System Engineering Process to Design a Low-Cost Ground Station for Defense Applications

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Abstract **- Space systems are composed of three Segments: Space, Launch, and Ground Segment. Although the first one is employed to achieve the mission objectives, a reliable ground station is a crucial resource for maintaining a mission in operational conditions. A Ground Segment can be implemented, considering higher or lower cost. It depends on the complexity of the desired system. This work aims to present a design process to implement a low-cost and low-complexity station, using Software-Defined Radio for receiving communications from space and monitoring signals from emitters on the ground. A simple use case employing Bifilar and Quadrifilar Helix Antennas for meteorological satellites is presented. Next, an example of an application in Electronic Warfare is presented, where the data fusion of data from space and ground emitters is suggested to provide geolocation information and identification through the d-interleaving process. The results show that a Ground Station can be developed with low complexity and low cost.**

Keywords **- Ground Station; Software-Defined Radio; Satellite Signal Monitoring.**

I. INTRODUCTION

Ground Segments are an essential element of Space Systems. They are responsible for the reception, processing, and transmission of data between satellites and ground operators [1]. Their function goes beyond simple data reception: ground stations are vital for mission control, orbit planning, system integrity verification, and the dissemination of information collected by onboard sensors [2].

With the rise of small satellites, such as CubeSats, and the proliferation of open-access technologies, there has been a growing demand for low-cost, and versatile solutions for space data reception [3]. At the same time, some applications, such as defense, require reliable platforms, also low cost, capable of interception, tracking, and analysis of signals across different bands of the electromagnetic spectrum, including terrestrial, maritime, and space environments [4].

Following this context, this work proposes the implementation of a low-cost Ground Segment based on flexible and adaptable technologies, such as Software-Defined Radio (SDR) [4], combined with customized antennas, including a Quadrifilar Helix Antenna (QFH) as proof of concept. Furthermore, this work suggests an approach to designing a low-cost station for the defense.

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The station was initially designed to receive signals from meteorological satellites in the 137.5 MHz band. However, the design of modular architecture allowed an expansion to receive data in many frequency bands used by CubeSats (VHF, UHF, and S-band), amateur radio (144-146 MHz and 430-440 MHz), aeronautical signals (ADS-B at 1090 MHz), as well as transmissions from drones and other mobile platforms Table I.

TABELA I. MONITORED FREQUENCY BANDS

Frequency (MHz)	*Application*	*Examples*
137.100 137.912	Meteorology (APT/HRPT)	NOAA-15, NOAA-18, METEOR-M2s
144 – 146	Amateur Radio (VHF)	Cubesats, Beacons
433 – 440	Amateur Radio (UHF)	Cubesat Telemetry, Drones
855 / 915	IoT / LoRa / Drones	Remote Control, Telemetry Links
1090	Aeronautical (ADS-B)	Civil/military aircraft tracking

Specifically for drones, different frequency bands are used depending on the function of the signal. The 2.4 GHz band is widely used for remote control and telemetry, while 5.8 GHz is common for real-time video transmission. Frequencies such as 433 MHz and 915 MHz are used in long-range telemetry links with protocols like MAVLink, and bands such as 1.2 GHz and 1.3 GHz are employed for video transmission with low interference. Security and remote identification systems operate in the 868 MHz (Europe) and 915 MHz (America) bands, often using technologies like LoRa.

In addition to modularity, the system was designed with a focus on portability, allowing its use in temporary tactical operations or remote areas. The structure supports different antenna types—fixed, mobile, or embedded—according to the mission and type of signal being captured. This flexibility enables the station to function as a multi-target signal tracking and monitoring platform in terrestrial and maritime scenarios.

The Ground Segment was also designed following the concept of Ground Segment as a Service (GSaaS), which allows the design of the station to meet the needs of the desired customer services. It means the possibility of changing parts of the modular systems according to the client's interest [5].

So, in addition to its ability to receive signals from satellite systems, the station has potential to be applied on the surveillance of the air, sea, and land domains. For example, to support Electronic Warfare (EW) Operations, including the execution of signals intelligence (SIGINT) activities, such as monitoring orbital systems and foreign satellite passes. By combining these capabilities in a portable and reconfigurable platform, the solution can contribute directly to strengthening national sovereignty in the spectral domain and autonomy in accessing critical spaceborne information.

This paper is organized into six sections. First, the introduction provides an overview of the proposed ground segment system. The second section presents the process used to build the ground station, which considered the Space System Engineering methodology. The third section presents the implementation of a ground station focusing on receiving meteorological data as proof of concept. The fourth section summarizes the results of the ground station implementation. A description of a use case for Defense applications is the object of Section V. Section VI ends the paper by presenting the final considerations.

II METHODOLOGY

Although the ground station was concepted with low complexity, the development followed a requirement-driven approach, based on Systems Engineering principles for space applications [6], [7], and [8]. The methodology adopted was summarized in four main steps: (i) from the Concept of Operation, the functional requirements were elaborated; (ii) from the functional requirements, a modular design was performed; (iii) after some developments and items acquisitions, the prototype was implemented; finally, (iv) the verifications and tests were performed for the system validation.

In the first step, mission requirements were defined to enable reception across multiple frequency bands — including VHF, UHF, L, S, and SHF — focusing on meteorological data reception and CubeSat monitoring as primary objectives. aeronautical signal detection, drone tracking, and tactical communications were considered as secondary objectives. Software-Defined Radio (SDR) was chosen as the core system element, which was acquired based on its spectral flexibility and software adaptability, minimizing dependence on dedicated hardware [4].

Next, the Ground Segment's architecture was designed prioritizing modularity, portability, and low energy consumption. Interchangeable subsystems were considered, such as QFH and bifilar antennas for specific frequency bands. Due to the low power demand of the main components — such as SDRs and low-consumption microcomputers — there is potential for using rechargeable batteries and solar panels as power sources in remote or mobile tactical operations.

The prototype was built using a Raspberry Pi microcomputer connected to a wide-spectrum RTL-SDR receiver. The platform was conFig.d with SDR++ for dynamic frequency scanning and spectral visualization, and SatDump for both automated satellite tracking and decoding of meteorological and CubeSat signals. Orbital tracking support was provided by GPredict and Look4Sat, free software used to forecast satellite pass windows and optimize system operation timing.

Antenna orientation for tracking the satellite passes was required only for the bifilar antenna tests, since the omnidirectional QFH antenna did not require directional adjustment. Nevertheless, it must be highlighted that the bifilar antenna was acquired with the SDR while the QFH antenna was developed by the author and it is under test and validation phase. So, tests with the QFH revealed a high noise level, which compromised signal decoding quality and indicated the need for further investigation.

During operation with both antennas, impedance matching between the 50-ohm coaxial transmission line and antenna elements proved essential. Significant mismatches led to standing waves (high Voltage Standing Wave Ratio - VSWR), reducing reception efficiency. To mitigate these effects, SDR++ scanning techniques were used to identify and correct improper coupling [9].

Python scripts were developed for automating spectral scanning, calibration, and resonance peak detection, enabling real-time antenna performance monitoring and spectral event identification.

The final stage involved practical validation. Tests were conducted with NOAA and Meteor-M2 meteorological satellites in the 137.5 MHz band, verifying signal quality, automated detection reliability, and data extraction capabilities. Additional spectral observations included aeronautical signals (ADS-B), drone telemetry, CubeSat beacons, and amateur radio transmissions, analyzed using real-time spectrograms and medium-resolution FFT spectral density.

This iterative approach not only validated the station's technical feasibility but also identified limitations (*e.g.*, unexpected interference) and optimization opportunities for future adaptation to operational environments such as EW, SIGINT, and environmental applications.

Finally, the station only operates in passive mode. No transmission was used in this methodology.

III IMPLEMENTED ARCHITECTURE

The ground station's architecture was based on three fundamental principles: modularity, portability, and flexibility to operate across multiple frequency bands. This first model was developed with a focus on receiving meteorological data, which can already be applied to a variety of activities. Among these are:

a) academic: aimed at students in the final years of elementary school, high school, undergraduate, or professional education, whether to spark motivation for the space sector or for basic instruction in ground station operations.

b) operational: remote locations or environments where direct reception of orbital data may be useful.

c) research environments: for research into the application of SDR and antenna functionalities.

However, once this proof-of-concept stage is complete, new functionalities are expected to be added that will enable the ground station to be applied to optical image processing, radar image processing, and the defense sector, specifically in EW through Electronic Intelligence (ELINT) activities.

The conceptual solution was composed of three main modules presented in Fig. 1 (Adapted from [8]) as Modular Ground Segment as a Service, from now on referred as NST-GSaaS Project.

From right to left of Fig. 1, the Space Segment is presented as the source of the signals to the NST-GSaaS. The spacecraft images display two orange arrows (representing data), one that come from a NOAA meteorological satellite (top) and a generic CubeSat (botton).

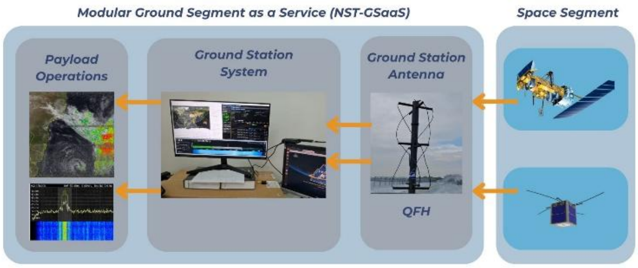

Fig. 1. Modular Ground Segment as a Service (Adapted from [8]), referred as NST-GSaaS Project.

The signals are received by the Ground Station QFH antenna Module (center right Fig. 1), which is responsible for telemetry reception [5], [8]. Although Fig. 1 shows just the QFH antenna, multiple antennas can be connected via low-loss coaxial cables. For this architecture, two main configurations were tested. First, a QFH antenna was used for receiving signals from polar-orbiting meteorological satellites. Despite its omnidirectional coverage, high background noise was observed, requiring investigation into coupling issues or local interference.

A bifilar directional antenna was also used for LEO satellite communication. Mounted on a manually adjustable base, it required orientation based on azimuth and elevation. SDR++ was used to scan and optimize spectral matching, considering that impedance matching was critical with both antennas. Mismatches led to reflections and standing waves, increasing the Voltage Standing Wave Ratio (VSWR) and degrading signal quality.

Continuing Fig. 1 (center left), the Ground Station module distributes the signals to the Ground Station System, which is responsible for time management, tracking, data acquisition, processing, and storage. The core of this module is a Raspberry Pi 5 microcomputer connected to an RTL-SDR receiver. This module allows reception of signals in the VHF (137–146 MHz), UHF (400–470 MHz), and other bands used by CubeSats, amateur radio, ADS-B (1090 MHz), and drone systems.

The Raspberry Pi runs SDR++ for spectral scanning and SatDump for tracking, decoding, and demodulation. Python scripts automate peak detection, data logging, and event marking. The system also manages data downloads and supports integration with visualization tools. The receiver operates with adjustable bandwidth and high sensitivity, compatible with leading spectral analysis software. Additional features include local storage, Wi-Fi network access for remote operation, and optional integration with tools like Look4Sat and GPredict for orbital tracking. Fig. 2 presents the interface view combining GPredict (satellite tracking map, on the left) and SatDump (automated decoding and spectral visualization, on the right and bottom) during real-time reception in the 137.5 MHz. Once processed, the data is distributed to the Payload Operation Module.

Fig. 2. Interface view combining GPredict (satellite tracking map) and SatDump (automated decoding and spectral visualization) during real-time reception in 137.5 MHz.

IV. RESULTS

The Payload Operation Module (left Fig. 1) analyzes the image, processes it, and distributes it to the users. In sequence, Fig. 3 presents the spectrogram captured using SatDump, showing peak signal intensity at approximately 137.9 MHz. Fig. 4 presents a portion of a decoded meteorological satellite image received using the implemented NST-GSaaS. Note on the left of this Fig. a thin yellow line which indicates the geographic limits of Brazil.

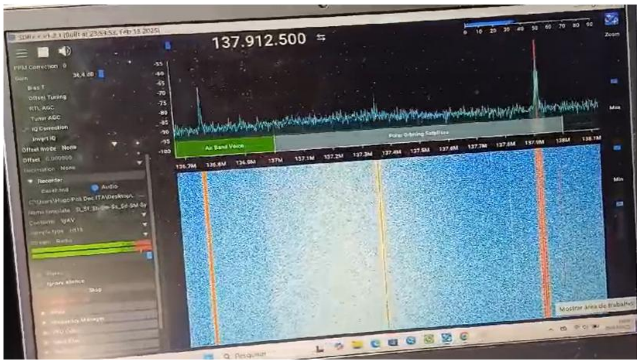

Fig. 3. Spectrogram captured using SATDUMP, showing peak signal intensity around 137.9 MHz.

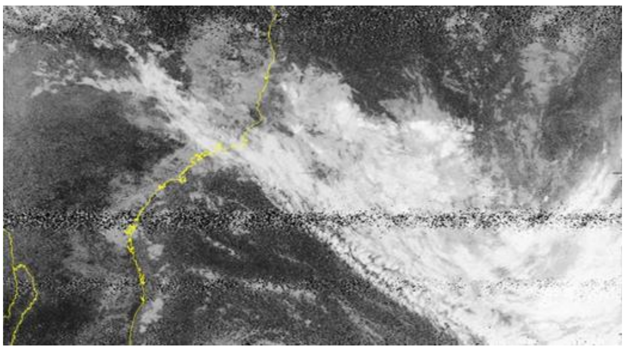

Fig. 4. Decoded meteorological satellite image received using the implemented NST-GSaaS.

The modular design allows future upgrades with new antennas, integration into larger station networks, and deployment in real-time spectral analysis tasks for security and strategic applications.

These results confirm the station's effectiveness across multiple bands, with practical applications in meteorological observation, satellite tracking, aeronautical and amateur signal analysis.

V. USE CASE FOR DEFENSE

Despite being built with low-cost components, the proposed station shows strong potential for use in defense and security contexts. Its modularity, portability, and multi-band capability enable integration at different operational levels, from monitoring to decision support.

A key application is in passive EW, via interception and analysis of signals from satellites, aircraft, drones, and ground communications. The NST-GSaaS can be customized to detect unusual spectrum activity, identify unauthorized transmissions, contribute to electromagnetic situational awareness, and provide geolocation, combining these functionalities with satellite data through a data fusion process.

In Signals Intelligence missions (SIGINT), the NST-GSaaS can collect and analyze transmissions in open or semi-open networks, identifying sources, frequencies, modulation patterns, and behaviors. This supports real-time tactical decisions and strategic signal intelligence databases.

For example, the system's ability to capture typical drone communication signals (433 MHz, 915 MHz, 2.4 GHz, 5.8 GHz) enables surveillance of low-altitude aerial space in critical or border areas. Tools like SDR++ and SatDump enable real-time visualization of spectral activity, aiding intrusion detection, signal jamming, and unauthorized transmissions in use.

Now consider Fig. 1, customized at Fig. 5 for EW applications. The source of the signals can be provided by the Space Segment or emitters on the ground, sea, or air.

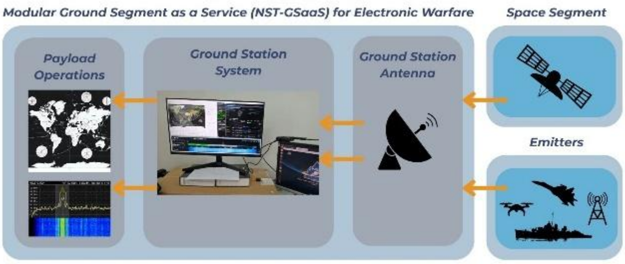

Fig. 5. Modular Ground Segment as a Service customized for Electronic Warfare (EW) applications.

The signals are detected by the Ground Station antenna Module, which can be customized for the range of frequencies needed for monitoring. The De-interleaving process can be implemented in the Ground Station System Module to enable the function of separating the interleaved pulses from each emitter, allowing identification of the radar's characteristics such as radio frequency (RF), amplitude (power), direction of arrival (DOA), time of arrival (TOA), pulse width (PW), pulse repetition interval (PRI), among other parameters [10]. These features can be implemented using Python or MATLAB, beyond the actual tools available in the Module.

The Payload Operation Module can be customized to fuse ground data with orbital data, providing not only detailed information about the emitters but also their geolocation data. In other words, the NST-GSaaS-EW can work as an Electronic Warfare Support Measures (ESM) outfit with the advantage of integration in the same system information provided by the Space Segment, considering low complexity and low cost.

This use case presentation does not cover NST-GSaaS's potential.

The station also supports orbital system monitoring, including tracking foreign LEO satellites used for imaging or tactical communications. Correlating orbital predictions with spectrum analysis can help detect anomalous behavior and classify space-based assets, contributing to Space Situational Awareness (SSA).

Thanks to its portability and minimal infrastructure needs, the system suits field deployments, military exercises, and mobile command support. It can integrate into C4ISR networks and provide near-real-time situational data.

In summary, the station serves as a tactical spectral surveillance platform, with use cases including monitoring satellite passes and foreign orbital systems; tracking RF signals from emitters like aircraft and drones; analyzing spectral occupancy in conflict or strategic areas; supporting SIGINT and passive EW operations; and assisting in field training and autonomous signal collection missions; among other applications for Defense.

VI FINAL CONSIDERATIONS

This paper presented the design, implementation, and validation of a functional, low-cost Ground Segment prototype, defined as NST-GSaaS, focused on civil and defense applications.

A use case focused on meteorological applications was built as proof of concept, demonstrating the system's ability to be customized for defense applications. The developed architecture proved to be modular, portable, and flexible, enabling the reception and analysis of signals from meteorological satellites, CubeSats, aircraft, and drones.

Practical testing demonstrated that even with affordable components such as RTL-SDR and Raspberry Pi, it is possible to obtain reliable results across several frequency bands. Software tools such as SatDump, SDR++, GPredict, and Look4Sat proved effective in automating tracking, decoding, and spectral detection tasks.

Strategically, the NST-GSaaS shows potential for spectral surveillance, SIGINT, passive EW, and orbital monitoring. Its capacity to operate with minimal infrastructure and in field conditions expands its utility for expeditionary scenarios, training, and integration into C4ISR environments.

Future work may include structural improvement of the QFH antenna, testing new compact directional antennas, expanding to S-band reception, and integrating Artificial Intelligence (AI) for automatic spectral pattern classification. Creating a spectral events database associated with orbital activity is also a natural evolution.

Summarizing, NST-GSaaS proposed here is a viable, accessible, and functional solution for educational projects, scientific missions, and strategic defense applications, contributing to democratizing space technology and enhancing national sovereignty in the spectral and orbital information domains.

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