EMMN - Reports about a Multi-Mission Ground Station on Cubesats tracking

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Abastract

The Estação Multi-Missão de Natal (Natal Multi-Mission Station) (EMMN) resulted from the updating process of a legacy satellite tracking system, belonging to the Instituto Nacional de Pesquisas Espaciais (National Institute of Space Research) (INPE). As a ground station, the objective is to provide a secure communication link between operators and their respective orbiting satellites. To this end, the ground segment automatically acts as a broker between satellite and operator, providing the latter with an encrypted data link, using a Virtual Private Network (VPN), and reconfigurable Radio Frequency (RF) channels, in Very High Frequency (VHF), Ultra High Frequency (UHF) and S bands. EMMN's operational architecture uses Open-source software and solutions based on Distributed Systems, in an Ethernet network, which allows for better scalability and maintenance of each component of the functional complex. The services are “triggered” by an automatic system for scheduling satellite passes, whose priorities are predefined, initiating an orchestration of distributed services using the Message Queuing Telemetry Transport (MQTT) protocol. At this point, three main operations are performed in the orchestrated process, one related to the radio, another to the tracking system, and a third to communication between ground segments involved in the operation. The first task activated is made up of the collaboration between a Software Defined-Radio (SDR) and a micro-controlled set of switches, to interconnect the required antennas to signal amplifiers. This allows the channel configuration for the UHF, VHF, and/or S bands, and further configures the signal processing in SDR to modulate/demodulate the signals according to the target satellite. Another task activated is the Antenna Tracking System, formed by an electromechanical set which has been also updated to a microcontrolled scheme. It performs tracking based on an ephemeris table generated by transferring the Two-Line Element (TLE) of the satellite to be tracked, automatically obtained from the Internet. The last task is the remote communication system, which enables the external satellite operator to access the station through a secure communication channel, via Transmission Control Protocol (TCP) and VPN, providing access to Telemetry, Tracking and Command (TT&C) service and providing full compliance of mission-specified ground-to-ground communication protocols. This paper will present the report of the experiences of using the EMMN involving its multi-mission operations, with data derived from tracking some satellites.

1. Introduction

The growing number of Cubesats and Nanosats in Low Earth Orbit (LEO) has provided the emergence of demands in the space sector, such as the need to modify earth stations for the multi-mission concept. An example is the adaptation of Radio Frequency (RF) links on the ground segments to different compositions, allowing the tracking of the elements of different space missions [1].

Aiming at this context, the Instituto Nacional de Pesquisas Espaciais (Brazil's National Institute of Space Research) (INPE) updated a legacy satellite tracking system, located in the Natal city, resulting in the Estação Multi-Missão de Natal (Natal Multi-Mission Station) (EMMN). The station's new role is to cooperate in missions as a link broker, providing scheduled tracking services and reconfigurable RF Front-End link access via encrypted data channels. The abstraction of part of the Telemetry, Tracking, and Command (TT&C) tasks, allows a Satellite Operator to dedicate its efforts to the use of the communication and mission control application.

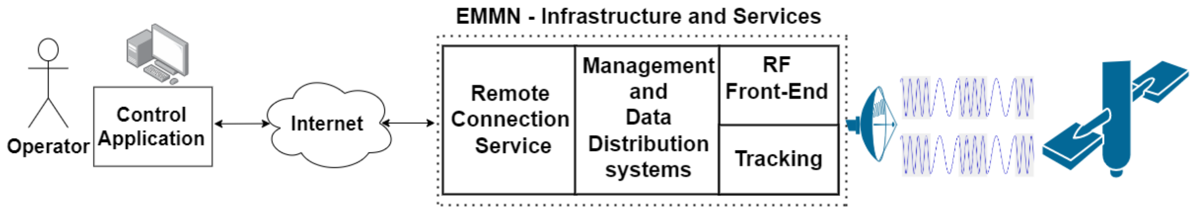


Figure 1: EMMN services' diagram of use in satellite communications.

EMMN's new architecture uses the orchestration of virtualized and networked services, which manipulate an electromechanical antenna rotation system and provide an operator with access to the station's other systems via a Virtual Private Network (VPN). With the proper permissions, the operator will be able to perform TT&C actions, with the RF Front-End acting on reconfigurable radio channels in different modulations, such as Very High Frequency (VHF), Ultra High Frequency (UHF), and S bands. The links are guaranteed by a switching system of antennas and amplifiers together with a Universal Software Radio Peripheral (USRP) [2]. To meet the multi-mission objective, the main orchestrated tasks are divided into the following systems: Management and Data Distribution, Tracking, Radio and Remote Communication. The first task acts as an activity aligner, while the other three are the main services of the station.

2. Related works

This section presents documents with information and works related to earth stations and space missions, helping in the understand the concepts of multimission and can also serve as a basis for projects in the sector.

Documents with recommendations for projects are available in the literature, addressing end-to-end communications with spatial elements. A set of standards for mission planning are the documents of the Consultative Committee for Space Data Systems (CCSDS), especially [3] and [4]. These documents present information on requirements and necessary operations for various services involved in space missions. The reference [3] informs about each segment in end-to-end communication, while the reference [4] details the content of messages between the elements involved.

In [5], some definitions of essential elements for multi-mission stations are presented, also helping in the modeling of RF links. Another reference that deals with the formation of the RF front-end and tracking system is [1], describing the architecture for stations and indicating the relationship of the multi-mission concept with the context of varied RF links and tracking of space elements in different orbits.

To establish different radio links, some solutions introduce the use of Software Defined-Radio (SDR), which allows for part of the communications to be done without the need to change hardware, through digital signal processing on computers. In [6], the use of Yagi-Uda and Helical Antennas associated with LNAs in the RF front-end stage, and the use of "RTL-SDR dongle" in the digitization and information processing stage are adopted. In [7], the concept of a multi-mission station uses VHF, UHF and S channels with Yagi antennas connected to LNAs and USRPs as SDR model. The RF elements are associated with two-axis rotation equipment.

In [8] a station concept is demonstrated using a rotation system and USRP for tracking small satellites in the S and X bands. A concept for the application of associated multi-mission receiving stations in a global network is found in [9], which describes different ways of implementing the station's antennas and indicates the use of "Raspberry Pi" and "RTL-SDR dongle" as radio processing components.

As a concept of interaction of stations or sector activities in a local or global network, an example can be found in [10]. In this work, a VPN system is used to interconnect sectors and users, ensuring security with encrypted data. It also uses dedicated RF structures and USRP. Many efforts for network services are developed using systems virtualization, conceptually presented in [11] and in the implementation of [12].

The EMMN's solution shares several concepts found in the literature, differing in the forms of the implementation of the services. It resembles the form of the virtualization of systems and network operations with access via VPN. It differs in the form of implementation for RF operations in multi-mission, acting not only with the use of USRP and rotation system but also in the microcontrolled connection between antennas and radios' Uplink/Downlink channels. Another highlight is the implementation of the Message Queuing Telemetry Transport (MQTT) [13] protocol for data sharing and operations synchronization.

3. EMMN's System

To meet the multi-mission context, EMMN had its infrastructure upgraded to provide remote access to the RF Front-end, serving TT&C activities for different missions. To this end, a solution was developed based on distributed network systems, consisting of both open-source and local solutions for software and hardware. A great advantage of this concept is the possibility of using the virtualization of the tools, which facilitates the maintenance, expansion, and distribution of the operational load of the assets.

Each element associated with the network adds an important feature to the activities, but the operations need to be aligned for the set to act in the mission's purpose. The solution used for alignment was the application of the MQTT protocol, which uses a "broker" system as a network centralizer to distribute data between activities, helping in the task of synchronization and coordination of operations.

To provide remote access to the reconfigurable RF Front-end, the infrastructure operates in 4 main service layers, namely: Manager and Data Distribution System; Tracking System; Radio System; Remote Communication System. Figure 2 shows the connection between the layers, as well as the remote operator's access channel to the services. The next subsections describe the contribution of each service group to a trace operation.

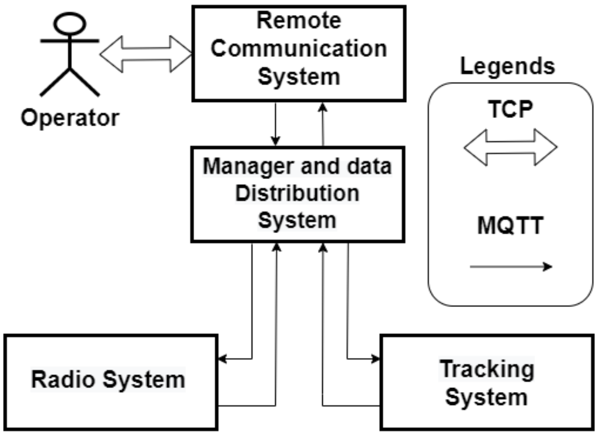


Figure 2: EMMN Summarized Architecture.

3.1. Manager and Data Distribution System

For multi-mission purposes, a necessary layer for an operation is the Manager and Data Distribution System, which will act as an event "trigger" for EMMN's main services. This layer provides the information necessary to initiate the activities of tracking, as well as to designate the configuration of the communication channels.

The block has four main tasks to ensure systems synchronization. The first application is the "Operations Manager", responsible for signaling activities to other blocks of the EMMN architecture, such as scheduling the tracking times for each satellite. These times are determined based on the Two-Line Element (TLE) provided for the mission.

Another task of the layer is the "Satellites Manager" service, which acts as the Application Programming Interface - Representational State Transfer (API-REST) for the other blocks' layers. The Station Manager is in charge of this service, by manually entering the satellites' information, such as satellite identification, Norad Number, TLE, Uplink and Downlink channel settings (frequencies, modulations, and baud rate). For TLE data, the default option is an automatic update of this parameter, via a request to CelesTrak [14].

During a tracking act, the third activity of the block is the "Orchestrator". This element acts upon receiving a call from the "Operations Manager", in order to activate the event. Faced with the request, the orchestration service collects the information necessary for the other actors to perform the desired activity, injecting the data in the proper order and intended destinations. To exemplify a trace, as shown in Figure 3, the "Operations Manager" sends data to the "Orchestrator", which collects the rest of the information in the "Satellites Manager" API, and then injects all the data into the respective "Data Distribution" (Broker MQTT) for task alignment. Continuing, the satellite's TLE will be transmitted in an MQTT topic and received by the "Tracking System" and the "Radio System"; the duration of the pass will be transmitted to the respective MQTT topic and then forwarded to the "Radio System" and "Remote Communication System".

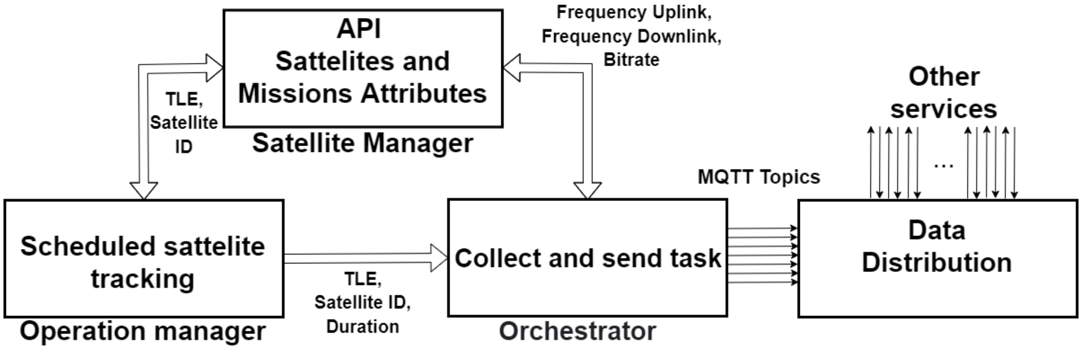
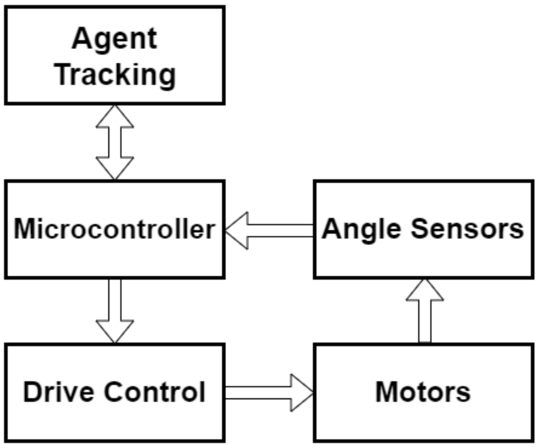


Figure 3: Flowchart of the Manager and Data Distribution System layer.

3.2. Tracking System

This complex is composed of a mechanical structure inherited from an old INPE project, which accommodates the S, UHF, and VHF band antennas, as seen in Figure 4((1)). The layer's task is to improve the performance of the RF Front-End by rotating the antennas and directing them toward the tracked element.

((1)) EMMN Antenna Complex.



((2)) Tracking control diagram.

Figure 4: EMMN tracking structure and its control synthesized diagram.

The mechanism positions the antennas using microcontrolled motors, with the microcontroller having a USB interface for receiving direction commands or querying the current antenna pointing. The simplified diagram of activities of the scheme can be seen in Figure 4((2)). The requests are received by the "Agent tracking" software that manages the rotations, taking decisions derived from the data received in the MQTT topics and from the readings via USB.

During a tracking event, the "Agent tracking" software receives the TLE to be used to create an ephemeris table, which indicates the antenna targeting times. The required annotation is converted by the management software into a data packet, which transfers the information via USB to the hardware that performs the action.

The piloting base is formed by microcontrolled hardware, with sensing through "resolvers" sensors for reading the azimuth and elevation angles, and signals applied to the motor rotation control drivers. The movement takes place by checking the angles by the “Resolvers”, followed by the application of the control signal to the drivers that smoothly rotate the motor axes in the desired direction. Operation is maintained until the structure is capable of the required Azimuth and Elevation.

3.3. Radio System

The layer focuses on the station’s RF Front-End configuration, selecting from the link antennas to the signal encoding and decoding scheme. In order to meet the objective, an antenna switching scheme and a signal processing script activation service were created. The general structure and its connections can be seen in Figure 5.

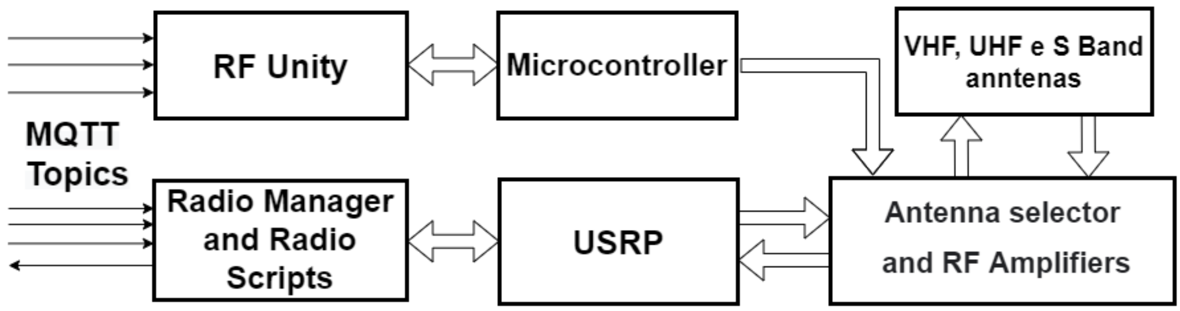


Figure 5: Diagram of the EMMN Radio System.

In Figure 5 is possible observe the antennas switching scheme. This system uses three operational blocks that control the selection of which antennas are connected to each Channel. The first block is the “RF Unity”, which interfaces the EMMN network with the second block (Microcontroller). The third block (Antenna selector and RF Amplifiers) is responsible for switching the antennas and RF amplifiers.

With the information injected by the “Orchestrator” into the link frequency topics, the “RF Unity” sends a sequence of bytes via USB to the microcontroller system. The message designates which antennas should be associated in the Uplink and Downlink. Antennas and their attributes can be viewed in the Table 1.

The bottom track of Figure 5 introduces how to execute the signal processing task. In this segment, a USRP associated with configuration scripts and signal processing generated by a GNU Radio application is used. [15]. The combination of artifices provides a radio scheme that works with different modulations and demodulations, without the need to modify the hardware.

The “Radio Manager” software interfaces radio scripts with mission radio calls. It also checks satellite ID information to activate two scripts, one for modulation and one for demodulation, which process the data together with the synchronized USRP.

The scripts use a block encoding scheme, generated by the GNU Radio application [15], whose block library provides numerous information processing options. There are blocks for interfacing with the network via the MQTT protocol, for adjusting the USRP configuration (such as frequencies and doppler shift correction), as well as for receiving telecommands to be transmitted and providing the decoded telemetry. Some blocks were developed locally.

Table 1: EMMN antennas.

Antenna	Model	Frequency range (MHz)	Gain (dBi)
VHF	YAGI-UDA 2x7 Elements	145 - 150	12.34
UHF (01)	YAGI-UDA 2x15 Elements	395 - 405	15.5
UHF (02)	YAGI-UDA 2x15 Elements	432 - 440	16.2
S	Parabolic 3m diameter	2.200 - 2.300	33.8

3.4. Remote Communication system

The last layer proposes to allow the remote user access to the services of the EMMN local network, especially the "Radio System". The task is comprised of the pf-Sense firewall service, the OpenVPN VPN solution, and the "Remote Module" script, developed locally for the mission. The representation of the connections and infrastructures involved in the operation can be seen in Figure 6.

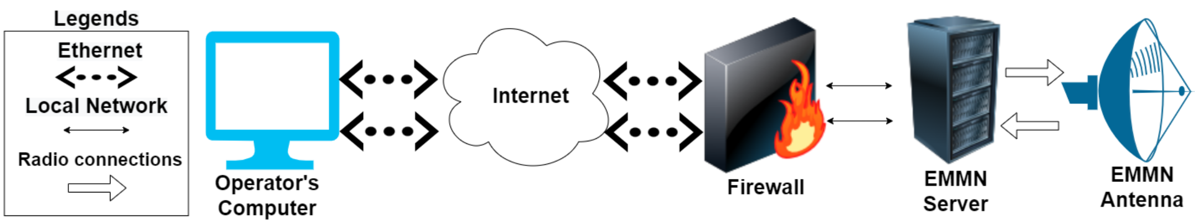


Figure 6: Network structure flowchart.

The functionalities are accessed using credentials provided to the satellite operator, generated by the firewall service, and sent to the operator in advance. Using the credentials, encrypted access is allowed by the firewall and then the connection to the "Remote Module" is established. Among the access releases, there is the connection via TCP sockets, in which two exclusive ports are previously defined in the operations of the mission: one for transmitting telecommands and another for receiving telemetry.

The execution of the communication script is performed by the "Remote Module Manager". The purpose of the management service is to measure the duration of a pass and activate the mission's "Remote Module" during the duration of the pass, in which the activated script is developed according to the mission's ground protocols.

The "Remote Module" performs two main operations. One of them is the intermediation between TCP telecommand and telemetry channels with the respective MQTT topics. The other operation, when necessary, is related to the mission protocol conference layer, normally implemented between ground segments.

4. Reports on Cubesats Trackings

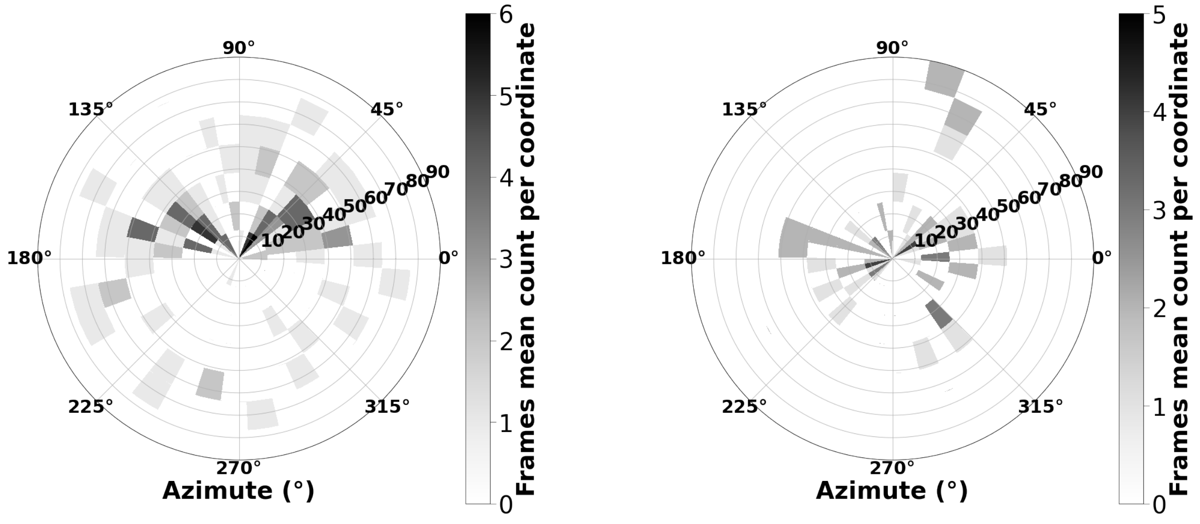
This section shows data derived from executed operations by EMMN. The information derives from data collected in surveys with orbiting satellites. It aims to evaluate the performance of automated tracking, gauging the establishment of different radio links in the reception of telemetry from different sources. The approach uses two CubeSats that have different radio link configurations. They were chosen because they are in operation, according to the SatNOGS project database [9]. The link information can be seen in Table 2.

Table 2: Cubesats transceivers characteristics.

Cubesat	NORAD	Frequency	Modulation	Data rate
ITASAT	43786	148.86 MHz	BPSK	1200 bps
Platform-1	52770	400.36 MHz	GMSK	9600 bps

The records are related to the pointing angles of the antennas, on tracking events, over 30 days. The data refers to the azimuth and elevation axes during a tracking, with the acquisition of information on the pointing direction whenever telemetry is decoded by the message reception script and published in the MQTT topic of telemetry.

In Figures 7((1)) and 7((2)) histograms are shown in polar format, in which it is possible to notice the reception of telemetry in different combinations of antenna angles during the tracking of these satellites. In the Figures 7((1)) and 7((2)), concentric circles represent azimuth and radii represent elevation. Rectangular regions indicate groups of nearby angles with the occurrence of decoded signals. The darker, the more receptions occurred. In this way, it is possible to notice the change in the direction of the antennas in the most varied points, as well as the incidence of signals received from a particular satellite over several passes in the stipulated period.



((1)) Itasat ((2)) Platform-1

Figure 7: Polar Coordinates Histograms plot from CubeSats tracking data.

The reconfigurations of the RF link and signal processing proved to be successful using the combination of automated switching of the antennas associated with the USRP and the signal processing scripts. Nevertheless, improvements are always necessary for the performance of the radio system, but the advantage of using the approach used in the EMMN scheme is that the modifications are carried out only in the processing scripts, without making it necessary to change the hardware.

During the tracking events, a computer external to the station’s network executed a script for TCP connections, simulating the connection of a remote operator and establishing connections with the “Remote Modules” developed for each satellite. The simulated connection occurred as shown in Figure 6, with the reception of telemetry decoded during the passage by the operator. Using the devices and protocols used, the signals that were decoded were sent to the satellite telemetry topic, to then be transmitted to the script of the remote machine, with a delivery rate of 100% of packets to the destination application of the operator.

5. Conclusion

In this paper, the solution implemented by EMMN for Multi-Mission Ground Station tasks was presented. The application of the proposal used begins with the updating of the legacy tracking system, which allowed increasing the line of sight time of the station's UHF, VHF, and S antennas concerning the satellite in its passage. In addition to the possibility of tracking any spatial element using TLEs, the solution used the concept of reconfigurable radios using USRP and automatic antenna switching, allowing the multi-mission concept to be implemented.

The function that allows remote access has made the station's reach to other missions wider, giving other teams that have satellites access to a ground station without extra investments. Based on the reported experiments, it is possible to note the performance of the EMMN for various missions.

In general, the modularization and use of distributed systems allowed the station to act in the multi-mission task, allowing improvements, as highlighted in the tracking experiment, to be implemented without modifying hardware or the structure of the operational framework.

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