NEW CHALLENGES FOR GROUND SEGMENT DEVELOPMENT: SCIENTIFIC SMALL SATELLITE MISSIONS.

Julio Filho A. C.(1), Pereira A. C. O. J.(2), Dos Santos W. A.(3), Cisotto M. V.(4), Tikami A.(5), Bueno L. A. R.(6), Brito A. F.(7), Florentino A. J. A.(8), Teixeira L.(9), Camargo L. A. P(10), Junqueira B. C.(11), Horna A. P.(12)

(1,2,3,4,5,6,7,8,9,10,11,12) National Institute for Space Research (INPE), São José, dos Campos, São Paulo - Brasil, 55 12 3208.6615,
(1)cassiano.filho, (2)acarlos.pereira, (3)walter.abrahao, (4)marcus.cisotto, (5)auro.tikami, (6)luiz.bueno, (7)antonio.brito, (8)angelo.florentino, (9)lincoln.teixeira, (10)lazaro.camargo, (11)bruno.junqueira [@inpe.br], (12)mrandresph@gmail.com

Abstract

The National Institute for Space Research has promoted means of technological and scientific development, meeting internal and external demands through mission analysis, project coordination, management, and development, including remote sensing satellites, such as CBERS and Amazonia families, and small satellites for scientific applications, as well as the ground segment development. The ground segment must be compliant with the requirements defined by the space segment in the early stages of mission development and ensure synergy between these segments. In this scenario, the ground segment options for small satellites expand, and it is essential to consider the trade-off between data quality, data volume and cost. In the recent past, several missions relied on amateur radio ground stations to support of small satellites operation, and the amateur radio community has proven invaluable to small satellite missions. Nowadays, with increasing mission complexity and data requirements, more projects are looking at non-amateur ground stations which are part of ground segment. The ground segment for small satellites is typically based on the VHF-UHF bands, and it should meet the increasing demand for S-band and X-band telecommunications, as well as the need for reception, storage, and dissemination of high-quality scientific data. This paper presents the INPE’s ground segment development, including the Telemetry, Tracking and Command (TT&C) ground stations, the Reception and Recording Stations, the Satellite Control Center (SCC) Systems, to support scientific small satellite missions, in particular, the Scintillation Prediction Observations Research Task (SPORT). SPORT mission addresses the preconditions leading to equatorial plasma bubbles, and it is an international partnership between National Aeronautical and Space Administration (NASA) and the Brazilian Space Agency (AEB). Across NASA, American universities and the Aerospace Corporation provide the scientific instruments. Through AEB, the Technical Aeronautics Institute of the Brazilian Air Force Command Department (DCTA/ITA), and the National Institute for Space Research (INPE) contribute to the mission development. The paper also describes an overview of the spacecraft and mission objectives under the responsibility of the DCTA/ITA teams. It presents the ground segment integration, the planning for control and operation of the SPORT satellite, under the leadership of INPE's multidisciplinary teams, including the data storage and dissemination by Brazilian Monitoring and Study of Space Weather (EMBRACE). The design´s status, lessons learned, and the contributions to overcome challenges associated to development the ground segment for small satellites, and ensure the mission accomplishment are presented in this paper.

***Keywords**: Equatorial Plasma Bubbles, EMBRACE, Ground Segment, Satellite Control Center, SPORT.*

1. Introduction

The National Institute for Space Research (INPE), within its competences, can promote means of technological and scientific development by meeting internal and external demands through project coordination, mission analysis, management and development, such as remote sensing satellites (CBERS family, Amazonia-1) and the small satellites for educational and technological applications, as well as the ground segment development.

The ground segment must be compliant with the requirements defined by the space segment in the early stages of mission development and ensure synergy between these segments. In the recent past, several missions relied on amateur radio ground stations to support of small satellites operation, and the amateur radio community has proven invaluable to small satellite missions. Nowadays, with increasing mission complexity and data requirements, more projects are looking at non-amateur ground stations which are part of ground segment.

A complex mission, which based in a small satellite, is the Scintillation Prediction Observations Research Task (SPORT) [1]. SPORT mission addresses the preconditions leading to equatorial plasma bubbles, and it is an international partnership between National Aeronautical and Space Administration (NASA) and the Brazilian Space Agency (AEB).

NASA Marshall Space Flight Center coordinates this research by overseeing the launch to orbit and the scientific instruments. Aerospace Corporation, University of Texas, Utah State University, Alabama University and NASA Goddard Space Flight Center (GSFC) provide the scientific instruments.

Through AEB, the Technical Aeronautics Institute of the Brazilian Air Force Command Department (DCTA/ITA) is responsible for spacecraft development and integration; and the National Institute for Space Research (INPE) contributes with the infrastructure of the Integration and Testing Laboratory (LIT), ground segment development, mission operations, and science data management.

The science data will be distributed from and archived at the INPE Brazilian Monitoring and Study of Space Weather (EMBRACE) regional space-weather forecasting center, and mirrored at the NASA GSFC Space Physics Data Facility (SPDF).

This document is organized as follows: section 2 presents the space system and its segments; section 3 outlines the SPORT mission, instruments and platform; section 4 describes the current INPE's ground segment; section 5 presents the INPE ground segment for the SPORT mission; and section 6 the conclusions

2. Space System

A generic space system comprises the space segment and the ground segment. A **space segment** - spacecraft - consists of a service module and payloads follows ECCS [2, 3] and NASA [4] guidelines and CCSDS [5, 6] recommendations as presented in Fortescue et al. [7], Larson and Wertz [8], and ref. [9]. A **ground segment** comprises the hardware, software and human resources needed to manage and control a spacecraft, monitoring and analyzing its operation in orbit, and data distribution to the user.

The ground segment consists of (i) the Telemetry, Tracking and Command (TT&C) ground stations, (ii) the Satellite Control Centre (SCC), and (iii) the Application Segment.

TT&C ground stations [10] are in charge of establishing communication between the ground segment and the spacecraft, and SCC is responsible for the plan and executes all activities related to the spacecraft's control.

Application Segment comprises (i) the Reception and Recording Stations, (ii) the Mission Center that plans and coordinates the spacecraft data acquisition, stores the data, and makes them available to users.

Figure 1 illustrates a space system and its segments, it refers to the CBERS-4A mission, successfully launched in 2019 [10]. It is a partnership between the INPE and the China Academy of Space Technology (CAST). Another example of a space system [10] is the Amazonia-1, successfully launched in February 2021. It is the first remote sensing satellite fully designed, integrated, tested and operated by Brazil. It is a project coordinated by the Ministry of Science, Technology and Innovations (MCTI) and conducted by INPE in partnership with the AEB.

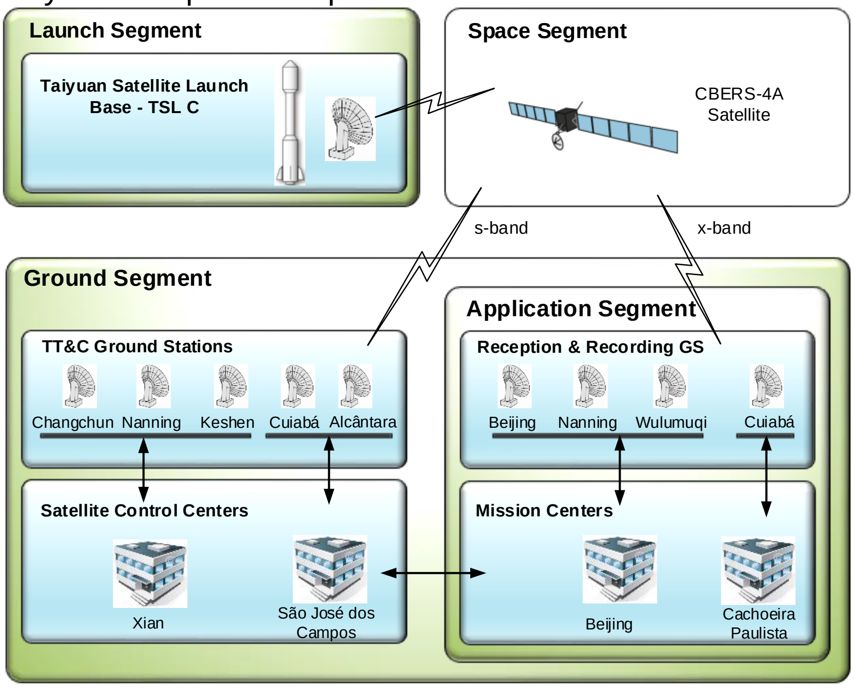

Figure 1: A typical Space System and its Segments [9, 10].

2.1. Brief of Ground Segment Evolution

Space agencies have been engaged in efforts to optimize financial resources, reduce ground segment development and deployment time. Several ground segment architectures have been proposed to meet the requirements of interoperability and cross support. In order to solve the problems associated with the large number of interfaces for exchanging services between ground stations and satellite control centers, the CCSDS, in a collaborative effort with space agencies, recommends a set of standardized services for interoperability and cross support [9, 10].

This set of standardized services, called Space Link Extension (SLE) Protocol Services [6] and their management activities provide interoperability and cross support among space agencies. Many space agencies have adopted the CCSDS recommendations of SLE Protocol Services [11], for example: ASI, CNES, DLR, ESA, ESOC, INPE, JAXA, and NASA, and by private companies.

Furthermore, cross support research and applications meet the objectives of the Interagency Operations Advisory Group (IOAG) [12]. The main goal of IOAG is the achievement of full interoperability among **member space agencies**: ASI, CNES, CSA, DLR, ESA, JAXA, NASA, and UK Space Agency.

3. SPORT Mission

The Technical Aeronautics Institute of the Brazilian Air Force Command Department (DCTA/ITA) is in charge of spacecraft development, integration, and tests [1].

The purpose of Scintillation Prediction Observations Research Task (SPORT) is to provide science data to a systematic study of the state of the pre-bubble conditions at all longitudes sectors to enhance understanding between geography and magnetic geometry. This phenomenon is the primary source of radar reflections in the equatorial F-region ionosphere and cause strong scintillations on radio signals passing through them.

SPORT will address two specific questions about these phenomena:

1) What is the state of the ionosphere that gives rise to the growth of plasma bubbles that extend into and above the F-peak at different longitudes?
2) How are plasma irregularities at satellite altitudes related to the radio scintillations observed passing through these regions?

3.1. Technical approach and instruments

SPORT, 6U CubeSat, is composed of two main systems: Payload and Platform, called Observatory.

The main characteristics are apogee and perigee of 400 km, inclination 51.64°, R.A. Ascending Node of 251.89°, Argument of Perigee 221.34°, Period of 1.54h, Orbits Numbers of 15.46, Data Storage capability of ~29GB, and nominal mission lifetime of 2 (two) years.

The **Payload** system consists of six instruments [1, 13], showed on Figure 2:

- **I**on **V**elocity **M**eter (**IVM**) to measure the velocity and direction of the íon component of ionospheric plasma at the sensor location (that collid with satellite), provided by University of Texas.
- **C**ompact **T**otal **E**lectron **C**ontent **S**ensor (**CTECS)** to obtain electron density profiles at low latitudes and to detect the presence of scintillation. CTECS is a GPS occultation sensor, provided by Aerospace Corporation.
- **E**lectrical **F**ield **P**robe (**EFP**) is used to measure only one component of both DC and AC electric fields for identifying disturbed regions of the ionosphere, provided by Utah State University (USU).
- **L**angmuir **P**robe (**LP**) to measure plasma density, as well as temperature, the floating potential, and the space potential. It is provided by USU.
- **S**wept **I**mpedance **P**robe (**SIP**) will be used to determine the absolute electron density, irrespective of the payload charging, by monitoring the changing impedance of a short cylindrical probe excited over a range radio frequency.
- **M**iniaturized **S**cience **M**agnetometer (**MSM)** will provide high-resolution measurements of the ambient magnetic field with sufficient sensitivity to potentially observe perturbations due to pressure gradients, diamagnetic cavities. Its provided by NASA Goddard Space Flight Center (GSFC).

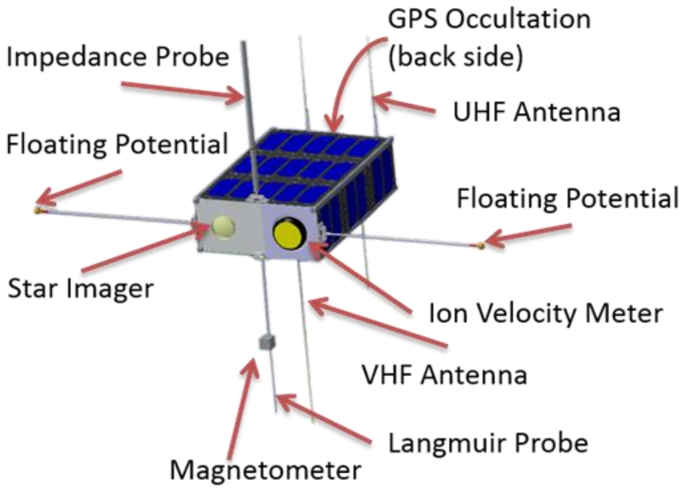

Figure 2: SPORT configuration and location of science instruments [1, 13].

The **Platform** system [1, 13] is responsible for controlling the satellite and consists of several subsystems describe below:

- **O**n**B**oard **C**omputer subsystem (**OBC**) is composed of three computers:
    - Control and Data Handler (C&DH) manages the SPORT by controlling the Attitude, VHF/UHF TT&C radio, Science Data, TM components;
    - Payload Data Handler (PLDH) interfaces with the Payloads' subsystems IVM, MSM and SIP, and send data to Data Storage Unit;
    - Data Storage Unit (DSU) stores all mission data packets to be transmitted to ground. Interfaces with CTECS for retrieving its Science Data and send to C&DH and PLDH.
- **E**lectric **P**ower **S**ubsystem (EPS) is the responsible for conditioning and distributing power to all components.
- **A**ttitude **D**etermination and **C**ontrol **S**ystem (ADCS) of the cubesat SPORT is responsible for providing stability in attitude through active control.

4. Current INPE's Ground Segment

This section presents the main systems that comprise ground segment of the INPE for space missions, (1) Reception and Recording Station, (2) Cuiabá and Alcântara TT&C INPE's Ground Stations and Satellite Control Center, (3) Natal TT&C Ground Station and (4) EMBRACE.

4.1. Reception and Recording Station

INPE, in 1973, started the activities of satellite tracking and data reception from the first remote sensing satellite, the Earth Resources Technology Satellite-1 (ERTS-1) of the Landsat Series [14].

Nowadays, the current Reception and Data Recording station - located in Cuiabá, in Mato Grosso State, Brazil) - operating in X-Band, receives and continuously records the data transmitted by Amazonia-1, CBERS satellites series, Landsat-5 and 7, SPOT-4, ERS-2, and Radarsat-1. The data are transferred to the Remote Sensing Data Center (Mission Center) in Cachoeira Paulista, in São Paulo State, for further processing and dissemination to end users, as illustrated in Figure 3.

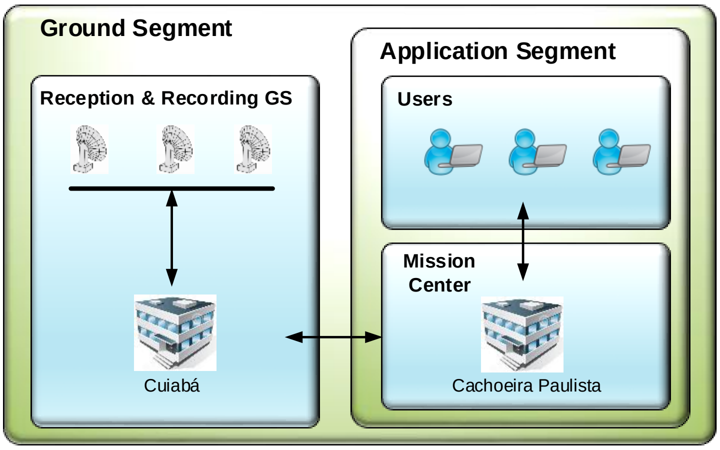

Figure 3: X-Band Reception and Recording Station.

4.2. Cuiabá and Alcântara TT&C INPE's Ground Stations and Satellite Control Center

Telemetry, Tracking and Command (TT&C) Ground Stations of INPE provide the link between the control personnel and the satellites [15, 16]. The Ground Stations operate in S-band and, are located in the cities of Cuiabá, (Mato Grosso state) and Alcântara (Maranhão state) in Brazil. This infrastructure was initially designed to support operations of the first Data Collection Satellite (SCD-1) launched in 1993. The basic infrastructure has been updated along the years.

TT&C ground station, Figure 4, comprises a RF Front End, an Antenna Control Unit, and a Time & Frequency. The functions of TM, TC, Ranging Data, Range Rate are based on Integrated Baseband System (IBS).

The IBS also enables the implementation of SLE protocol services [16] for cross support and interoperability between space agencies. In 2013, acceptance tests of the SLE protocol were performed in cooperation with the European Space Operations Centre (ESOC). On having the SLE protocol operational, INPE can rely on the support of other tracking stations distributed around the world to track its own satellites, and likewise provides tracking services to other international agencies.

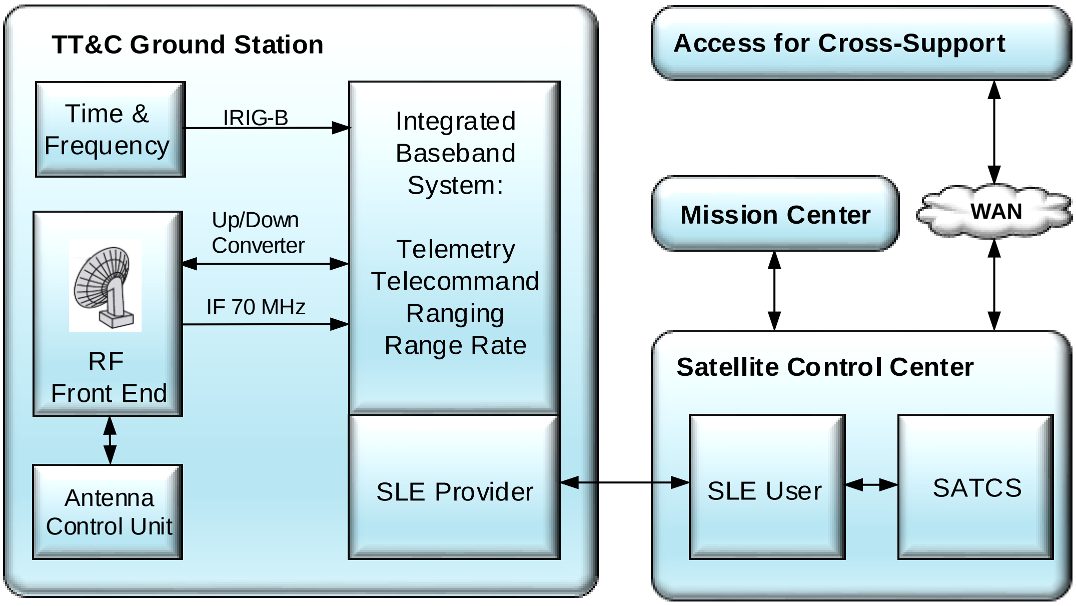

Figure 4: TT&C INPE's Ground Station and Satellite Control Center [16].

Satellite Control Center (SCC) [15], Figure 4, is located in the city of São José dos Campos, São Paulo state, Brazil. SCC is responsible for planning and executing all activities related to satellite control, and the rapid reaction in case of anomalies of a satellite. The SCC's main functions are orbit and attitude control, maneuvers calculation, operational payload configuration, and real-time monitoring of the satellite health.

The SCC structure includes a software system named **SAT**ellite **C**ontrol **S**ystems (SATCS). A specialized team from the General Coordination of Space Engineering, Technology and Science (CGCE) at INPE developed SATCS. It was designed to be an easily configurable and personalized system.

4.3. Natal TT&C Ground Station

Natal Multi-Mission Station (EMMN), Figure 5, is located at the Northeast Regional Center of the INPE, city of Natal, state of Rio Grande do Norte, Brazil. The EMMN Ground Station is designed to operate in the VHF (144 - 149 MHz), UHF (395 - 405 MHz and 432 - 440 MHz) and S-Band (2100 - 2300 MHz) frequency bands, receiving payload and telemetry data and transmitting satellite telecommands operating in low orbits [17].

The Station's radio frequency systems make use of Software Controlled Radios (SDR), which offers the flexibility of quickly reconfiguring parameters such as the type of modulation (FSK, AFSK, BPSK, GMSK, G3RUH), coding (AX-25), data rate (1200, 2400, 4800, 9600).

The station performs autonomous tracking of several satellites according to a schedule and obeying a priority scale. According to ref. [18], the missions tracked are CONASAT, FloripaSat, ITASat, NanoSatc-BR.

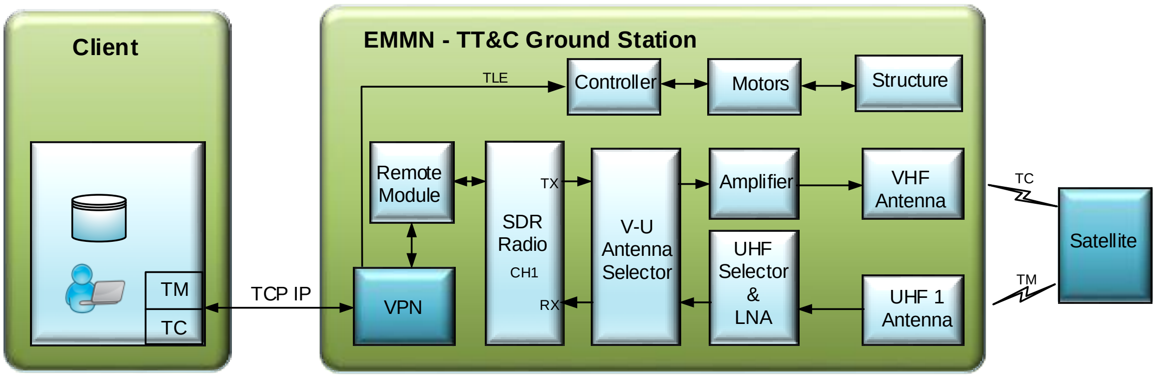

Figure 5: Natal INPE's Ground Station.

4.4. EMBRACE

EMBRACE Program [19], acronym in Portuguese "**E**studo e **M**onitoramento **BRA**sileiro de **C**lima **E**spacial" - Brazilian Space Weather Study and Monitoring, was created, in 2007 by INPE, to monitor the Sun-Earth space environment, the magnetosphere, the upper atmosphere and the effects of induced currents on the ground to predict possible influences on technological and economic activities.

Recently, EMBRACE acquired an antenna, installed in Cuiabá, Mato Grosso state, Brazil, for reception of data from the Constellation Observing System for Meteorology, Ionosphere, and Climate2 (COSMIC-2). COSMIC-2 is a network of six radio occultation observation satellites of the GNSS satellite constellation used to collect atmospheric data used in weather forecasting, and space weather monitoring and prediction.

5. INPE's Ground Segment for SPORT Mission

SPORT mission posed new challenges for the implementation of the ground segment. The ground segment will allow attending the higher rate revisits, associated the controlling, data reception, support and interoperability to all ground facilities, which requires an architecture to support them. This architecture should be attending remote sensing satellites, such as CBERS and Amazonia families; radio occultation observation satellites, COSMIC-2; and small satellites for scientific applications.

The contributions to overcoming the challenges associated with the development of the ground segment for small satellites and ensure the mission accomplishment are the integration of the ground segment, the planning for control and operation of the SPORT satellite, under the leadership of INPE's multidisciplinary teams, including data storage and dissemination by the Brazilian Space Weather Monitoring and Study (EMBRACE).

SPORT [1, 13] will use ground segment, Figure 6, comprises by INPE TT&C ground stations located at Natal (northeast) and Cuiabá (center west) with additional system for operation in UHF and VHF bands, under control of Satellite Control Center (SCC), located in São José dos Campos. For scientific data downlink (ERD), the SPORT will use two X-band antennas located at Cuiabá (center west) and Cachoeira Paulista (southeast).

The SCC at INPE headquarters in São José dos Campos will remotely operate TT&C ground stations using SATellite Control System for SPORT (SATCSport) and communication private links. The mission operations at INPE involve the support and operational teams, ground system infrastructure (hardware and software) and facilities, as well the real time (SATCSport) and non-real time flight dynamics software.

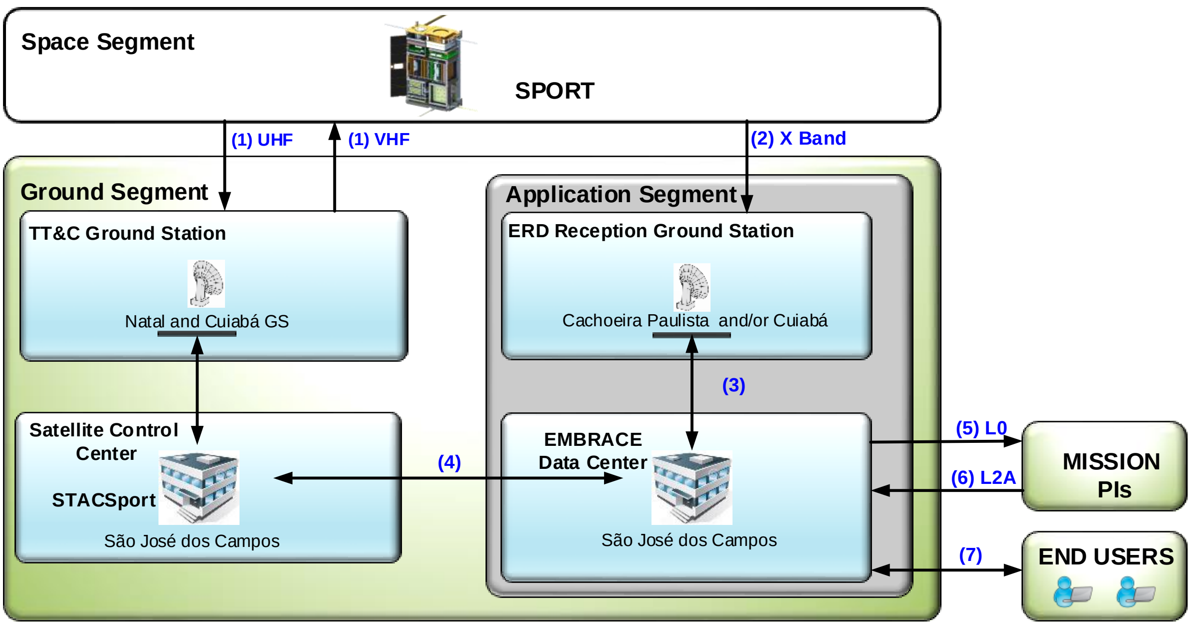

Figure 6: INPE's Ground Segment for SPORT Mission.

The data center at EMBRACE will receive the data and distribute decommutated instrument and engineering data to the instrument teams (Mission PIs) for data reduction.

The reduced instrument data will be sent back to EMBRACE from each instrument team, where it will be processed, archived, and ingested into space weather analysis models and tools [1].

SPORT has a fully open data policy consistent with NASA data policies. EMBRACE will be the SPORT mission data distribution center for the science and end user communities. The data will be mirrored and archived at the NASA Goddard Space Flight Center (GSFC) Space Physics Data Facility (SPDF).

6. Conclusions

The requirements of the INPE's different missions involve definitions as communication band; uplink and downlink rate; protocols; onboard processing; remote reconfiguration of service and payload modules, and classically, determine the design and development of missions and posed new challenges for the implementation of the ground segment.

From the Ground Segment perspective, partnerships for space systems development should follow a strong standardization of system engineering procedures, consistent and traceable documentation, management, and implementation of the ground segment and its interfaces with the space segment. Furthermore, the challenges and complexity for the development of the ground segment are the same, regardless of the satellites' dimensions and applications.

In July 2022, the Aeronautical Technical Institute of the Brazilian Air Force Command Department (DCTA/ITA) delivered the SPORT satellite to Nanoracks payload hosting services provider, https://nanoracks.com/, and its launch to the ISS is scheduled for November 2022.

TT&C stations, Reception and Data Recording stations, and EMBRACE are in the final integration and testing phase. The Satellite Control Center is in the final stages of preparation of the launch campaign, training of the tracking and operations teams.

Acknowledgments

We thank all our coworkers at the Brazilian National Institute for Space Research (INPE) for support.

References

[1] Spann J., Swenson C., Durão O., Loures L., Hellis R., Bishop R., Le G., Le G., Abdu M., Krause L., Fry C., Denardini C., Shibuya L., Casas J., S. Nazh-Stevenson S. N., Muralikrishana P., Costa J., Eberly E., Mesmer B., Padua M. B., Wrasse C. "The Scintillation Prediction Observations Research Task (SPORT): An International Science Mission using a CubeSat", Proceeding 31nd Annual AIIA/USU Small Satellite Conference, Logan UT, USA, 2017, SSC17-XIII-03, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3695&context=smallsat

[2] European Cooperation for Space Standardization (ECSS) (2003). "ECSS-E-70-41A. Space engineering - ground systems and operations telemetry and telecommand packet utilization". <http://www.ecss.nl/>.

[3] European Cooperation for Space Standardization (ECSS) (2008) "ECSS-E-ST-70C. Space engineering - ground systems and operations". <http://www.ecss.nl/>.

[4] National Aeronautics and Space Administration (NASA). (2013) “NASA Procedural Requirements - NPR 7123.1B. Systems Engineering Processes and Requirements”. Washington, DC.

[5] CCSDS TM Space Data Link Protocol. Recommended Standard. CCSDS 132.0-B-1. Blue Book. Issue 1. Washington, D.C., September 2003.

[6] CCSDS Cross support concept - Part 1: Space Link Extension Services - CCSDS 910.3-G-3. Washington, D.C, 2006.

[7] Fortescue, P.; Stark, J.; Swinerd, G. (2003) "Spacecraft systems engineering 3". Chichester, UK: John Wiley. ISBN: 678 ISBN 0-471-61951-5.

[8] Larson, W.J.; Wertz, J. R. (Ed). (1999) "Space mission analysis and design 3". Dordrecht, Netherlands: Kluwer Academic, 1999. ISBN: 969306936 ISBN 1-881883-10-8.

[9] Julio Filho, A. C., Ambrosio, A. M., Ferreira, M. G. V., “Model-Based System Engineering (MBSE) applied to Ground Segment Development of Space Missions: New Challenges”. In: International Astronautical Congress, 72th Online Proceedings...2021

[10] Julio Filho, A. C.; Ambrosio, A. M.; Ferreira, M. G. V. (2021) " The Ground Segment: A proposal Framework based on concepts of Dynamic Management of the Space Link Extension Protocol Services”. In: International Conference on Space Operations 16th, Cape Town, South Africa.

[11] CCSDS Space Communication Cross Support – Architecture Description Document - Informational Report. CCSDS 901.0-G-1. Green Book. Issue 1. Washington, D.C., November 2013.

[12] The Interagency Operations Advisory Group https://www.ioag.org/default.aspx. Accessed Jul 2021.

[13] https://www.nasa.gov/mission_pages/sport/index.html

[14] Julio Filho A. C., Ambrosio, A. M., Ferreira, M. G. V., Bergamini, E. W., “New Challenges for Dynamic Management of the Space Link Extension Protocol Services: The Amazonia-1 Satellite Ground Segment”. In: SPACEOPS Conference, Marseille, France. Proceedings...2018. DVD.

[15] Julio Filho, A. C., Ambrosio, A. M., Ferreira, M. G. V., Loureiro, G., “The China-Brazil Earth Resources Satellite - CBERS-4A: A proposal for Ground Segment based on the Space Link Extension Protocol Services”, in: International Astronautical Congress, 70th IAC. Washington D.C., United States, 2019.

[16] Julio Filho, A. C.; Ferreira, M. G. V.; Ambrosio, A. M. . The Ground Segment: A proposal Framework based on concepts of Dynamic Management of the Space Link Extension Protocol Services. In: 16th International Conference on Space Operations, 2021, Cape Town, South Africa.

[17] Jotha, L. S. “Estação multimissão de Natal - manual técnico.” São José dos Campos: INPE, 2020. 90 p. IBI: <8JMKD3MGP3W34R/436TMAB>. (sid.inpe.br/mtc-m21c/2020/09.02.14.30-MAN). Available in: <ibi:8JMKD3MGP3W34R/436TMAB>.

[18] https://ccsl.ifrn.edu.br/portfolio-de-projetos/emmn-estacao-multi-missao-de-natal/.

[19] http://www2.inpe.br/climaespacial/portal/wp-content/uploads/2020/08/PROGRAMA_EMBRACE.pdf