Development of a Low-Cost Ground Segment Capable of Receiving Data from Nanosatellites: a Partnership between Brazil and Portugal

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Abstract

Two universities joined forces to develop a shared ground segment (Ground Stations and Mission Operation Centers) for satellite signals reception, capable of working together autonomously in a network to receive telemetry data and decode information. The main objective of this cooperation and network is to, firstly, give both universities an infrastructure capable of receiving signals in VHF and UHF. Secondly, and most importantly, it aims to create an exchange of experiences between students from these universities while also contributing to the regional development of each country in nanosatellite data reception technology. The ground segment itself provides mutual data collection on a private server, using two ground stations located in different hemispheres to expand global coverage and minimize revisit time, which also contributes to supplying the nanosatellite telemetries database, which is being built in Portugal. The server architecture allows both universities to schedule future passes of their chosen satellites, recording them in a log file that can be used in future studies, enabling research groups to gain experience in signal processing analysis. The modular system is developed entirely using Commercial Of-The-Shelf (COTS) components and 3D printed parts, including Antennas, Amplifiers, Filters and also SDRs (Software Defined Radio), leaving the door open to new integrations that can expand frequency coverage, or system performance improvements. The design supports a wide variety of missions, operating on amateur radio frequency in VHF (2 m band of 144-146 MHz) and UHF (70 cm band of 430-440 MHz), enabling remote access and remote control of the antennas and their recorded data.

All the ground segment architecture, hardware, and software, as well as its operational procedures, are discussed in this paper and can be found in detail on our public repository in GitLab. As of March 21st, it has completed several observations for verification. The results are being processed on a low-cost computer (Raspberry Pi4) connected to an SDR which in turn connects to the antennas. The assembly of this interface intends to give a friendly user experience and, if desirable, an easy expansion of this system. The project developed can be easily replicated in other locations around the world, mainly because of its low price and ease of use.

Keywords

Antennas, COTS, Ground-Station, Low Cost, Nanosatellites

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Acronyms/Abbreviations

BPF *Band-Pass Filter*

COTS Commercial Off-The-Shelf

GUI Graphical User Interface

LNA Low-Noise Amplifier

MODCOD Modulation and Coding

NAS Network Attached Storage

OS Operating System

RHCP Right Hand Circular Polarization

SatNOGS Satellite Network of Open Ground Stations

SDR Software-Defined Radio

VNC Virtual Network Computing

1. Introduction

CubeSats have been widely used due to the growing wave of nanosatellites, mainly due to the recent democratization of the use of space, made possible by the so-called New Space. More and more nations, organizations, and universities are developing, assembling, integrating, testing, and launching their small satellites into space, whether for scientific experimentation or for carrying out complex missions. With the number of launches of nanosatellites increasing from 10 in 2007 to more than one hundred in 2017 [1], and the possibility of application for educational purposes and not only, the development of ground stations have become more important than ever.

Aiming to expand the student's knowledge and the amount of telemetry data from nanosatellites, the Alma segment, Figure 1, is a partnership between the University of Beira Interior in Portugal and the Federal University of São João del-Rey in Brazil, that consists in the creation of a shared ground-station network that allows students from both universities to make use of an antenna that is placed far from them, on another continent, providing telemetry data from various satellite missions. This partnership is intended to offer students the possibility to develop the ground segment from the beginning, receiving signals from nanosatellites, challenging them to build and decode signals, introducing them to basic concepts of satellite tracking, as well as knowledge of satellite operations and orbital mechanics. Being developed by students, the cost of this ground segment is an important variable. Therefore, a low-cost approach was applied, achieving an overall cost of €1134.

Figure 1. The Alma cooperation patch mission.

Thus, in Section 2, some literature is presented where it is possible to glimpse the development of other ground segments for educational applications in some research institutions; Section 3 presents all the hardware, specifications, and operating frequencies of the ground stations proposed in this work, one in Brazil and one in Portugal; In Section 4, the software for antenna operation and control is described, as well as the overall system architecture. Finally, Section 5 contains some results and lessons learned from this cooperation between Portugal and Brazil for the development of the ground segment, and Section 6 presents the next steps and future upgrades.

This project aims to, hopefully, motivate students and researchers to be involved in future projects whilst gaining hands-on experience in space operations and ground segment architecture, enhancing the visibility of space initiatives at both universities.

2. Current low-cost ground segments

Most of the actual low-cost ground segments use Commercial off-the-shelf (COTS) components such as antennas, low-noise amplifiers (LNA), filters, software-defined radios (SDR), diplexers, and computers. In addition, most of them are based in the Satellite Network of Open Ground Stations (SatNOGS), which is an open-source global network of satellite ground stations all over the world. This network enables people to use other ground stations, expanding user available coverage. Additionally, this facilitates the access of space-based data far more often than they can with a static one.

Some examples of the development of low-cost ground stations can be found, for educational purposes at the University of Alabama [2] and in [3] where teaching approaches to this type of project were explained. Most recently, in [4], a ground station was designed to be modular and to use commercial off-the-shelf (COTS) products such as SDR to reduce the total cost as well as the construction time.

Building your own ground stations network is expensive and can bring financial and regulatory issues since different countries have different regulations on accessing the available frequency spectrum. Thanks to the Satellite Network of Open Ground Stations (SatNOGS), it is possible to spend little money on a ground station when compared with professional ones and join a network of nearly 300 active ground stations. However, despite knowing the value of this powerful network, with this paper, the idea was to do something different than simply joining an already defined ground stations network. Our main goal was to develop our own network, allowing students to gain experience on the development behind an already established ground segment and making them feel and go through the difficulties that appear on this journey. So, from the partnership between Portugal and Brazil, Alma Segment was born.

3. Ground segment hardware

The hardware associated with the ground segment varies depending on whether the ground station is directional or omnidirectional.

In Portugal, with regards to communication, a directional ground station was built, made of two high-gain Crossed-Yagi antennas - one in UHF (70cm band), and the other in VHF (2m band). Despite not joining the SatNOGS available network, its rotator v3.0.1 [5] was built to move the antennas, being the price the deciding factor in comparison to other commercial options [6]. Both dipoles on the two antennas are driven by one signal, with different phases, making it possible to achieve circular polarization. To increase the signal reception in VHF, a low-noise amplifier (LNA), as well as a Bandstop filter were introduced, the last being capable of attenuating broadcast FM frequencies (typically >40dB, 80-115 MHz), while ensuring VHF Airband. On the UHF side, just a low-noise amplifier (LNA) was added.

Figure 2. Directional ground station in Portugal

Additionally, an enclosure box was fixed to the two frames of the rotor, with a hole to pass all the cables from the switches of the end-stops and the stepper motors. Inside the enclosure box, was organized all the hardware needed for the rotor operation (Arduino, CNC controller with A4988 drivers and its power supply unit), the hardware needed for remote access operation (Raspberry Pi4 and its respective power supply unit), and last but not least two RTL-SDRs connected to the microprocessor.

Also, to understand what the constraints of the place are where the ground station in Portugal is located, altitude and azimuth were measured.

Table 1. Ground Station Location Constraints

Azimuth	Minimum Elevation
0º-90º	10º
90º-230º	8º
230º-360º	22º

The full 360º panoramic view can be seen in Appendix A.

In Brazil, the ground station employs a designed and 3D built Turnstile Antenna. It has Right Hand Circular Polarization (RHCP) and was projected to receive signals at frequencies ranging from 434 MHz to 439 MHz. This type of antenna is basically made of two dipoles with a 90º phase difference between the dipoles, Figure 3.

The first step was to set the center frequency at 435.500 MHz. Then, to find the wavelength (λ), Eq.1 was used:

$$\lambda = c / f \qquad (1)$$

where c is the speed of light and f is the desired operating center frequency. Next, to find the dipole total length, Eq.2 was used, where X is the dipole length.

$$X = (\lambda/2) * 95\% \qquad (2)$$

After that, to get the size of the reflectors, Eq. 3 was employed

$$Y = (\lambda/2) \qquad (3)$$

Finally, the distance between the dipoles (Z) and the reflector, needs to be calculated, and for that Eq.4 was used:

$$Z = (\lambda/4) \qquad (4)$$

The parameters obtained for the design using the previous equations were: $\lambda = 0.68$ m, $X = 0.32$ m, $Y = 0.34$ m, $Z = 0.17$m.

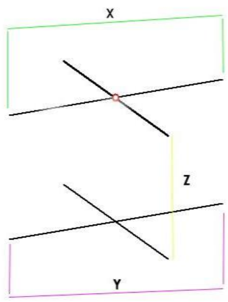

Figure 3. Turnstile 3D Design: Calculated dimensions in m.

To verify and validate the Turnstile design, and to ensure more precision in the calculation of the length of the dipoles a free software called MMANA-GAL[7] was used to simulate and optimize the antenna. In Figure 4 the radiation diagram obtained from the simulation is illustrated:

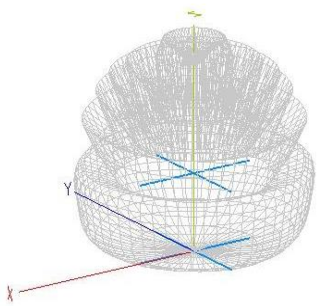

Figure 4. Turnstile Radiation Pattern

The main idea of this ground station in Brazil is to be as cheap as possible, but with the possibility to receive the same satellite signals that Portugal's ground station receives.

Besides the Turnstile Antenna, to build this ground station, two more components were employed, one Low Noise Amplifier (LNA) to amplify the signals received by the antenna and one Band-Pass Filter (BPF) to reject signals outside the 434 MHz to 439 MHz range. The combination of this equipment is fundamental to increase the quality of the received signals.

Figure 5. Turnstile Antenna Design

For a full list of all the hardware used in the project and to get more information about the development process, simulations and software deployments, we managed to list everything on our public GitLab Repository [8].

4. Software and Architecture

The architecture of the ground segment is defined as in Figure **6** and uses two ground stations capable of receiving signals on their own.

In the case of the ground station in Portugal, a Raspberry Pi4 and an Arduino Uno were used as the main processing unit. The Raspberry Pi controls the Arduino which, in turn, controls the rotor. Since the decision was to use a Raspberry Pi, an OS was to be chosen. A very good option would be PiSDR image [9], which is a very popular Linux distribution and known amongst amateur radio enthusiasts, because of its pre-installed software like Gpredict, GNURadio and gqrx, however it was not used because most of the software it contains would not be used in this ground segment, thus, slowing down the system unnecessarily.

Ultimately, there is no Operating System (OS) that is perfect for every user, and it mostly boils down to personal preference and/or necessity. For instance, in this project, Raspbian Buster 32-bit was used because one of the software requirements was the need for 32-bit architecture, as explained in the paragraph below.

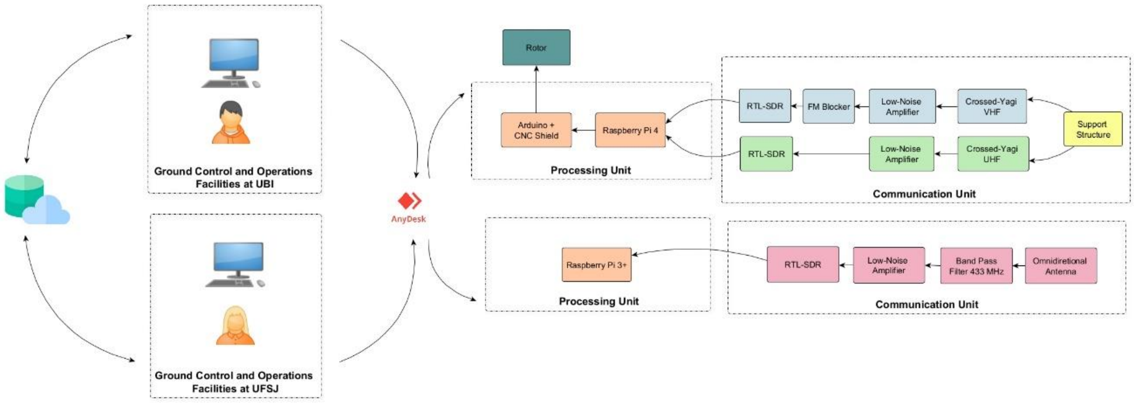

Figure 6. Ground Segment Overall Architecture

To allow for remote access, different tools were tested such as: Anydesk, Virtual Network Computing (VNC) and Team Viewer. Despite all the tests, none compares in terms of performance to Anydesk, and because of that, it was chosen. However, this performance came at a cost: Anydesk was not ready for 64-bit architectures (as of March 19th). This was the main reason for the need of a 32-bit OS.

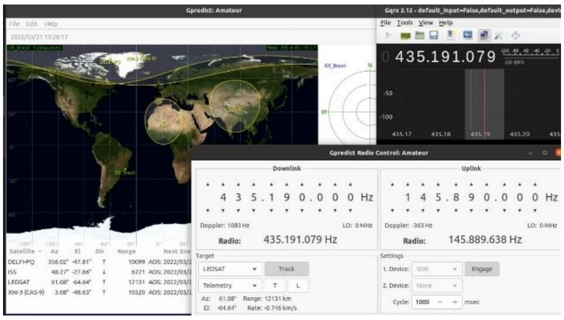

Figure 7- Remote access to the ground station using Anydesk

To control the rotor, a radio control library called Hamlib was used. This library contains software that handles the stepper motors by receiving serial data containing certain objective angles and, so, calculating the respective steps needed to achieve such angles. The serial data is sent from the Raspberry Pi to the Arduino by GPredict, which outputs the respective angles that both the elevation and azimuth stepper motors should be at (corrected for both ground station altitude and location). With Anydesk installed on both Raspberry Pi's, it's possible to have a Graphical User Interface (GUI) of the computer environment that contains all the software needed for remote operation.

For instance, it also allows to see the selected satellite's future passes and check the current pass to see if the satellite is in line of sight with the ground station, and then engage the antennas to follow the nanosatellite while correcting the Doppler effect. Also, a Network Attached Storage (NAS) server, hosted in Portugal, is being used to save all the records obtained from nanosatellites.

5. Results

As of 21st of March, reception in Portugal was not done yet, due to some losses in the coaxial cables, and delay in the building time of the rotor and the station itself, in comparison with the foreseen timeline. However, in Brazil, 5 observations were done with an average number of packets of 15 per observation. Satellites tracked include, LEDSAT and WX-3 (CAS-9).

5.1. Lessons Learned

Throughout this project, several valuable lessons were learned. Bring your tools - during the building and assembly process of the rotor in Portugal, there was always, a day's delay due to the lack of necessary tools and material that was forgotten. Materials such as: electrical wire insulating

tape, soldering machine and solder, ethernet cables, extra screws and nuts always proved to be important when needed.

Be prepared for bad weather - Ground stations are located most of the time in high locations and, most importantly, out in the open. Normally there would be no issue but, when there's an exposed electrical circuit, it is always a bad idea not to cover it up. So, bring your umbrellas.

A strong foundation is key - A project is only as strong as its weakest link and more often than not, it is the foundation. In this kind of project, shortcuts often lead to such situations which, in turn, brings out delays, disappointment and frustration.

Work smart, plan in advance - Plan your work and avoid unnecessary overtime. Even if things go sideways, remember to stop, and think. As simple as that.

Be prepared for spacecraft operations- Training is an important step for operating and tracking satellites, take precautions and stay one step ahead right before the acquisition of signal.

6. Conclusions

This paper shared the first cooperative ground segment between the University of Beira Interior (UBI) and the Federal University of São João del-Rei (UFSJ). After many receptions in both ground stations, nanosatellites were tracked, and their telemetry was received. However, the ground station in Brazil received and decoded fewer packets because it used an omnidirectional antenna which, in consequence, results in less gain and less performance for receiving for example CubeSats whose transmission power is normally 1W.

Future steps of this partnership will be the update of the ground segment, which at the moment is only capable of receiving signals, to include the possibility of transmission and consequently send telecommands to the same nanosatellites. This can be done by upgrading the Software Defined Radio (SDR) to one that has Rx/Tx capabilities, options in the market include half-duplex, and full-duplex versions for more expensive alternatives however, maintaining the idea of keeping it as low-cost as possible, it is intended to be used a new low-cost SDR with the capacity of transmission whose name is CaribouLite. Additionally, the idea is to develop an API to host the interface to the rotor and a dashboard to facilitate user experience by allowing them to check and request ground station usage for satellite tracking and data collection. Now that the ground segment is available and running, it will be possible to work on signal processing methods with real records from nanosatellites, learning Modulation and Coding (MODCOD) schemes and in the end, obtaining valid frames from nanosatellites. To view the antenna moving towards the satellite, ensuring the correct movement in the operations of the station, in Portugal a camera will be added.

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Appendix A

References

[1] R. Atem de Carvalho, J. Estela, M. Langer, Nanosatellites Space and Ground Technologies, Operations and Economics, Wiley & Sons Ltd, 2020.

[2] C. Simpson, A. Burjeck, W. Patton, E. Hacket, C. O'Neill, Ground Station and Infrastructure Development at the University of Alabama Tuscaloosa, *International Astronautical Congress*, Washington D.C, 2019.

[3] C. Simpson, A. Burjeck, W. Patton, E. Hacket, C. O'Neill, A Satellite Ground Station for Teaching Digital and Wireless Communications, *IEEE*, 2016.

[4] H. Jazebizadeha, H. Bathory, A Satellite Communication Experiential Learning Activity for Undergraduate Students in Aerospace Engineering, *International Astronautical Congress*, Virtual, 2020.

[5] SatNOGS Rotator Documentation: https://wiki.satnogs.org/SatNOGS_Rotator_v3, last visited: 10th March 2022.

[6] Commercial Yaesu Rotator: https://www.wimo.com/en/g-1000dxc, last visited: 13th March 2022.

[7] Antenna Design MMANA-GAL Software: http://gal-ana.de/basicmm/en/, last visited: 16th March 2022.

[8] Alma Segment Gitlab: https://gitlab.com/spacelabubi/alma-segment, last visited: 20th March 2022.

[9] PiSDR Github Repository: https://github.com/luigifcruz/pisdr-image, last visited: 20th March 2022.