

# On the use of Data-Driven approach for Verification and validation of SPORT cubesat-based satellite interoperability with Natal Multi-Mission Ground Station

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## Abstract

This paper outlines a comprehensive data-driven approach for the verification and validation (V&V) of the SPORT (Scintillation Prediction Observations Research Task) CubeSat satellite mission at the Natal Multi-mission Ground Station (EMMN). The increasing complexity and demand for V&V in multi-mission ground station environments, marked by the concurrent operation of multiple missions, underscore the need for robust V&V frameworks that ensure the operational effectiveness and reliability of satellite systems. Traditionally, space systems engineering has followed a conservative approach, emphasizing the reuse of established and validated ground segment components to minimize risks and control costs. However, with the commercialization of space and the increasing launch of commercial vehicles, there is a shift towards more flexible and adaptive V&V practices. Conventional methods, characterized by their linear, sequential nature and reliance on extensive documentation and manual testing, face significant challenges in terms of cost efficiency, time constraints, and adaptability. These methods often lack the flexibility to respond to rapid changes, making them less suitable for modern satellite missions, which frequently use commercial off-the-shelf components and satellite constellations. The EMMN V&V strategy for SPORT integration leverages a data-driven methodology to address these challenges, enhancing operational efficiency and reliability. This approach is particularly challenging in multi-mission settings like EMMN, where managing multiple missions while maintaining high reliability and responsiveness is crucial. The SPORT CubeSat-based satellite underwent comprehensive interoperability testing at EMMN, beginning with protocol verification for AX.25 and CCSDS, essential for maintaining robust communication links between the satellite and the

ground station. Telemetry, Control, and Command (TMTC) testing confirmed the station's ability to both receive telemetry and send control commands effectively. Operational engineering validation focused on integrating the SATCS V1 (Satellite Control System) with EMMN via a remote link, as SATCS was the chosen software for the SPORT mission operations. Although EMMN is designed to be mission-agnostic, SATCS was operated from the Satellite Control Center (CCS) at INPE's headquarters in São José dos Campos, SP. The validation process also included testing the RF Unit of the SPORT satellite's engineering model to evaluate its radio signal transmission and reception capabilities, critical for mission success. The V&V process for SPORT communication with EMMN was structured into phases, starting with a semi-formal verification of individual components in simulated environments, followed by real-time validation using system and machine logs under actual operational conditions. This phased approach allowed for comprehensive assessment and early detection of integration issues, thereby ensuring reliability. The data-driven methodology enhances operational efficiency, reduces dependency on manual testing, and achieves significant cost savings, making it an attractive option for multi-mission ground segments. In conclusion, the V&V process of the SPORT CubeSat mission demonstrates the vital role of data-driven methodologies in ensuring mission success within complex and dynamic space environments. The framework, which integrates real-time data analysis and phased validation, offers a solution to challenges in satellite communication with ground segment.

## Keywords

Data-Driven Techniques, Verification and Validation, Multi-Mission Stations, Small Satellites, ECSS, Ground Segment Engineering, Software Development

## ACM Reference Format:

Moisés Cirilo de Brito Souto, Fátima Mattiello-Francisco, Manoel Jozeane Mafra de Carvalho, and Hilario José Silveira Castro. 2018. On the use of Data-Driven approach for Verification and validation of SPORT cubesat-based satellite interoperability with Natal Multi-Mission Ground Station. In *Proceedings of Space Mission Operations and Ground Data Systems: Toward Space Sustainability (SPACEOPS '25)*. ACM, New York, NY, USA, 4 pages. <https://doi.org/XXXXXXXX.XXXXXXX>

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SPACEOPS '25, May 26 to 30, 2025, Montreal, Quebec, Canada  
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ACM ISBN 978-1-4503-XXXX-X/18/06  
<https://doi.org/XXXXXXXX.XXXXXXX>

## 1 Introduction

In recent years, the increasing complexity of satellite operations and the growing demand for Verification and Validation (V&V) solutions in multi-mission ground stations have presented significant challenges for space systems engineering. Traditionally, conservative approaches to space systems development, focused on reusing validated components, have successfully minimized risks and controlled costs. The prevailing design philosophy in the space industry has traditionally been "design once, use often," emphasizing the reuse of verified and validated components to mitigate risks and costs [4]. This conservative philosophy is particularly evident in the way satellite system designs have been approached. Historically, the choice of the launch vehicle played a central role at the beginning of satellite systems engineering, determining many aspects of the satellite's design because of the launch vehicle's specifications and constraints. However, recent commercialization of space and the proliferation of commercial vehicle launches demand more flexible and adaptive V&V practices. Conventional methods, characterized by linear and sequential processes and a heavy reliance on extensive documentation and manual testing, struggle to meet the demands of cost efficiency, shortened timelines, and adaptability in dynamic environments.

The increasing demand for shared ground facilities in small satellite missions underscores the need for efficiency and agility in verifying and validating multimission properties to ensure ground station readiness.

In this context, the SPORT (Scintillation Prediction Observations Research Task) CubeSat [8], a satellite mission designed to investigate ionospheric conditions, was integrated into the Natal Multi-Mission Ground Station (EMMN) using an innovative data-driven V&V methodology. The integration of CubeSat missions in multi-mission ground station environments, such as EMMN, presents specific challenges, particularly in maintaining operational reliability and responsiveness while managing multiple missions concurrently. Therefore, it is essential to adopt a V&V approach that addresses these needs without compromising system effectiveness or robustness.

In this context, the systematic verification and validation of EMMN in support of the SPORT mission through data-driven techniques represent a significant advancement in the field of space engineering.

The significance of this research lies in the need to optimize Ground Stations V&V processes, considering the complexity and diversity of missions sharing these infrastructures. The complexity of these traditionally documented and time-consuming processes highlights the need for innovative approaches, such as data-driven techniques, to enhance the efficiency and accuracy of ground operations.

To provide a comprehensive context, it is crucial to understand the challenges faced in verifying and validating multi-mission properties, involving the integration of various systems and ensuring compliance with operational requirements. The methodology used in this study will be detailed to provide insights into the adopted approach and the procedures employed in the systematic verification and validation of EMMN. Furthermore, the research will be characterized by a mixed methodological approach, combining

qualitative and quantitative elements for a comprehensive and in-depth understanding of the processes involved in preparing Ground Stations for small satellite missions.

The article is structured as follows: The Related Work section contextualizes previous research and existing methodologies in the field of V&V for ground stations, highlighting advancements and challenges in applying data-driven techniques. Additionally, it addresses key topics such as the SPORT mission and the EMMN system, providing a comprehensive background for understanding their relevance to the study. Methodology section details the data-driven techniques used in the V&V of EMMN for the SPORT mission, describing the processes of systematization and optimization of V&V through data-driven approaches. The Case Study presents the V&V of EMMN for the SPORT Mission, the results of applying data-driven techniques in the V&V of EMMN, and the analysis of the benefits obtained in terms of efficiency, accuracy, and agility in preparing the Ground Station for the SPORT mission. The Discussion reflects on the relevance and impact of data-driven techniques in the V&V of Ground Stations for small satellite missions, comparing them with traditional approaches and identifying lessons learned. Finally, the Conclusion synthesizes the main results and contributions of the study, providing recommendations for future research and practical applications of data-driven techniques in the V&V of Ground Stations.

## 2 Related Work

The Scintillation Prediction Observations Research Task (SPORT) project is an international mission designed to study the effects of ionospheric variability at low latitudes and its influence on the propagation of radio signals. The SPORT CubeSat was developed to analyze the conditions that lead to the formation of Equatorial Plasma Bubbles (EPBs) and their relationship with phenomena such as ionospheric scintillation and plasma depletions, using a combined approach of in situ measurements and ground-based observations [8].

The mission is a collaborative effort between institutions in the United States and Brazil, including NASA, INPE, and ITA, and has faced significant challenges from its testing and integration phase to its orbital operation, with key lessons learned during the observatory's validation and commissioning process [6].

The data collected by SPORT, including measurements of electron density, temperature, and ion composition, are crucial for understanding the evolution of ionospheric irregularities and improving predictive models, contributing to the advancement of space weather research and its impact on global communications [5].

One key reference for the SPORT mission is the ITASAT project, developed at Instituto Tecnológico de Aeronáutica (ITA), which served as a precursor in CubeSat-based space operations, providing valuable engineering and operational experience for small satellite missions [6]. Similarly, the NanoSatC-BR initiative has contributed significantly to space weather studies, focusing on magnetospheric and ionospheric interactions [5].

A crucial aspect of the SPORT mission is its ground segment, which plays a fundamental role in ensuring reliable telemetry, tracking, and command (TT&C) operations. The Brazilian National Institute for Space Research (INPE) is responsible for mission operations, utilizing pre-existing satellite control infrastructure adapted specifically for the SPORT CubeSat. The INPE's Satellite Control Center (CCS) manages spacecraft control remotely, integrating a tailored version of the Satellite Control System (SATCSport) to handle operations via UHF/VHF communication links for command uplink and telemetry downlink, while scientific data is transmitted via X-band ground stations for further analysis at the EMBRACE space weather center [1].

Expanding on the SPORT mission, the success of any space-based scientific endeavor relies not only on the satellite itself but also on an efficient ground segment responsible for communication, operations, and data management. The SPORT ground segment, developed by the Brazilian National Institute for Space Research (INPE), plays a pivotal role in ensuring mission success by providing satellite tracking, control, and data reception. The mission operations are centralized at INPE's Satellite Control Center (CCS) in São José dos Campos, where the SATCSport system is used for telemetry, tracking, and command (TT&C) operations. The ground stations at Cachoeira Paulista (CP), Cuiabá (CB) and Natal (NTL), facilitate X-band downlinks, ensuring continuous retrieval of scientific data, while the EMBRACE data center is responsible for data storage and distribution to mission stakeholders [1].

A key element in this architecture is the Natal Multi-Mission Ground Station (EMMN), managed by INPE's Northeastern Space Coordination (INPE/COENE). Originally developed for the SACI mission in the 1990s [7], the EMMN has been modernized with software-defined radio (SDR) technology, open-source tools, and web-based applications to support a variety of CubeSat missions, including SPORT. The station operates in VHF/UHF/S-band, allowing for real-time monitoring and control of small satellite missions. Currently, EMMN supports missions such as ITASAT-1, NanoSatC-BR1/BR2, and SCD-1/2, demonstrating its versatility and importance in Brazil's space infrastructure [1].

The integration of the EMMN into SPORT's ground segment marks a significant milestone in INPE's long-term strategy to establish a network of regional ground stations, enabling coordinated nanosatellite operations across different mission profiles. This station will also serve as a critical asset for the Natal Multi-Mission Ground Station (EMMN) in future initiatives, including missions associated with the Brazilian Multi-Mission Platform (PMM), further expanding Brazil's capabilities in space operations, Earth observation, and communication satellites [2].

Given its modular and reconfigurable nature, the EMMN introduces additional complexity in its verification and validation (V&V) processes. Unlike traditional monolithic ground stations, which operate with fixed configurations for specific missions, EMMN must dynamically adapt to different communication protocols, radio frequency bands, and mission-specific data handling requirements [3]. This variability necessitates a structured V&V approach to assess system interoperability, latency, and data integrity across multiple missions.

The verification process involves evaluating the SDR-based communication architecture, which enables flexible reconfiguration of

radio links without hardware modifications. Ensuring compatibility between SDR processing modules, the antenna tracking system, and remote operator interfaces is critical for seamless operations. The validation phase focuses on end-to-end performance testing, assessing link reliability, signal processing accuracy, and compliance with Consultative Committee for Space Data Systems (CCSDS) standards.

A key challenge in the validation of EMMN is the interoperability assessment between multiple mission architectures. Missions utilizing different modulation schemes, frequency bands, and encryption protocols require a robust testing framework capable of simulating real-world satellite passes, signal degradations, and Doppler shift effects.

Given its software-defined radio (SDR) architecture, distributed processing, and remote accessibility, the station's verification and validation (V&V) process is essential to ensuring its interoperability and mission readiness. Unlike dedicated ground stations, which are designed for a specific mission profile, EMMN must dynamically adapt to varying communication protocols, frequency bands, necessitating a structured validation approach.

The SPORT mission utilizes a customized version of the SATCS for TT&C operations [1]. The SATCS framework, which has been employed in INPE's ground segment for large-scale satellite missions, was tailored for CubeSat operations through the SATCSport adaptation. Within this context, EMMN serves as a remote, multi-mission ground station, integrating into SPORT's mission operations by providing UHF/VHF-based TT&C services.

A critical aspect of the EMMN verification process involved its integration with the SATCS infrastructure, ensuring that the station could reliably process and relay telemetry and command data for SPORT.

These tests focused on assessing data integrity, real-time responsiveness, and command execution latency, particularly in scenarios where SPORT's pass opportunities were limited, requiring efficient data exchange.

The EMMN is designed to be agnostic to the specific operational requirements of individual missions. However, to ensure interoperability across diverse mission profiles, the station must anticipate and accommodate a wide range of technical characteristics associated with satellite communication and ground segment operations.

Despite its mission-agnostic nature, EMMN must implement predictive compatibility strategies, particularly concerning radio frequency (RF) configurations, network latency constraints, and real-time data processing requirements. These considerations are crucial in multi-mission environments where the station must support concurrent operations with satellites utilizing different TT&C specifications, including protocol encapsulation methods, encryption standards, and telemetry data rates. Ensuring that EMMN can dynamically adapt to these constraints without requiring hardware modifications is a key aspect of its verification and validation (V&V) framework.

Moreover, the interoperability of EMMN extends beyond its physical layer capabilities, encompassing software-defined radio (SDR) configurations, virtualized network management, and remote operational control. By leveraging distributed system orchestration, the station can autonomously adjust its internal parameters in response to mission-specific operational demands, ensuring seamless

integration with mission control centers while minimizing the need for manual reconfiguration. This approach allows the station to maintain high availability and reliability across varying mission lifecycles, from LEO CubeSat constellations to larger-scale Earth observation and communication platforms.

In this context, the EMMN verification process must assess not only hardware and software performance but also the station's ability to align with expected mission parameters. The following sections will outline the methodological approach adopted for EMMN's V&V for operational deployment, detailing the test scenarios, interoperability assessment strategies, and performance validation procedures employed to ensure its readiness for multi-mission satellite tracking and control.

### 3 Methodology

### 4 Case Study

### 5 Discussion

### 6 Final Remarks

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Received 20 February 2007; revised 12 March 2009; accepted 5 June 2009