UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Escuela Técnica Superior de Ingeniería de Telecomunicación

# Estación terrena para comunicaciones con satélites LEO

Trabajo Fin de Máster

Máster Universitario en Ingeniería de Telecomunicación


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## Ground Station for LEO satellite communications

**Keywords:**

Ground Station, SDR, Transceiver, Cubesat, VHF, UHF, C band

**Abstract:**

This Master's thesis deals with the design and development of a Ground Station for LEO satellite communications deployed at the Escuela Técnica Superior de Ingeniería de Telecomunicación of the Universitat Politècnica de València and its evolution towards a technological validator for the ground segment of space communications. The complete Ground Station communications system hardware (including transceivers, antennas, LNA, LNC, rotor, among others) and software architecture has been designed, deployed and validated. Flexibility has been achieved with the integration of Software Defined Radio, providing the ground segment with adaptability. The Ground Station is designed to operate in VHF, UHF and C-band and to work as a technological demonstrator capabilities of the designed Ground Station.

**Resumen:**

Este Trabajo Fin de Máster aborda el diseño y desarrollo de una Estación Terrena para comunicaciones por satélite LEO desplegada en la Escuela Técnica Superior de Ingeniería de Telecomunicación de la Universitat Politècnica de València y su evolución hacia un validador tecnológico para el segmento terreno de comunicaciones espaciales. Se ha diseñado, desplegado y validado el hardware completo del sistema de comunicaciones de la Estación Terrena (incluyendo transceptores, antenas, LNA, LNC, rotor, entre otros.) y la arquitectura software. La flexibilidad se ha logrado con la integración de la Radio Definida por Software, proporcionando al segmento de tierra adaptabilidad. La Estación Terrena está diseñada para operar en VHF, UHF y banda C y para funcionar como demostrador tecnológico de las capacidades de la Estación Terrena diseñada.

**Resum:**

Este Treball de Fi de Master aborda el disseny i desenvolupament d'una Estació Terrestre per a comunicacions per satèl·lit LEO desplegada a l'Escola Tècnica Superior d'Enginyeria de Telecomunicació de la Universitat Politècnica de València i la seua evolució cap a un validador tecnològic per al segment terreny de comunicacions espacials. S'ha dissenyat, desplegat i validat el maquinari complet del sistema de comunicacions de l'Estació Terrestre (incloent transceptors, antenes, LNA, LNC, rotor, entre altres.) i l'arquitectura programari. La flexibilitat s'ha aconseguit amb la integració de la Ràdio Definida per Programari, proporcionant al segment de terra adaptabilitat. L'Estació Terrestre està dissenyada per a operar en *VHF, UHF i banda C i per a funcionar com a demostrador tecnològic de les capacitats de l'Estació Terrestre dissenyada.

## Executive overview

The present Master's Thesis report titled "Ground Station for LEO satellite communications" develops in the text the following concepts, which are duly justified and discussed, focussing on the field of Telecommunications Engineering:

| **Concept (ABET)** | **Concepto (traducción)** | **Complies? (Y/N)** | **Where?** |
|---|---|---|---|
| **1. Identify:** | **1. Identificar:** | | |
| 1.1. Problem statement and opportunity | 1.1. Planteamiento del problema y oportunidad | Y | section 1.1 |
| 1.2. Constraints (standards, codes, needs, requirements & specifications) | 1.2. Toma en consideración de los condicionantes (normas técnicas y regulación, necesidades, requisitos y especificaciones) | Y | chapter 2 |
| 1.3. Setting of goals | 1.3. Establecimiento de objetivos | Y | section 1.2 |
| **2. Formulate:** | **2. Formular:** | | |
| 2.1. Creative solution generation (analysis) | 2.1. Generación de soluciones creativas (análisis) | Y | chapter 3 chapter 5 |
| 2.2. Evaluation of multiple solutions and decision-making (synthesis) | 2.2. Evaluación de múltiples soluciones y toma de decisiones (síntesis) | Y | chapter 5 chapter 6 |
| **3. Solve:** | **3. Resolver:** | | |
| 3.1. Fulfilment of goals | 3.1. Evaluación del cumplimiento de objetivos | Y | chapter 5 chapter 6 |
| 3.2. Overall impact and significance (contributions and practical recommendations) | 3.2. Evaluación del impacto global y alcance (contribuciones y recomendaciones prácticas) | Y | chapter 5 chapter 6 |

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*A mi abuelo*

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Chapter 1

# Introduction

## 1.1 Background and Motivation

In the contemporary world, space communications stands as a key component enabling global connectivity with low latency and huge reliability, even in low coverage areas where ground communications (base station, optical fiber,...) have not been deployed already or have suffered some failure. Satellite communications enable vital functionalities, such as mobile communications, global navigation, Earth Observation and scientific research, but also opens new research fields and innovation opportunities where space agencies and private companies such as Starlink, OneWeb or Amazon, are interested on.

In January 1946, United States of America successfully bounced a signal off the Moon with a radar transmitter at 111.5 MHz receiving it 2.5 s later in the Ground Station (GS), marking the beginning of the exploration of the solar system by radar (Project Diana) [1].

In October 1957, the Soviet Union launched Sputnik 1, the first artificial satellite to orbit Earth. It orbited the Earth with an apogee of 940 km and a perigee of 230 km with a period of 96 minutes. Sputnik 1 mission was to broadcast a "beep" to demonstrate the existence of the first artificial satellite from any point around the world. The launch of Sputnik 1 put pressure on the space race, but also it was a mayor contribution to science, space exploration and Earth Observation [2]–[4].

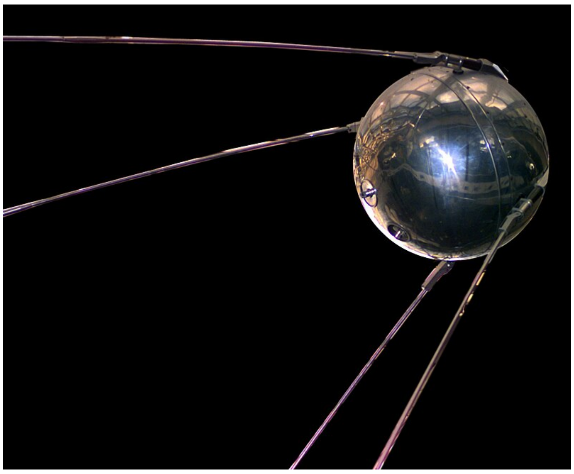

**Figure 1.1** – Sputnik 1 [5].

In April 1960, United States of America launched Tiros 1, the first weather satellite. It orbited the Earth with an apogee of 750 km and a perigee of 693 km with a period of 99 minutes. Tiros 1's mission was to test experimental television techniques designed to develop a worldwide meteorological satellite information system. and to test Sun angle and horizon sensor systems for spacecraft orientation. Tiros 1 gave the humanity the very first picture of Earth from space [2], [6].

From the launch of Sputnik 1 back in 1957 until the establishment of the CubeSat standard in 2012 [8], there were a total of 6644 satellite launches, but from 2012 until the last report in

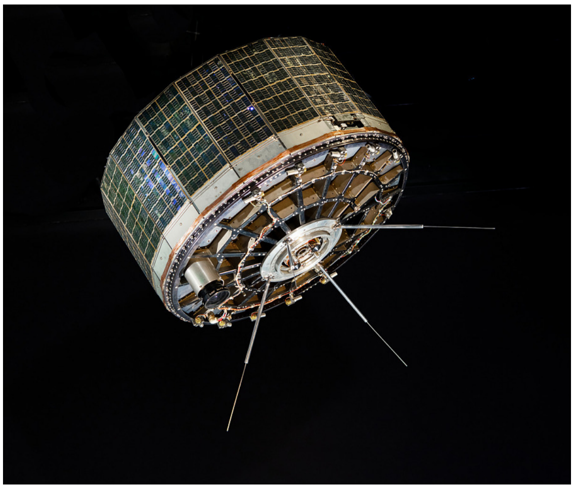

**Figure 1.2** – Tiros 1 [7].

2023 [9], there has been a total of 10619 launches.

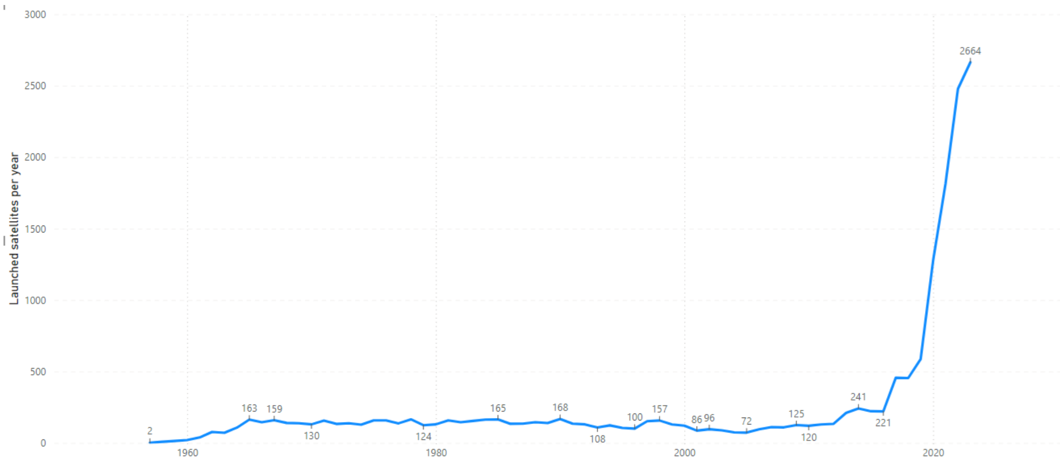


**Figure 1.3** – Launches per year (a) from 1957 to 2012 and (b) from 2013 to 2023.

Sending scientific missions to space environment has turn more and more accessible from both technology and economic points of view, and those missions need to be managed from a GS. Thus, along with the promotion of space communications comes the development of more robust GS to ensure links with higher capacity and reliability, but more flexible and adaptable to any scenario to be able to perform real-time operations and support multiple missions. GS is the gateway between the satellite and the Earth, but it is also the infrastructures designed to control, monitor and send instructions to the satellite. In this context, the Microwave Application Group of the Research Institute of Telecommunicatiosn and Multimedia Applications (GAM ITEAM-UPV) [10] together with Higher Technical School of Telecommunications (ETSIT), both belonging to the Universitat Politècnica de València (UPV) have developed a LEO satellite communications GS deployed at the ETSIT. This facility serves not only as a GS but also as a hub for research and as a platform to validate technology or conduct educational experiments.

## 1.2 Research objectives

The main purpose of this project is to design and develop a GS for satellite communications and tracking and the evolution towards a more flexible and interoperable system with the integration

**Figure 1.4** – iTEAM-UPV GS based at ETSIT of UPV.

of Software Defined Radio (SDR) that enables the expansion of the usage of the electromagnetic spectrum for space communications. This solution will allow new research in terms of design, implementation and demonstration of technologies: high-rate data links, satellite architectures and the practical demonstration of new services and applications.

In the first sections of the project, a review of the current state of the art and the latest trends in the technology that will be used throughout the development of the thesis will be made. In the following chapters, a solution (hardware and software) will be proposed for the communications subsystem (for VHF, UHF and C-Band) and for the GS satellite tracking subsystem. Then, SDR technology will be integrated in the communication subsystem to improve the flexibility and adaptability of the GS. Finally, different experiments will be listed and performed in different bands, to test the performance of the GS under different communication scenarios.

## 1.3 Scope and limitations

This project will cover the design and development of a GS to operate with amateur bands in VHF (144 MHz to 146 MHz), UHF (430 MHz to 440 MHz) and C-band (5.8 GHz to 6 GHz) both with commercial transceivers and SDR modules. Thus, the analysis of the signal and the RF components response will be carried out with atmospheric conditions of the GS's location (València, Spain) and the selected frequencies.

Since the iTEAM-GS could work as a technology validator for space communications, future research lines and improvements will be pointed out within the following sections.

## 1.4 Thesis methodology and organization

For the design of the iTEAM-GS, the author has done a bibliography research about GS RF architecture, commercial transceivers usage, satellite communications and SDR solutions. Once the final design of the earth station has been determined, commercial solutions for each component have been compared (based on data sheets) in order to obtain the most suitable component for the objectives. Those components have been procured from suppliers to the UPV and iTEAM-UPV. Apart from both directors of this master's thesis, experts in the field of radio links and local radio amateurs have been providing help in the design and configuration of the iTeam-GS. In Figure 1.5 you can see a graph of the estimated tasks and the planning for the realisation of this project in the form of a Gantt chart.

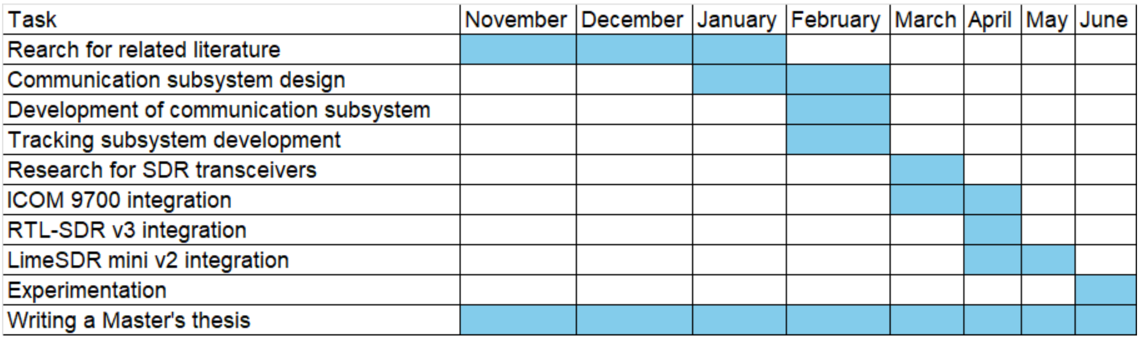


**Figure 1.5** – Gantt diagram for Master Thesis.

CHAPTER 2

# Context and state of the art

This chapter presents an overview of the fundamental concepts related to satellite communications, ground stations systems, Software Defined Radio technology insights and radio wave propagation.

## 2.1 Satellite Communications

Since the launch of Sputnik 1, satellite technology has become more mature, more profitable and more efficient. Satellites are crucial part in our lives: they are used for communications, multimedia, Earth Observation, scientific research, humanitarian purposes and other commercial applications. Depending on their missions, satellites are categorized by the orbit and operating frequency. The exchange of data across the globe become possible by satellite communications, which use the footprints of communication satellites orbiting the Earth [11].

### 2.1.1 Earth orbits

Johannes Kepler discovered the Kepler's laws of planetary motion between 1609 (first two laws) and 1618 (third law), which describe the motion of a body in the solar system. In [12], the three Kepler's laws are summarized as:

1. The planets move in ellipses with the Sun at one focus.
2. The line joining the Sun and a planet sweeps out equal areas in equal intervals of time.
3. The square of the period of any planet, $P$ is proportional to the cube of the semi-major axis of its orbit, $a$.

$$P^2 \propto a^3 \tag{2.1}$$

Any body launched into space, also known as a Keplerian body, fulfils Kepler's laws and is described by the Keplerian orbital elements [13]:

- $a$, the semi-major axis: a constant defining the size of the conic.
- $e$, the eccentricity: a constant defining the shape of the conic.
- $i$, the inclination: the constant angle between in the reference frame and in the orbital plane.
- $\Omega$, right ascension (or longitude) of the ascending node: the right ascension of the point where the spacecraft crosses from below to above the fundamental plane of the reference frame. The crossing point is called the ascending node.
- $\omega$, argument of periapsis: the angular distance along the orbit from the ascending node to periapsis.
- $\nu$, true anomaly: angle between the instantaneous position of the satellite and the perigee, measured from the focus.

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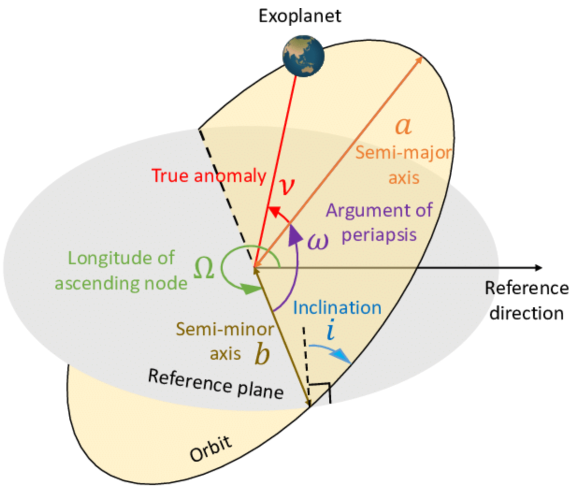


**Figure 2.1** – Keplerian orbital elements [14].

"An orbit is the curved path that an object in space (such as a star, planet, moon, asteroid or spacecraft) takes around another object due to gravity" [15]. From Earth and engineering point of view, satellite's orbits are defined by their height, the inclination angle and the orbit's eccentricity. This variables shape the orbital parameters (orbital period, time of sight, life, coverage radius, power balance and the nature of the satellite's mission).

Once the orbital height is selected, the **Leibniz' Vis Viva equation** is defined as in [16], where $v$ is the satellite velocity, $\mu = 3.986 \cdot 10^{14}\ m^3/s^2$ is the product of the gravitational constant, $G$, and the mass of the Earth, $M = 5.972 \cdot 10^{24}$ kg, the semi-major axis, $a$, and $r$, which is the sum of the radius of the Earth, $R_T = 6370$ km, and the instantaneous height of the satellite above the Earth surface, $h$.

$$v = \sqrt{\mu \cdot (\frac{2}{r} - \frac{1}{a})} = \sqrt{\mu \cdot (\frac{2}{R_T + h} - \frac{1}{a})} \tag{2.2}$$

Typically, satellites follow an elliptical orbit with a determined eccentricity. Orbits with zero eccentricity are known as circular orbits [17]. For circular orbits, the distance between the two bodies, $r$, is equal to $a$ and we get a simplification of the Equation 2.2 as Equation 2.3.

$$v = \sqrt{\frac{\mu}{a}} = \sqrt{\frac{\mu}{(R_T + h)}} \tag{2.3}$$

Combining Equation 2.3 and Equation 2.4, the **Orbital period**, $P$, of a body orbiting Earth can be calculated as in [16]:

$$P = \frac{2 \cdot \pi \cdot r}{v} \tag{2.4}$$

$$P = \frac{2 \cdot \pi \cdot a}{\sqrt{\frac{\mu}{a}}} = \frac{2 \cdot \pi}{\sqrt{\mu}} \cdot (R_T + h)^{3/2} \tag{2.5}$$

The **mean motion**, $n$, is the mean angular speed needed by a body to complete one circular orbit and it is calculated as follows [18]:

$$n = \sqrt{\frac{\mu}{a^3}} = \sqrt{\frac{\mu}{(R_T + h)^3}} \tag{2.6}$$

Keplerian orbital elements are summarized with the Two Line Element (TLE) format, which contain all the data related to the orbital elements in three lines, where line 0 is the keplerian body name and line 1 and two define the orbital elements (except for the semi-major axis, $a$, that can be extracted from the mean motion, $n$, described in the line 2) [19]–[21]:

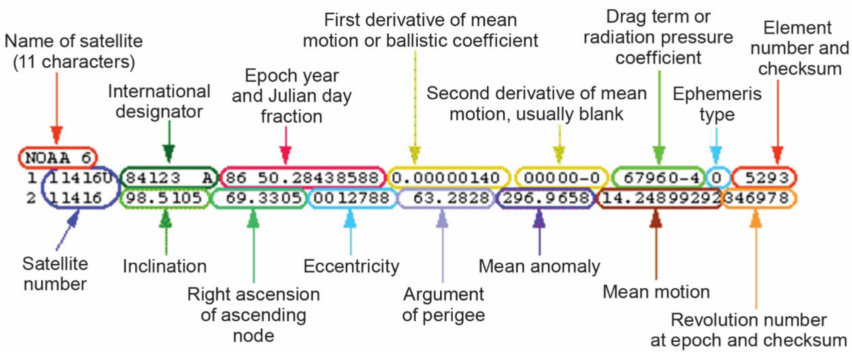


**Figure 2.2** – TLE format description [19].

Depending on the objective of each satellite, a satellite might need to follow a certain orbit. The movement of the satellite within its circular orbit is represented by altitude, radius velocity, and orbital time [17]. The circular orbits are categorized depending on their height above the Earth's surface.

#### 2.1.1.1 Geostationary Earth Orbit, GEO

High Earth orbits are the orbits with a height above 35786 km over the Earth surface's at the equatorial plane. Graveyard orbit and Geostationary Earth orbit (GEO) are both particular orbits at GEO with a height of 36050 km and 35786 km (± 200 km), respectively [15].

GEO satellites have an orbiting period of 23 hours 56 minutes and 4 seconds (exactly the same Earth rotation period) and a speed of 3.07 km/s. A satellite in GEO orbit appears stationary in the sky, allowing users to have an antenna pointing at a fixed position to exchange information with the satellite (without moving). GEOs are used to cover large sections of the Earth and be pointed at a specific point on the surface, for example, communication or TV broadcasting satellites. Although GEO satellites need to be in line of sight to be operated and to communicate with Earth, European Data Relay System (EDRS) [22] proposes GEO satellites to make use make use of inter satellite links [23] to enable permanent communications to Earth from other satellites (GEO or non-GEO).

The life of GEO satellites is very long (due to minimal dragging effects, among other factors) and it takes 3 satellites to cover all (habitable) regions on Earth, but the communication latency between satellites in GEO orbit is also very high (with around 240ms of latency). Besides, the cost of launching a satellite to GEO is substantially higher. Therefore, missions must be very specific, reliable and highly validated on Earth and the satellite's system must be able to handle environmental issues to last for a long time.

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#### 2.1.1.2 Medium Earth Orbit, MEO

Medium Earth orbit (MEO) satellites orbit at a height between 2000 km and 35786 km [15]. The orbit inclination depends on the mission and the plane can be tilted. Among other purposes, MEOs are used by global navigation satellite system (GNSS) such as Galileo [24], GPS [25], GLONASS [26] or BeiDou [27].

The communications with a MEO satellite present less latency than those with a satellite in GEO, the estimated life is larger than the expected from a satellite in a lower orbit, up to 20 satellites might be needed to cover all (habitable) regions on Earth and, since MEO satellites have a shorter orbital period, they also have a shorter time of visibility.

#### 2.1.1.3 Low Earth Orbit, LEO

Low Earth Orbit (LEO) satellites travel at a height between 160 km and 1500 km over the Earth's surface. The inclination of the orbit depends on the mission, allowing different inclinations and prograde or retrograde motion [15]. The ISS [28] orbits at a height of 450 km [1], which allow astronauts and scientific missions to travel easily and LEOs are the the most commonly used orbit for Earth Observation (since they are able to take high resolution images due to their proximity to the Earth's surface).

The communication with a LEO satellite has the lowest latency of the three Earth circular orbits (since the propagation distance is the lowest), but also the lowest estimated life (due to the atmospheric drag that LEO satellites suffer). In order to be able to cover all (habitable) regions on Earth, 30 satellites are needed. The great interest in this orbit comes from its launching costs, in comparison with GEO or MEO, which allow scientific missions and commercial projects to be deployed easily and with lower economic risks.

A LEO satellite orbits at 7.6 km/s (at a height of 450 km) and the time of sight is the lowest (between 5 and 15 minutes depending on the inclination angle and the height). Thus, in order to exchange information with one satellite, the user should have either an antenna with a great beamwidth or a communication system with tracking capabilities. This is the reason why communications satellites operate in conjunction with multiple satellites to give uninterrupted coverage, creating a create a net around Earth called constellations, such as Starlink [29], OneWeb [30] or Kuiper [31].

### 2.1.2 Spectrum usage in satellite communications

Satellite communications are experiencing a fast development in the fields of scientific, technical and economic applications, driven by the reduction in the cost of launching and orbiting satellites in LEO and the growth of internet-based applications. Satellite communications are the basis for telecommunications, media broadcasting, navigation, exploration, observation and other applications. As radio-based applications increase, spectrum saturation follows and complicates previous communications.

The trend in satellite communications is to use higher frequencies, which have greater available bandwidth, but which are more attenuated with the distance (due to atmospheric and rain

[1] The ISS decays to lower orbits and is relaunched every few days to maintain an average altitude of 450 km.

attenuation added to free space loss). There are two possible ways to address the problem: by using technology that increases the efficiency of spectrum usage (e.g. with beamforming antennas [32]) or by using technology that is capable of handling high power while not being affected by radiofrequency rupture effects (Multipactor [33], Corona [34] and Passive Intermodulation [35]). Although there are lines of research addressing the problem of spectrum saturation, spectrum needs to be organised and structured to reserve its use for applications that need it, which is is regulated by International Telecommunication Union (ITU) [36] in SM.1131-0 [37] recommendation.

The electromagnetic spectrum is divided into groups of frequencies, called bands, which are named for convenience, as it is shown in [38], [39]. In this thesis we will address the design of a GS communication system for the VHF band, UHF band and C-band.

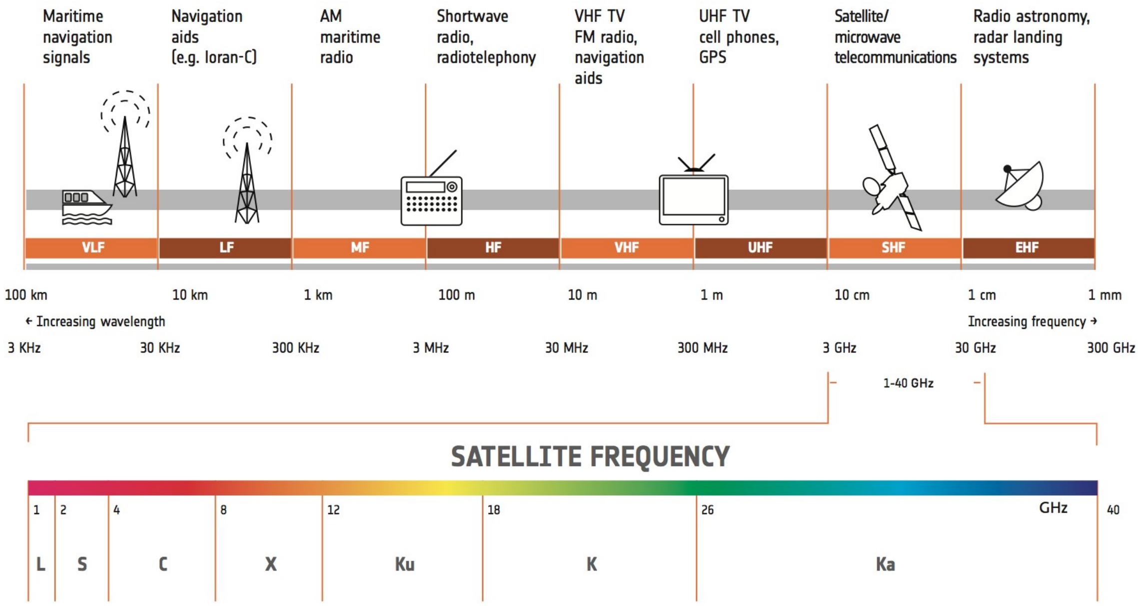



**Figure 2.3** – Satellite frequency bands [38].

## 2.2 Satellite communications systems

A system is a set of elements (or subsystems) that interact to achieve a specified purpose that can not be achieved individually. The logical description of a system represents the mission of the system and functionalities required to fullfil that mission, while the physical description of a system focus on how to achieve those functionalities based on certain requirements [40], [41]. The specification of a system boundary is mandatory in the definition process. Thus, a satellite communications system is composed of two different and independent systems.

### 2.2.1 Space segment

The space segment is the part of a satellite communications system placed in space to fulfil the space mission objectives [40], [42].

The space segment is composed by all the equipment above 100 km of altitude used for satellite communications: the satellites, which are conform by a Payload (the on-board hardware and software dedicated to produce mission data and then relaying it back to Earth [40], [43]) and a bus (which provides hosting environment for Payload to function [40], [44]).

2

### 2.2.2 Ground segment

The ground segment in satellite communications refers to the terrestrial based infrastructure and equipment responsible for communicating with and controlling satellites, which enables the management and monitoring of satellites and the data collection and distribution, and ensures the quality of service, providing the link between the satellite and the user [40], [45].

The ground segment is composed by all the equipment below 100 km of altitude used for satellite communications, concerning data and control: GS, satellite and network control centre[2], mission centre, user terminal[3], launch facilities and IT facilities.

For this project, we will only consider a LEO circular orbit and we will design, develop, implement and validate the appropriate ground segment communication system.

## 2.3 GS for satellite communications

GS is an essential part of space communications and is part of the ground segment with the function of the GS is to provide the radio interface for communications between satellites and users. GS can have both transmit and receive capabilities (or one of them) [17], [40].

### 2.3.1 GS functions

Satellites are meant to send information to and/or receive information from Earth, which are received or transmitted by the GS. The downlink data can be either Telemetry, Tracking and Command (TT&C) or Payload Data Transmission (PDT) [46]:

#### 2.3.1.1 Telemetry, Tracking and Command, TT&C

A constant and reliable data link between satellites and ground segment is needed in every phase of a mission. TT&C allows control and command data to be shared with GS through a RF data relay link. TT&C is critical for satellite operations, requiring advanced hardware and software for communication, monitoring, and control. It ensures that the satellite performs properly, adapts to changes, and carries out its mission effectively while in orbit.

Telemetry is the data received from the spacecraft (about the status of its systems or some payload data), Tracking system send information related to the satellite position and Commands are used to upload information to the satellite [40], [46]. TT&C can also cover inter-satellite-link data [23].

[2] Typically, control segment has been differentiated from ground segment, but at edition date, it is included as a part of the ground segment classification.

[3] Typically, user segment has been differentiated from ground segment, but at edition date, it is included as a part of the ground segment classification.

2

#### 2.3.1.2 Payload Data Transmission, PDT

PDT refers to the mission payload data, which is the main scientific, technological or commercial purpose of the satellite. The communication protocol, data rate (which is higher than the TT&C) and codification depends on the mission [40], [46].

### 2.3.2 GS architecture

The GS architecture and technology depend on the application and the nature of the mission: requirements, satellite orbits, communication needs, and technical constraints. The GS architecture ensures seamless communication, reliable data exchange, and efficient control of satellite operations to achieve the mission's objectives [17], [40].

The block diagram of the communication subsystem architecture (antenna and RF front end) of a GS with a single antenna and separate uplink and downlink branches is shown in the Figure 2.4. This design allows the GS to optimise data reception and transmission, ensuring minimum signal loss and maximum communication efficiency. Depending on the data received (TT&C or payload data), the GS routes the data to the control link (which manages telemetry and sends commands) or to the gateway link (which stores all mission-related data) [40].

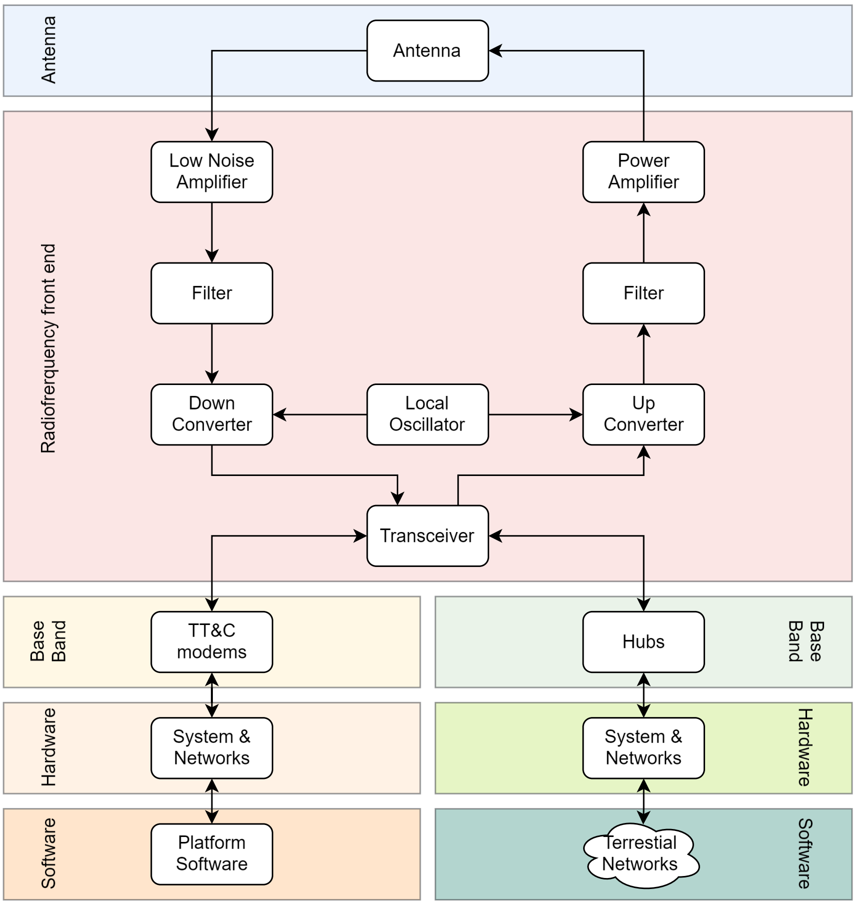



**Figure 2.4** – Block diagram of the GS communication subsystem.

In addition, GS must be able to accurately track the satellites and continuously adjust the antenna direction to maintain an optimal link as the satellites orbit the Earth. This tracking capability is especially important when establishing communication with a satellite in LEO (i.e.

moving rapidly across the sky and in contact with a GS for relatively short periods of time) [40].



## 2.4 Software Defined Radio

SDR is defined as an antenna, an analog-to-digital converter (ADC) and a set of Digital Signal Processing (DSP) combined with a system in which a software radio is hosted for real-time communications [47]. The (high level) architecture that fulfils this definition is shown in Figure 2.5, although the definition used in each study depends on the author and the field of study.

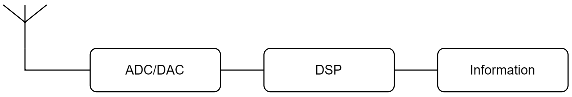



**Figure 2.5** – SDR high level architecture [48].

In the receiver branch, the RF signal (analog) received from the antenna passes through an RF front end (amplifier, filter and frequency shifter) before being digitised by an ADC. The digital data can now be processed by software running on a CPU controlled by a Field Programmable Gate Array (FPGA) [48], [49]. The transmitter branch is the opposite way around. A block diagram of the commercial RLT-SDR solution is shown in Figure 2.6.

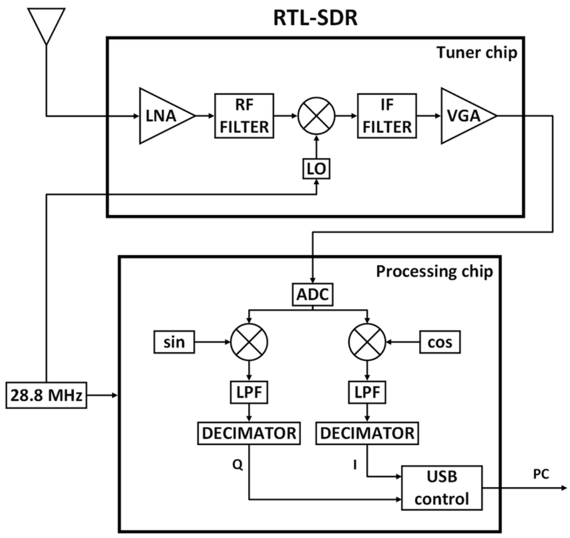



**Figure 2.6** – RTL-SDR block diagram [50].

The evolution of SDR technology and systems is enabled by advancements in technologies such as RF front-end, ADC, DSP, and FPGA. A crucial milestone in the evolution and integration of SDR is the ability to process data (that is, the computational capacity), especially in high data rate links.

Software-based applications used in RF enable a reconfigurable and flexible architecture radio, making the adaptability of an SDR solution dependent on the flexibility of the radio waveform, which can be changed through software without modifying the SDR platform [48].

In terms of telecommunications and RF engineering, SDR technology has the capability to process RF signals and replicate the response of traditional RF components through software. This adaptability is also the SDR main strength for commercial telecommunications agents: a

SW based communication system that can be uploaded faster and at lower cost [48]. SDR integration into satellite communications is widely beneficial, as it provides the satellite to be SW upgraded according to advances in communications algorithms, and to adapt the functionality of the satellite during its lifetime [48], [49], [51].

2

## 2.5 Radio wave propagation

The calculation of the power budget and the propagation conditions of an electromagnetic wave is an essential tool in the design of Earth-to-space communication systems, as it allows estimating the feasibility and performance of signal transmission between the satellite and the GS.

This section will use the ITU Recommendation ITU P.618-14 [52], a globally recognised guide that provides detailed guidelines for the accurate calculation of power budget and atmospheric propagation. This recommendation sets out key methods and parameters for accurate estimation of mean losses affecting communication, but also refers to other ITU recommendations for more precise calculations and parameters.

It should be noted that the propagation effects in a communication link depend (among other factors) on the conditions in which the link is established (visibility, weather,...). This section analyses the power budget considering the worst scenario for the link, but the study is particularised to the location of the iTEAM-GS (Valencia, Spain).

### 2.5.1 Free-Space Path Loss

Free Space Path Loss (FSPL) is the attenuation that occurs when electromagnetic waves travel through the space and it is the main attenuation contribution in satellite communications. The FSPL equation assumes an ideal scenario without considering factors such as obstacles, atmospheric conditions, or reflections, which can significantly affect the actual received signal strength in real-world situations. The $L_{FSPL}$ (dB) are defined as in Equation 2.7.

$$L_{FSPL} = 20 \cdot \log_{10}\left(\frac{4 \cdot \pi \cdot d_{sat-gs} \cdot f}{c}\right) \tag{2.7}$$

The LEO orbit has a height between 160 km and 1000 km. In this project, we will assume a height of 500 km, a minimum inclination mask ($\varepsilon_{min}$) of 10° (which is a very conservative inclination due to FSPL and atmospheric attenuations) and an intern angle ($\psi$) of 0.25 rad there is a maximum distance (also known as slant-path) between the satellite and the iTEAM-GS, $d_{sat-gs}$, of 1694.493 km (see Figure 2.7 and Equation 2.8).

$$d_{sat-gs} = (R_T + h) \cdot \frac{\sin(\psi)}{\cos(\varepsilon_{min})} = 1694.493\ km \tag{2.8}$$

Therefore, for our scenario of interest and according to Equation 2.8 and Equation 2.7, we have the following $L_{FSPL}$ (dB) for the three operative bands:

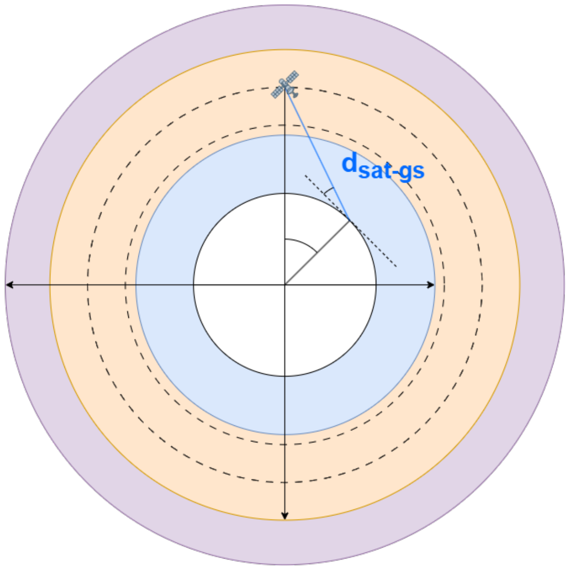



**Figure 2.7** – LEO Orbit geometry.

$$\begin{cases} L_{FSPL}|_{144\text{ MHz}} = 140.19\text{ dB} \\ L_{FSPL}|_{432\text{ MHz}} = 149.73\text{ dB} \\ L_{FSPL}|_{5.8\text{ GHz}} = 172.29\text{ dB} \end{cases} \tag{2.9}$$

### 2.5.2 Non ionospheric propagation

Non-ionospheric propagation effects refer to various phenomena or influences that affect electromagnetic signals passing through mediums other than the terrestrial ionosphere, such as water in its different states of matter. These effects must be taken into account at all frequencies, but become critical for frequencies above 1 GHz and at low inclination angles. The non-ionized atmosphere consists of two layers, namely the Troposphere (6 km to 20 km) and the Stratosphere (20 km to 50 km). From a height of 50 km onwards, we enter the Ionosphere.

#### 2.5.2.1 Atmospheric gases absorption

Atmospheric gas losses are due to power absorption by the resonance effect of water vapour ($H_2O$) and oxygen ($O_2$) particles, and are mainly dependent on the operating frequency, the angle of elevation and the altitude above sea level at which the GS is located. To determine the fading, an attenuation index provided by Recommendation ITU-R P.676-13 [53].

The specific attenuation at frequencies up to 1000 GHz, due to dry air and water vapour ($H_2O$), can be accurately evaluated at any value of pressure, temperature and humidity as a summation of the individual spectral lines from oxygen ($O_2$) and water vapour ($H_2O$), together with small additional factors for the non-resonant Debye spectrum of oxygen ($O_2$) below 10 GHz, pressure-induced nitrogen attenuation above 100 GHz and a wet continuum to account for the excess water vapour ($H_2O$) absorption found experimentally. The exact value of the atmospheric gas attenuation can be calculated following ITU-R P.618-14 (where these effects are taken into account for any operating frequency), but for the present project and given that the operating frequencies do not exceed 10 GHz, the value shall be approximated by the atmospheric gas at-

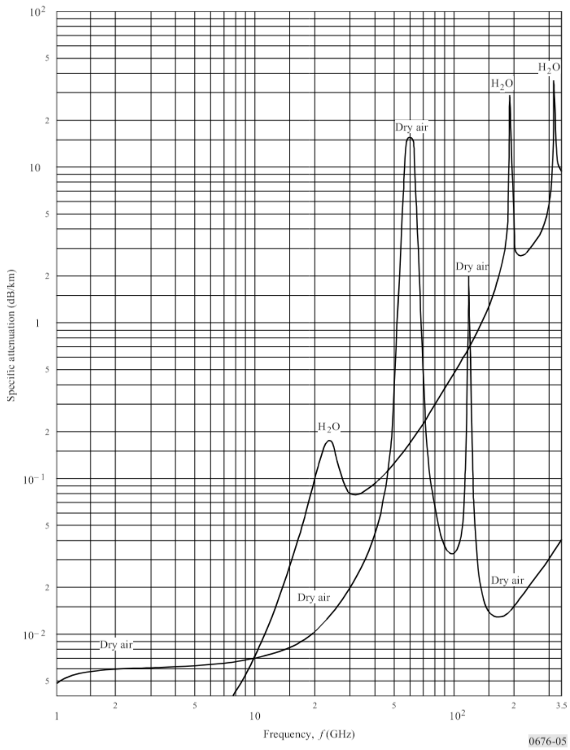



**Figure 2.8** – Specific attenuation due to gases absorption [53].

tenuation using Figure 2.8.

The highest concentration of atmospheric gases is in the Troposphere (h = 10 km). Thus, the slant path is 57.59 km as shown in Equation 2.10. Thus, we get the following attenuations due to gases absorption for each band of interest:

$$d_{troposphere} = \frac{10km}{\sin(\varepsilon_{min})} = 57.59\ km \tag{2.10}$$

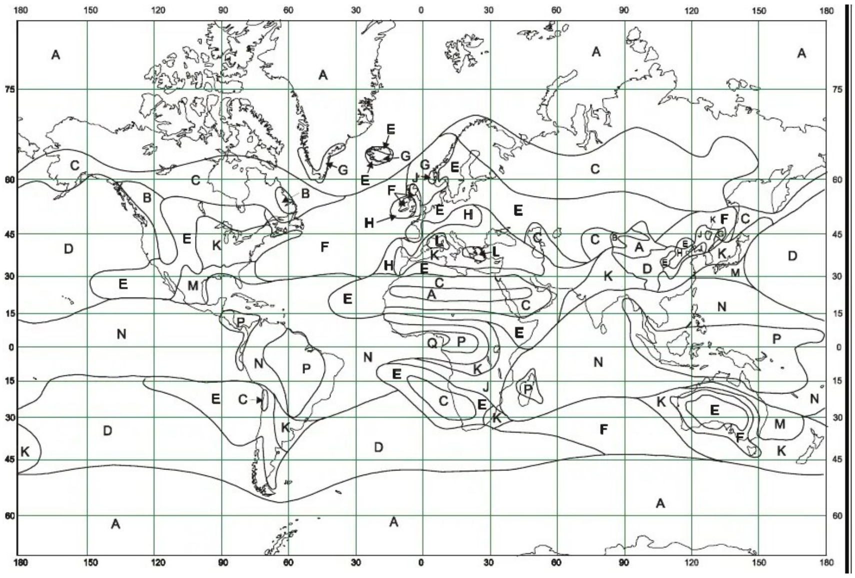
$$\begin{cases} L_{Gas}|_{144\text{ MHz}} = \gamma_{Gas}|_{144\text{ MHz}} \cdot d_{troposphere} \approx 4 \cdot 10^{-3} dB/km \cdot 57.59km = 0.2303\text{ dB} \\ L_{Gas}|_{432\text{ MHz}} = \gamma_{Gas}|_{432\text{ MHz}} \cdot d_{troposphere} \approx 4 \cdot 10^{-3} dB/km \cdot 57.59km = 0.2303\text{ dB} \\ L_{Gas}|_{5.8\text{ GHz}} = \gamma_{Gas}|_{5.8\text{ GHz}} \cdot d_{troposphere} \approx 6.5 \cdot 10^{-3} dB/km \cdot 57.59km = 0.3743\text{ dB} \end{cases} \tag{2.11}$$

#### 2.5.2.2 Hydro-meteors absorption

Hydro-meteors attenuation refers to the weakening or loss of signal strength in wireless communication systems caused by atmospheric conditions involving suspended water ($H_2O$) particles (such as rain, fog, snow or clouds). Recommendation ITU-R P.838-3 [54] shall be used to predict the attenuation model for rainfall. The specific attenuation $\gamma_{Hyd}$ (dB/km) is obtained using the power-law relationship (Equation 2.12), where $R$ is the rain rate in mm/h.

$$\gamma_{Hyd} = k \cdot R^{\alpha} \tag{2.12}$$

Depending on the geographical location of the GS, the attenuation by hydro-meteors can be higher or lower. For this purpose, the map of rainfall regions is used, which segregates the world map into zones according to rainfall intensity, droplet size and atmospheric pressure statistics. In the case of the iTEAM-GS, it is located in Valencia, Spain, so the assigned isopleth is K, as can be seen in Figure 2.9. Since the iTEAM-GS is located in an area with a low probability of precipitation, we will keep the conservative but not restrictive protection value of 99.9%. Therefore, the value of $R$ will be 12 mm/h.



**(a)**


| Porc. tiempo. Isopletas (mm/h) | 1,0 | 0,3 | 0,1 | 0,03 | 0,01 | 0,003 | 0,001 |
|---|---|---|---|---|---|---|---|
| A | < 0,1 | 0,8 | 2 | 5 | 8 | 14 | 22 |
| B | 0,5 | 2 | 3 | 6 | 12 | 21 | 32 |
| C | 0,7 | 2,8 | 5 | 9 | 15 | 26 | 42 |
| D | 2,1 | 4,5 | 8 | 13 | 19 | 29 | 42 |
| E | 0,6 | 2,4 | 6 | 12 | 22 | 41 | 70 |
| F | 1,7 | 4,5 | 8 | 15 | 28 | 54 | 78 |
| G | 3 | 7 | 12 | 20 | 30 | 45 | 65 |
| H | 2 | 4 | 10 | 18 | 32 | 55 | 83 |
| J | 8 | 13 | 20 | 28 | 35 | 45 | 55 |
| K | 1,5 | 4,2 | 12 | 23 | 42 | 70 | 100 |
| L | 2 | 7 | 15 | 33 | 60 | 105 | 150 |
| M | 4 | 11 | 22 | 40 | 63 | 95 | 120 |
| N | 5 | 15 | 35 | 65 | 95 | 140 | 180 |
| P | 12 | 34 | 65 | 105 | 145 | 200 | 250 |
| Q | 24 | 49 | 72 | 96 | 115 | 142 | 170 |

**(b)**

**Figure 2.9** – Rainfall regions categorised by isopleths worldwide in (a) and zoomed to Spain in (b) [54].

Both $k$ and $\alpha$ coefficients are determined by the operative frequency and polarization by using Equation 2.13 and Equation 2.14, respectively, and the constants $k_H$, $k_V$, $\alpha_H$ and $\alpha_V$ can be get from Figure 2.10. We see that for values below 1 GHz the value of the constants is not specified, so we will estimate the worst case for the VHF and UHF bands and approximate it to 1 GHz.

$$k = [k_H + k_V + (k_H - k_V) \cdot \cos^2(\theta) \cdot \cos(2\tau)]/2 \tag{2.13}$$

$$\alpha = [k_H \cdot \alpha_H + k_V \cdot \alpha_V + (k_H \cdot \alpha_H - k_V \cdot \alpha_V) \cdot \cos^2(\theta) \cdot \cos(2\tau)]/2k \tag{2.14}$$

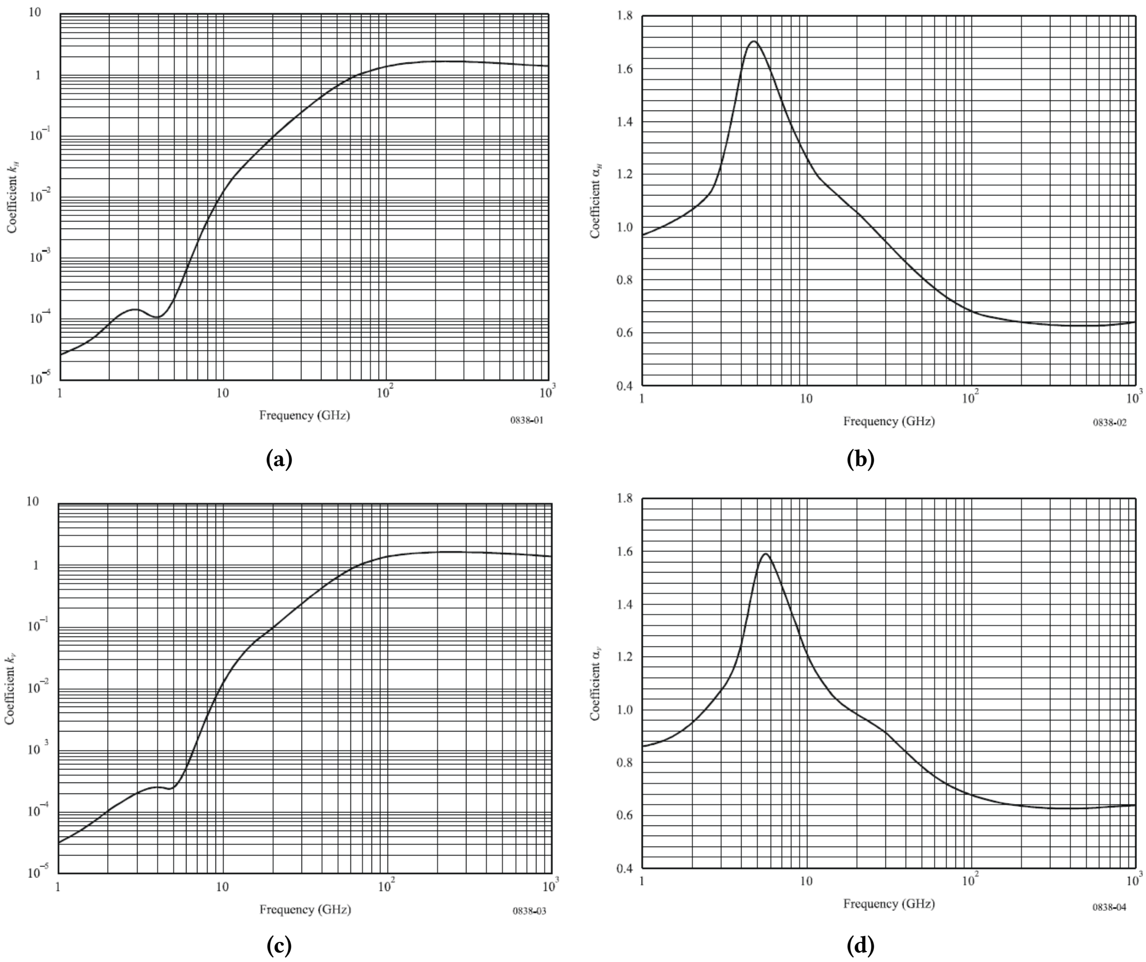



**Figure 2.10** – Coefficients $k_H$ in (a), $\alpha_H$ in (b), $k_V$ in (c) and $\alpha_V$ in (d) [54].

The highest concentration of atmospheric gases is in the Troposphere (h = 10 km). Thus, the slant path is 57.59 km as shown in Equation 2.10. We obtain the following attenuation for each band of interest:

$$\begin{cases} L_{Hyd}|_{144\text{ MHz}} = \gamma_{Hyd} \cdot d_{troposphere} = 0,00027 dB/km \cdot 57.59 km = 0.015\,64\text{ dB} \\ L_{Hyd}|_{432\text{ MHz}} = \gamma_{Hyd} \cdot d_{troposphere} = 0,00027 dB/km \cdot 57.59 km = 0.015\,64\text{ dB} \\ L_{Hyd}|_{5.8\text{ GHz}} = \gamma_{Hyd} \cdot d_{troposphere} = 0,0273 dB/km \cdot 57.59 km = 1.5664\text{ dB} \end{cases} \tag{2.15}$$

### 2.5.3 Ionospheric propagation

Ionospheric propagation effects impact electromagnetic communication by interacting with electromagnetic waves in the Earth's ionosphere. The ionosphere has a high concentration of charged particles, including free electrons and ions that affect the propagation of electromagnetic waves. These effects may be significant, especially when operating at frequencies below 1 GHz.

The ionosphere is composed of two distinct layers: the Mesosphere (50 km to 85 km) and the Thermosphere (85 km to 690 km). Above the 690 km mark that denotes the Thermosphere, the Exosphere lies (690 km to 10000 km). However, its effects will not be examined as the scenario of interest altitude is 500 km.

2

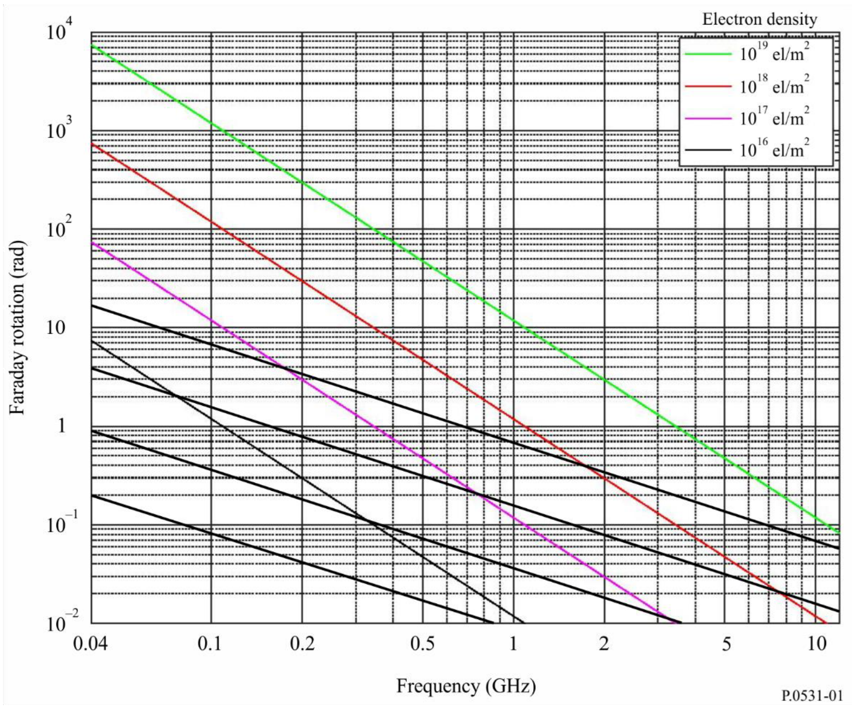



**Figure 2.11** – Faraday rotation angle [55].

#### 2.5.3.1 Faraday rotation

As an electromagnetic wave propagates through the ionosphere, it undergoes a gradual rotation in its plane of polarization due to the presence of the Earth's magnetic field and the anisotropy of the plasma medium. This is known as the Faraday effect and can affect the received power. The ITU [55] shall be used to calculate the attenuation associated to Faraday rotation.

The magnitude of the Faraday rotation, $\gamma_{FR}$, depends on the frequency of the electromagnetic wave, the strength of the magnetic field and the electron density of the plasma. The losses due to the Faraday rotation can be calculated from Equation 2.16, where $\gamma_{FR}$ is the rotation angle (rad) obtained from Figure 2.11.

$$L_{Faraday\ Rotation} = -20 \cdot \log[\cos(\gamma_{FR})] \tag{2.16}$$

Thus, for our bands of interest, we obtain the following attenuations:

$$\begin{cases} L_{Faraday\ Rotation}|_{144\ \text{MHz}} = \gamma_{FR}|_{144\ \text{MHz}} = 1.22\ \text{dB} \\ L_{Faraday\ Rotation}|_{432\ \text{MHz}} = \gamma_{FR}|_{432\ \text{MHz}} = 1\ \text{dB} \\ L_{Faraday\ Rotation}|_{5.8\ \text{GHz}} = \gamma_{FR}|_{5.8\ \text{GHz}} = 0.006\ \text{dB} \end{cases} \tag{2.17}$$

Chapter 3

# Satellite communication subsystem for Ground Station

This chapter presents an analysis of the radio frequency subsystems designed for the iTEAM-GS, including antennas, active and passive components, cables and control elements (sequence control and polarization switch). The base architecture of the iTEAM-GS is shown in Figure 3.1.

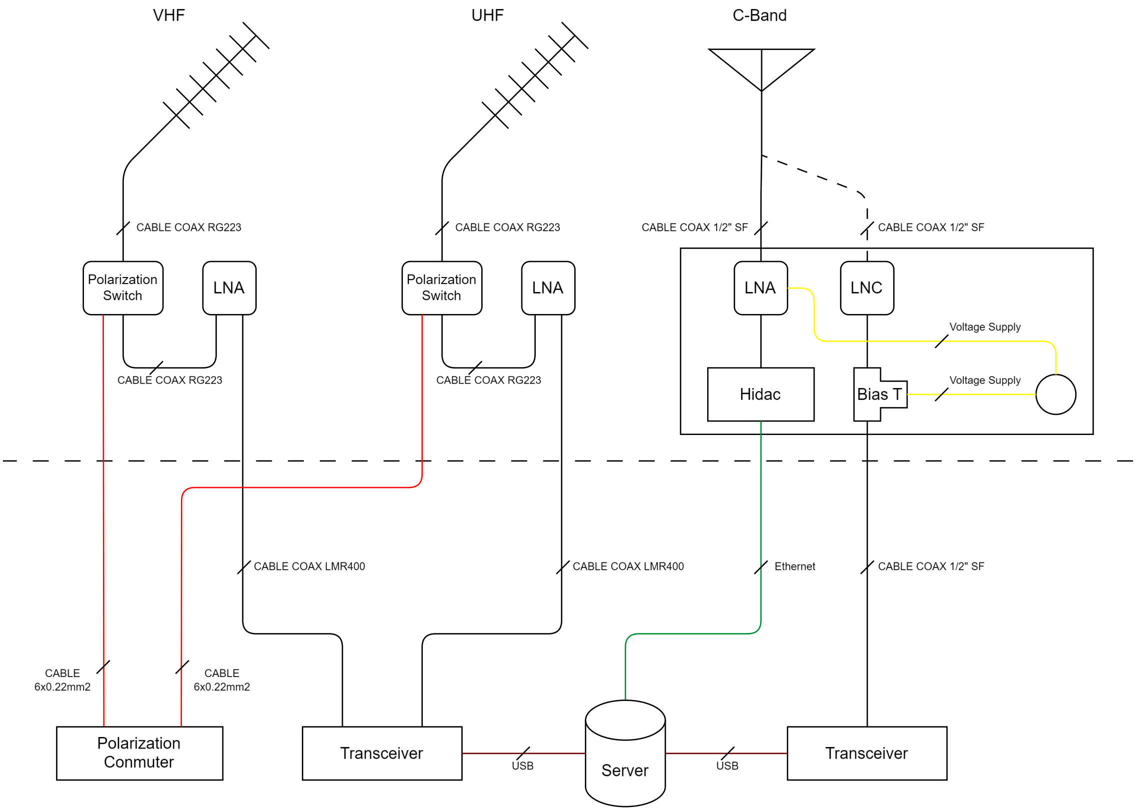



**Figure 3.1** – iTEAM-GS communication subsystem architecture.

iTEAM-GS is a Satellite GS located at Universitat Politècnica de València with the capability to receive Telemetry, Tracking and Command (TT&C) in VHF and UHF bands and data in C-Band.

## 3.1 Antennas

The antennas will be the front-end that will allow the radiolink to be established. The amateur frequency bands are defined by the International Amateur Radio Union (IARU) [37], [56], [57].

The type of antenna chosen will depend on the different frequency bands to be used in the radio link. The directivity of the antennas will be enhaced for receiving signals across all three bands, which translates into a better SNR reception than omnidirectional antennas . Accurate pointing of the GS will be necessary to ensure that the maximum amount of energy is focused. Finally, we must match the polarization of the antennas to the received signal polarization to enhance the reception , which also correlates to the antenna's design and topology.

### 3.1.1 VHF band

The VHF band operates in the amateur radio band from 144 MHz to 146 MHz, which in terms of wavelength is 2 m (Equation 3.1).

$$\lambda = \frac{c}{f} = \frac{c}{145 \cdot 10^6\ Hz} = 2.068\ m \tag{3.1}$$

In order to improve the directivity of the antenna, a cross-yagi topology has been chosen. The directivity of cross-yagi antennas varies with the number of elements and the element spacing with a logarithmic relationship, with an horizontal asymptote of 15dB, as we can see in Figure 3.2 [58]. It makes sense to add more elements to the boom to improve directivity, but this will also add weight. In addition to the number of elements, their crossed distribution along the horizontal and vertical axes will allow us to operate in four polarizations (horizontal, vertical, circular to the left and circular to the right). Finally, the design of the VHF antenna must be optimised and adapted to a commercial offer.

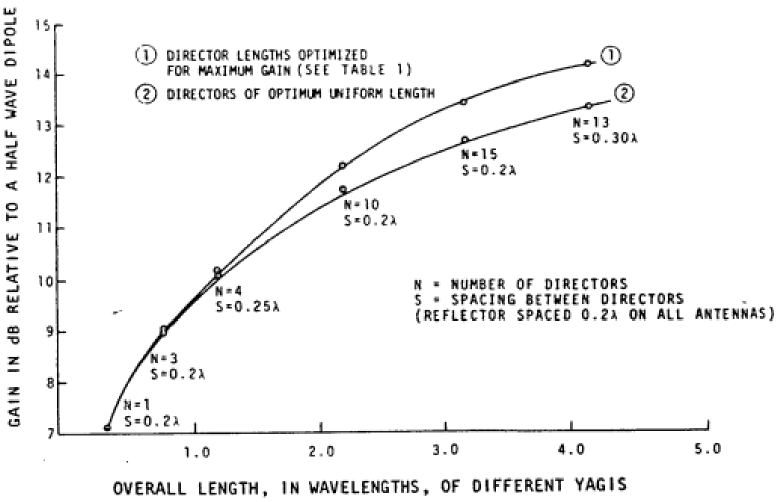
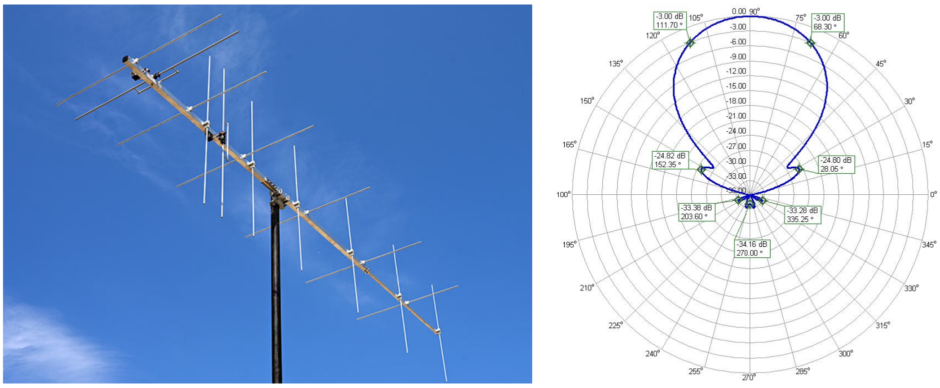



**Figure 3.2** – Comparison of gain of different length Yagis showing the relationship between directors optimized in length to yield maximum gain and directors of optimum uniform length [58].

The iTEAM-GS uses the **YU1CF (2 m antenna size)** [59] for the VHF band, which is a 14 elements (7 elements in the horizontal axis -one reflector, one driving dipole and 5 director dipoles- and 7 elements in the vertical axis) with a mean distance between dipoles of 520 mm attached to a 3.5 m boom with a gain of 12.7 dBi. As can be seen in Figure 3.3b, the Half-Power BandWidth (HPBW) is 43.4°, which correspond with a directivity of 16.58 dB (see Equation 3.2) [60]. The polarization switch, Figure 3.3, allows user to select between the four possible polarizations. Thus, the chosen VHF Cross-Yagi antenna has an efficiency of 85.11% (see Equation 3.3).

$$D = 10 \cdot log_{10}[\frac{4 \cdot \pi}{\Omega_A^2}] = 10 \cdot log_{10}[\frac{4 \cdot \pi}{(43.4° \cdot \frac{\pi}{180})^2}] = 13.4\ dB \tag{3.2}$$

$$\eta = \frac{G}{D} = \frac{10^{1.27}}{10^{1.34}} = 85.11\% \tag{3.3}$$



**(a)** **(b)**

**Figure 3.3** – VHF-Band Antenna in Cross-Yagi topology in (a) and azimuth radiation pattern [59] in (b).

### 3.1.2 UHF band

The UHF band operates in the amateur radio band from 430 MHz to 440 MHz, which in terms of wavelength is 70 cm Equation 3.4 for the center frequency of 435 MHz:

$$\lambda = \frac{c}{f} = \frac{c}{435 \cdot 10^6\ Hz} = 0.689\ m \tag{3.4}$$

The iTEAM-GS uses the **YU1CF (0.7 cm antenna size)** [61] for the UHF band, which is a 30 elements (15 elements in the horizontal axis and 15 elements in the vertical axis) with a mean distance between dipoles of 173 mm attached to a 3.5 m boom with a gain of 16.7 dBi. As can be seen in Figure 3.4b, the HPBW is 27.8°, which correspond with a directivity of 25.899 dB (see Equation 3.5 [60]. The polarization switch, Figure 3.4, allows user to select between the four possible polarizations. Thus, the chosen UHF Cross-Yagi antenna has an efficiency of 87.7% (see Equation 3.6).

$$D = 10 \cdot log_{10}[\frac{4 \cdot \pi}{\Omega_A^2}] = 10 \cdot log_{10}[\frac{4 \cdot \pi}{(27.8° \cdot \frac{\pi}{180})^2}] = 17.27\ dB \tag{3.5}$$

$$\eta = \frac{G}{D} = \frac{10^{1.67}}{10^{1.727}} = 87.7\% \tag{3.6}$$

**(a)** **(b)**

**Figure 3.4** – UHF-Band Antenna in Cross-Yagi topology in (a) and azimuth radiation pattern [61] in (b).

### 3.1.3 C band

The C-band band operates in the amateur radio band from 4 GHz to 8 GHz, which in terms of wavelength is 50 cm (see Equation 3.7) for the center frequency of 6 GHz:

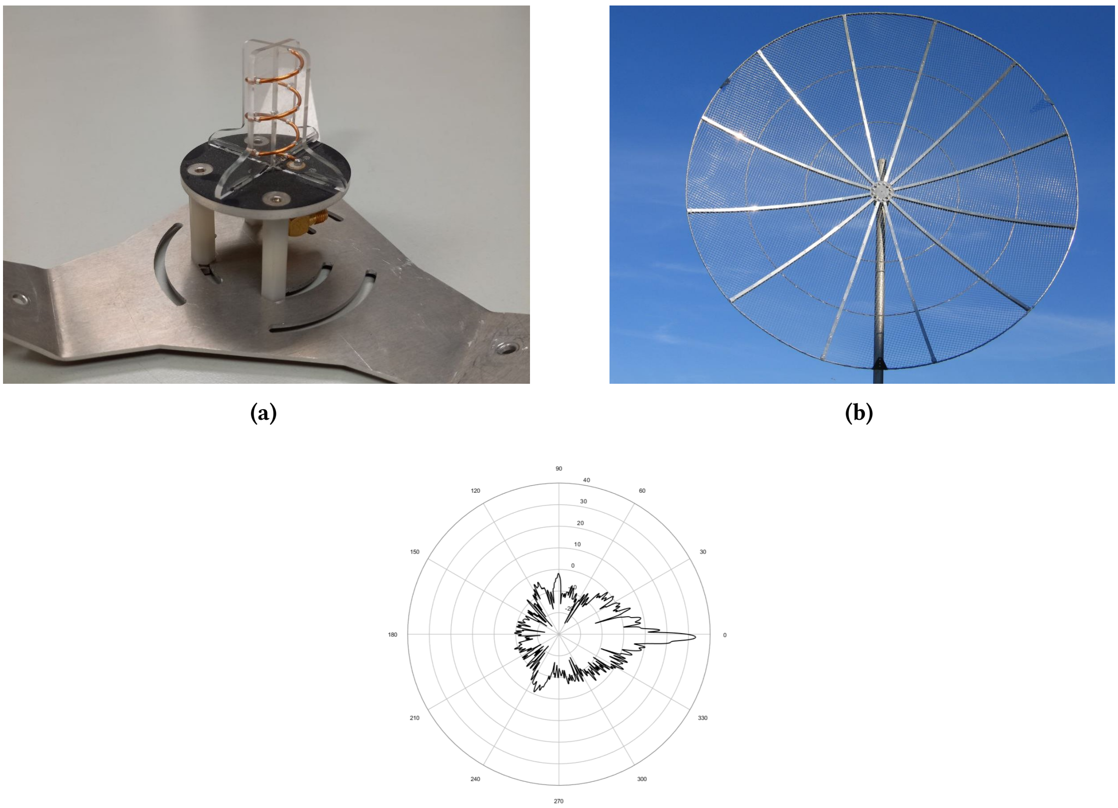
$$\lambda = \frac{c}{f} = \frac{c}{6 \cdot 10^9 \ Hz} = 0.05 \ m \tag{3.7}$$

In this case and due to the small wavelength, it will be used a parabolic antenna fed with a helical focus, designed and manufactured by the Antennas and Propagation Lab (APL) at iTEAM-UPV (Figure 3.5) for this band.

In order to improve the antenna's gain, iTEAM-GS will have a reflector of 1.9 m of diameter and f/D of 0.45. The reflector is conformed by a mesh of 2.8 mm, which reflects all the frequencies below 10.71 GHz (see Equation 3.8). All supplied mounting parts are stainless steel and or Aluminium [62].

$$f = \frac{c}{\lambda} = \frac{c}{2.8 \ mm} = 10.71 \cdot 10^9 \ Hz \tag{3.8}$$

The complete configuration (helical feed + reflector) has been measured in the APL's anechoic chamber and it has a directivity of 33.26 dBi in the XZ plane and 31.11 dBi in the YZ plane. We will use 32.185 dBi for future calculations.




**(a)** **(b)** **(c)**

**Figure 3.5** – C-Band feed antenna at focus in (a), reflector in (b) and C-Band antenna and reflector azimuth radiation pattern in (c).

## 3.2 Microwave components

The antennas presented in section 3.1 have been selected for our application and for receiving the signal power from satellites, but it will be necessary to use microwave components in both transmission and reception, such as amplifiers or frequency converters in order to adapt GS to the communication link.

3

### 3.2.1 Microwave filters

The iTEAM-GS does not make use of microwave filters in either communication direction. This is one of the key points of improvement for future versions of the iTEAM-GS. However, some of the components mentioned throughout section 3.2 have built-in filtering, so this should be taken into account when using them outside their working band.

The system's ability to work as a technology demonstrator can serve as a test base for future studies and designs of microwave filters.

### 3.2.2 Low Noise Amplifier

The downlink's propagation losses [63] are the most significant losses when compared to atmospheric attenuation (detailed data and calculations has been examined in section 2.5). Therefore, the iTEAM-GS needs an amplification stage at reception to pre-amplify the received signal before demodulation, but it is critical for this stage not to introduce more noise into the signal in order to receive the highest possible SNR.

The iTEAM-GS makes uses of the **Electronic SP-200 VHF** low noise amplifier for the VHF band [64], the **Electronic SP-70 UHF** low noise amplifier for the UHF band [65] and the **MKU LNA 572 AF** for the C band [66]. The models and technical specifications for the three operative bands are summarized in Table 3.1.

| **Model** | **SP-200 VHF** | **SP-70 UHF** | **MKU LNA 572 AF** |
|---|---|---|---|
| **Frequency range** | 144 - 146 MHz | 430 - 440 MHz | 5710 - 5810 MHz |
| **Noise figure @ 18 °C** | typ. 0.5 dB | typ. 0.7 dB | typ. 0.8 dB |
| **Gain** | 10 - 20 dB | 12 - 22 dB | min. 25 dB |
| **Supply voltage** | 12 V - 14 V | 12 V - 14 V | 9 V - 15 V |
| **Current consumption** | 240 mA | 320 mA | 30 mA |
| **Input connector / impedance** | N-Female | N-Female | SMA-male |
| **Output connector / impedance** | N-Female | N-Female | SMA-female |
| **Weight** | 760 g | 760 g | 75 g |

**Table 3.1** – Low noise amplifiers models and specifications used for iTEAM-GS.

### 3.2.3 Linear Amplifier

Although the main mission of the iTEAM-GS is to receive TT&C and data from satellites, it must be able to send commands to the satellite to ensure correct reception in the satellite segment. Therefore, this iTEAM-GS needs an amplification stage in the transmission.


(a) (b)

(c)

**Figure 3.6** – VHF Low noise amplifier model [64] in (a), UHF Low noise amplifier model [65] in (b) and C-Band Low noise amplifier model for the transmission subsystem [66] in (c).

The iTEAM-GS will use the **RM Italy LA 250** amplifier (Figure 3.7) [67] which has an amplification stage of 10 dB in the [140 MHz, 150 MHz] frequency range with a typical noise figure of 1.5 dB (@ 18 °C).

| **Model** | **LA 250** |
|---|---|
| **Frequency range** | 140 MHz - 150 MHz |
| **Gain** | 10 dB |
| **Suply Voltage** | 13 VDC ± 1 V 40 A |
| **Weight** | 4 kg |

**Table 3.2** – Linear amplifier model and specifications used for iTEAM-GS [67].


**Figure 3.7** – Linear amplifier for the transmission subsystem [67].

### 3.2.4 Low Noise Converter

As it will be pointed out at section 3.3, the C-Band cables has great losses with the distance. Although the iTEAM-GS has been designed with a direct C-Band cable from the C-Band LNA to the station, a low noise frequency down converter will be installed to convert the signal from C-Band down to UHF band, and then transmit it via a UHF cable to the station so that the GS have less losses than by using the C-Band cable as a substitute to the low noise amplifier path presented in subsection 3.2.2.

The iTEAM-GS uses of the **KU LNC 5560 C PRO** low noise converter for the C-band subsystem (Figure 3.8) [68] which has an amplification stage of 35 dB in the [5500 MHz, 6000 MHz] frequency range with a typical noise figure of 1.5 dB (@ 18 °C).

| **Model** | **KU LNC 5560 C PRO** |
|---|---|
| **Frequency range** | 5500 MHz - 6000 MHz |
| **Noise figure @ 18 °C** | typ. 1.5 dB |
| **Gain** | 35 dB |
| **Supply voltage** | 9 V - 36 V |
| **Current consumption** | 180 mA |
| **Input connector / impedance** | N-female |
| **Output connector / impedance** | BNC-female |
| **Weight** | 230 g |

**Table 3.3** – Low noise converter model and specifications used for iTEAM-GS [68].


**Figure 3.8** – Low noise converter model [68].

## 3.3 Cables

The connections between all the RF components of the three subsystems are coaxial cables in order to get as lower losses as possible. The iTEAM-GS control room is based one floor under the antennas, thus, signal transmission between the roof (where the antennas are located) and the control room is a great source of cable and connector losses. The cables specifications are summarized in Table 3.4.

| **Model** | **Cable coax. RG223** | **Cable coax. LMR400** |
|---|---|---|
| **Band** | VHF | VHF |
| **Frequency range** | 144 MHz | 144 MHz |
| **Attenuation @ 25°C** | 0,15 dB/m | 5,0 dB/m |

| **Model** | **Cable coax. RG223** | **Cable coax. LMR400** |
|---|---|---|
| **Band** | UHF | UHF |
| **Frequency range** | 432 MHz | 432 MHz |
| **Attenuation @ 25°C** | 0,28 dB/m | 8,8 dB/m |

| **Model** | **Cable coax. 1/2" SF** | **Cable coax. 1/2" ANDREW** |
|---|---|---|
| **Band** | C-Band | C-Band |
| **Frequency range** | 5825 MHz | 5825 MHz |
| **Attenuation @ 25°C** | 0,3379 dB/m | 0,1971 dB/m |

**Table 3.4** – Cables used for the iTEAM-GS specifications.

## 3.4 Control elements

### 3.4.1 Sequence control

There are some commercial transceivers that have an integrated sequencer, but iTEAM-GS makes use of a sequencer to control the transmission and reception and their respective amplifications. The commutation between transmission and reception is made by the transceiver with a PTT function. The chosen sequencer is the **DCW-2004**, which allows the operator to manually switch on and off the power supply to the amplifiers feeding the iTEAM-GS ([69]).


(a) (b)

**Figure 3.9** – Sequencer model front in (a) and back in (b).

### 3.4.2 Polarization switch

As it was pointed out in section 3.1, the VHF and UHF antennas can be configured in the four polarizations since the models are Crossed polarized Yagis antennas. In order to be able to configure the polarization dynamically, a Polarization Switch is needed to combine the horizontal and vertical signals in either the uplink and the downlink directions. The chosen polarization switches for the iTEAM-GS is the **WIMO Polarization remote switch VHF** for the VHF subsystem ([70]) and the **WIMO Polarization remote switch UHF** for the UHF subsystem ([71]). Both polarization switches are configured with a 4 wire DC control cable.

(a) (b)

**Figure 3.10** – Polarization switch models for VHF subsystem in (a) and for UHF subsystem in (b).

## 3.5 Transceiver

In order to both transmit and receive data from the satellites, the GS needs a transceiver to operate the signal. The transceiver will be connected to a computer for both telecommand the transceiver and process the signal.

The iTEAM-GS uses an **ICOM-9700** (Figure 3.11) [72] transceiver to communicate with LEO satellites. The ICOM-9700 can transmit and receive on the amateur frequencies of the VHF band ([144-146MHz]) and the UHF band ([430-440MHz] and [1.240-1.300MHz] [1]) and can operate in analog (AM and FM) and digital (CW, SSB, RTTY, DV and DD) modes with an output power up to 2 dBW @ 144 MHz and a sensitivity up to -126 dBm (0.1 $\mu$V).


**Figure 3.11** – ICOM-9700 [72].

The transceiver is located at the UPV-GS control room and connected to the server via USB. The VHF RF front-end and the UHF RF front-end are connected to the VHF connector and the UHF connector respectively, and the operating band is selected via the ICOM-9700 user interfaces (the transceiver screen or a server).

### 3.5.1 ICOM-9700 settings

ICOM-9700 is enabled to carry out satellite communications with its satellite mode configuration [73]. This functionality allows users to communicate in half-duplex mode with the satellite at the

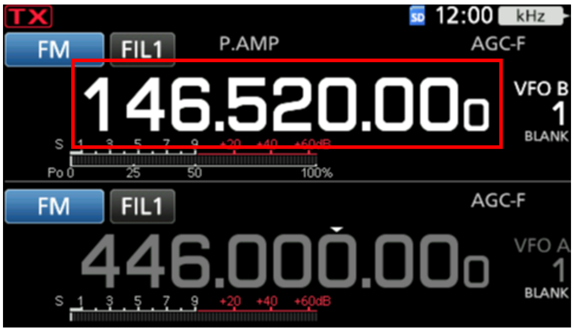
[1] With down conversion sampling.

same or different operative bands and to adjust the Doppler shift in both frequencies (downlink and uplink) manually.

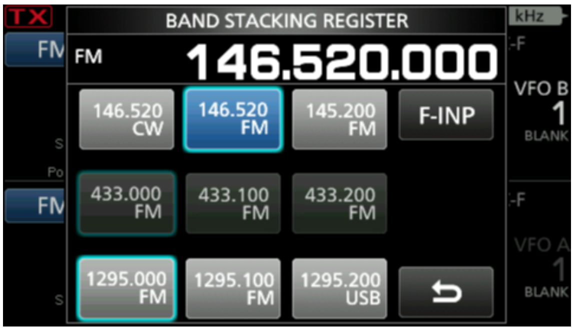
Since the objective of the iTEAM-GS is to process the data (operating RTTY [74]) in the server, the ICOM-9700 must be configured to be controlled via USB, which allows users to remotely control the transceiver with commands [73], [74]).

#### 3.5.1.1 Operative frequencies

The Variable Frequency Oscillator (VFO) frequency can be seen in the main screen. In case the layout shows the two VFOs' frequencies (VFO A or VFO B), the operative VFO frequency is the highlighted one, as shown in Figure 3.12a. The operative frequency can be set by two modes: by storing them in memory, as in Figure 3.12b, or directly entering a frequency manually, as in Figure 3.12c.




(a)




(b)


(c)

**Figure 3.12** – ICOM-9700 operative frequency in (a) and frequencies setting stored in memory in (b) and set manually in (c) [73].

#### 3.5.1.2 Operating mode

In order to properly transmit and receive the data, the operating mode of the GS and the satellite must be the same. The ICOM-9700 can operate the modes listed in Table 3.5 as shown in Figure 3.13. ICOM-9700 can operate data mode in AM, FM or SSB by using Audio Frequency Shift Keying (AFSK) [74].

| Mode | Mode key | Operating mode | |
|---|---|---|---|
| Single-sideband | [SSB] | USB | LSB |
| Continuous Wave | [CW] | CW | CW-R |
| Radio TeleTYpe | [RTTY] | RTTY | RTTY-R |
| Amplitud modulation | [AM] | AM | |
| Frequency modulation | [FM] | FM | |
| Digital Video | [DV] | DV | |
| Data modem | [DD] | DD | |
| Data mode | [DATA] | LSB | LSB-D |
| | | USB | USB-D |
| | | AM | AM-D |
| | | FM | FM-D |

**Table 3.5** – ICOM-9700 operating modes.

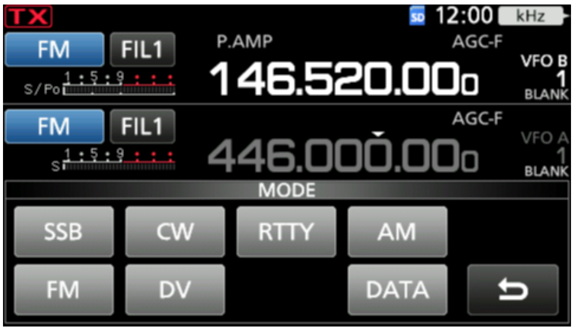



**Figure 3.13** – ICOM-9700 operating modes setting [73].

### 3.5.1.3 External and digital pre-amplifiers

ICOM-9700 can feed the LNA selected for the iTEAM-UPV via the RF cable. For this, it is needed to set the supply voltage for the desired band as shown in Figure 3.14.


**Figure 3.14** – ICOM-9700 external preamplifier supply settings per operative band (Menu > SET > Connectors > External P.AMP) [73].

Since the signal sent by the satellite suffers a very high attenuation, it is highly recommended to make use of the digital pre-amplification function offered by the ICOM-9700 transceiver. Both configurations are set in the function menu as shown in Figure 3.15.

### 3.5.1.4 Digital filtering

The digital filtering bandwidth can be set between wide (FIL 1), mid (FIL 2) or narrow (FIL 3) as shown in Figure 3.16. Depending on the operative bandwidth, this configuration must be


**(a)** **(b)**

**Figure 3.15** – ICOM-9700 functions settings [73].

properly set to filter the received signal.

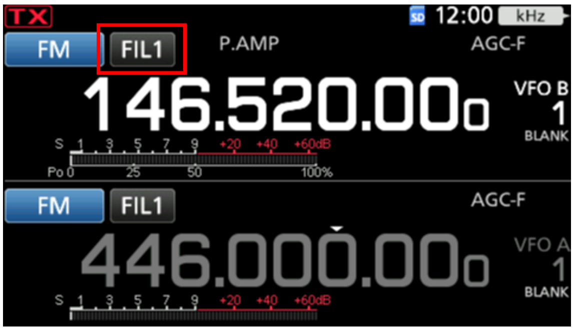



**Figure 3.16** – ICOM-9700 digital filtering selection [73].

### 3.5.1.5 RF Gain and Squelch

The RF gain and the squelch (RF/SQL) refer to the transceiver sensitivity. With a minimum RF/SQL gain (maximum counter clock wise), the GS will receive signals with very low signal strength (low sensitivity), but also a high amount of noise. On the contrary, with the maximum RF/SQL gain, the GS will only receive signals with very high signal strength (high sensitivity), but also less noise. Therefore, the RF/SQL setting must be balanced [73]. The RF/SQL can be set as shown in Figure 3.17.

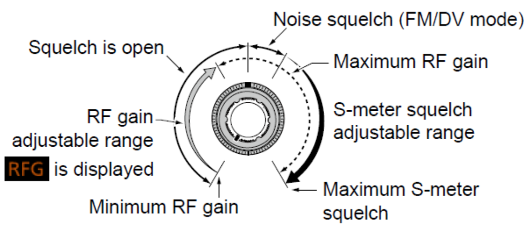


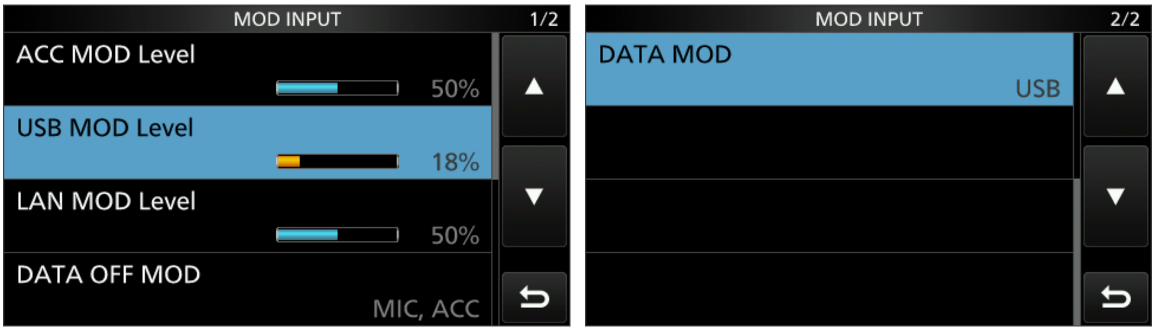

**Figure 3.17** – ICOM-9700 RF/SQL setting [73].

### 3.5.1.6 USB connection

The ICOM-9700 is connected to the server [2] with a **USB Type B cable**. The GS need to establish the communication between ICOM-9700 and the server though the USB port and to configure

[2]The server must have the USB driver installed as described in [73].

that communication as shown in Figure 3.18.

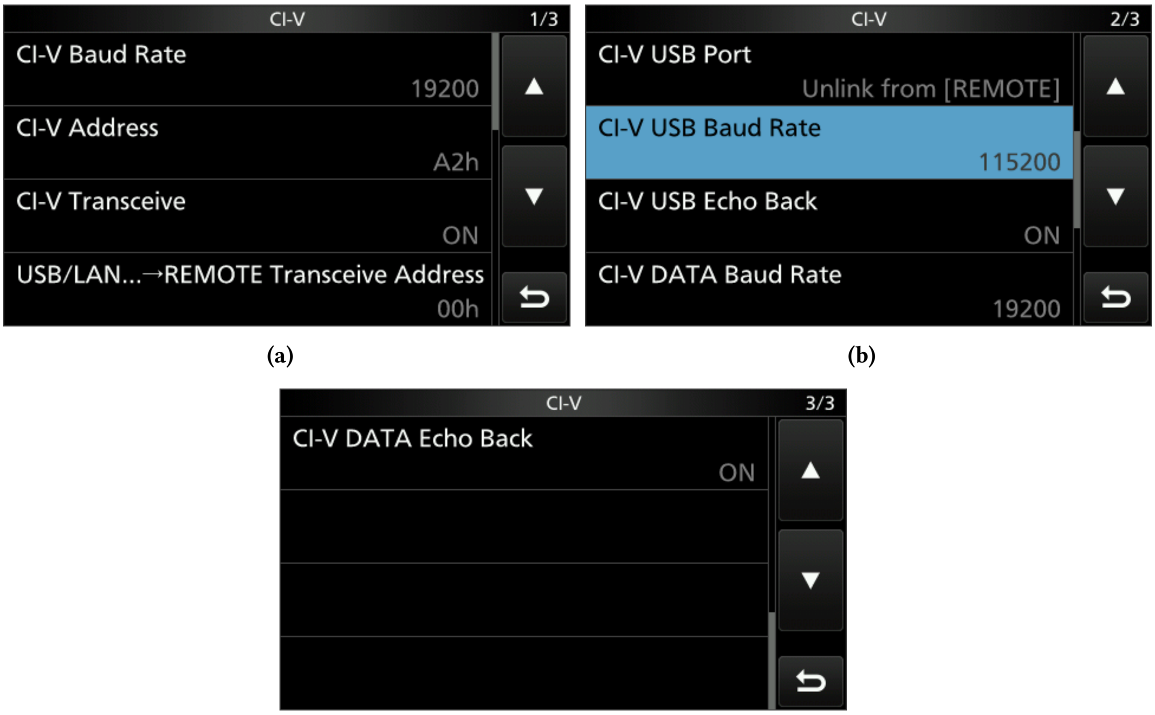



(a) (b)

**Figure 3.18** – ICOM-9700 Mod input settings (Menu > Set > Connectors > MOD Input).

#### 3.5.1.7 Communications Interface 5 commands

Communications Interface 5 (CI-V) is ICOM's proprietary interface to control the transceiver [75]. The connection between the ICOM-9700 and the computer must be synchronized and it is done by properly setting the configuration of the CI-V commands as shown in Figure 3.19.




(a) (b)

(c)

**Figure 3.19** – ICOM-9700 CI-V settings (Menu > Set > Connectors > CI-V).

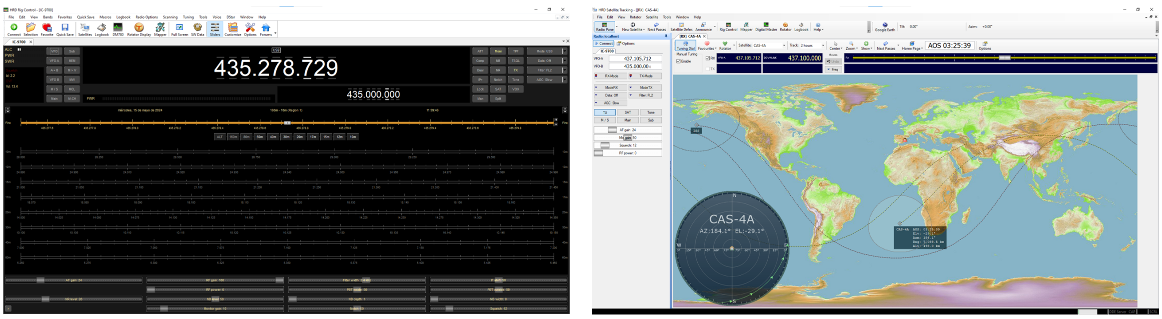
## 3.6 Satellite communication subsystem software

There are plenty of software tools that facilitates the operations with the GS depending on the purpose of the mission (satellite communications, SSTV, CW, radio-observation, earth observation or weather prediction, among others).

The ICOM-9700 is very flexible and there are some digital signals that can be demodulated in the transceiver itself, but iTEAM-GS uses a dedicated software tool for the signal processing before storing the data. The transceiver must be properly configured for satellite communications purposes and computer telecommand as detailed in subsection 3.5.1, but the settings can be set remotely with the proprietary software tool **RS-BA1** [76].

### 3.6.1 Frequency tuning software

**Ham Radio Deluxe** (HRD) [77] is an integrated suite of software products for amateur radio including rig control, logging, digital communications, satellite tracking, and rotator control. HRD modules can share the input and output COM port. **HRD Rig Control** module (Figure 3.20a) is integrated with **HRD Satellite Tracking** module (Figure 3.20b) to enable remote control of the transceiver for satellite communication (frequency tuning and operation mode), as well as to adjust the frequency shift suffered by the signal in satellite communication links.




(a) (b)

**Figure 3.20** – HRD Rig Control module interface in (a) and satellite Tracking module interface [77] in (b).

### 3.6.2 Downlink

Each satellite operates in a specific mode, and a non-packed signal can be demodulated by software such as MixW [78] or HRD [77], which will provide us with the complete information. Digital communications differs from other amateur radio communication subsystems in that they are packetized. As each satellite is managed by its own operator, the communications protocol (and, where appropriate, data encryption) are set by the operators. Consequently, the information demodulated is of little practical use without the specific unpacking process, which is carried out by a software program also known as an interpreter. Therefore, the signal received by the transceiver must be demodulated (by transceivers or dedicated software tools) and unpackaged (by a specific software interpreter) in order to obtain the data carried by the signal.The complete iTEAM-GS software architecture for the downlink can be seen in Figure 3.21.

In order to demonstrate the methodology followed to obtain the information emitted by a satellite, we will choose satellite GreenCube (IO-117) [79], which broadcasts the downlink at the frequency of 435.310 MHz, in USB operative mode and in 0k3/1k2/2k4 bauds FSK modulation. Once GreenCube has been chosen in HRD, the frequency tuning (and frequency shift adjustment) and the operative mode will be done automatically, as discussed in subsection 3.6.1.

Demodulation will be performed by the free software **Soundmodem** [80] (greentnc ssb.10, in this proof of concept), a Packet-Radio TNC that uses a sound card as a modem and supports

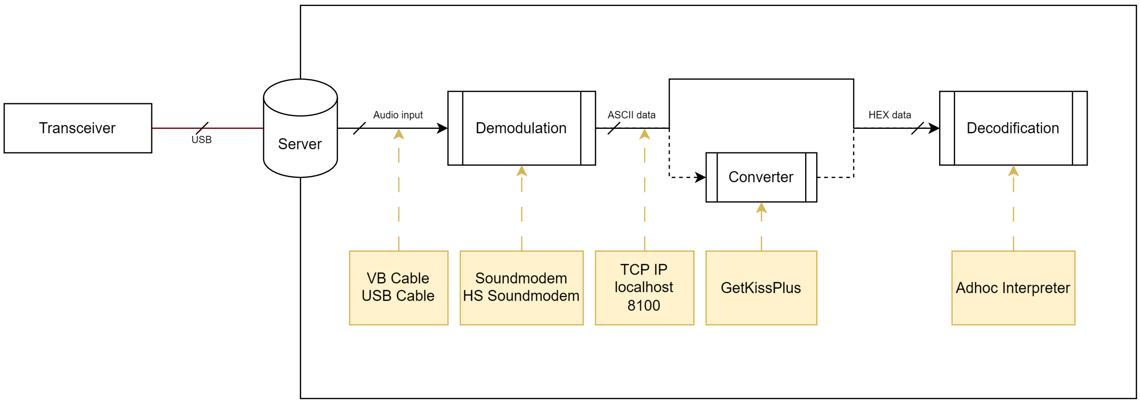
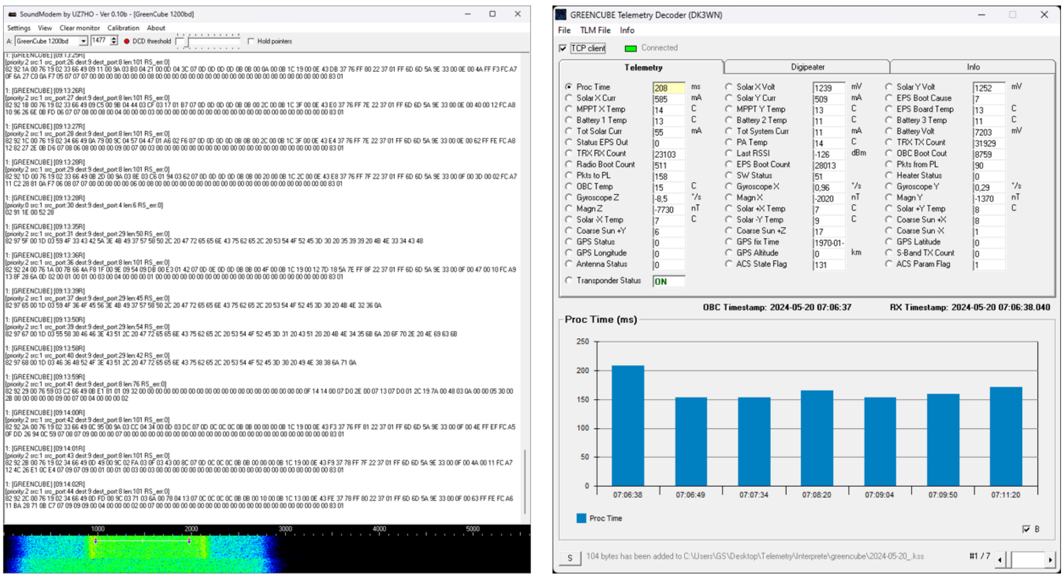



**Figure 3.21** – iTEAM-GS satellite communication subsystem software for downlink.

the AX.25 protocol [81]. Through the Soundmodem software, the modulation can be set and the software will demodulate the signal to obtain the information [3].

The "Keep It Simple, Steel" Standard (KISS) is an ASCII text file which contains the telemetry received by the satellite. The KISS file will be the input file for the software that will unpack the received information (and display it on a dashboard, in the case of a more sophisticated software). For the proposed use case, the interpreter that will unpack the information is **GreenCube Telemetry Interpreter** [82], as shown in Figure 3.22b.




**(a)** **(b)**

**Figure 3.22** – Demodulation software via Soundmodem software [80] in (a) and unpacking of the received data via specific interpreter [82] in (b)

[3]In this version of Soundmodem, the software extracts the data in Hexadecimal format, but there may be versions where the extracted data is in ASCII format, which require conversion to Hexadecimal for the decoding process.

3

Chapter 4

# Satellite tracking subsystem for Ground Station

The three antennas that will be used in the iTEAM-GS has a great directivity (13.4 dB, 17.27 dB and 32.185 dB, respectively), but the three of them have to be properly pointed to ensure that the maximum amount of energy will be received.

The first approach to increase the received SNR will be the integration of a satellite tracking subsystem composed by a rotor and a satellite tracking software. The schematic of this version of the iTEAM-GS can be seen in Figure 4.1.

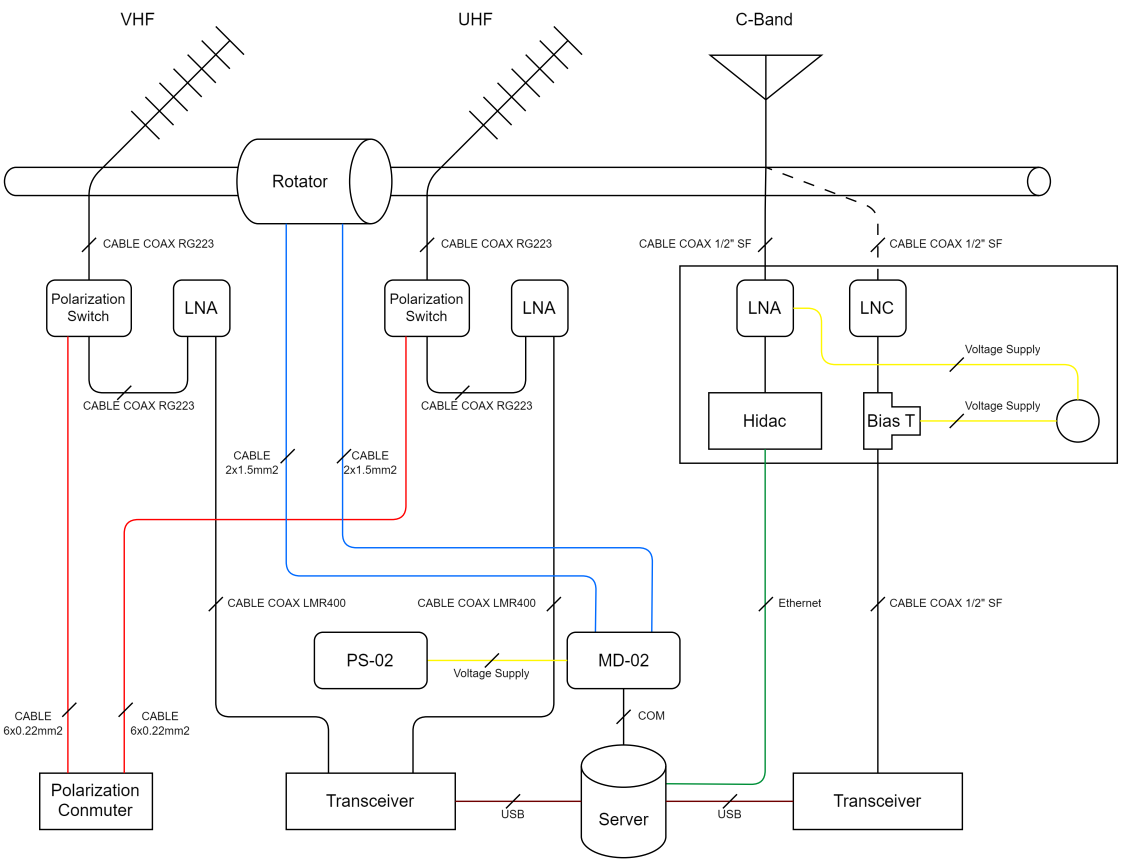



**Figure 4.1** – iTEAM-GS communication subsystem integrated with a satellite tracking subsystem architecture.

## 4.1 Rotor

The iTEAM-GS makes use of the **SPID type RAS/HR Azimuth & Elevation Rotor** [83] for the tracking subsystem, which also includes the **MD-02** rotor controller and the **PS-02** power supply.

The SPID rotor (Figure 4.2a) provides precise control over the direction in which the antenna is pointed, allowing the iTEAM-GS to direct their antennas towards specific signals in space or towards particular locations on Earth with the capability to move in both Azimuth and Elevation


(a)


(b)

**Figure 4.2** – Rotor [83] in (a) and rotor controller [83] in (b).

with a resolution of 0.2°. Thus, this rotor is especially useful in applications where it is necessary to track specific signal sources in space, such as satellites.

The SPID controller, the MD-02, is designed to manage and control the rotor movements in terms of azimuth and elevation and can be operated either manually, with the manual interface, or remotely, with the connection to a server or computer.

The rotor will be mounted on a structure over the rooftop of the final emplacement. In this case, the structure will be deployed over the rooftop of the Escuela Técnica Superior de Telecomunicaciones [84]. The three antennas will be mounted on an horizontal mast so that we can point them from the iTEAM-GS operation room. The controller and the power supply will be allocated in the iTEAM-GS operation room where they can be controlled.

## 4.2 Satellite tracking subsystem software

### 4.2.1 Satellite tracking software

The satellites' TLE information is get from **Celestrak** [85], which is an online platform that provides data and services related to satellite orbit tracking and prediction. There are plenty of satellite and keplerian body tracking software in the market used by radio users and astronomers to predict and track the path of artificial satellites and other objects in orbit around the Earth. This type of software uses TLE to calculate and predict the position and trajectory of objects in space.

The iTEAM-GS uses **Orbitron** [86] software, a satellite tracking software with an intuitive

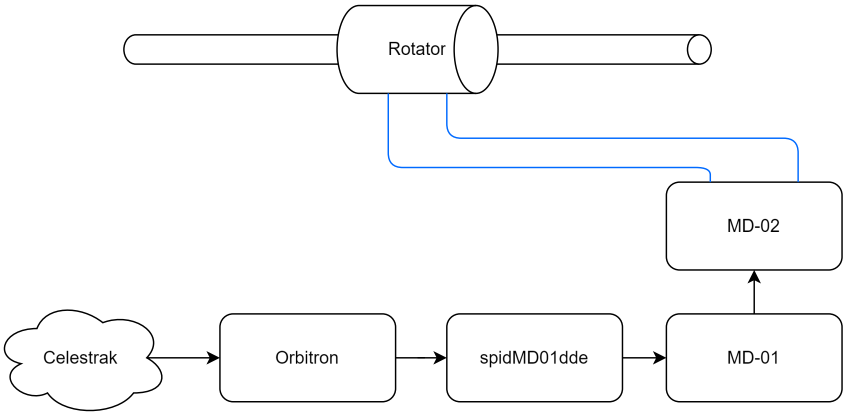



**Figure 4.3** – Complete rotator architecture for the satellite tracking subsystem.

graphic interface (Figure 4.4) that provides accurate predictions of satellite orbits, allowing users to know the visibility of satellites from their geographical location in real time or in the future. The software provides detailed information about each satellite (such as name, catalogue number, frequencies or Doppler shift) while allowing the user to customise the observer's location and iTEAM-GS features for more accurate predictions. The selection of the satellite to be tracked by the iTEAM-GS is done in the Orbitron interface Figure 4.4.

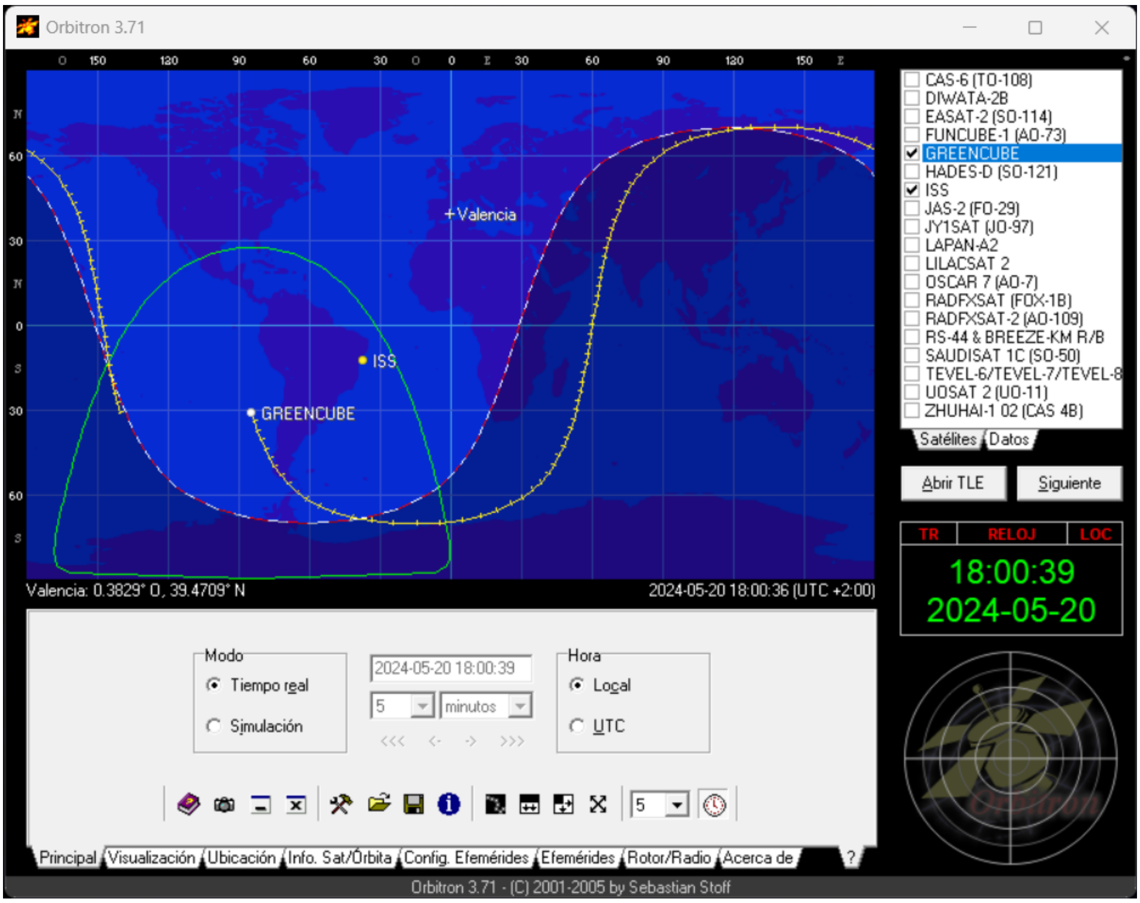



**Figure 4.4** – Orbitron satellite tracking subsystem software [86].

## 4.3 Rotor controller software

The satellite tracking data is sent to the rotor controller software via **spidMD01dde** [87], which is a firmware to configure the controller more easily and to send basic rotation commands to the rotor.

The SPID [83] uses the **MD-01** [88] controller software to send this information to the **MD-02** [83] hardware controller. The coordinates (given by Orbitron through spidMD01dde) are translated into azimuth and elevation data to control the rotor Figure 4.3.

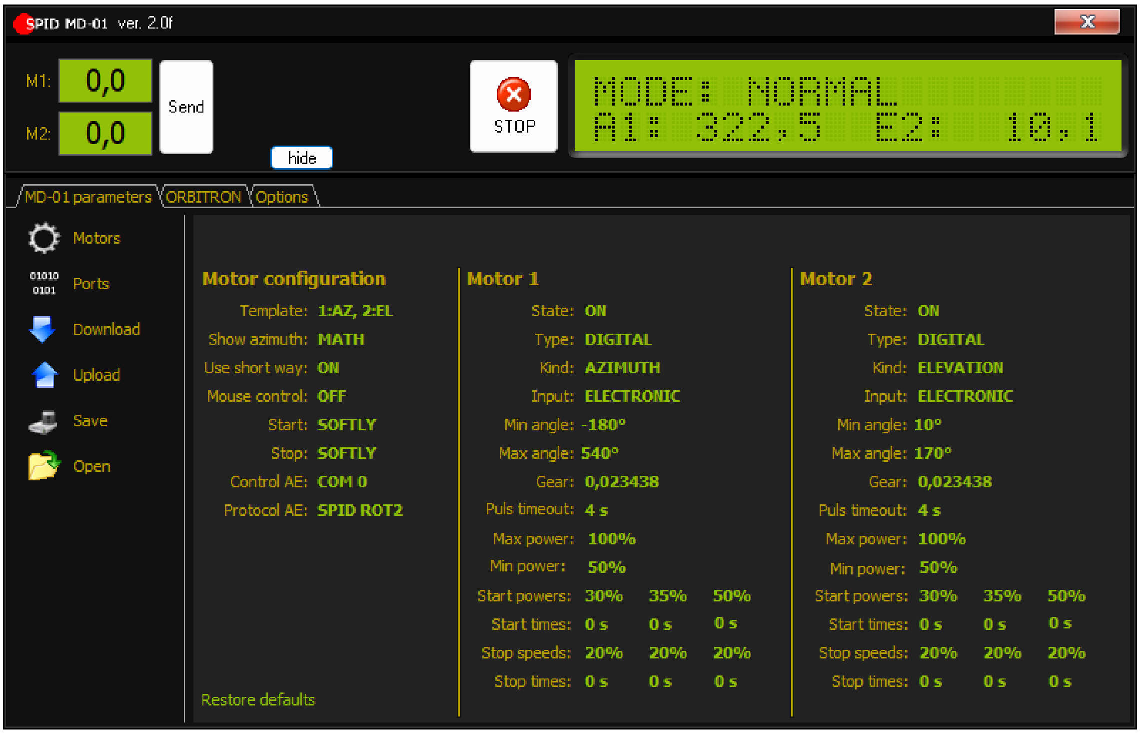



**Figure 4.5** – MD-01 software interface [88].

Chapter 5

# Virtualized Ground Station based on Software Defined Radio

After establishing the satellite communication subsystem and demonstrating its correct performance in chapter 3 (supported by the satellite tracking subsystem described in chapter 4), this section addresses the virtualization of the described iTEAM-GS functionalities by means of the integration of the communication system based on SDR technology.

The use of SDR will make the iTEAM-GS capabilities more flexible by implementing the functions of the RF components via code, thus enabling station adaptability and allowing the use of novel technologies (such as cognitive radio or regenerative radio). For this purpose, the ICOM 9700 transceiver will be replaced by SDR modules. The iTEAM-GS will make use of the **RTL-SDR v3** [89] and the **LimeSDR mini v2** [90] modules.

The interesting aspect about the integration of SDR technology into the iTEAM-GS is that it can be done straightforwardly and without requiring too many changes in the architecture, the software or the operating methodology of the station. However, it is important to note that, obviously, if a communication system is adapted for certain bands, working outside these bands can have destructive effects on the signal: increased attenuation effects (e.g. due to increased reflective losses as a result of impedance mismatch) or malfunctioning of certain RF components. For this section, we will address the integration of SDR technology for use in the VHF and UHF amateur radio bands. The control signal will be injected by means of a BiasT as shown in Figure 5.1.

## 5.1 Ground Station with RTL-SDR v3

The RTL-SDR v3 [89] is a highly popular device in the SDR field. Manufactured by RTL-SDR Blog, it is based on the RTL2832U chip. It is notable for its affordability and ease of use, making it a popular choice for both amateurs and professionals. Its typical frequency range is between 500 kHz and 1.7 GHz, allowing the user to explore a wide variety of radio bands. Furthermore, its compact size and USB connection make it portable and easy to transport. The strength of the RTL-SDR is that it is a low-cost SDR solution that allows users to experiment with this technology at a lower risk. However, this dongle is only capable of receiving.

### 5.1.1 Software Defined Radio with RTL-SDR v3

The integration of the RTL-SDR v3 module will also implicate the adaptation of the iTEAM-GS software architecture presented in section 3.6. As previously mentioned in chapter 5, SDR technology requires programming the module to obtain a signal at its output with the characteristics desired by the operator.

In the case of the RTL-SDR v3 module, we can make use of the **SDR#** [91] software, which is an intuitive user interface with support for various SDR devices, including the RTL-SDR v3 module. The SDR# software allows demodulation, display and recording of received signals in

5

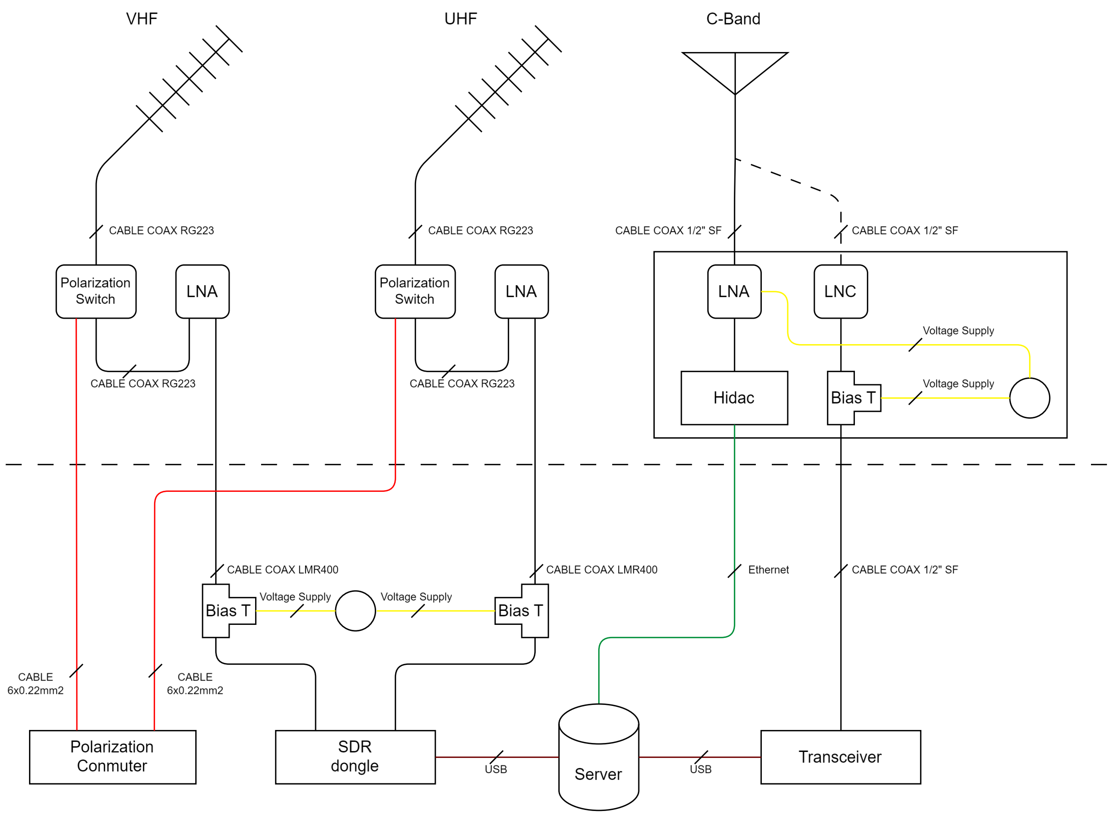



**Figure 5.1** – SDR dongle integration with iTEAM-GS architecture.


**Figure 5.2** – RTL SDR v3 dongle [89].

real time. Furthermore, it allows the extension of functionalities by means of software plug-ins.

The frequency tuning is similar to that outlined in section 3.6, but the frequency tuning and mode setting will be done via the SDR# software (see Figure 5.3). Thus, the Doppler shift adjustment will be done manually by tuning the frequency.

### 5.1.2 Downlink

As it was done in section 3.6, we will use the GreenCube (IO-117) to demonstrate the operation and methodology for receiving information from the satellite. The demodulation and decoding process will be the same as the one done using the ICOM 9700 the appropriate version of the Soundmodem software will be used, which will demodulate the signal to give the data in Hexadecimal that will be unpackaged by the GreenCube Interpreter.

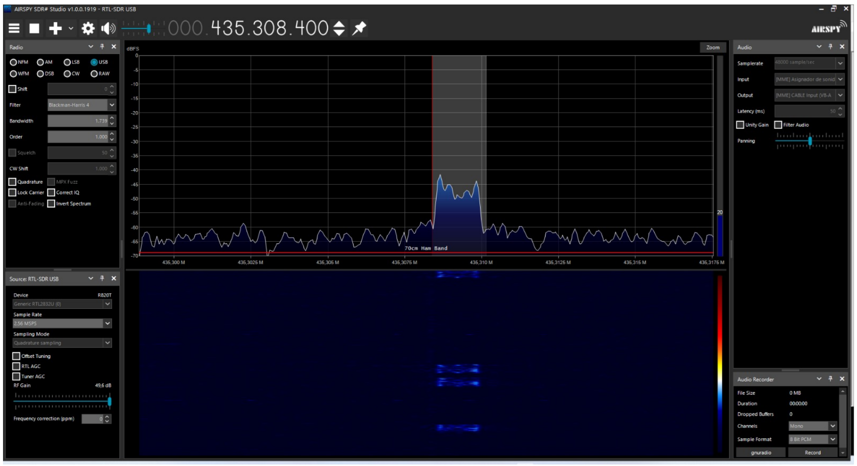
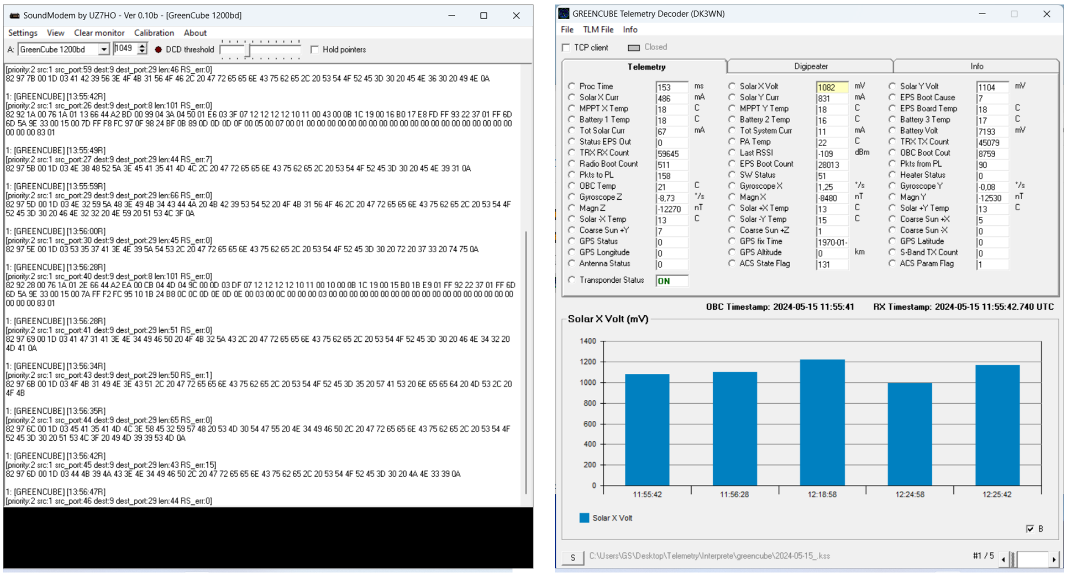


**Figure 5.3** – RTL-SDR v3 tuning to receive GreenCube downlink signal via SDR#.



**(a)** **(b)**

**Figure 5.4** – Demodulation software via Soundmodem software [80] in (a) and unpacking of the received data via specific interpreter [82] in (b).

## 5.2 Ground Station with LimeSDR mini v2

The LimeSDR mini v2 [90] is a novel device compared to the RTL-SDR. Manufactured by Lime Mycrosystems, the LimeSDR is based on the LMS7002M chip and is capable of transmitting and receiving over a wide range of frequencies (from 10 MHz to 3.5 GHz). Although its cost is slightly higher than that of the RTL-SDR, it is still very affordable for research or amateur radio tasks. However, the novelty of the module hinders the firmware and software integration with the iTEAM-GS.

### 5.2.1 Software Defined Radio with LimeSDR mini v2

The LimeSDR mini v2 cannot be used with the free SDR# software, so its integration with the iTEAM-GS has been done using the open source software **GNU Radio** [92]. GNU Radio is a free software development environment for creating SDR applications with greater versatility

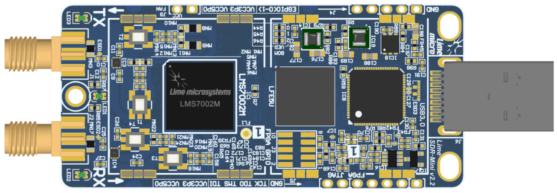


**Figure 5.5** – LimeSDR mini v2 dongle [90].

and flexibility in signal processing than other software. It has a large bibliography and community and it can be used for any SDR dongle and communication scenario. In addition, the ability to synthesise blocks that perform specific signal processing tasks allows for portability and extensibility of GNU Radio programs.

Frequency tuning and operating mode setting in GNU Radio must be configured using blocks, so the Doppler shift setting must be done manually. In addition, this development environment requires the integration of modules for signal demodulation and unpacking (both tasks were performed by the sound modem software in the version with the ICOM 9700 and the RTL-SDR). The program designed for this purpose is shown in Figure 5.6.

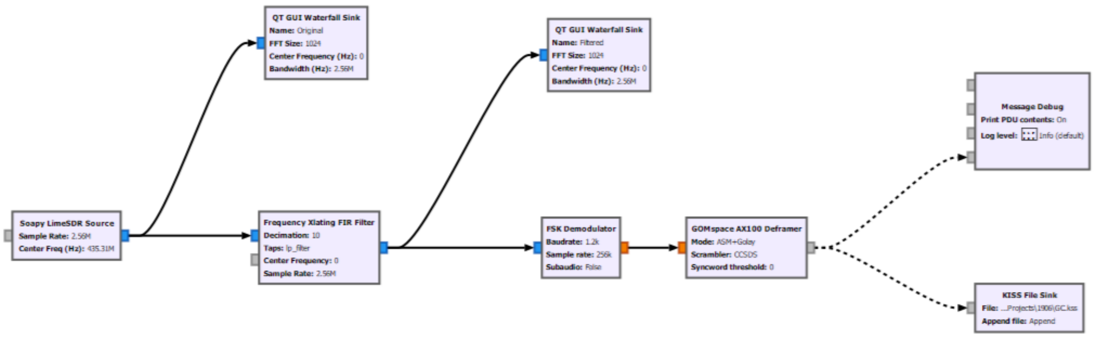



**Figure 5.6** – Demodulation and unpacking software via GNU Radio [92].

### 5.2.2 Downlink

As with the ICOM 9700 and RTL-SDR, the GreenCube (IO-117) satellite test case will be used to demonstrate the proposed functionality and methodology for receiving satellite communications. The program (shown in Figure 5.6) will generate a .kss file that will be introduced into the specific GreenCube interpreter (see Figure 5.7) to unpack the telemetry sent by the satellite.

The receiver will be the LimeSDR mini v2, which we will access using the "Soapy LimeSDR Source" block of the gr-soapy package. The sampling rate will be 2.56 Msps to obtain the bandwidth of the UHF amateur radio band, but the centre frequency will be that of the GreenCube, i.e. 435.310 MHz. In addition, a receiver gain of 12 dB has been applied in addition to the gain provided by the RF front end.

Once the signal is received, it is digitised for processing in the server. In this case, the first block is a FIR filter that performs frequency shifting, decimation (with a value of 10, so that the signal is output at a sampling rate of 256 KHz) and anti-aliasing filtering.

The properly tuned and filtered signal goes to the FSK demodulator of the gr-satellites package. Here the baud rate of the received signal is selected (in this case 1200 baud).

Once the signal has been demodulated, the data is packetized according to the appropriate protocol. The GreenCube uses the CCSDS protocol. The data is stored in .kss files, which can then be imported into the appropriate interpreter.

In addition to the signal processing blocks, GUI sink blocks have been added to monitor the signal in the different processing stages, as well as the "GUI sink block" to monitor the signal in the different processing stages, as well as the "Message Debug" block to view the unpacked data in real time from the console.

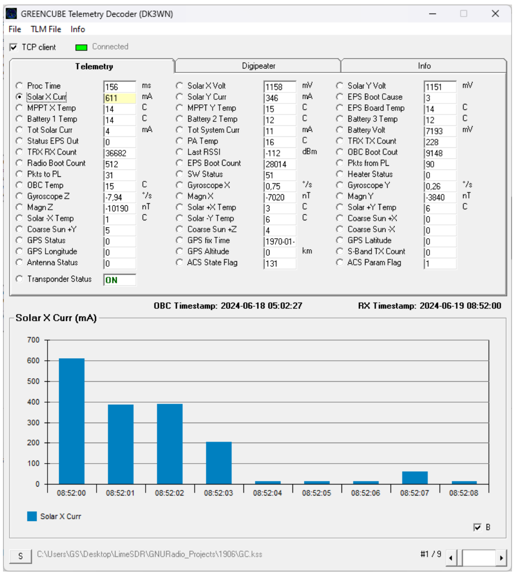



**Figure 5.7** – Unpacking of the received data via specific interpreter [82].

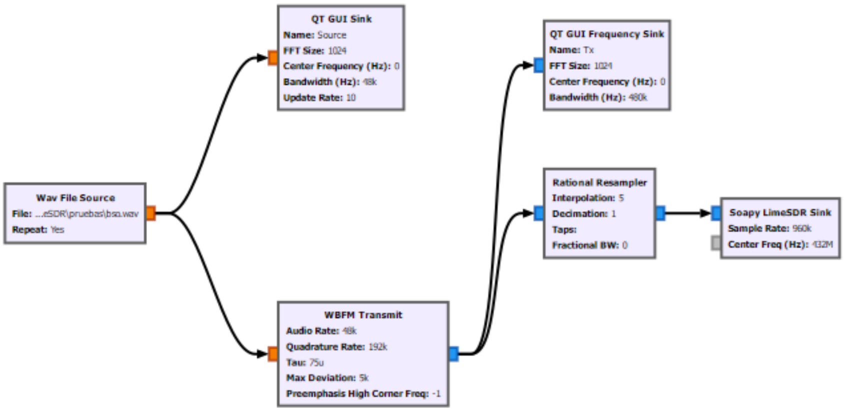
### 5.2.3 Uplink

To demonstrate the transmission capability of the LimeSDR mini v3 (without entering the electromagnetic spectrum for safety reasons), the transmit output was connected to the receive output using an SMA cable. In this case, a .wav file was modulated in FM on the transmitter programmed with GNU Radio (see Figure 5.8a), sent through the transmit port to the LimeSDR and received through the receive port to be demodulated on the receiver programmed with GNU Radio (see Figure 5.8b).

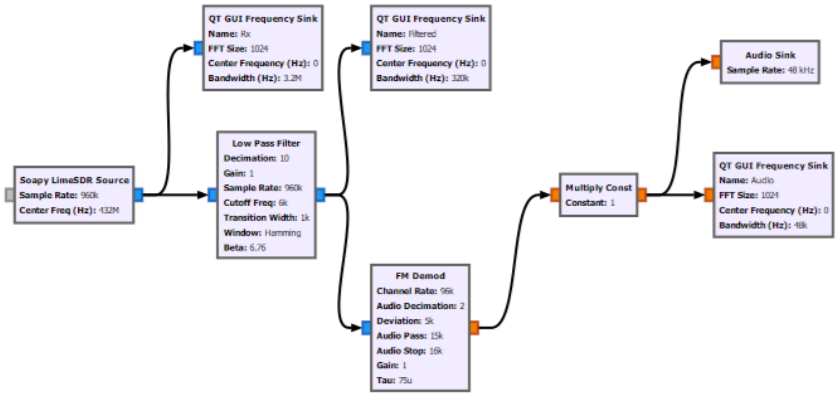
An audio file in .wav format (recorded at 48 kHz) stored on the server was used for the experiment. FM modulation was chosen as the modulation type. The "WBFM Transmit" block modulates the signal with a deviation of 5 kHz and an output sample rate of 192 kHz. The modulated signal is interpolated using the Rational Resampler block (by a factor of 5). Finally, the processed signal is sent on the 432 MHz frequency via LimeSDR (using the "Soapy LimeSDR Sink" block from the gr-soapy package).

#### 5.2.3.1 Reception with LimeSDR mini v2

The signal is received by the LimeSDR mini v2 at its receive port and is sampled at 960 kHz (at a center frequency of 432 MHz) with the "Soapy LimeSDR Source" block of gr-soapy. The signal is filtered and decimated (by 10) by the Low Pass Filter block and then demodulated (in FM) and




**(a)**




**(b)**

**Figure 5.8** – LimeSDR mini v2 (a) transmitter programmed in GNU Radio and (b) receiver programmed in GNU Radio.

decimated (by 2) to be output to the computer's audio output with an audio rate of 48 kHz. In addition, GUI sink blocks have been added to monitor the signal during processing.

#### 5.2.3.2 Reception with RTL-SDR v3

The same transmission experiment was also performed using the RTL-SDR v3 for reception, showing the flexibility of both the transmitter dongle and the receiver programmed with GNU Radio (see Figure 5.9).

The FM-modulated signal is transmitted by the LimeSDR mini v2 and received, in this case, by the RTL-SDR v3 with the "Soapy RTLSDR Source" block. It will sample the signal at 960 KHz and the center frequency of 432 MHz. The signal will be filtered and decimated by the "Low Pass Filter" block to enter the FM demodulator which, again, will decimate the signal by 2 to reach the audio output of the computer with an audio rate of 48 kHz.

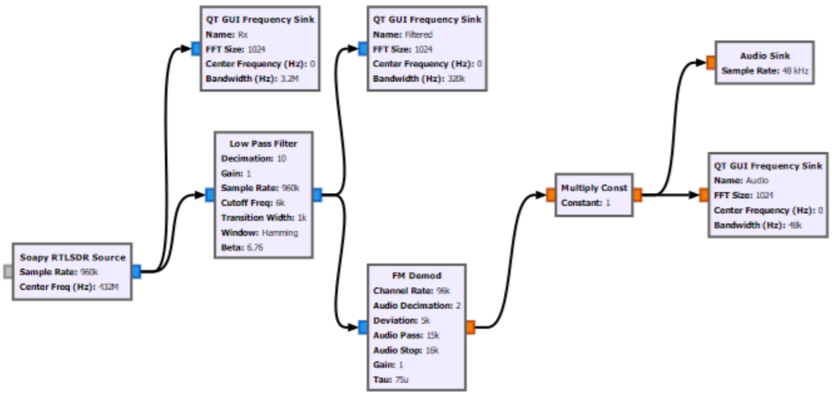



**Figure 5.9** – RTL-SDR v3 receiver programmed in GNU Radio [92].

Chapter 6

# Experimental communications

During the course of this project, a series of experiments have been carried out to validate the performance of the iTEAM-GS. In addition to the experiments carried out with the GreenCube satellite (IO-117), this chapter summarises a series of field tests carried out with the iTEAM-GS (in its various versions), demonstrating the success and flexibility of the infrastructure and architecture designed.

## 6.1 International Space Station communication

On 9 February 2024, the UPV reached a milestone in space communications by making live contact with the ISS through the Amateur Radio on the International Space Station (ARISS) [93] initiative and with the collaboration of the UPV RadioClub [94].


**Figure 6.1** – Poster of the UPV contact with the ISS.

The contact was made using the infrastructure detailed in this project, which ensured the success of the experiment thanks to the easy adaptation of the GS. It consisted of setting up a link in the VHF bands, using the architecture presented in chapter 3 (based on the ICOM-9700 transceiver). The reception of the signal during the entire passage was supported by the tracking system.

The main objective of the communication was to establish contact with the astronaut Loral O'Hara (KI5TOM) [95] on board the ISS and to promote STEM careers. During the contact, students were able to ask questions about life in space, the scientific experiments conducted on board and the future prospects for space exploration. The experiment was a success both technically and as an educational experience.

## 6.2 Slow-Scan Television reception

Slow-Scan Television (SSTV) images are transmitted from the International Space Station and other ARISS-compatible satellites and received by radio amateurs around the world [96]. The iTEAM-GS is capable of receiving and decoding SSTV images in real time, producing results with high resolution and low error rates. The space agencies conduct SSTV experiments to promote scientific activities, public outreach and international cooperation.

The experiment was carried out on 31 October 2023. During the pass, the antennas were pointed at the ISS by the tracking system and tuned to the ISS broadcast frequency (145.800 MHz) (taking into account the frequency shift). The images were decoded by the dedicated RX-SSTV software [97] with results as shown in Figure 6.2. In this case, the experiment was successfully conducted using both the ICOM-9700 (described in section 3.5) and the RTL-SDR (described in section 5.1).




(a) (b)

**Figure 6.2** – SSTV images acquired with iTEAM-GS.

## 6.3 Weather data from National Oceanic and Atmospheric Administration

Earth Observation is one of the main applications of satellites in LEO orbit. The National Oceanic and Atmospheric Administration (NOAA) [98] is responsible for describing and predicting changes in the environment by studying the oceans, atmosphere, space and sun in the United States of America, and these images can be received from anywhere on the planet. NOAA satellites transmit on 137 MHz (i.e. outside the amateur radio bands) in FM modulation and in right handed circular polarized (RHCP). The images are in Automatic Picture Transmission (APT) format [99]. Thus, receiving these images was a good demonstration of the adaptability of iTEAM-GS thanks to the flexibility provided by the integration of SDR technology.

During the development of this thesis, meteorological images were acquired from the NOAA-15 [100], NOAA-18 [101] and NOAA-19 [102] satellites. These images were acquired using RTL-SDR v3 and the configuration described in section 5.1. The signal is decoded using the free WXtoImg software [103]. One example of the result of the experiment is shown in Figure 6.3 (with a political map overlaid).

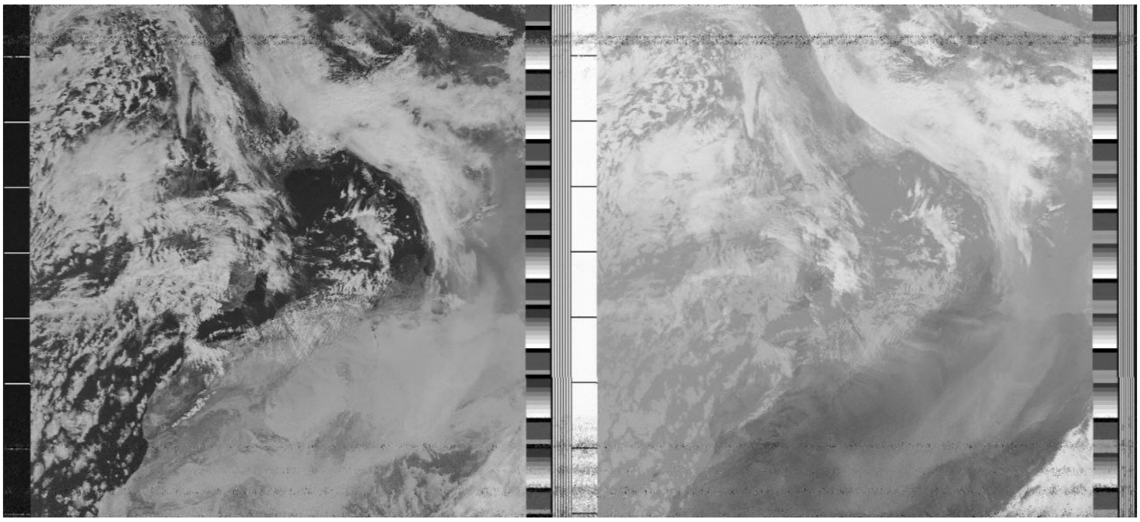


**Figure 6.3** – NOAA image acquired by iTEAM-GS.

Chapter 7

# Conclusions

In the course of this project, a GS that is capable of communicating with LEO satellites inside and outside the amateur radio bands has been developed, using different modulations and codings, and in real time. The contents of this document cover technical and practical aspects of the communication and tracking subsystems that make up the complete GS system. The technology (both hardware and software) will continue to evolve, but the general approach of the document is intended to serve as a guide and summary of the technical and practical requirements in the design, implementation and operation of a GS.

In harsh environments such as space, the signal processing capability of SDR modules can extend the life of a mission or satellite. However, in any communications system there will always be an RF front-end that needs to be tuned to the operating frequency band to achieve a higher signal level. This condition limits the flexibility offered by the integration of SDR technology, which will always depend on the hardware components used in the GS system. When working with very low power level signals (as in the case of signals emitted by cubesats), a few dBs of power can make the difference between receiving or not receiving the desired image or telemetry. Therefore, the flexibility provided by software needs to be extended to RF hardware by developing components with high operating bandwidth that are adaptable or reconfigurable.

In order to demonstrate the operation of the iTEAM-GS, field tests have been conducted on data acquisition, information exchange or image and packet reception. The iTEAM-GS's capacity as a technology validator has been amply demonstrated and, due to the adaptability and flexibility of the technology, can serve as the basis for experiment proposal. Despite the extensive experimentation possibilities offered by an infrastructure such as iTEAM-GS, field testing of space communications under real conditions is very limited.

Space industry standardisation (with initiatives such as the Digital Intermediate Frequency Interoperability -DIFI- consortium [104]) and GS virtualisation promote and drive the digital transformation of space communications and the associated cost reduction. At a time when the space industry is driven by private actors, it is public-private cooperation (with projects such as those that have enabled the development of iTEAM-GS) that will guarantee the democratisation of space and the technological sovereignty of states.

## 7.1 Future research lines in Ground Stations

There are many motivations for using and integrating SDR technology into projects. The adaptability and flexibility offered by SDRs allows projects to have a longer lifetime and to upgrade to new standards or algorithms, but also facilitates the use of existing radio applications [48]. It is essential to extend this adaptability to the RF front-end with research lines on reconfigurable RF components.

Space is a hostile and challenging environment for any field of knowledge, which is why international and scientific collaboration must be fostered to achieve goals in a more robust way. Projects and initiatives such as DIFI [104] or SATNOGS [105] demonstrate the power of international collaboration to achieve common goals. The participation of iTEAM-GS in a global GS network will allow the continuous monitoring of the future Polytech-1 [106] cubesat and the promotion of satellite communications experiments.

The increase in computing power opens up the possibility of exploring technologies, such as cognitive radio, that were previously only at a conceptual level. Cognitive Radio uses the adaptability and flexibility offered by SDR to improve radio resources (the electromagnetic spectrum) through decision-based reconfiguration based on contextual information from radio links [107].

Finally, the digitisation of GS and RF components is already a reality. The know-how for the development of a proprietary and open source SDR board will facilitate the university community in the emergence of new lines of research in the field of space communications and microwave applications. Among them, the design of GNU Radio programs to perform automatic satellite control tasks.

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Appendix A

# Sustainable Development Goals

The Sustainable Development Goals are a collection of seventeen interlinked objectives designed to serve as a "*shared blueprint for peace and prosperity for people and the planet, now and into the future*". This project is in line with the following Sustainable Development Goals:

**4. Quality education.** Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.

**9. Industry, Innovation and Infrastructure.** Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

**12. Responsible consumption and production.** Ensure sustainable consumption and production patterns.

**13. Climate action.** Take urgent action to combat climate change and its impacts.

**14. Life below water.** Conserve and sustainably use the oceans, seas and marine resources for sustainable development.

**15. Life on land.** Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

**16. Peace, justice and strong institutions.** Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.

**17. Partnership for the goals.** Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development.

| **Sustainable Development Goal** | | **Degree of relation** | | | |
|---|---|---|---|---|---|
| **SDG No.** | **Name** | **High** | **Medium** | **Low** | **Not applicable** |
| 1 | No poverty | | | | x |
| 2 | Zero hunger | | | | x |
| 3 | Good health and wellbeing | | | | x |
| 4 | Quality education | x | | | |
| 5 | Gender equality | | | | x |
| 6 | Clean water and sanitation | | | | x |
| 7 | Affordable and clean energy | | | | x |
| 8 | Decent work and economic growth | | | | x |
| 9 | Industry, Innovation and Infrastructure | x | | | |
| 10 | Reduced inequality | | | x | |
| 11 | Sustainable cities and communities | | | | x |
| 12 | Responsible consumption and production | x | | | |
| 13 | Climate action | | x | | |
| 14 | Life below water | | x | | |
| 15 | Life on land | | x | | |
| 16 | Peace, justice and strong institutions | | | x | |
| 17 | Partnership for the goals | x | | | |

**Table A.1** – Relationship of the work with the Sustainable Development Goals of the 2030 Agenda.

**Thank you for reading this Master's Thesis.**