduate students, through Science, Technological & Innovation Initiation at INPE/MCTIC, in the main areas of Engineering, Computer Sciences and Physics.

Students have a significant weight on the Project's technical and scientific branches, since their tasks provide results for each subsystem. The results are consequence of their hard work developed in conjunction with the UFSM's and INPE's specialists (Engineers, Technologists and Researchers), which are the primary providers of information.

The brand new Laboratory of Integration and Tests of Nanosatellites (LITN), established at CRS/COCRE/INPE-MCTIC at the end of 2017, provides a unique environment for students to perform hands-on training, by the usage of the Engineering Model of the first satellite of the Program: the NANOSATC-BR1 (or NCBR1). LITN provides to students the adequate tools to perform basic Assembly and Integration operations on a CubeSat Platform, as well as necessary Tests, that is, ATT - Assembly, Integration and Tests, with the equipment from the Ground Station (GS), which is now fully integrated to the LITN workbench (Figure 1).

Figure 1: The Santa Maria Ground Station Control Room (GS) & the Laboratory of Integration and Tests of Nanosatellites (LITN), integrated at the CRS/COCRE/INPE–MCTIC, in Santa Maria, RS.

Students from the new Aerospace Engineering and others Engineering courses at the Federal University of Santa Maria (UFSM) can now use instruments, such as calipers (Figure 2) and micrometers (Figure 3), at LITN, to evaluate correctly mechanical and mass properties of satellite components.

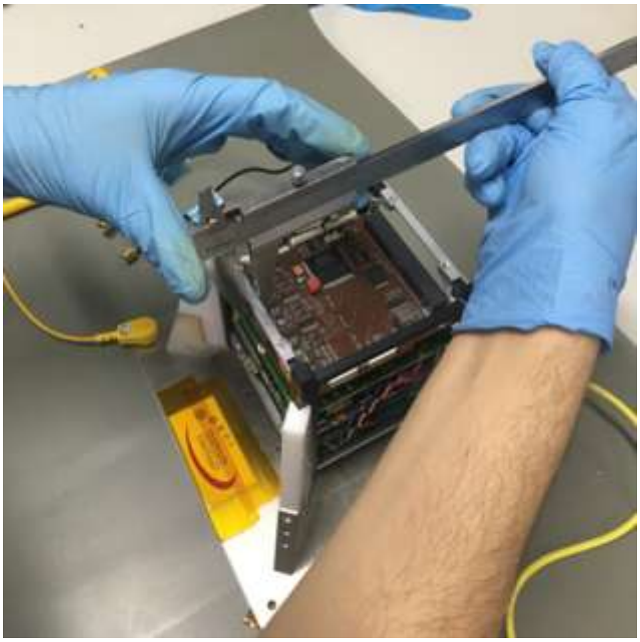

Figure 2: Aerospace and others Engineering Student at LITN using a caliper to perform measurements in a CubeSat.

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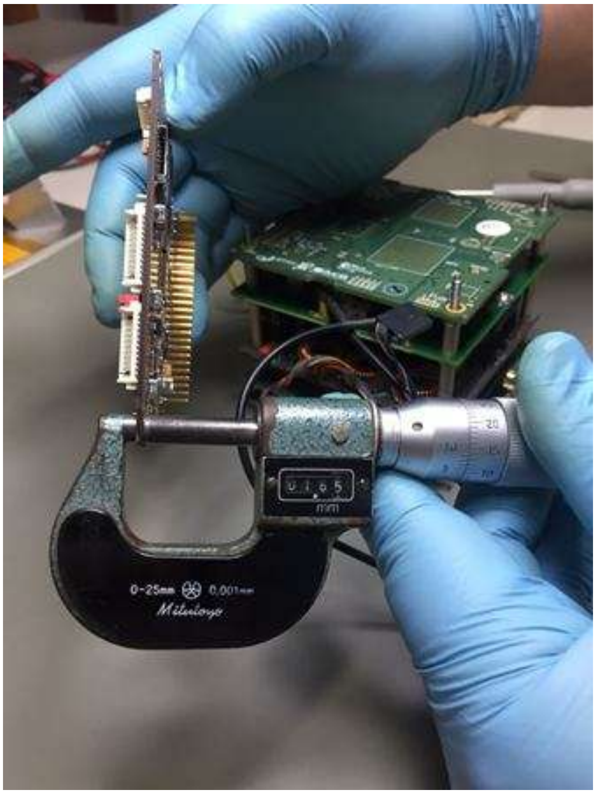

Figure 3: Electrical Engineering Student at LITN using a micrometer to evaluate the thickness of a PCB.

Through the NANOSATC-BR Program, it was possible to approximate the Brazilian Space Program to Universities, such as UFSM, UFRGS, UFRN, UFABC, UFMG and USP. Therefore, the Program provides hands-on training and learning with Aerospace Engineering & Technologies and Space Weather issues.

Students also had the opportunity to perform further training at universities and space industries abroad: TU - Berlin, University of Wurzburg and DLR in Bremen in Germany; Innovative Solutions In Space - ISIS - Delft in The Netherlands; La Sapienza – Università Degli Studi di Roma, TU- Roma, in Italy; University at Buffalo, University of Tennessee and NASA - Goddard Space Flight Center in the USA. Funding came from several institutions, such as the CubeSat Dutch company Innovative Solutions in Space (ISIS), the Van Allen Project-NASA, the Brazilian Space Agency (AEB) and the Brazilian Program Science without Borders – SwB.

2.1 NANOSATC-BR Missions

The Program already consists of two CubeSats, the NANOSATC-BR1 and NANOSATC-BR2 (Figure 4) and has the possibility of launching three other CubeSats in the next five years, operating them in space for at least six months each. These new missions aim to study and monitor the Geospace and Space Weather.

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The NANOSATC-BR1 concept was developed to (i) monitor, in real time, the Geospace, the disturbances at the Earth's Magnetosphere-ionosphere system over the Brazilian Territory, and (ii) contributes to the determination of their effects on regions such as the South America Magnetic Anomaly (SAMA). Its payloads are:

- A XEN-1210 three-axis magnetometer with a resolution of 15nT from the Dutch company XI - Xensor Integration (www.xensor.nl);
- One board has the XEN-1210 magnetometer, which is the scientific payload. It is responsible for measuring the perturbations associated with the SAMA.

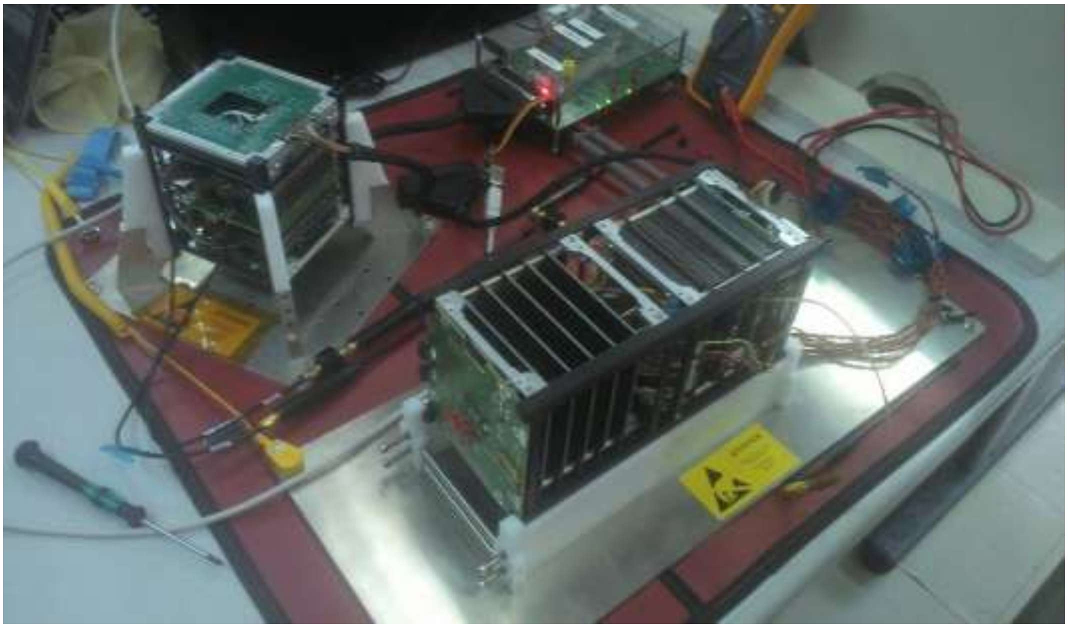

Figure 4: The NANOSATC-BR1 and NANOSATC-BR2 Engineering Model Platforms.

The NANOSATC-BR1 Technological Mission carries a FPGA (Guareschi et al. 2010) and one integrated circuit (IC) designed by the Santa Maria Design House (SMDH), together with the Graduate Program in Microelectronics from UFRGS the Federal University of Rio Grande do Sul (UFRGS), that were developed for space use due to their radiation resistance. The two technological payloads then use two different techniques for fault tolerance due to radiation in space: design (IC) and embedded (software) FPGA. These were the first circuits designed in Brazil for space applications.

2.2 NANOSATC-BR1: Current Situation

The NANOSATC-BR1, is a 10x10x11.3 cm cube, weighing 0.965 kg. Its name and up and down frequencies link were determined by The International Amateur Radio Union – IARU, in 2011.

The NANOSATC-BR1's Engineering Model Platform (EM), the Flight Model Platform (FM), the Ground Support Equipment and the Ground Station for the INPE-UFSM's NANOSATC-BR1 mission and equipment were provided,

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integrated and pre-tested by the ISIS company from Delft, The Netherlands, except for the integration of the flight model done at the INPE/MCTIC's Integration and Testing Laboratory (LIT). The full Assembly, Integration and Tests (AIT) of the complete CubeSat (platform and payload) were also done at LIT with support of NANOSATC-BR Program master students. The NANOSATC-BR's Ground Station Network (GS) is already installed and in operation: GS(INPE-CRS), at CRS/COCRE/INPE-MCTIC, Santa Maria, RS, and GS(INPE-ITA) at ITA/DCTA-MD, in São José dos Campos, SP, in Brazil (Figure 5).

The NANOSATC-BR1 was launched as a tertiary payload by ISIS in the event ISILAUNCH 07, by a DNEPR launcher, at The Yasny Launching Base, in The Donbarovsky Region, Russia, on June 19th, 2014 – Launch time (T): 19:11:11 UTC - Local time at Yasny: 01:11.

The NANOSATC-BR1 already completed more than four years and a half in orbit sending payloads and subsystems data. All payloads and subsystems, except the batteries in the power subsystem, continue to operate normally. The battery can no longer hold a charge because a probable damage caused by intense magnetic solar storms in September-October 2014. After that the operation had to save energy on board with different commands from ground, such as to enlarge the time interval between the beacon transmissions and to turn off periodically one or two of the payloads. This strategy gave another year and a half operating with these conditions through the use of INPE and a partnership with other amateur radio stations to get onboard telemetry files, besides the beacon. In the last year though, the batteries can no longer hold the minimum voltage to avoid swiching the CubeSat to the safe mode. However, the NANOSATC-BR1 can still transmit when it is in Sun sight. Weekly Mr. Reiner Rothe, a German amateur radio and Mr. Paulo Leite (PV8DX), an amateur radio from Boa Vista, RR, Brazil, are performing the NANOSATC-BR1 tracking downloading telemetry data and sending systematically these files to the Program's data base, at INPE, in São José dos Campos, SP, in Brazil.

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Figure 5: The NANOSATC-BR's Ground Station Network (GS) was installed and is in operations: on the left - The GS(INPE-CRS) at CRS/COCRE/INPE-MCTIC, in Santa Maria, RS, and on the right - The GS(INPE-ITA) at ITA/DCTA-MD, in São José dos Campos, SP, in Brazil.

2.3 The Nanosatc-BR1Technological Payload - The SMDH-IC Results

The Santa Maria Design House (SMDH), dealing with design techniques and its in-house development software library, has designed Integrated Circuits (IC) for space application regarding Total Ionization Dose (TID): instantaneous radiation dose effects denominated Single Event Effects (SEE) and Displacement Damage (DD). An Application Specific Integrated Circuit (ASIC) was developed for 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.

The SEE tolerance of two shift-registers, with 256 stages and 8 inverters between each chain, is shown in Figure 6. The blue bar corresponds to the shift registers designed using the conventional digital cells provided by the foundry. On the other hand, the red bars represent the radiation hardened digital cells de-signed by SMDH. It is remarkable to mention that radiation hardened cells designed by SMDH proved tolerance to SEE with X-rays events of severity R1 and R2 (Medeiros et al. 2014; Noval et al. 2016) - Minor and Moderate Radio Blackouts, respectively. Concerning the R3 event (Medeiros et al. 2014; Noval et al. 2016) - Strong Radio Blackout, the designed cells reported some errors by SEE. The amount of errors in the shift-registers designed using the standard cell library is comparatively larger than the others shift registers using a rad-hard cell library.

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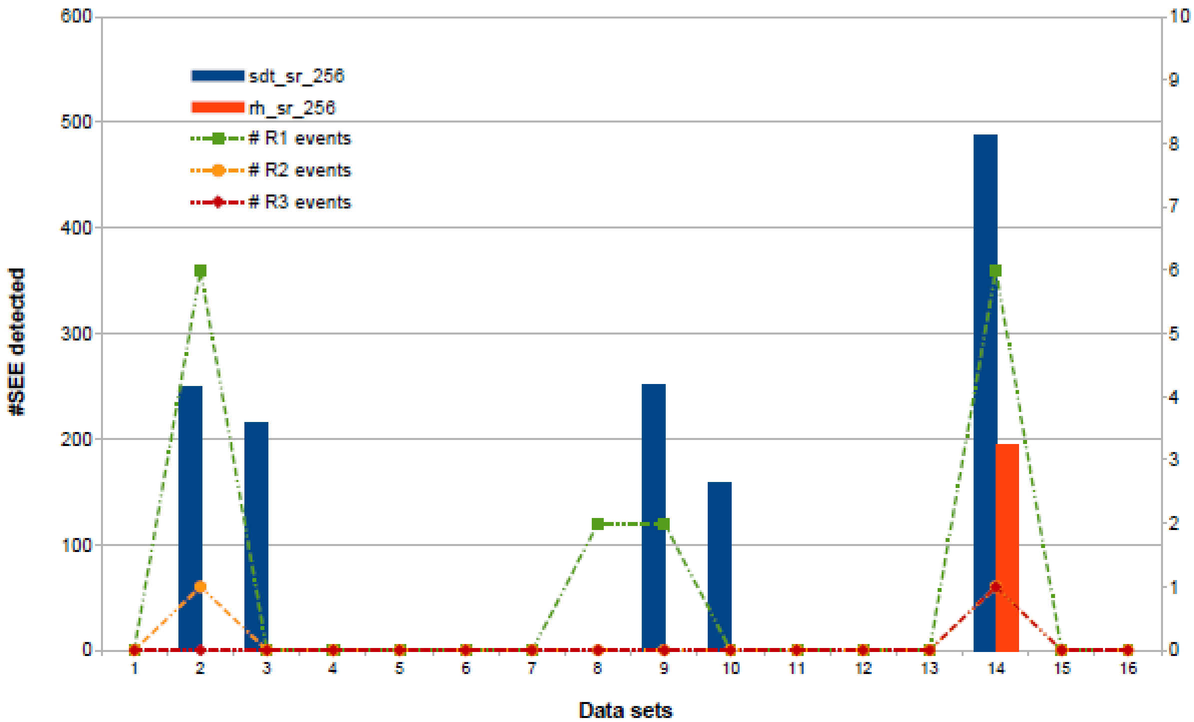

Figure 6: The NANOSATC-BR1 SEE tolerance comparison of two shift-registers (256 stages, 8 inverters) (Medeiros et al. 2014; Noval et al. 2016).

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 R3 occurrence and thus estimate the tolerance of customized cells. The fluency of Solar Energetic Protons – SEPs (Medeiros et al. 2014; Noval et al. 2016) during September 2014 at different levels of energy is shown in Figure 7. During the first two weeks were reported SEPs with energies above 100 MeV.

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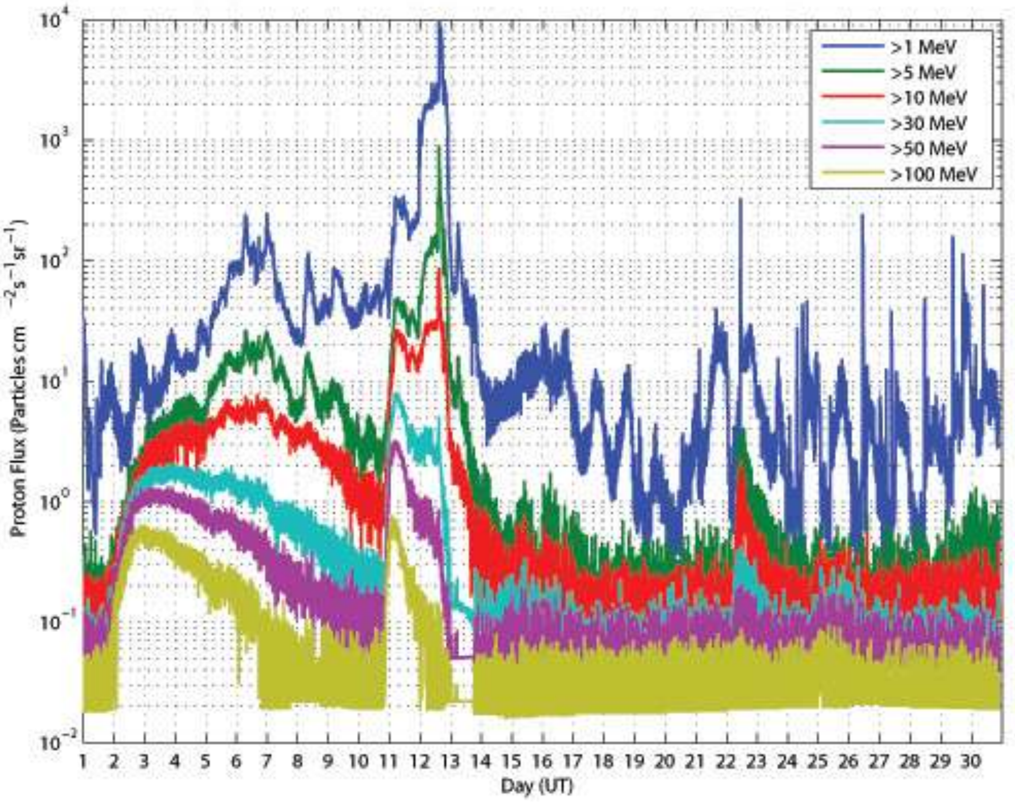

Figure 7: The Solar Energetic Protons - SEPs detected by GOES-15 satellite during September 2014 (Medeiros et al. 2014; Noval et al. 2016).

2.4 The FPGA Results

A second technological experiment was a fault tolerant software developed by the Federal University of Rio Grande do Sul - UFRGS, through its Informatics Laboratory, in order to provide radiation resistance to an FPGA. The FPGA used was a ProASIC3E with an SEL effective threshold of 68 MeV cm^2/mg. The results obtained with this FPGA in NANOSATC-BR1 were not conclusive. A more radiation sensitive FPGA with a larger area for the bit-flip sensor will be used in the following CubSat of the Program, the NANOSATC-BR2 (see below).

2.5 The Geomagnetic Field Intensity Results Detected by the NANOSATC-BR1 Mission Payload

The NANOSATC-BR1 data were collected by the Scientific Mission Payload, which is 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) in the same altitude. A map of the total intensity of

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the Geomagnetic field for an altitude at 614 km over South America, in the domain of the SAMA (Heirtzler, 2002), is presented in Figure 8. The spatial variation of the total intensity of the Geomagnetic field varies between 24000 nT and 17000 nT at the center of the SAMA, signalized by a black star in Figure 8. The Nanosatellite Earth Tracking and Control Station, GS(INPE-CRS), in Santa Maria - RS, is lying near the center of SAMA. The red line in Figure 5 indicates the approximate orbit of the NANOSATC-BR1 on August 17, 2014, from 10:57h to 11:07h. During this period, the NANOSATC-BR1 moved from the South Pole towards the geographic North Pole.

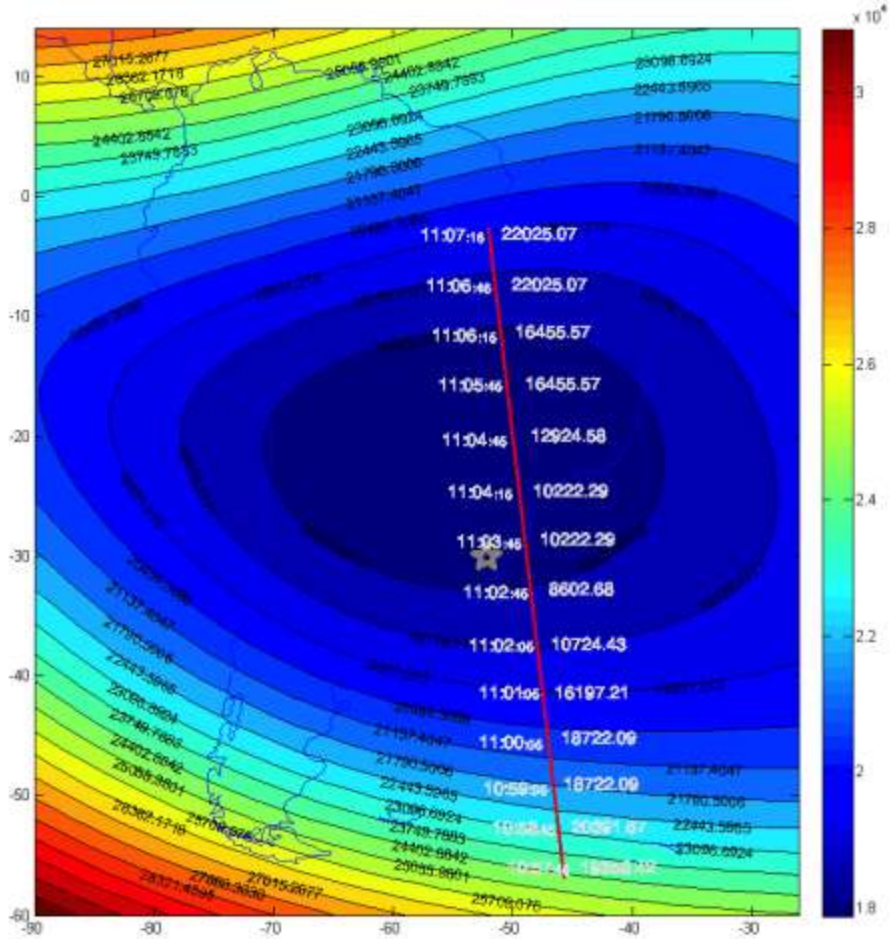

Figure 8: SAMA Geomagnetic Field total Intensity modeled by the IGRF – 10 and NANOSATC-BR1 Scientific mission payload measurements at 614 km altitude in 2014 for the Geomagnetic Field. The gray star indicates the location of the Tracking and Control Station, GS(INPE-CRS), in Santa Maria - RS, which located near the center of the SAMA.

2.6 NANOSATC-BR2 – current situation

Since the NANOSATC-BR2 is a 2U CubeSat, (10x10x22.6 cm), it permits a more ambitious mission than its predecessor, the NANOSATC-BR1, with three major objectives: academic and capacity building, scientific mission and technological

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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 the precise location with services such as the GPS. The payload equipment for the scientific mission will be a Langmuir probe and a XEN-1210 magnetic field sensor based on the Hall effect. The Langmuir probe is ordinarily available in a larger size; however, it has been miniaturized for a small satellite mission.

In order to finalize the NANOSATC-BR2, which is now also known by the acronym NCBR2, its platform was developed to satisfy the payload equipment's requirements. The onboard data handling (OBDH) software is a key element for payload integration in NANOSAC-BR2. It is a software developed at INPE by graduate students of the Space System Engineering Course (INPE/CSE) in collaboration with emergent companies also led by INPE´s former students. A short Verification and Validation (V&V) process was defined, addressing the interoperability and robustness issues on the interactions among the OBDH and the mission payloads (Conceição, et al. 2016.) Model-based Testing approaches support the integration testing of the communicating software-intensive systems with the use of a fault-Injection mechanism for robustness verification purposes (Pallamin, D. A. and Mattiello-Francisco, F. 2017), (Batista et al. 2018).

The NANOSATC-BR2 also has the first satellite attitude determination subsystem, fully developed in Brazil, from software to hardware, as one of its experiments. It has triple redundancy using three micro-processors with one in hot standby. It is a joint project led by the UFMG with UFABC and INPE. The NANOSAC-BR2 CubeSat will also carry two other technologic experiments as version two of those that are flying in NANOSAC-BR1. It also carries an amateur radio communication experiment from Amateur Radio in Space - Brazil (AMSAT-Br) and Brazilian Amateur Radio Broadcasting League (LABRE). The experiments are:

- SDATF - Attitude Determination System Tolerant to Failure - First Brazilian System Attitude Determination, with triple redundancy, manufactured in CubeSats standards and with its own attitude determination algorithm, using the solar sensor platform and a magnetometer made in cooperation by INPE/MCTIC with UFMG (Electronics Engineering) and UFABC (Aerospace Engineering); presently in integration and testing with the NANOSATC-BR2 EM platform;

- Langmuir Probe - Delivered for testing and integration with the NANOSATC-BR2 EM platform and the onboard software - OBDH;

- Communication Experiment Packet (store forward) - AMSAT-BR and SP-LABRE.

- CubeSat board with three experiments: FPGA - UFRGS; Magnetometer; IC - SMDH/UFSM, first unit scheduled for delivery up to May 2019.

All of those payloads are being integrated and tested with the OBDH software in the Engineering Model (EM), except the version two of the board flying in NANOSAC-BR1, during the final of the integration phase.

The entire platform flight software was developed in Brazil, by researchers and engineers from INPE/MCTIC, taking advantage of the experience of NANOSATC-BR1. The technical people also have the support from students graduated at INPE/MCTIC on the course of the Space System Engineering (CSE), undergraduate and graduate students and third parties

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startup company created by former INPE/MCTIC graduate students. The Control Law for the control software has also been developed in house.

The Project has already received the budget from AEB for contracting the launch and future operation of NANOSATC-BR2 in orbit. The NANOSATC-BR2 is planned to be launched in the fourth term of 2019. Likewise NANOSATC-BR1 and other CubeSats projects, the NANOSATC-BR2 will be launched in a piggyback launch, as a tertiary payload. The launch opportunities, as well as the Launch Vehicle, are under discussion.

2.7 NANOSATC-BR3 & NANOSATC-BR4 – current situation and planning the future

The Engineering Models of both NANOSATC-BR1 and NANOSATC-BR2 are intended to become, soon, the next CubeSats for the NANOSATC-BR Program: NANOSATC-BR3 & NANOSATC-BR4. Therefore, it will be possible to plan the following scientific experiments and build the next payloads based on the experience obtained with previous missions.

The NANOSATC-BR1 Engineering Model is currently based on the Laboratory of Integration and Tests for Nanosatellites – LITN. It stimulates students from the new Aerospace Engineering and related courses from the Federal University of Santa Maria (UFSM) to learn Assembly, Integration and Tests (A.I.&T) techniques and to obtain practical experience with necessary tools for the daily life of a professional. In order to effectively make the Engineering Model platform to become a Flight Model, it is necessary several adjustments such as to build solar panels and develop the payloads boards and components for future missions. This whole process will start right after the launch of the NANOSATC-BR2, expected to occur during 2019.

As well as the NANOSATC-BR1 Engineering Model, the NANOSATC-BR2 Engineering Model will be used to become one of the future CubeSats of the Program, the NANOSATC-BR4. It is currently being tested and used by Software Engineers from INPE, in São José dos Campos – SP, being represented by Figure 9.

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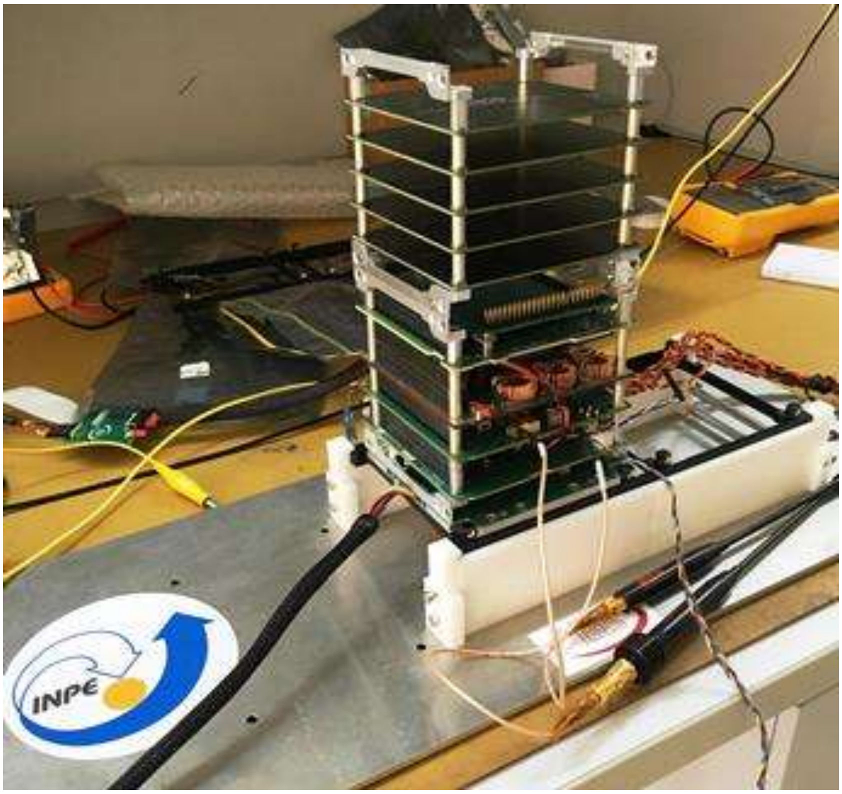

Figure 9: NANOSATC-BR2 Engineering Model being tested at INPE's headquarters in São José dos Campos, SP.

Both payloads and scientific missions will be discussed with Doctors, Researchers and Engineers from INPE's Team, UFSM and other Brazilian Universities. The future missions from the NANOSATC-BR Program represent the continuity of the Project and the beginning of other Aerospace Programs in the south of Brazil for the next decade.

Conclusions

Since it provides to young people contact with low cost and fast development on Space Technology, the Brazilian: INPE-UFSM, NANOSATC-BR, CubeSats Development Program, proved to be an excellent tool for developing a new generation of Scientists, Engineers and Researchers in Aerospace Technologies in Brazil.

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 models (the NANOSATC-BR1 & NANOSATC-BR2 Projects) should be taken into account in this sense.

Acknowledgments

The authors thank the Brazilian Space Agency - AEB, SEXEC/MCTIC, COCRE/INPE-MCTIC, UFSM-FATEC and to USP's LSITEC Association for the support, opportunity and grants for the Brazilian INPE-UFSM NANOSATC-BR, CubeSats Development Program, with its CubeSats: the NANOSATC-BR1 & the NANOSATC-BR2 Projects.

The authors thank Dr. Juliano Moro and Fernando Sobroza Pedroso for collaboration, to Santa Maria Design House - SMDH/FATEC, to Professors Dr. Ricardo Reis and Dr. Fernanda G. L. Kastensmidt from the Graduate Program in Microelectronics, Informatics Institute from UFRGS, to UFABC (Eng. Aeroespacial - Dr. Luiz Siqueira Filho), UFMG. (Eng. Eletrônica - Dr. Ricardo Duarte), the CITAR-FINEP Project, and to MCTIC-CNPq/INPE(PCI-PIBIC-PIBIT) and FAPERGS Programs for fellowships.

The authors thank and acknowledge to Eng. Abe Bonnema and the ISIS's Board of Directors for the grant, tutorial and logistics support at Delft, Yasny and Brazil for the Brazilian students and for the NANOSATC-BR, CubeSats Development Program.

The Program and NANOSATC-BR1 Project thank to Mr Reiner Rothe, radio amateur from Germany and to Mr Paulo Leite (PV8DX), radio amateur from Boa Vista, RR, Brazil, for tracking, downloading and sending systematically these data to the Program's data base, at INPE, in São José dos Campos, in Brazil.

Drs Nelson Jorge Schuch, Marlos Rockenbach da Silva and Odim Mendes thank CNPq for the fellowships under the numbers 300886/2016-0, 301495/2015-7 and 307083/2017-9, respectively.

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