The Scintillation Prediction Observations Research Task (SPORT): A Spacecraft Development for an International Mission

Luís Eduardo Vergueiro Loures da Costa, Lidia Hissae Shibuya Sato, Mangalathayil Ali Abdu, Valdemir Carrara, Pedro Albuquerque, Hélio Santos, Linélcio Santos, Emerson Oliveira, Denis Guilgim, Ana Carolina Jeronymo, Jonas Bianchini, Jessica Azevedo, Breno Crucioli
Instituto Tecnológico de Aeronáutica
Praça Marechal Eduardo Gomes, 50 - Vila das Acácias, São José dos Campos - SP, 12228-900; +55 (12) 3947-6989
loures@ita.br

James Spann, Linda Krause, Shelia Nash-Stevenson, Eric Eberly
NASA Marshall Space Flight Center
320 Sparkman Drive, Huntsville, AL 35805; +1 (256) 544-8477
jim.spann@nasa.gov

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

Otavio Durão, Clezio Denardin, Joaquim Costa
Instituto Nacional de Pesquisas Espaciais
Av. dos Astronautas, 1.758 - Jardim da Granja, São José dos Campos - SP, 12227-010; +55 (12) 3208-6933
otavio.durão@inpe.br

Rod Heelis
University of Texas at Dallas
800 W Campbell Rd, Richardson, TX 75080; +1 (972) 883-2111
heelis@utdallas.edu

Rebecca Bishop
The Aerospace Corporation
El Segundo, California, EUA; +1 (310)-336-1750
rebecca.l.bishop@aero.org

Guan Le
NASA Goddard Space Flight Center
Greenbelt, MD 20771, Building 21, Room 256; +1 (301) 286-1087
guan.le@nasa.gov

ABSTRACT

The SPORT project is an international collaborative space mission among institutes in Brazil and United States to explore the space weather, more specifically to provide to the scientific community that studies the ionosphere more data that can aid to improve their understanding about the conditions that leads to scintillations. The purpose of this paper is to present the efforts of the Brazilian team at the *Instituto Tecnológico de Aeronáutica* (ITA) to develop the spacecraft considering the aspects of this international mission. The paper is divided into the introduction and explanation of the SPORT mission that includes the description of the SPORT Observatory. This paper also presents briefly the Spacecraft System Engineering process adopted by ITA development team and ends with the spacecraft description and observatory expected results.

INTRODUCTION

In 2015 an approximation of Brazilian and American organizations resulted in an intention of developing an international mission in the field of space weather. Is part of this partnership, from USA, NASA Marshall Space Flight Center, NASA Goddard Space Flight Center, Utah State University, University of Texas at Dallas and Aerospace Corporation, supported by U.S. Southern Command. From Brazil the Brazilian National Institute for Space Research (INPE) and the Technical

Institute of Aeronautics under the Brazilian Air Force Command Department (DCTA/ITA). The mission of this international partnership is to address the compelling but difficult problem of understanding the preconditions leading to equatorial plasma bubbles that leads to scintillation and affects directly some services provided on Earth, communications and navigation, for instance. This mission is called Scintillation Prediction Observation Research Task (SPORT) [1]. The SPORT mission will be accomplished by a 6U CubeSat where the payloads will be provided by the USA partners, whilst the Spacecraft and the Ground Segment and Operations by the Brazilian side. The Spacecraft is under development by the Technical Institute of Aeronautics (ITA) and the Ground Segment and Operations is being prepared by INPE. The science results will be shared to the scientific community of both countries through an existing portal of EMBRACE/INPE ("*Estudo e Monitoramento do Clima Espacial*"). In the next section is presented an overview of the SPORT Observatory and it is given a focus on the SPORT Spacecraft, the development strategy and Spacecraft architecture to accomplish the payloads requirements and to be in accordance with the existing Ground Segment from INPE. In the next section it will be presented how system engineering has been applied in the spacecraft development considering the particularities of an international mission and the challenges to define a resilient spacecraft architecture by explaining the spacecraft model philosophy and architecture intended to be used.

THE SPORT MISSION

The weather forecast is important because it helps everyone, every day. It aids farmers to plan and schedule the crops, it helps governments and countries to develop strategic measurements to have previsions for water volume, floods, hurricanes, etc. Weather forecast helps everyone to decide what to wear on day-by-day. So, weather forecast is well known by everyone. What people usually don't know is that there is another weather forecast that is as well important, the space weather. In the context of this paper, the following definition of Space Weather [2] is used:

"*Space weather encompasses the conditions and processes occurring in space, which have the potential to affect the near-Earth environment and/or the human being or the current technological assets*".

Expenses over trillion U.S dollars can result from severe geomagnetic storms as presented in the report Severe space weather events – Understanding societal and economic impacts: A workshop report, December 2008" [3] issued by the Space Studies Board of the U.S. National Academies that addressed the impacts of space weather events on human technologies. Such a scenario would result from a storm of the magnitude of one that occurred in September 1859 [4].

In the last decades several international projects have been proposed to improve space weather research and to develop space weather forecast around the world, for instance [5], but a limitation of the collected data from the existing and previous missions is mostly caused due to the lack of repeatable observations over altitude regions to encounter plasma structures that penetrate the F peak.

The SPORT proposal is to fly a set of instruments on a 6U CubeSat to measure the in-situ total plasma density, the bulk plasma drift, the L-band Fresnel scale, coupled with spectrometers to observe smaller scales. SPORT will also fly a GPS occultation receiver to provide spatially distributed height profiles of the plasma number density to specify the magnitude and height of the F peak density. These data, gathered from a CubeSat in a mid-inclination circular orbit near 400 km altitude, coupled with ground observations, will be used cumulatively to specify the state of the ionosphere and individually to detect the presence of ionospheric structure and to infer the presence of scintillation. The SPORT science and its payload are described in [1].

The management of the SPORT mission has strong leadership in key positions, clarity of the roles and division of responsibilities, and clean simple interfaces between institutions, as shown in Figure 1.

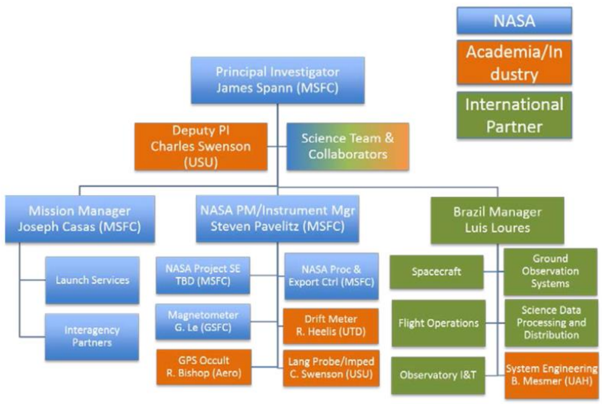

Figure 1: SPORT Responsibility Chart

SPORT OBSERVATORY

The SPORT observatory is the set of integrated onboard equipments and scientific instruments of the CubeSat. The observatory was divided into Spacecraft and Payload, as shown in Figure 2, that also includes the Ground Support Equipments (GSE) that are necessary.

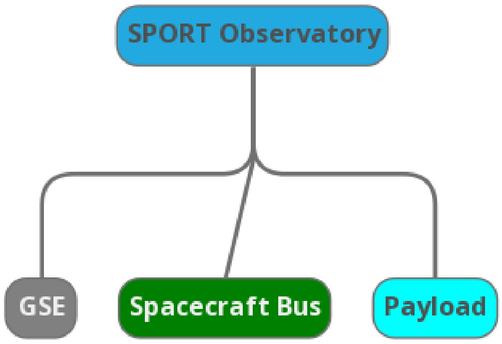

Figure 2: SPORT Tree

The integration and test of the SPORT observatory will be managed by ITA and take place at the INPE LIT facility infrastructure. NASA MSFC is in charge to coordinate its actions with ITA, including providing personnel on site to monitor the integration activities and problem resolution. After integration and test, the completed observatory is delivered to NASA MSFC, where it is confirmed to meet requirements. NASA MSFC then coordinates the launch of the observatory. INPE and ITA are also responsible for ground observation systems and the mission operations/data management. The science data will be distributed from and archived at INPE, mirrored at the GSFC Space Physics Data Facility (SPDF).

Figure 3 presents the SPORT layout highlighting the Payload area and the Spacecraft area.

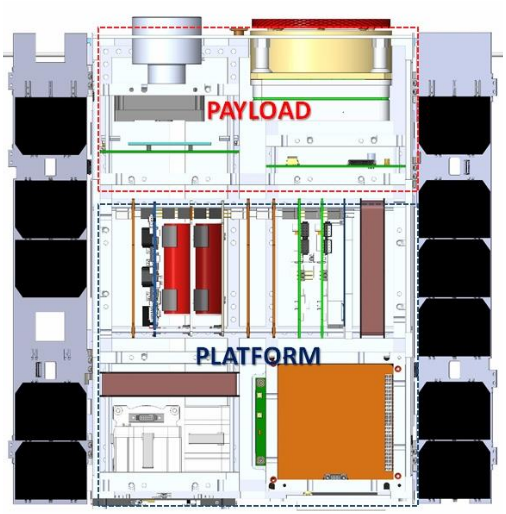

Figure 3: SPORT Layout

SPACECRAFT PROJECT MANAGEMENT AND SYSTEM ENGINEERING

The methodology for the research organization follows tailored standards such as ISO 14300 – Space Systems – Program Management – Part 1: Structuring a project and ECSS-M-30-A – Project Phasing and Planning and for this mission the project life cycle is divided into:

a. Phase 0/A – Mission Analysis;

b. Phase B – Preliminary Definition;

c. Phase C – Detailed Definition;

d. Phase D – Production/Ground Qualification;

e. Phase E – Utilization;

f. Phase F – Disposal.

In short, the objectives related to each phase are the following:

Phase 0/A - Mission Analysis and Phase B - Preliminary Definition

During the phase 0/A the mission was defined and the mission objectives were evaluated against science objectives. The schedule was initially proposed and milestones confirmed with the partners to have a definition of the project schedule.

During the phase B the requirements were confirmed, and the interfaces were verified. The proposed design was checked with respect to the science and mission objectives. The systems engineering processes and the verification and test plans were defined in mission level. An engineering analysis were performed at the main satellite domains (spacecraft and payload). The safety, risk, cost and schedule were assessed at system level. The phase ended with the realization of the System Requirement and Preliminary Design Reviews together, held in U.S. at University of Texas at Dallas, with instrument and spacecraft representative attending in person.

Phase C - Detailed Definition

During this phase, with is the current project phase, the assurance is provided that the integrated spacecraft design, mission orbit and instruments are in accordance with the mission and science requirements prior to final assembly, integration and test. The finalization of system compatibility, design, mission operations, safety assessments, costs and schedule relationships are addressed. The Review Test, verification/validation planning are confirmed. The phase ends with a Critical Design Review held at ITA/INPE with Project leaders attending in person.

Phase D - Production/Ground Qualification

During this phase the whole spacecraft will be assembled, integrated and tested. A detailed configuration verification of spacecraft will be performed. The work encompasses not only flight hardware and Ground Support Equipment (GSE) but also any deliverable items. All aspects of qualification, verification & validation, and acceptance testing will be addressed. An Acceptance Review is planned to be held at ITA/INPE with project leaders attending in person.

After these process, NASA will assume the responsibility for the observatory. The review results in certification of the flight readiness to be signed by members of the operational team, the acceptability of the system for flight, and the readiness of the system to achieve all flight objectives. The phase ends with the Flight Readiness Review (FRR), which the system will be certified as flight worthy hold in U.S. at NMSFC, with instrument and spacecraft representative attending in person.

Phase E – Utilization

During this phase a checkout of launch and orbit will be performed. A verification of observatory health will be conducted to confirm space and ground systems are ready to begin nominal science operations. The phase ends with the Commissioning Readiness Review (CR) hold at mission operations site with Project representatives attending in person, other by telecon.

Phase F - Disposal

During this phase the involved institutes and organization analyses the decision to terminate or decommission the system. A confirmation if the observatory is safe for decommissioning is required. The phase ends with the Mission Closeout Review (MCR) hold at science operations site with Project representatives attending in person, other by telecon. During the MCR and with the agreement of the institutions involved, the mission can be extended for an additional year, depending on the health of the observatory, its operability, the meaningfulness of the data collected and the financial resources available at that time. If the mission is extended, at the end of the year a new MCR shall take place to decide the end of mission or its extension.

System Engineering

One of the challenges of the SPORT mission was to define an effective system engineering process to be implemented in the spacecraft development considering the particularities of an international mission where the many institutes and organization involved already have their own standards and cultures regarding to system engineering. Dependencies of international agreements between countries were also a barrier at the beginning of the project, so it was necessary to develop a strategy to work with the information available at each phase of the project.

The strategy was to develop the spacecraft and define the architecture in what we called Project Loops. The main idea was to divide the system in four architectures, as shown in Figure 4. This approach is presented in System Engineering Analysis, Design, and Development: Concepts, Principles, and Practices [6]

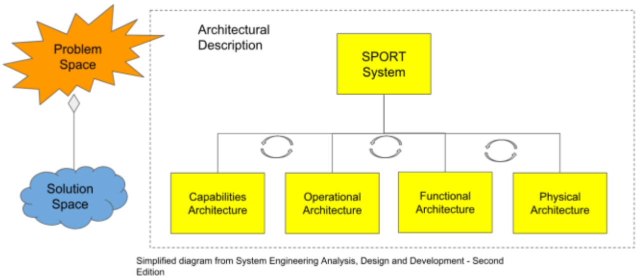

Figure 4: SPORT System Architectural Description

In each project loop the purpose is to gather more specific and detailed information, in the sense to specify the spacecraft necessary features in each of the four architectures and the relationship among them, considering that changes in one architecture requires a feedback in the other three. For example, a new capability required to the spacecraft may lead to a necessity to change or to add an operational node and change or add a new function in the spacecraft. This new function needs to be assign to a physical element, that can be an existing one or it may require a new part. In this way it is possible to track the changes and the impacts in the overall system and change the system incrementally and in such a way, modularly.

In the first project loop it was analyzed the mission and how its affects or define the system of interest to the group – the spacecraft. The second loop lead to the systems definitions, the third loop the spacecraft interfaces with other subsystems and preliminary studies. In the fourth loop it was defined the spacecraft possible solutions and in the fifth loop the consolidation of the preliminary solution. To the development group the closure of the fifth loop was the SPORT SRR/PDR review, held in the USA, according to the project management schedule.

Capabilities Architecture: The capabilities architecture stands for defining the user needs, i.e., understand what the statement of the mission is, and once it is identified, define the capabilities required to attend the user needs, as well as to understand the risks and feasibility of the mission. In the capabilities architecture the team defined the mission need, Goals and Objectives, studied and defined a Concept of Operation (ConOps). Based on this information it was idealized the mission possible scenarios (in all phases of the mission lifecycle) and from these scenarios and the user needs the identification of the mission and system requirements. In the capabilities architecture the mission risks and hazards were identified and the issued according to the specific plan.

Operational Architecture: In the operational architecture the purpose is to define the operational behavior of the system of interest, the conditions in what it may occur and the operational nodes. To define the operational behavior of the system studies are made to define the States, Modes and Use Cases and the Operation Modes in all phases of the mission lifecycle. An analysis of the coverage area and area of interest to measure the characteristic of the ionosphere was also completed. The analysis results are inputs to the spacecraft models.

Functional Architecture: It stands for the efforts to define all the functions the system shall have and their relationship with the capabilities expected by the users and the operational architecture. The functional architecture later is translated to the physical architecture. So, it is an important step, once it translates the user needs and mission statement into functions that can be reached by physical elements. In this step the Generic Functional Architecture were defined and it was defined the basic software architecture and software functionalities. The logical interfaces and power interfaces were identified and represented.

Physical Architecture: By the end it is the implementation of the solution that best fits the user's expectations. In this step a Generic Physical Architecture is defined, dividing the spacecraft into the subsystems and correlating each equipment with the functional architecture. To aid the definition of the components a Morphological Chart and selection criteria are used. Once defined the components it was possible to start the development of the spacecraft models (based on a physical architecture). Some models are: Power Budget Model, Data Budget Model, Mass Model, Attitude Control Model, Mechanical Model, Thermal Model.

Observatory Models Philosophy

The SPORT observatory has been designed to have a high rate of success during operation. So, the solution relies on COTS (Commercial of the shelf) parts with successful flight proven heritage and high Technology Readiness Level (TRL).

The Engineering Model (EM) of the SPORT Observatory relies on Flight Model (FM) parts for some subsystems, such as onboard computers, energy and power subsystem, but evaluation parts are also considered to be used in the mechanism system of antennas and booms, transceivers and transmitters, and others equipments. The EM also includes simulators of subsystem for: ADCS Sensors, ADCS Actuators, experiments command & telemetry channels and experiments data channels. Engineering Model of new developments are provisioned and for these ones, specific qualifications tests are required. In the EM, profile tests will be performed to get the satellite signature, such as power consumption profile, spacecraft magnetic profile, subsystems behavior profile, EMI profile and so on.

The SPORT Observatory is not intended to have a Qualification Model (QM), instead it is proposed a Protoflight Model (PFM), in this model the qualification level tests are performed considering acceptance time intervals and cycles. The model is also functionally tested to define and confirm the satellite signature and test profiles.

SPACECRAFT DESCRIPTION

Once the spacecraft components are not from a single supplier, special care was taken to assure the compatibility among these commercial components and the in-house developed boards selected as the best option to attend the SPORT requirements.

Following the experience of the team on previous project, the ITASAT CubeSat [7], during the definition of the physical architecture the idea of modularity was kept during the development, where modularity means the flexibility to exchange parts of the space bus with minor or no changes on the other elements of the satellite.

The spacecraft can be divided into subsystems, as usual is most of the satellites. The main subsystems of the spacecraft are: a) Structure Subsystem (STS); b) Power Supply Subsystem (PSS); c) Thermal Control Subsystem (TCS); d) On Board data Handling (OBDH); e) Attitude Control Data System (ACDS); f) Tracking, Telemetry and Command (TT&C); g) Harnesses and h) Payloads. Figure 5 shows the spacecraft high level product tree.

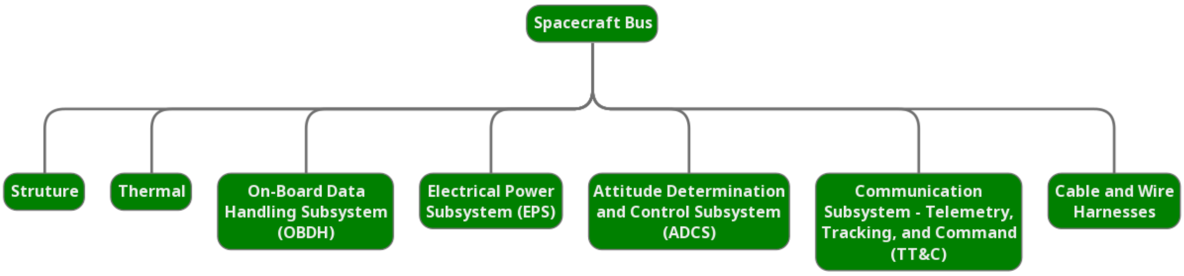

Figure 5: Spacecraft Tree

Considering the SPORT orbital requirements (depicted on Figure 6) for the base science of one-year mission to occur sometime between 2020 and 2022 in a circular orbit within ±10 km with a nominal insertion altitude in the range of 350 ~ 450 km and an inclination in the range of 45 to 55 degrees the SPORT Spacecraft development team has performed analysis to define de de-orbit time, power availability, contact times to the ground station, thermal behavior, mechanical behavior, power consumption, attitude control stability, data budget for instance. Some of the results are presented in the spacecraft description.

Figure 6: SPORT Orbital Plane

For the planed orbit the lifetime until the reentry in the Earth atmosphere is around 4 years for an estimated mass of 9 kg of the observatory, considering the area-to-mass ratio to naturally decay the satellite. It has significant margin in meeting the de-orbit requirement of <25 years after the operational mission.

For this orbit parameters the SPORT Spacecraft has the capacity to generate in the worst-case scenario 9,8 W of power using deployable solar panels (solar cells efficiency of 28%) in the flight direction shown in Figure 7.

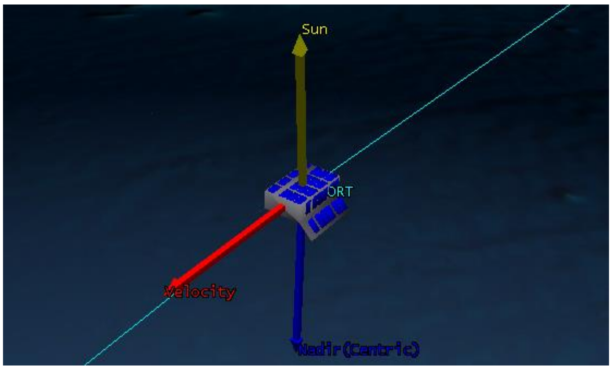

Figure 7: SPORT Flight Direction and Solar panels. Simulation 3^{rt} Nov 2019, Angle β 9,5 degrees.

Considering this scenario, the SPORT Observatory power budget is summarized in **Table 1** for some of the operational modes of the CubeSat, showing that there is power margin to the safe operation of the satellite in the considered scenarios of operation. The observatory power consumption table considers the equipment's peak consumption and respective duty cycle to determine the Orbit Average Power (OAP) for each equipment.

Table 1: SPORT Power Budget Summary

SYSTEM	Marg	SAFE MODE				ATTITUDE MODE				NOMINAL MODE			
		INIT.		MIN		DET		POINT		MEAS		HOUS.	
		W	W+%	W	W+%	W	W+%	W	W+%	W	W+%	Watts	W+%)
Payload	20%	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	2,81	3,38	1,50	1,80
Spacecraft	20%	3,16	3,79	0,97	1,16	1,14	1,36	2,51	3,01	2,17	2,60	2,40	2,88
Bat Loss	20%	0,13	0,16	0,13	0,16	0,13	0,16	0,13	0,16	0,13	0,16	0,13	0,16
Total		**3,29**	**3,95**	**1,10**	**1,32**	**1,27**	**1,52**	**2,64**	**3,16**	**5,11**	**6,14**	**4,03**	**4,83**
Solar Panels	**10%**	**9,88**	**8,89**	**9,88**	**8,89**	**9,88**	**8,89**	**9,88**	**8,89**	**9,88**	**8,89**	**9,88**	**8,89**
Additional Power Margin			56%		85%		83%		64%		31%		46%

To provide energy during eclipse and during pick power consumption, a COTS Lithium-ion battery pack is intended to be used and a COTS power conditioning and distribution unit will be used to convert the energy from solar panels and distribute to the observatory. In the actual configuration it is possible to provide to the payloads regulated power lines of 3.3V, 5V and unregulated power lines from 12~16,8V, which is the battery voltage range (V_bat). The energy and power subsystem include the remove before flight mechanisms, under and over voltage protections.

The communication system of the SPORT observatory is divided into spacecraft channel and science data channel. The uplink channel, for commanding the satellite, will rely on VHF frequency, AFSK modulation and configurable data rate of 1.2 kbps to 9.6 kbps. For this mission a single channel for uplink is provided. The downlink channel, for observatory telemetry data, is divided in two groups. One for spacecraft telemetry that will rely on UHF frequency, BPSK modulation, and data rate from 1.2 kbps up to 9.6 kbps, which provides a telemetry downlink capacity of 576 kbits (low rate) up to 4608 kbits (high rate). In this link, the maximum output power is 22 dBm. The second is dedicated to payload data (science data) and relies on X-Band frequency with higher data rate and higher output power. The desired data rate is up to 50 Mbps, and output power from 30 to 33 dBm. For this orbit (Figure 6), the contact time between the spacecraft and the ground segment, located in Brazilian territory as shown in Figure 6, is in average about 6 minutes and there are about 6 revisits per day.

The onboard data processing considers a distributed system, where one computer is dedicated to onboard data handling functions and the second computer is selected to concentrate the attitude control and data system functions. This allows having a more flexible configuration and higher data processing capacity. The in-house software development, for onboard data handling and satellite attitude control systems, allows the optimization of the necessary functions and a specific software development architecture is implemented in the project. Previous experience of the team in the software development is also applied and software re-use is intended to be used.

Due to the payloads characteristics, the satellite needs attitude stabilization and pointing, so the satellite is 3-axis stabilized. The attitude control system is based on sun sensor, gyrometers, magnetometers and a star tracker as sensors and magnetic air coils and reaction wheels as actuators to achieve the mission requirements. As explained, a dedicated onboard computer is used to process all data related to the attitude control system.

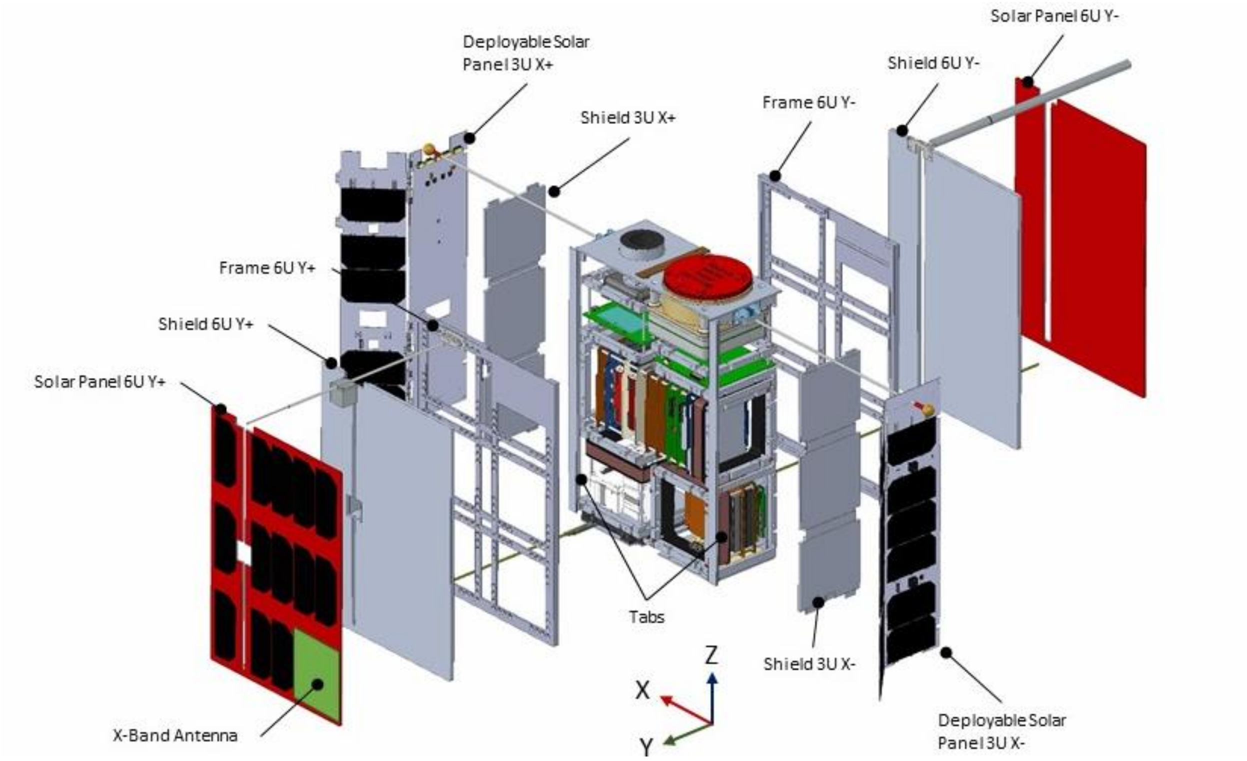

Figure 8: SPORT Exploded View

SPORT MISSION EXPECTED RESULTS

The most important consequence of the SPORT mission is to make available, free of charge, by means of the EMBRACE system, all the collected data of the ionosphere. This policy of free distribution of data for the international and national community is one of the key points of the whole program. EMBRACE has a very professional state of the art system that not only grants the availability of data but is also robust enough to assure the stability of the distribution worldwide.

For ITA the expected result is to consolidate the CubeSat development at the Institute, creating a replicable system engineering process to be applied in future projects, considering international partners. Others expected results are the consolidation of the spacecraft development and spin-off developments, the consolidation of the software architecture to be applied in future projects, the establishment of a feasible and reliable AI&V process.

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 32nd Annual AIAA/USU Conference on Small Satellites, August 2017.

2. Denardini C.M., S. Dasso and J.A. Gonzalez-Esparza. “A review on Space Weather in Latin America: from Space Research to Space Weather and its Forecast”. Advances in Space Research, Volume 58, Issue 10, Pages 1916-1939, 2016

3. Space Studies Board of the U.S. National Academies. “Severe Space Weather Events – Understanding societal and economic impacts”. Report, 2008

4. Baker, D. N. “What Does Space Weather Cost Modern Societies?” Space Weather 7, S02003, doi:10.1029/2009SW000465, 2009.

5. Martin, I.M., A.A. Gusev, et al. “About the origin of high electrons in the inner radiation belt”. Journal of Atmospheric and Terrestrial Physics, Volume 57, Issue 2, pages 201-204, 1995.

6. Wasson, C. S. “System Engineering Analysis, Design, and Development: Concepts, Principles, and Practices”, 2nd edition, 882 pages, December 2015.

7. Shibuya Sato, L. H., E. Fonseca, et al. ITASAT Project - The new project philosophy and lessons learned. 1st IAA Latin America Cubesat Workshop, December 2014. Brasilia, Brazil.