In this document, the theoretical, legal and technical aspects required to design and implement a communication system for the establishment of a reliable Earth-satellite link for the GranaSAT-I Cubesat are studied and detailed. This project has been performed as a Master's thesis in the context of the Telecommunication Engineering Integrated Master's degree in the University of Granada, Spain.

Emilio José Martínez Pérez is the author of this Master's thesis. As a student, he has participated in many projects within the space framework, such as the GranaSAT project, DLR and SNSB/ESA BEXUS programme, ESA's Summer of Code in Space programme, and a traineeship at ESA-ESAC.

Andrés María Roldán Aranda is professor in the Department of Electronics and Computer Technology at the University of Granada.
He is the tutor of this master's thesis as well as the academic head of GranaSAT, the aerospace group at the University of Granada.

MASTER'S THESIS

DESIGN AND IMPLEMENTATION OF A COMMUNICATION SYSTEM FOR THE GRANASAT-I

Emilio José Martínez Pérez

2016 2017

UNIVERSITY OF GRANADA
TELECOMMUNICATION ENGINEERING
MASTER'S THESIS

Design and implementation of a Communication System for the GranaSAT-I Cubesat

Emilio José Martínez Pérez

2016 / 2017

Tutor: Andrés María Roldán Aranda

“Design and implementation of a Communication System for the *GranaSAT-I* Cubesat”

ESTUDIOS DE INGENIERÍA DE TELECOMUNICACIÓN

"Design and implementation of a Communication System for the GranaSAT-I Cubesat"

CURSO 2016 / 2017

REALIZADO POR:

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DEPARTAMENTO:

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Design and implementation of a Communication System for the *GranaSAT-I* Cubesat

Emilio José Martínez Pérez

PALABRAS CLAVE:

Sistema de comunicación, Cubesat, picosatélite, *GranaSAT-I*, GranaSAT, aviónica, diseño, fabricación, placa de circuito impreso, Radio Frecuencia, banda UHF, banda VHF, estación terrena, enlace de comunicación satelital.

RESUMEN:

En este documento se estudian y detallan numerosos aspectos teóricos, legales y técnicos necesarios para llevar a cabo el diseño y la implementación de un sistema de comunicación capaz de establecer un enlace estable tierra-satélite para el Cubesat *GranaSAT-I*. Este trabajo se ha realizado como *Proyecto Fin de Carrera* para la obtención de los estudios de Ingeniería en Telecomunicación de la Universidad de Granada, España.

KEYWORDS:

Communication System, Cubesat, pico-satellite, *GranaSAT-I*, GranaSAT, avionics, design, implementation, Printed Circuit Board, Radio Frequency, UHF band, VHF band, ground station, satellite communication link.

ABSTRACT:

In this document, the theoretical, legal and technical aspects required to design and implement a communication system for the establishment of a reliable Earth-satellite link for the *GranaSAT-I* Cubesat are studied and detailed. This project has been performed as a *Master's thesis* in the context of the Telecommunication Engineering Integrated Master's degree in the University of Granada, Spain.

D. Andrés María Roldán Aranda, profesor del departamento de Electrónica y Tecnología de los Computadores de la Universidad de Granada, como director del Proyecto Fin de Carrera de D. Emilio José Martínez Pérez.

Informa que el presente trabajo, titulado:

"Design and implementation of a Communication System for the GranaSAT-I Cubesat"

ha sido realizado y redactado por el mencionado alumno bajo mi supervisión, y con esta fecha autorizo a su presentación.

Granada, a   de septiembre de 2017

Fdo. Andrés María Roldán Aranda

Los abajo firmantes autorizan a que la presente copia de *"Design and implementation of a Communication System for the GranaSAT-I Cubesat"* se ubique en la Biblioteca del Centro y/o departamento para ser libremente consultada por las personas que lo deseen.

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Fdo. Emilio José Martínez Pérez   Fdo. Andrés María Roldán Aranda

ESTUDIOS DE INGENIERÍA DE TELECOMUNICACIÓN

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REALIZADO POR:

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DIRIGIDO POR:

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Fdo:	Fdo:	Fdo:

Poyekhali!
Yuri Gagarin, 12th April 1961

Agradecimientos:

A Irene, Emilio, Patricia y Marta por haberme ofrecido siempre un punto de apoyo con el que mover el universo. Sobran las palabras, gracias de corazón. También a mi familia y amigos, por estar siempre a mi lado y ayudarme durante todo este tiempo. Sin ellos nada de esto hubiera sido posible.

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Chapter 1

Introduction

The following master's thesis was wrote as part of the 3+2 Telecommunications Engineering Integrated Master's degree (MEng). The objective of this work was to design and implement a Communication System for the *GranaSAT-I* Cubesat.

GranaSAT is an aerospace development group from the University of Granada (UGR), which is made up entirely of students and is under the supervision of professor Dr. Andrés María Roldán Aranda.

Figure 1.1 – *Granasat logo*

The GranaSAT project, whose logo is shown in Figure 1.1, began as a student initiative. In 2013, several students interested in aerospace engineering wanted to focus their technical studies on the aerospace scope, and decided to participate in the REXUS/BEXUS programme, which is defined as [1]:

"The REXUS/BEXUS programme is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA)."

GranaSAT team was accepted to participate in the BEXUS 18/19 campaign thanks to the proposal of a multi-sensor attitude determination system (Attitude Determination System (ADS)) based on a Star Tracker, a Horizon Sensor and a magnetometer-based ADS [2], [3].

The development took a year of working on the design, implementation and test tasks. On the 8th of October 2014 the experiment was launched within the stratospheric flight from the Esrange facilities, in Kirune (Sweden).

The instrumentation aboard the stratospheric balloon run for the more than two hours of flight, time enough to perform the required measurements and take thousands of pictures as shown in Figure 1.2, ten Gigabytes in total. Data was satisfactory gathered, which let GranaSAT team successfully test the operational behaviour of the ADS system.

Figure 1.2 – *GranaSAT Multi-sensor ADS stratospheric flight*

The author of this document was part of the student team participating that year in the BEXUS programme. With the role of team leader, he was responsible for the project management, budget management, test campaign, electronics design, Printed Circuit Board (PCB) design and implementation, magnetometer-based ADS module and launch campaign management.

Performing a scientific and engineering project –where each development stage has been carried out– allowed the GranaSAT team to get valuable experience within the aerospace framework, and encouraged them to continue working on more ambitious projects. Additionally, once the participation was finished and after the successful work developed within the BEXUS programme [4], the GranaSAT group increased in popularity among the educational community and many students wished to join the team.

The level of trust increased, which made it possible for the GranaSAT team to face new scientific and engineering challenges with greater complexity and based on a long-term project. Thus, the decision for the next project was to design, implement and operate a Cubesat mission from scratch: *GranaSAT-I* was born.

1.1 Problem statements

As detailed in Chapter 2, a Cubesat is a small satellite –in dimensions and weight– that due to its features is commonly developed by the educational and amateur community, although an increasing number of engineering companies are including these pico-satellites in their product catalogue.

A satellite –and a Cubesat by extension– is made up of different systems and subsystems. Some common systems conforming a satellite are:

- Payload: Composed of scientific instrumentation, digital television transponders, Global Navigation Satellite System (GNSS) transmitter, etc.
- Structural System: Holds and offers physical place to systems.
- Thermal System: Maintains the spacecraft in an optimal working temperature.
- Power System: Supplies the power to the rest of systems.
- Attitude and Orbit Control System: Determines and modifies spacecraft attitude and orbit if needed.
- Communication System: Allows the communication between satellite and Earth.

If we try to identify a critical satellite system, probably the focus could be on the Communication System (COMM). This is due to the fact that there is no point in having a satellite in the space without any chance to communicate with.

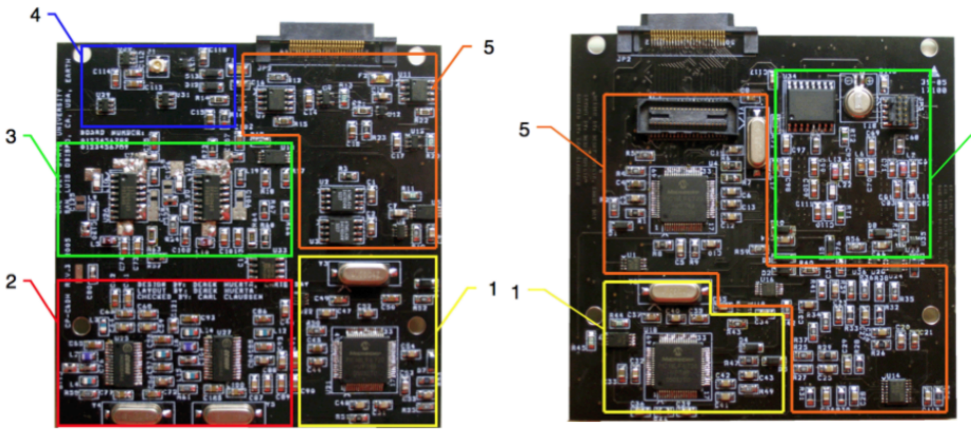


Figure 1.3 – *CP-2 COMM System, up and down side. Source: [5]*

Regarding to the COMM System, it is the one in charge of the establishment of a communication link between the ground segment and the satellite in itself. As an example, an image of the COMM system from the **CP-2** mission is shown in Figure 1.3.

Since the very beginning of the development of the *GranaSAT-I*, the COMM System was identified as critical and one of the systems whose development should begin as soon as possible. In addition, a long documentation phase was expected, and together with the complex Radio Frequency (RF) design and its implementation and a verification phase, they made of this system a very long and ambitious master's thesis project.

1

1.2 Objectives and motivation

Since building from scratch an Engineering Qualification Model (EQM) of the Communication System in a year's time is an impossible task because the time required is longer than the available for the master's thesis, it was decided to design and implement the Engineering Model (EM) of the system.

An Engineering Model is the first step to perform throughout the design of a complex system. This model is used as a test prototype, which provides a physical support to check if the requirements were fulfilled, to identify any overheated component or noisy signal, to develop or improve the firmware, to check if the system components are able to work properly, or to use it as a bench-test for destructive testing, among others.

Once the project has progressed, potential design errors have been solved and requirements have been fulfilled, the Engineering Model is ready to be tested according to the launcher rules, and it takes the name of Engineering Qualification Model. When the system has passed the test, it is qualified as a Flight Model and it is ready to fly.

Therefore, the main objective of this project will be to set a starting point for the COMM System, where future students could identify possible improvements, solve mistakes, test it and, in brief, improve the design in order to achieve an Engineering Qualification Model for the *GranaSAT-I* mission.

To fulfil the above-mentioned objectives, the project was split up in several phases:

(1) To study and understand the theory behind a satellite communication.

(2) To identify the system requirements for the COMM System.

(3) To design the COMM System that is able to fulfill the requirements set.

(4) To make a good use of the heritage work done before by the GranaSAT team.

(5) To identify in advance any issue that might arise during the design phase.

(6) To learn and manage the appropriate methods to avoid these issues.

(7) To build and implement an Engineering Model of the COMM System.

(8) To validate, despite time constraints, the Engineering Model in the best possible way.

(9) To provide enough firmware and Software to future students.

(10) To set a test planning and future improvements to achieve an EQM COMM System.

(11) To provide quality documentation and lessons learned from the engineering process to increase the GranaSAT team *know-how*.

1.3 The engineering design process

Throughout the development of the work, the classical approach of an engineering design process will be followed. It states that a typical engineering design process is a series of steps that an engineer needs to follow when they want to propose a suitable solution for a specific problem. Figure 1.4 depicts the complete engineering design process.

The engineering process is an iterative process out of necessity. After approaching a solution to the problem and creating a prototype of the engine, usually the engineer finds out that one assumption was incorrect, identifies an improvable part of the design, or simply faces a problem completely unexpected. Hence, it will be necessary to review the design several times in order to obtain a product that solves the initial problem one hundred percent.

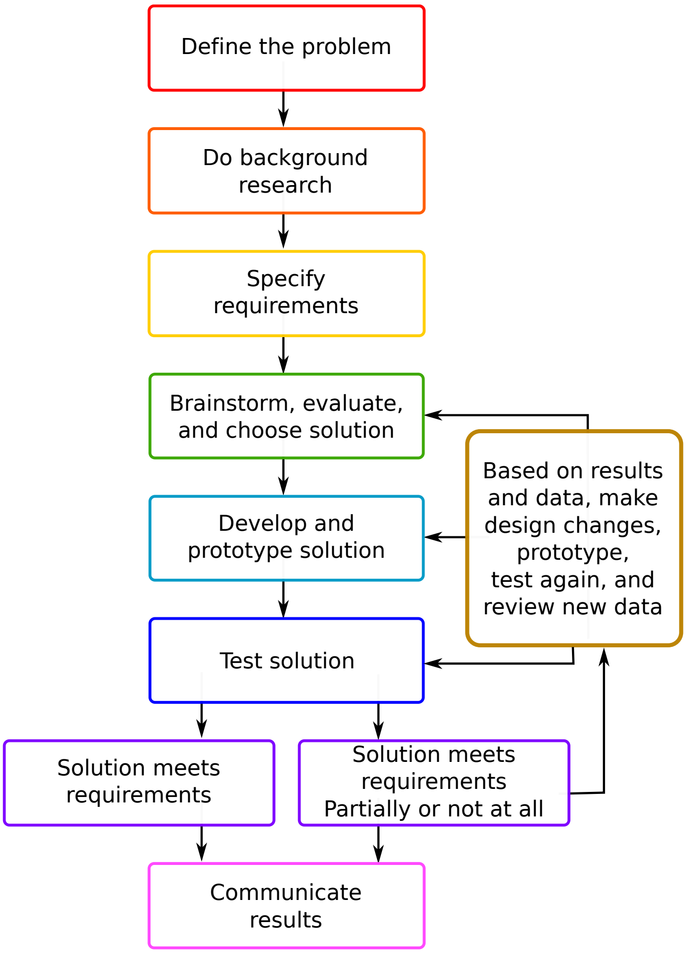


Figure 1.4 – *Engineering design process. Source: sciencebuddies.org*

This master's thesis has been structured in such a way that each chapter can be associated with one step of the design process. The only deviation in this work with respect to the process is that –due to time constraints– only a single iteration has been carried out. Therefore, some required improvements will not be developed and will be outlined as future work.

1

1.4 Chapter Description

Following the objectives previously listed, the project was developed after planning the next structure:

- **Chapter 2: Background study:**
  This chapter contains the basic knowledge needed to understand and justify the whole work conducted. A review of the Cubesat framework is presented (2.1), together with some former Cubesat missions (2.2). Moreover, the satellite communication theoretical fundamentals are described (2.3). Finally, radio regulations that will determine the features of the project are identified (2.4).

- **Chapter 3: Ground Station:**
  This chapter denotes the relevance of the Ground Station as part of the COMM system to establish a satellite communication link. The Link Budget tool is presented and justified (3.1). Moreover, the work performed by the author within two Ground Stations –GranaSAT Ground Station (3.2) and ESAC amateur Ground Station (3.3)– is described.

- **Chapter 4: System requirements and constraints:**
  This chapter addresses the requirements and constraints of the system. First, a quick overview about space standards applied along the project is presented (4.1), and then all the requirements and constraints defining the system are identified (4.2). Finally, a requirement traceability work is performed (4.3).

- **Chapter 5: Project planning:**
  In this chapter, a basic approach of the project management is described. A Work Breakdown Structure (WBS) (5.1) for the GranaSAT-I mission is carried out. Also, a list of the resources available to perform the project is presented (5.2).

- **Chapter 6: System design:**
  In this chapter, the design for the Engineering Model of the Communication System is described thoroughly. Also, the architecture of the system is provided (6.1). Then, the physical considerations are considered (6.2), as well as the interfaces of the system (6.3). The chapter continues with the electronic design of the modules (6.4) and the design of the PCB (6.5).

- **Chapter 7: System verification and testing:**
  This chapter contains the verification procedure chosen to carry out the verification phase (7.1). In addition, a general overview of the test planning is outlined (7.2), which is required to fulfil all the system requirements. Finally, the status and the results of the verification procedure are shown (7.3).

- **Chapter 8: Conclusions, future work and lessons learned:**
  In the last chapter, the conclusions reached after the work (8.1), the future lines identified throughout the development phase (8.2) and the lessons learned (8.3) after finishing the master's thesis are described.

Chapter 2

Background study

2.1 Cubesat project overview

The Cubesat concept was conceived in the late 90's decade as an university project created and supported by Stanford University and California Polytechnic State University (Cal Poly). The project was forged ahead with the goal of creating and proving a standardised pico-satellite in such a way that allowed to develop the satellite from the mission concept to the final design in a short period of time [6].

The advantage of reducing the design and implementation time is translated into lower costs, allowing therefore many institutions the opportunity to create their own satellites. Such a thing implies a higher accessibility to space, which was impossible to conceive before the creation of the Cubesat standard.

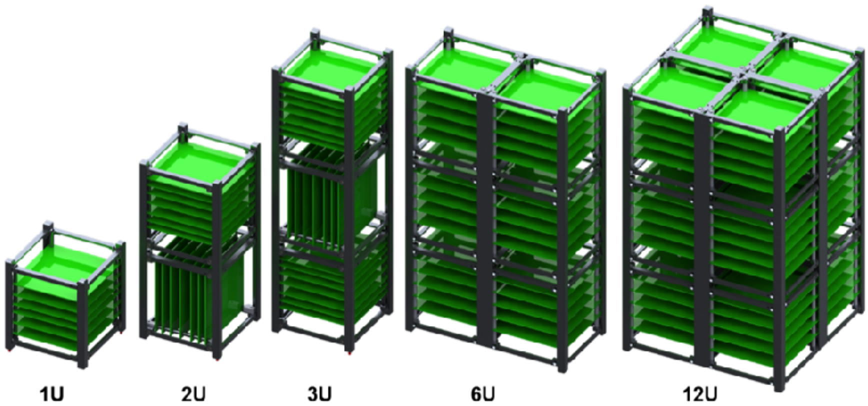


Figure 2.1 – *Cubesat form factor choices. Source: Radius Space*

The standard specifies how the Cubesat configuration and dimension shall be, defining a 1U Cubesat as a 10 x 10 x 11 cm body, with a mass lower than 1.33 kg. Many other requirements, such as mechanical, electrical and operational, are defined [6]. In addition, a Cubesat is not a size-restricted satellite and many form factors are achievable by combining several units, depending on the mission needs. See Figure 2.1, where a typical configuration of standardised form factors is shown.

Deployment

A further asset stemming from the small size of a pico-satellite is its deployment easiness. The Cubesat deployment into orbit is performed by using a mechanism named Poly Picosatellite Orbital Deployer (P-POD), or any other variation from this such as the JEM Small Satellite Orbital Deployer (J-SSOD) or the NanoRacks CubeSat Deployer (NRCSD), among others.

These deployment systems allow to place into orbit several Cubesats in one go. At the same time, several P-PODs can be stacked together in the launch vehicle as a secondary payload when a primary payload is not using the whole room available on it. This procedure enables Cubesats to afford and share the expenses, maintaining the Cubesat deployment in a *reasonably* reduced cost –around $50 000.

(a) *3 1U Cubesat deployed from ISS. Source: NASA ISS038-E-003872*

(b) *Cubesat deployment system animation. Source: JAXA [7]*

Figure 2.2 – *Cubesat deployment form from ISS*

Figure 2.2a and 2.2b show the deployment into orbit of three 1U Cubesats from the International Space Station (ISS) by using the J-SSOD deployer placed at the Kibo laboratory's arm ISS Module of the Japan Aerospace Exploration Agency (JAXA) [7].

New Design Concept

Another changes introduced by Cubesats on the aerospace engineering field are the techniques and solutions used throughout the design phase. Usually, regular space missions add to systems the convenient redundancy and high reliable components in order to increase the probability of mission success in an environment with hazardous conditions. With a mass of around 1kg, a Cubesat cannot be a reduced copy of traditional satellites: instead newer designs are used as well as Commercial-Off-The Shelf (COTS) products to reduce costs.

As in almost every design, the simpler it is, the easier to find failures in it. Therefore, in Cubesats where there is neither redundancy nor space for complex systems, the design philosophy to follow is the known as the Keep it Simple and Stupid (KISS) principle, which advocates for maintaining a design simple by avoiding adding unnecessary complexity to systems.

By performing a simple design, the amount of unexpected failures during flight may be reasonably enclosed, increasing therefore the reliability of the systems and the probability of a successful mission.

Reliability

In spite of all cautions taken during the design phase, the probability of in-orbit failure is still high in comparison with larger commercial satellites. This fact is known and accepted by the Cubesat community because the reduction of the expenses in several orders of magnitude compensates the higher chances of the mission failure.

2

Going further in failure and reliability issues, some studies have been performed by using statistical analysis –within the Cubesat historical framework– to determinate mission failure rates and the main causes that provoked them. An interesting study available is *"Reliability of CubeSats – Statistical Data, Developers' Beliefs and the Way Forward"*, carried out by M. Langer and J. Bouwmeester [8].

Some interesting facts can be highlighted from this work [8]:

- An acute drop of reliability rate is caused by Dead-On-Arrival (DOA) cases –the satellite never works after a successful deployment. The percentage of Cubesats facing this issue is between 12.9 % and 24.4 % of the total studied.
- After 100 days in orbit, the reliability rate is between 87.1 % and 75.6 %.
- After 720 days in orbit, the reliability rate is between 65.5 % and 48.5 %.
- For DOA cases, the main reason of failure is unknown – 33 %.
- After 90 days in orbit the subsystems causing a critical failure are the EPS, COMM and OBC – 36 %, 29 % and 21 % respectively.

Orbit lifetime and Cubesat lifespan

As a result of a lack of long term system reliability, the lifespan expected for a Cubesat is short.

On the other hand, because pico-satellites are often the secondary payload in a launch vehicle, they are placed into the same orbit than the primary payload. Consequently, not always the orbit lifetime is tailored to the satellite lifespan, which results in Cubesat being a risky space debris.

Space debris problem is being restrained by placing Cubesats into a short-lifetime orbit. Such a thing is only achievable if the launch vehicle allows a custom deployment for the Cubesat mission, something that can be performed from the ISS or special launchers that can deploy the secondary payload in a separate orbit [9].

2.2 Former Cubesat missions

With the advantages and assets introduced by Cubesats in the aerospace engineering field, many universities and other institutions quickly started to develop, launch and operate their own satellite missions.

During the last ten years, hundreds of universities and companies have been involved with the Cubesat Community somehow. This is easy to check by taking a look at some public databases that are periodically updated with new launches and missions. Two of the most complete databases currently available are **Nanosats** [10] and **Michael Swartwout's Database** [11].

From these databases, it is possible to find interesting information about the trend of Cubesats. By analyzing the **Nanosats** database, the following facts can be obtained:

- Until 2016, more than 510 Cubesat were launched.
- In January 2017 there were more than 200 Cubesat in orbit.
- Preferred Cubesat sizes are 1U –15.8 %– and 3U –52.8 %.
- More than 36.6 % of Cubesats launched belonged to university projects.
- The preferred bands of communication used for downlink are the UHF band –58 %– and the X band –30 %. A distribution of downlink communication band modules used is shown in Figure 2.3 [10].

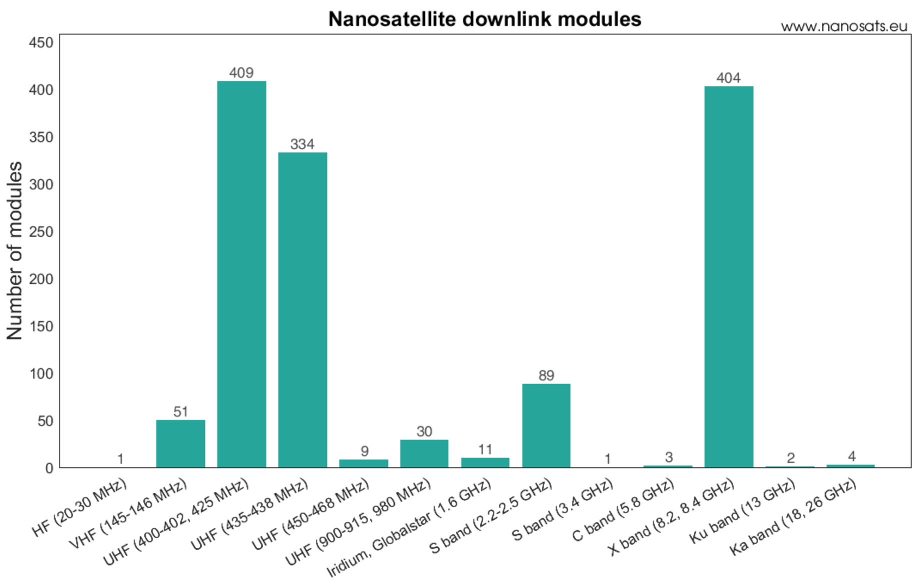


Figure 2.3 – *Downlink communication bands and frequencies. Source: Nanosats.eu [10]*

Although many Cubesats have been deployed into orbit throughout the past years, a bunch of them have positively impressed and inspired the work at GranaSAT on a daily basis. These missions are: **XATCOBEO**, **CUTE-1**, **AAUSAT-3** and **CP-6**. In Table 2.1 the main features for these four Cubesats are shown.

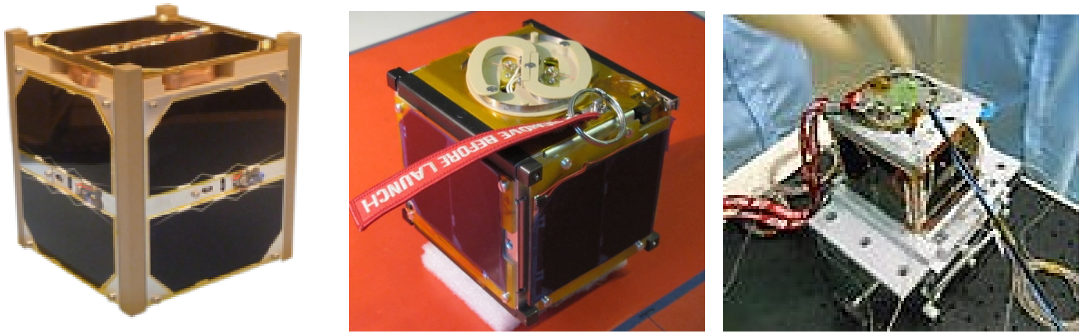
Mission	XATCOBEO	CUTE-1	AAUSAT-3	CP-6
Developer	University of Vigo, Spain and INTA	Tokyo Institute of Technology, Japan	Aalborg University, Denmark	California Polytech. State University, USA
Year of Launch	2012	2003	2008	2009
Launch Vehicle	VEGA	Rockot KS	PSLV-C20	Minotaur-1
Form Factor	1U	1U	1U	1U
Battery Capacity [mAh]	1250	1400	2200	1400
Downlink Frequency [MHz]	437 (UHF band)	430 (UHF band)	437 (UHF band)	437 (UHF band)
Uplink Frequency [MHz]	145 (VHF band)	144 (VHF band)	437 (UHF band)	437 (UHF band)
ADS	None	Gyroscopes, Accelerometers and Sun Sensor	Magnetometers and Gyroscopes	Magnetometers
A-ACDS	None	None	Magnetorquers	Magnetorquers
Main Payload	Panel Deployment and SDR COMM tech demonstrator	COMM, ADS, and and Panel Deployment tech demonstrator	SDR AIS Receiver	A-ACDS tech demonstrator
Lifespan	2 years and 5 months (In orbit time)	More than 8 years	1 year and 7 months	Info not available

Table 2.1 – *Comparative of former Cubesat missions. Sources: [12], [13], [14], [15].*

2.2.1 ESA's "Fly Your Satellite!" programme

A special mention should be made to three Cubesats that have been part of the ESA's Fly Your Satellite (FYS) programme [16]:

- **AAUSAT4**, from Aalborg University, Denmark
- **e-st@r-II**, from Politecnico di Torino, Italy
- **OUFTI-1**, from Université de Liège, Belgium



(a) *AAUSAT4* **(b)** *e-st@ar-II* **(c)** *OUFTI-1*

Figure 2.4 – *Cubesat that was part of the FYS programme. Source: [16]*

FYS is an educational programme of the ESA Education Office with the goal of providing an expert mentoring to selected European universities in the development of their own Cubesat mission.

The participation in this programme implies the mentoring of ESA experts through different development phases, such as the design, manufacturing, assembly, testing or launch. Also, ESA provides financial support to attend different workshops and training courses during the programme, the test sessions and the launch.

The first FYS edition started in 2013 by selecting 6 Cubesat projects to participate in the first phase of the programme. In 2016, three of these projects were selected to be placed into orbit using as a launch vehicle a Soyuz VS14 [16].

Because the likelihood of the GranaSAT group applying for the next FYS call for proposals is high, it is important to remark the relevance of the study of these three missions that have already been launched thanks to the FYS programme.

AAUSAT4

It is a Cubesat from Aalborg University, in Denmark [17]. The goal of its mission is to test an improved version of an Automated Identification System (AIS) developed at their facilities [17]. By adding an AIS receiver to the Cubesat, it enables the possibility of tracking and identification of vehicles that are using an AIS transponder, regardless of how far they are from inhabited areas [18]. Figure 2.4a shows the model of the AAUSAT4 Cubesat. Table 2.2 summarizes some technical details of the mission [18][19].

E-st@r-II

This Cubesat belongs to the Politecnico di Torino, in Italy [20], and it is a technological demonstrator satellite. By including an Active Attitude Determination and Control System (A-ACDS) designed and manufactured by students, they expect to demonstrate the good functionality of the system controlling both the attitude of the satellite and the angular velocities of the spacecraft [18]. Figure 2.4b shows the model of the e-st@ar-II Cubesat. Also, in Table 2.2 some technical details of the mission are summarized [18][19].

2

OUFTI-I

The OUFTI-1 is a Cubesat from the Université de Liège, in Belgium [21]. It is the first satellite to implement the Digital Smart Technology for Amateur Radio (D-STAR) voice and data protocol, which allows digital communication between radio links in the amateur band. The goal of this Cubesat is to test the mission as a satellite D-STAR repeater [18]. Figure 2.4c shows the model of the OUFTI-1 Cubesat. Table 2.2 summarises some technical details of the mission [18][19].

Fly Your Satellite! Cubesat			
Cubesat	AAUSAT4	e-st@r-II	OUFTI-1
University	Aalborg, Denmark	Torino, Italy	Liège, Belgium
Form factor	1U	1U	1U
Mass at launch [g]	850	980	920
Power [W]	1	2.75	2
Solar array dimensions	6 solar array of 8x8 cm	5 solar array of 7x7 cm	5 solar array of 7x7 cm
Download Frequency [MHz]	437.425	437.485	145.980
Main Payload	SDR AIS	A-ACDS	D-STAR

Table 2.2 – *Technical data summary of FYS Cubesat missions*

2

2.3 Theoretical fundamentals

The objective of this section is to identify and explain the basics of satellite communication theory relevant for the development of a Cubesat COMM system. Many books have been written about space communication, and for this reason, the author strongly recommends to check the references included in this section for additional information.

2.3.1 Satellite Orbits

An artificial satellite is defined as a body placed in orbit around the Earth or another planet. All celestial bodies in any orbit, regardless of their origin or nature, will follow Kepler's Laws of planetary motion [22].

Kepler's Laws:

- The orbit of each satellite is an ellipse with the Earth centred at one focus.
- The line joining the satellite and the centre of the Earth sweeps out equal areas during equal intervals of times.
- The square of the period of a satellite is proportional to the cube of the semi-major axis of its orbit.

Orbital Parameters:

Orbits are unambiguously defined only by the next six parameters [23]. Figure 2.5 depicts these parameters:

- **Semi-Mayor Axis (a):** Defines the size of the orbit.
- **Eccentricity (e):** Defines the shape of the orbit.
- **Inclination (i):** Defines the orientation of the orbit with respect to the Earth's equator.
- **Argument of perigee (ω):** Defines where the low point of the orbit is with respect to the Earth's surface.
- **Right ascension of the ascending node (Ω):** Defines the location of the ascending and descending orbit with respect to the Earth's equatorial plane.
- **True Anomaly (υ):** Defines where the satellite is within the orbit with respect to perigee.

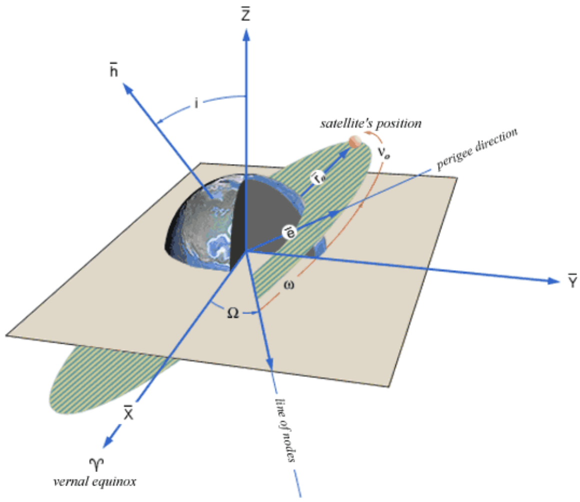


Figure 2.5 – *Graphical representation for the orbital parameters. Source: NASA [23]*

Two-line element set:

Two-Line Element set (TLE) is the name that receives a kind of information that encodes a list of the orbital parameters of an Earth's satellite. With the use of the TLE it is possible to know the trajectories of the body orbiting Earth and to predict the current or any future position of it. An example of TLE for the ISS is:

```
ISS (ZARYA)
1 25544U 98067A   17046.51674720  .00002527  00000-0  45049-4 0  9992
2 25544  51.6442 284.8397 0007107 191.9940 240.2193 15.54369543 42836
```

Low Earth Orbit:

Based on Orbital Parameters, there are infinite types of orbits available for satellites, but each orbit will imply an asset that –depending on the purpose of the mission– may be utilised in its favour.

As for the *Semi-Mayor Axis* parameter in particular, a Low Earth Orbit (LEO) has the special characteristic of being placed at an altitude from 200 km to 2 000 km. A LEO orbit offers a series of advantages for Cubesat that makes it the most used orbit for this kind of pico-satellites. Some of the next advantages will be studied and explained in the following sections:

- The satellite is as closer as possible to Earth. This reduces the amount of power necessary to allow a communication link.
- Atmospheric drag: The satellite will experience an orbital decay at the time when the expected mission lifespan is coming to an end, avoiding then to become a space debris.
- In operational and costs terms, it is the simplest orbit to place a satellite.
- For this altitude, the Van-Allen Belts are still strong and will continue protecting –although much less than in the Earth's surface– the Cubesat from solar radiation.

2

Slant Range to Satellite:

The distance between the Earth Station and the satellite will be used to determinate essential parameters for the communication performance.

$$d = \sqrt{(R+h)^2 - R^2 \cos(\theta)^2} - R \sin(\theta) \tag{2.3.1}$$

Where:

$R = 6\,371$ km (Earth's radius)
$h =$ Satellite altitude over Earth's surface [km]
$\theta =$ Elevation angle for the Ground Station [degree]

Doppler shift

The Doppler shift is the change in the frequency of a wave as the source and observer move towards each other. In our case, a satellite communication link, the relative motion between the Ground Station and the satellite –orbiting around the Earth– will generate a wavelength shifting in relation to the original carrier frequency. Figure 2.6 illustrates the effect for a frequency source in motion.

In satellite communications, since the orbital velocity is several km/s, the Doppler effect can reach up to tens of kHz. Such a variation can cause an evident reduction of the link performance. Therefore, a dynamic frequency correction shall be performed at the Ground Station.

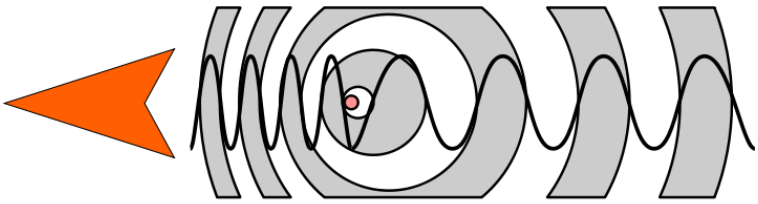


Figure 2.6 – *Change of wavelength caused by motion of the source. Source: Wikipedia*

Although the Doppler shift is included in this subsection, it is not an orbit characterisation or parameter in itself. The reason for such reference is because the effect is caused by the satellite motion within an orbit.

2.3.2 Satellite Link

The main goal for a satellite is to carry a payload with the purpose of performing any useful task, such as television broadcasting, science experiment, new technological demonstrator, etc. But meanwhile this main activity is performed, a **communication link** between Earth and the satellite shall be established in order to allow Ground Stations to receive payload data, or transmit mission control telecommands, among other tasks.

2.3.2.1 Link Considerations

A satellite link is made up of an **uplink** –to transmit from Ground Station to satellite– and a **downlink** –to receive from satellite to Ground Station. Satellite links are made by using a Radio Frequency (RF) path between the transmitter and the receiver, and the performance of communications will depend on how strongly the signal can be transmitted and how the signal is received at the radio equipment. Figure 2.7 depicts the basic parameters for a communication link.

2

Although the parameters used to define a communication link are extensive and assorted, the most relevant parameters are detailed below.

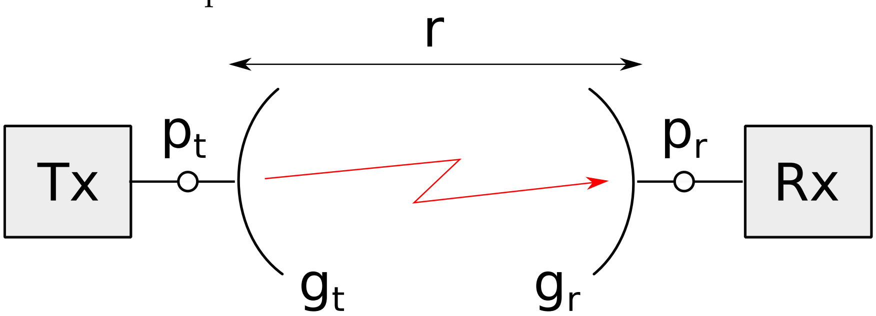


Figure 2.7 – *Basic parameters for a communication link*

Where:

p_t = Transmitter power $[W]$
g_t = Transmitter antenna gain
p_r = Receiver power $[W]$
g_r = Receiver antenna gain
r = Link path distance $[m]$

Equivalent Isotropically Radiated Power – EIRP

The Equivalent Isotropically Radiated Power (EIRP) is a definition employed to standardise the power transmission of a transmitter, regardless of the equipment or antenna utilised. EIRP establishes the amount of power that would be required to transmit a signal equally in all directions as if the transmission was made by an isotropic radiator of electromagnetic waves. EIRP is usually known as *effective radiated power*:

$$\mathrm{EIRP} = p_t\, g_t \qquad [W] \tag{2.3.2}$$

or in dB,

$$\mathrm{EIRP} = P_t + G_t \qquad [dB] \tag{2.3.3}$$

The use of expressions in dB units gives a powerful tool to engineers since it simplifies the task to a set of two operations of signal strength reference levels: additions –for signal level increase– and subtractions –for signal attenuation processes. This procedure allows to work regardless of the reference quantity –dB, dBW, dBm, dBμV, dBi, dBd or any other– as long as the *decibel* unit is utilised.

For example, for the case of a Cubesat, a typical EIRP can take a value between [24]:

$p_t = [20,\ 40]\ \mathrm{dBm}$
$g_t = [2.15\ \mathrm{dBi},\ 5.19\ \mathrm{dBi}]$ [Half-wave dipole, Quarter-wave monopole]

$$\mathrm{EIRP} = [20,\ 40]\ \mathrm{dBm} + [2.15,\ 5.19]\mathrm{dBi} = [22.15,\ 45.19]\ \mathrm{dBm}$$

2

Power Flux Density

In order to simplify, it is common to assume that electromagnetic waves propagate in free space by an isotropic wavefront, that is, the wavefront has spherical shape.

Although an *isotropic radiator* is a theoretical concept that is not possible to carry out in practise, performing such concept will ease the estimation of many parameters in the communication link. The only precaution to be taken is to always consider that it is placed in *far field* [$r >> 2\lambda$].

The power flux density (pfd) is a relevant parameter for a communication link at the receiver place. Considering that the transmitted power will be distributed in free space throughout a spherical wavefront, the pfd expresses the power received per square metre at a distance r from the origin of the radio wave source:

$$\mathrm{pfd} = \frac{\mathrm{EIRP}}{4\pi r^2} \qquad \left[\frac{W}{m^2}\right] \tag{2.3.4}$$

Received Power

At the reception place, the power coming into the receiver through the system will be the incident radio wave power flux density that the antenna is capable of converting into electric power:

$$p_r = \mathrm{pfd}\ A_{eff} \qquad [W] \tag{2.3.5}$$

A_{eff} is the *effective area* –or *effective aperture*– of the antenna, which depends on the antenna physical *aperture area* A $[m^2]$ and the *aperture efficiency*, η_A. This efficiency contemplates many non-ideal antenna physics factors, such as the reflected power in the antenna elements, ohmic losses, dielectric losses, etc.

A typical value for aperture efficiency may run from 0.55 for conventional circular parabolic antennas to 0.7 for high-efficiency antennas [25].

$$A_{eff} = \eta_A\ A = \frac{g_r\ \lambda^2}{4\ \pi} \qquad [m^2] \tag{2.3.6}$$

2

Free Space Path Loss

All radio waves will suffer a loss during their propagation in free space or regions with similar characteristics to free space –such as the Earth's atmosphere. These losses are called Free Space Path Loss (FSPL) and depend on the radio wave frequency and the path distance covered:

$$l_{FSPL} = \left(\frac{4\pi r}{\lambda}\right)^2 \tag{2.3.7}$$

This parameter is dimensionless, but it is often represented in dB,

$$L_{FSPL} = 20 \log \left(\frac{4\pi r}{\lambda}\right) \qquad [\mathrm{dB}] \tag{2.3.8}$$

Friis Equation

Once the different parameters conforming the communication link and the direct relation among them are known, it is possible to get a basic link equation to calculate the power at the receiver antenna.

Friis Equation is obtained by substituting equations 2.3.2, 2.3.4, 2.3.6 and 2.3.7 for equation 2.3.5:

$$p_r = p_t g_t g_r \left(\frac{1}{l_{FSPL}}\right) \qquad [W] \tag{2.3.9}$$

Expression that can be expressed in dB as:

$$P_r = P_t + G_t + G_R - L_{FSPL} \qquad [\mathrm{dB}] \tag{2.3.10}$$

The simplicity of Friss Equation is crucial since it allows adding in the equation new parameters that might affect the communication link and that were not considered at the beginning: new individual power losses are incorporated subtracting, and new individual power contributions are incorporated adding to equation 2.3.10.

Retuning to the image of the elemental parameters in a communication link –Figure 2.7–, it is possible to operate with them in order to obtain the power at the receiver by using the Friis Equation. This procedure is detailed in Figure 2.8.

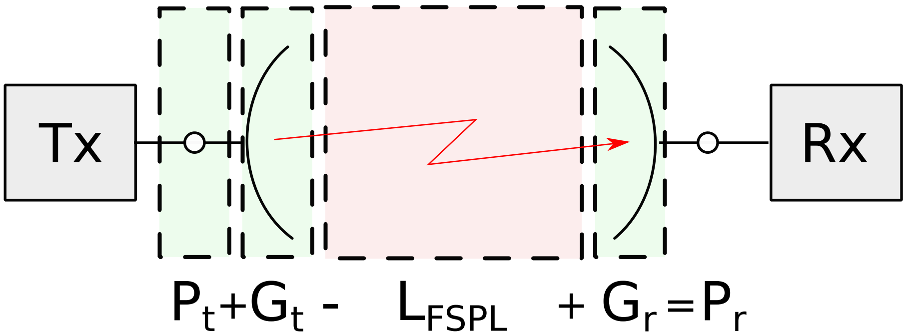


Figure 2.8 – *Friis Equation for elemental parameters in a communication link.*

Other Link Losses

Besides FSPL loss, there are actually many other losses in the system contributing to signal attenuation that shall be included in the *Friis Equation*. These losses are wide and varied, for instance and just to name some of them: losses by antennas mispointing, atmospheric events, system impedance mismatching or mispolarisation losses.

2

2.3.2.2 Noise Considerations

In addition to power and attenuation processes along the signal path, there is another element that shall be taken into account: **noise** in our communication link, that is: *undesired signals*.

Noise can be introduced into the radio path in any part of the link because of numerous factors, and due to physical processes it cannot be removed from the system. This is why engineers must learn how to minimise the effects produced by noise introduced in their radio equipment and how to deal with it.

Thermal Noise

Thermal Noise is the biggest contribution of noise in RF systems. It is originated by every element in the receiver because of the random thermal motion of electrons inside circuitry, for both passive and active components.

The **noise power**, n_N, introduced by each element in the system, is quantified by modelling its noise contribution as a source of thermal noise. This procedure is named *equivalent noise temperature* and is defined as the temperature of a passive resistor producing a noise power per unit bandwidth that is equal to the one produced by the device [25]. Noise power generated by a device is defined by the *Nyquist* formula:

$$n_N = k\, t_e\, b_N \qquad [W] \tag{2.3.11}$$

Where:

$k =$ Boltzmann Constant $[1.39 \times 10^{-23}\ \mathrm{Joules/K\ or}\ -228.6\mathrm{dB/K/Hz}]$
$t_e =$ Equivalent noise temperature of the noise source [K]
$b_N =$ Noise bandwidth [Hz]. Bandwidth of the RF carrier.

The noise power, n_N, is independent of frequency and it is uniformly distributed across the bandwidth. Thus, it is common to express the noise power as a **noise power spectral density**:

$$n_0 = \frac{n_N}{b_N} = k\, t_e \qquad \left[\frac{W}{Hz}\right] \tag{2.3.12}$$

Radio Noise

The source of Radio Noise may be both natural and human: emissions from power transmission lines, radiation from electrical systems, atmospheric gases, radiation from lightning discharges, cosmic background radiation, the Sun, the Moon and even the stars, among other sources [25].

The effects of Radio Noise are introduced in the system as an increment of the antenna temperature. Since this noise is present anywhere the antenna is pointing to, it is also known as *sky noise*.

Antenna Noise

Besides Radio Noise, the *Antenna Noise* is another type of noise inserted into the system through the antenna. This noise is originated from the absorptive power losses caused to the radiowave by the antenna physical structure in itself. *Antenna noise* is usually modelled as a thermal noise known as *Antenna Noise Temperature*.

Manufacturers usually consider the *Antenna Noise Temperature* in aperture efficiency, η_A, and therefore it is not necessary to include it directly into the link budget. A typical value of the antenna noise temperature is about some tens of degrees K.

Noise Figure

The Noise Figure (NF) is a way to quantify the noise introduced by a device to the communication path link. It is defined as the ratio of the desired signal power to noise power ratio at the input of the device, to the signal power to noise power ratio at the output of the device [25]:

$$nf = \frac{\frac{p_{in}}{n_{in}}}{\frac{p_{out}}{n_{out}}} \tag{2.3.13}$$

The NF can be translated into a value of equivalent noise temperature:

$$t_e = t_o \left(10^{\frac{NF_{dB}}{10}} - 1\right) \qquad [K] \tag{2.3.14}$$

Where:

t_o = Input reference temperature. Usually set at 290 K.

This parameter is often used to characterise the noise generated by signal amplifiers. A typical value of NF for commercial Low Noise Amplifier (LNA) runs from 0.5 dB to 3 dB approximately.

For a system made up of several devices in cascade, the noise contribution of each element will refer to the precedent elements, being the first stage the most relevant for the overall NF, the second one less important, and so on [26].

For a n-stage cascade of devices, the expression above –called *cascade noise equation*– is often used to calculate the Noise Figure of the communication system:

$$NF_S = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + ... + \frac{NF_n - 1}{G_1 G_2 ... G_{n-1}} \qquad [dB] \tag{2.3.15}$$

2

Noise floor

Noise Floor is a parameter of receivers defined as the measure of the total power noise generated by noise sources within the system. Its utility is to define a minimum amount of power signal from which the receiver is able to detect any incoming radiowave. For this reason, Noise Floor is related to the *Sensitivity* of the receiver.

Noise Floor is calculated by using the Thermal Noise equation –Eq. 2.3.11– and the Cascade Noise Equation –Eq. 2.3.15:

$$\text{Noise Floor} = -174 \text{ dBm} + NF_S + 10\log(b_N) \qquad [\text{dBm}] \tag{2.3.16}$$

Where it has been considered a room temperature of 290 K.

Carrier-to-Noise Rate

At this point, the importance to maximally reduce the amount of noise in the system is clear, and also the total incoming RF power is determining, where *the more the better* applies. But how much incoming power is necessary in order to establish a good performance link? How much noise is tolerable at receiver to accomplish an acceptable communication link? To answer these questions, the ratio of RF carrier power to noise power is calculated. This expression measures the overall performance of the system:

$$\left(\frac{c}{n}\right) = \frac{p_r}{n_r} = \frac{p_t g_t g_r \left[\frac{1}{l_{FS} l_o}\right]}{k \; t_s \; b_N} \qquad [dB] \tag{2.3.17}$$

If the expression is split into known elements, in dB,

$$\left(\frac{C}{N}\right) = EIRP \; + 10\log(\frac{g_r}{t_s}) - (L_{FSPL} \; + \sum L_o) - B_N - 198.6 \; \frac{dBm}{Hz \; K} \qquad [dB] \tag{2.3.18}$$

Where:

EIRP = Is in dBm
$\frac{g_r}{t_s}$ = Is the *Figure of Merit* of the receiver $[\frac{dB}{K}]$
L_o = Are other losses that might arise at the system [dB]
B_N = Is the same bandwidth for both C and N $[\frac{dB}{Hz}]$

The $\left(\frac{C}{N}\right)$ ratio becomes, therefore, the best tool to describe the performance of a communication link. Usual values of $\left(\frac{C}{N}\right)$ for an acceptable communication link are about 10 dB [25].

Figure 2.9 shows a fragment of the Radio Spectrum for the frequency bands of the Commercial Radio Broadcasting service in Spain. In the figure the Noise Floor level and Carrier power signal are depicted, likewise the Carrier-to-Noise rate, which is the power level difference among them:

$$\left(\frac{C}{N}\right) = -71\ \text{dBm} - (-102\ \text{dBm}) = 31\ \text{dB}$$

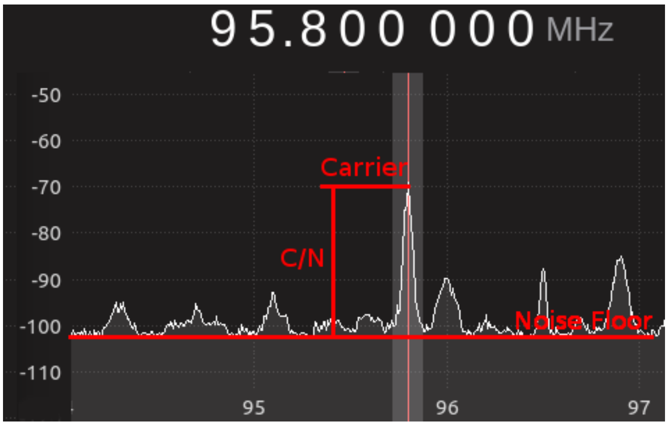


Figure 2.9 – $\left(\frac{C}{N}\right)$ *estimation for a carrier signal within the Commercial Radio Broadcasting service.*

2.3.2.3 Propagation Considerations

As mentioned in previous subsections, radiowaves may suffer numerous losses along the radio path. For example, in Friis Equation –Eq. 2.3.10– and Carrier-to-Noise Equation –Eq. 2.3.18–, a parameter that collects those losses, L_o, was introduced. Additional losses are caused by the way the radiowave propagates through the medium, which receives the name of *propagation mechanism*. There are many *propagation mechanisms* defined by the Institute of Electrical and Electronics Engineers (IEEE) [27]:

- **Absorption:** *"A reduction in the amplitude of a radiowave caused by an irreversible conversion of energy from the radiowace to matter in the propagation path."*
- **Scattering:** *"A process in which the energy of a radiowave is dispersed in direction due to interaction with inhomogeneities in the propagation medium."*
- **Refraction:** *"A change in the direction of propagation of a radiowave resulting from the spatial variation of the refractive index of the medium."*
- **Diffraction:** *"A change in the direction of propagation of a radiowave resulting from the presence of an obstacle, a restricted aperture, or other object in the medium."*

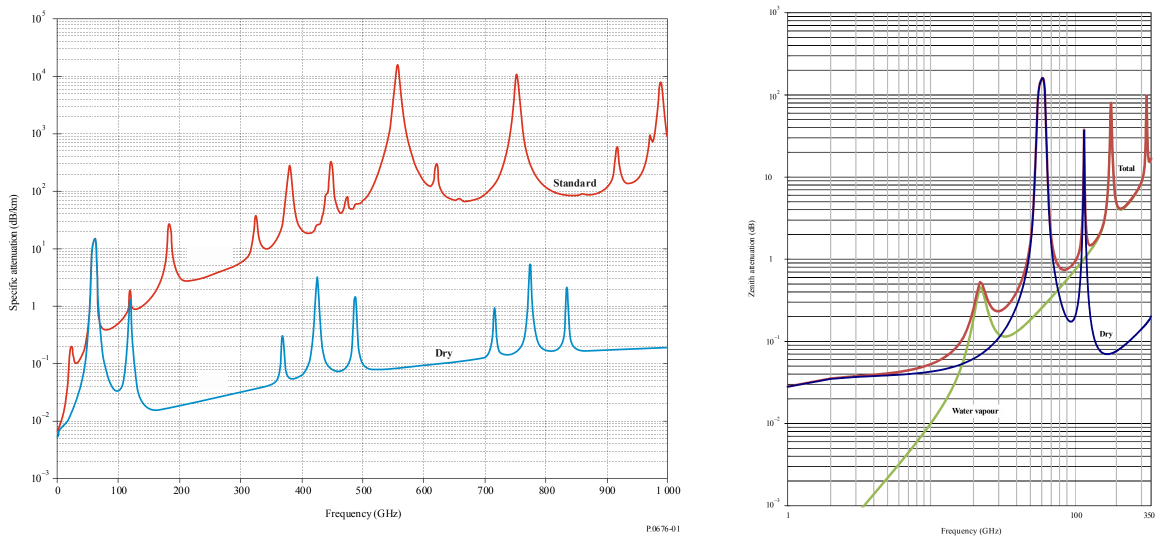
- **Multipath:** *"The propagation condition that results in a transmitted radiowave reaching the receiving antenna by two or more propagation paths."*
- **Scintillation:** *"Rapid fluctuations of the amplitude and phase of a radiowave caused by small scale irregularities in the transmission path with time."*
- **Fading:** *"The variation of the amplitude of a radiowave caused by changes in the transmission path with time."*
- **Frequency dispersion:** *"A change in the frequency and phase components across the bandwidth of a radiowave, cause by a dispersive medium."*

Diverse propagation mechanisms may take place at the same time and their effects are cumulative. The relevance of each mechanism will be subjected to other factors, such as solar activity, atmospheric conditions or own radiowave parameters –as wavelength.

Propagation mechanisms will modify the radiowave characteristics, introducing, consequently, losses to the radio path if their effects are not considered. Some main effects generated by the propagation mechanisms are described below.

Atmospheric Attenuation

When gaseous components are present in the radio path, the transmitted radiowave signal will experience a power attenuation due to an effect of *molecular absorption* at its electric/magnetic dipole resonance frequency. From all the resident gases in the Earth's atmosphere, only **oxygen** and **water vapour** show a resonance frequency sufficiently low to affect the satellite communication link.



(a) *From 0 to 1 000 GHz* **(b)** *From 1 to 350 GHz*

Figure 2.10 – *Specific attenuation due to atmospheric gases at sea level. [GHz] vs. [dB/km]. Source: [28]*

Figure 2.10 shows a set of charts of the Specific Attenuation [dB/km] caused by atmospheric gases, where in sub-figure 2.10a a broad frequency spectrum is represented, while in sub-figure 2.10b a lower spectrum band is considered.

Attenuation values are strongly dependent on the atmospheric conditions and both charts refer to a *standard atmosphere*, that is [28]: pressure = 1013.25 hPa; temperature = 15 °C; water vapour density = 7.5 g/m^3.

Oxygen has several absorption lines close to 60 GHz and another absorption line at 118.7 GHz. Water vapour, for its part, has its lines at 22.3 GHz, 183.3 GHz and 323.8 GHz. These absorption lines can be easily observed in Figure 2.10b.

For Cubesat missions, where usually low frequencies –under 10 GHz– are used, all of the atmospheric absorption lines are far from meaning a serious problem for the communication link performance.

Polarisation Rotation

Also known as *Faraday effect*, it refers to a rotation of the plane of polarisation when an electromagnetic wave goes through an anisotropic[1] medium in presence of a magnetic field (see Fig. 2.11). In the case of satellite communications, the effect is caused by the interaction of a radiowave with the Ionosphere –which consists of a plasma containing free electrons– and the Earth's magnetic field. The angle of rotation, θ, is defined by [25]:

$$\theta = 236\ B_{av}\ N_T\ f^{-2} \qquad [rad] \tag{2.3.19}$$

Where:

B_{av} = Average Earth's magnetic field $[Wb/m^2]$
N_T = Electron density at Ionosphere $[el/m^2]$

Since the Earth's magnetic field strength and the electron density are not known in advance, the effect will not be constant and the rotation will be hard to rectify in real time. For example, the electron density varies with the solar radiation, therefore the magnitude of rotation will be different throughout the day and night.

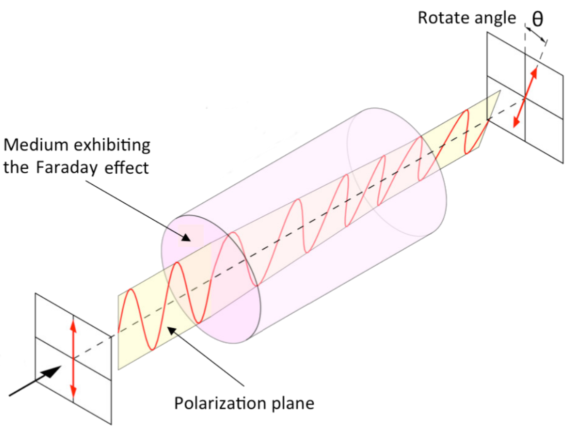


Figure 2.11 – *Faraday effect. Source: Adapted from Wikipedia*

[1]The magnetic permeability, μ, is a non-diagonal second rank tensor: $\mathbf{M} = \begin{vmatrix} \mu_1 & -i\mu_2 & 0 \\ i\mu_2 & \mu_1 & 0 \\ 0 & 0 & \mu_z \end{vmatrix}$

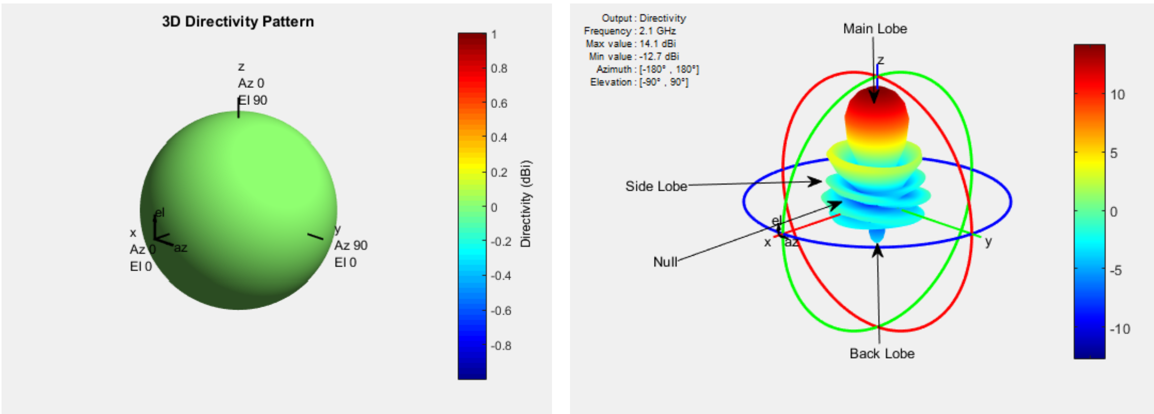
Regarding frequency dependence, the Faraday effect is considerable at low frequencies, where Cubesat missions usually place their carrier frequencies –as it will be explained in 2.4.3. For that reason, several considerations shall be taken in order to avoid their effects. In the line of avoiding the Faraday effect, it is remarkable to note that the Polarisation Rotation is an inherent trouble for radiowaves linearly polarised but it will not be present when a circular polarisation is used [25].

2

2.3.2.4 Antenna Considerations

Directivity

An antenna that radiates energy uniformly in all directions is defined as an antenna whose directivity is equal to one (0dB). For an antenna that has a pattern radiation in such a way that transmits or receives more power for a precise angle, it is said that it is a *directional* antenna and it presents a determinate directivity. Those antennas presenting a low directivity are also called *Omnidirectional*.



(a) *Isotropic antenna.* D = 0dBi **(b)** *Yagi antenna.* D = 14.1dBi

Figure 2.12 – *Two antennas with different directivity. Source: Mathworks – Atenna Toolbox*

This parameter is not related to the radiation efficiency, but for a communication system –with a fixed power transmitter– the higher the directivity, the further the communication that is possible to establish. In Figure 2.12, two radiation patterns are compared to two antennas with different directivity.

Gain

This antenna parameter describes how much power is transmitted in the direction of peak radiation in comparison with an isotropic antenna. The *Gain* concept is quite similar to *Directivity*, but in the *Gain* estimation, the power losses are taken into account due to antenna efficiency.

Gain and Directivity are reciprocal concepts, for this reason, they can be used in a communication link estimation for both transmission and reception sides.

For Cubesat missions, the antenna placed at the satellite is usually a single *quarter-wave monopole* or *half-wave dipole*, which are low gain antennas –5.19 dBi for quarter-wave monopoles and 2.19 dBi for half-wave dipoles. Although sometimes a monopole phased array or a deployable *helix* antenna are placed. The use of omnidirectional antennas is often preferred for those missions that are not able to control the attitude of their satellite and –therefore– cannot point the radiation peak to the Ground Station.

2

However, for the Ground Station side, it is preferred to use *high directive* antennas because it is easier to build on Earth a set of steerable antennas able to track the satellite position. This kind of antennas are usually **Yagi-Uda** antennas, often used for amateur Ground Stations, or **parabolic** antennas for professional Ground Stations –also used for high frequency links or GEO satellites. This topic will be studied in Chapter 3.

Polarisation

The polarisation of an antenna refers to the radiowave polarisation that is able to receive or transmit. The polarisation options for an antenna usually are Linear Polarisation (LP) –Horizontal Polarisation (HP) and Vertical Polarisation (VP)– or Circular Polarisation (CP) –Right-handed Circular Polarisation (RHCP) and Left-handed Circular Polarisation (LHCP). An electromagnetic wave circularly polarised is shown in Figure 2.13. For Cubesat missions –due to the *Faraday Effect*– it is common to place at the satellite both Linear Polarisation –only for downlink communication– and Circular Polarisation antennas. However at the Ground Station, RHCP and/or LHCP antennas are always placed in order to avoid the depolarisation rotation.

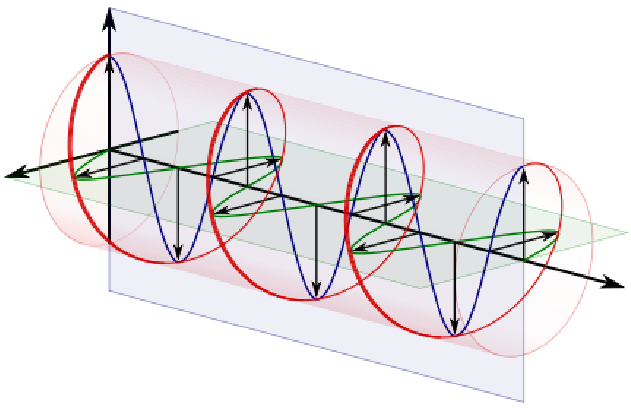


Figure 2.13 – *Circular Polarisation representation. Source: Wikipedia*

2.3.3 Digital Communication

As many other technologies, satellite communication systems are based on digital communication techniques. Doing a good use of digital features may improve the overall system performance and, therefore, increase the likelihood of success of the mission. In this subsection some key elements related to digital communications are introduced.

2.3.3.1 Digital Modulation

Modulation is the process of encoding the Base Band (BB) information from its original shape to another one, in such a way that the resulting signal is more suitable for transmitting through the channel. In the modulation process, some parameters of a high frequency *carrier signal* will be modified in accordance with the digital BB signal, often known as *modulator signal*.

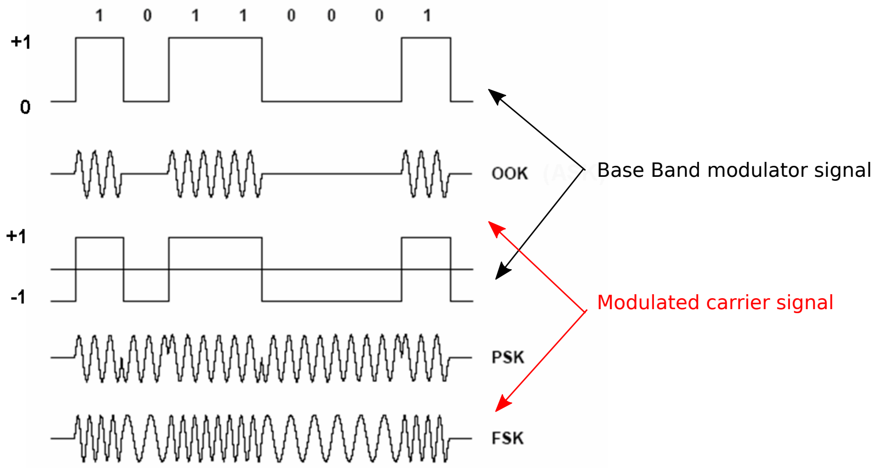


Figure 2.14 – *Samples of modulation processes. Source: Adapted from [29]*

There are three signal components that may be modified in a modulated signal: amplitude, frequency and phase, as it is depicted in Figure 2.14.

The process of recovering the original BB signal from the modulated signal is known as *demodulation*. In order to achieve a successful modulation-demodulation process, both modulator and demodulator shall use the same modulation scheme.

The process of demodulation carried out in the receiver may be performed by using two methods: *coherent demodulation* –the information of the carrier phase is employed– and *non-coherent demodulation* –the phase of the carrier is not taken into account. The use of *coherent demodulation* or *non-coherent demodulation* depends on the modulation scheme used, and it will affect the overall system performance as well.

Digital Modulation schemes

As noted above, there are three basic digital modulation schemes: Amplitude-Shift Keying (ASK), Frequency-Shift Keying (FSK), and Phase-Shift Keying (PSK). A modulated signal is represented as:

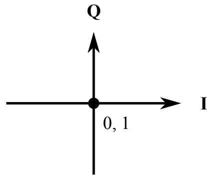
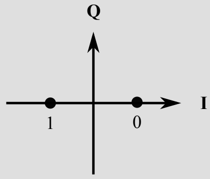
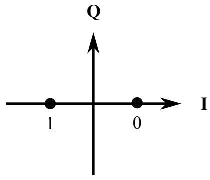
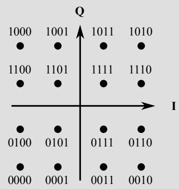
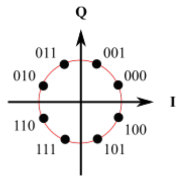
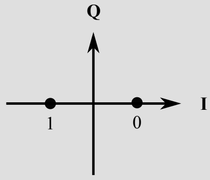
$$s(t) = A\cos(2\pi f_c t + \phi_n), \qquad (n-1)T_s \leqslant t \leqslant nT_s \tag{2.3.20}$$

Where:

A = Amplitude
f_c = Carrier frequency
ϕ_n = *n*th signal phase

For a digital modulation, signal parameters are quantized in accordance with the number of symbols M that are involved in the communication. A system using multiple symbols is known as a *M-ary* system. This characteristic is often noticed because of the modulation name: for example, for a M-ary system that uses 4 symbols ($M = 4$ [00, 01, 10, 11]) and is modulated by using conventional phase modulation, the modulation scheme will take the name of Quadrature Phase-Shift Keying (QPSK).

Digital modulation scheme samples

Modulation Scheme	**Varying element**	**Symbols M**	E_b/N_0 **Required* [dB]**	**Noise Immunity**	**Symbol Constellation**
OOK	A	2	23.2	Very bad	
BFSK	f_c	2	13.8	Good	
BPSK	ϕ_n	2	9.6	Very good	
16-QAM	A and ϕ_n	16	15.2	Very good	
8-PSK	ϕ_n	8	13.8	Very good	
GMSK	ϕ_n	2	9.6	Very good	

* For $P_B = 10^{-5}$

Table 2.3 – *Digital modulation scheme samples*

There is an innumerable amount of digital modulation schemes. In Table 2.3, some of the most representative modulation schemes in radio communication have been summarised. Since noise affects specially the amplitude, those modulation schemes that use the frequency or the phase to code the information will be more immune to noise effects.

Bit Error Rate – BER

Any noisy channel will introduce errors into the data bit stream. There is a direct relation between the *probability of bit error* P_B and the *carrier-to-noise ratio* $\left(\frac{C}{N}\right)$, being this second concept also related to the digital coding scheme employed. The term Bit Error Rate (BER) is an empirical measurement of the system bit error performance.

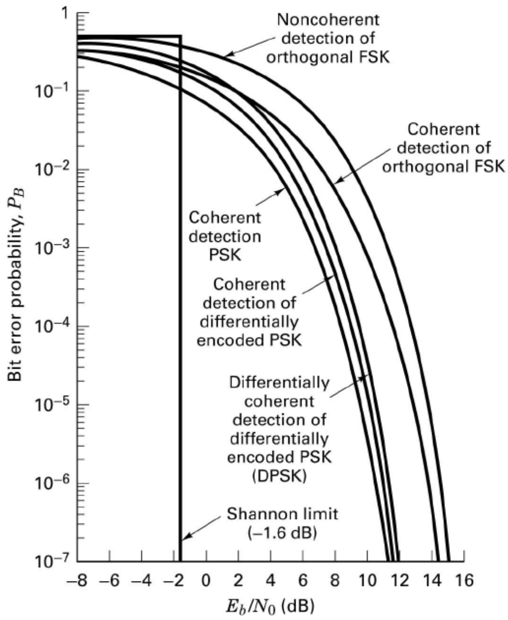


Figure 2.15 – *Bit error probability performance comparison. Source: [29]*

As previously stated, the *probability of bit error* is dependent on the *energy per bit density noise rate*, as well as on the coding used. For example, as shown in Figure 2.15, for a probability of error P_B lower than 10^{-5}, it is usually required a rate $E_b/N_0 \geqslant +9$ dB.

Shannon Theorem

For an Additive White Gaussian Noise (AWGN) channel, the maximum channel capacity C_C is given by the *Shannon theorem* [29]:

$$C_C = B \log_2 \left(1 + \frac{C}{N}\right) \tag{2.3.21}$$

Where:

C_C = Channel capacity [bit/s]
B = Channel bandwidth [Hz]
C = Carrier power [W]
N = Noise power [W]

In order to reach the maximum channel capacity, the expression 2.3.21 states a minimum value of the *energy per bit noise density ratio* $\left(\frac{E_b}{N_0}\right)$ if an error-free performance in the communication is desired. Since the probability of bit error is directly proportional to $\left(\frac{E_b}{N_0}\right)$, the statement implies that by choosing the appropriate coding scheme it is possible to obtain any bit rate r_b with an arbitrarily low probability of bit error rate, as long as $r_b \leqslant C_C$ [29].

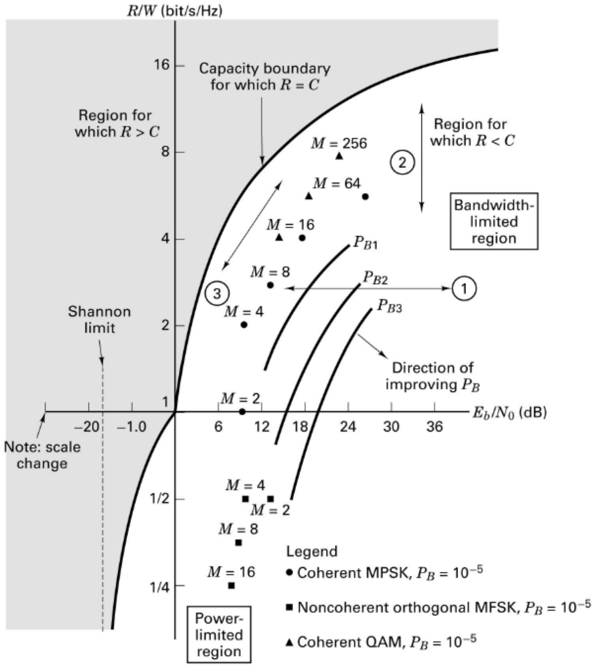


Figure 2.16 – *M-ary systems performance against channel capacity. Source: [29]*

The modulation scheme and number of symbol is related to the system performance. Figure 2.16 depicts the performance for different modulation schemes against the capacity boundary –that is, when bit rate r_B is equal to channel capacity C_C.

For systems limited by bandwidth, a high R/W performance is desired, and therefore the E_b/N_0 should be increased. In this scenario, coherent QAM and coherent MPSK present the best rate performance. On the other hand, when the system is limited by power E_b/N_0, the R/W performance is reduced –that is, the bandwidth is widened. In this case, the preferred modulation scheme is non-coherent MFSK.

2.3.3.2 Channel coding

The noise in a transmission channel will introduce errors in the data stream. By using coding techniques, the receiver will be able to detect those errors and correct them. Thus, a coded system increases the efficiency of the channel bandwidth use, allowing to get a higher E_b/N_0 than with uncoded systems [30].

Although numerous coding techniques exist –each offering different features and performance rates–, the overall main goal is to achieve a performance as close as possible to the theoretical Shannon limit. The most used technique is the known as

Forward Error Correction (FEC), which adds redundant bits to data bit stream in such a way that an error on it may be detected and corrected. The most common FEC types are:

- Linear Block Codes:
  - Cyclic Codes
  - BCH Codes
  - Low-Density Parity-check codes
- Convolutional codes:
  - Turbo codes

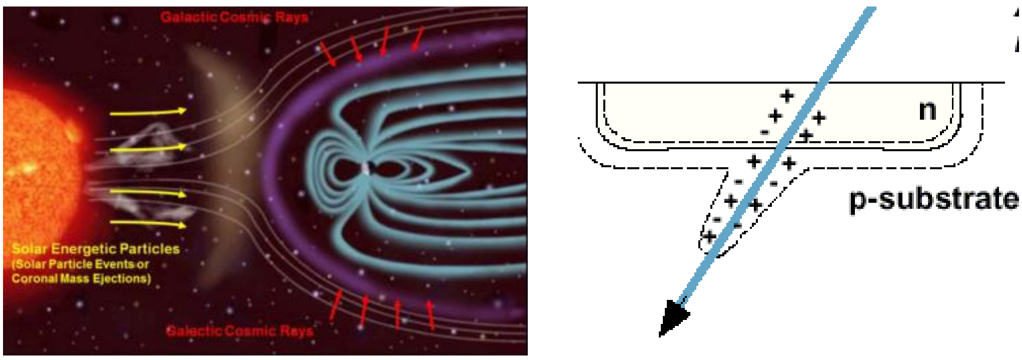
Turbo codes are a special case of Convolutional codes that concatenate several convolutional blocks in order to perform an iterative process. Nowadays the Turbo code technique is the one that best presents the performance.

2.3.4 Space Environment

Space is an environment with extreme conditions, but the Earth, luckily, is protected against the potential consequences by its atmosphere and magnetosphere. Once humans leave their comfortable planet and are out protection, some problems will arise and engineers should be ready to take them into account if they want to achieve a successful design.

2.3.4.1 Radiation

The solar system is flooded by hostile radiation coming from Galactic Cosmic Rays (GCR) and solar energetic particles. In summary, ionizing radiation can be simply explained as charged particles moving fast across space with such an energy that can go through regular mass. Once a spacecraft go through Van-Allen Belts –and is out of protection– it will start suffering the effects of these energetic particles colliding against its body [31]. Figure 2.17a illustrates how Van-Allen Belts protect Earth against the solar ionized particles.



(a) *Van-Allen Belts illustration. Source: NASA Photojournal PIA16938*

(b) *SEU effect. Source: [32]*

Figure 2.17 – *Radiation effect on Solar System and electronics*

Given that the electronic devices are made of millions of circuits and components, they will be sensible to the external energy, and could interact with it. The effects of radiation may be diverse, provoking a malfunctioning, degraded or destroyed system. These effects will appear as soon as a charged particle goes through the electronics and leaves an ionized track behind [32].

Single-event upset:

A Single-event Upset (SEU) results from a change of a bit register inside a chip, provoked when a charged particle ionizes the electronic medium. Figure 2.17b depicts the effect of a SEU event in a MOSFET transistor. It does not cause a destructive damage in the circuit but the whole system may be endangered if the correct value is not rewritten.

Resetting or rewriting the circuit to the correct value is required to recover the system behaviour. This shall be addressed by using redundant elements able to detect any malfunctioning in each single part of the system.

Single-event latchup:

A Single-event Latchup (SEL) occurs when a high energetic particle passes through an inner semiconductor junction happening in a short-circuit between two layers of the semiconductor. These events are hardware errors and they are destructive.

Ignoring SEL events may be the origin of a total and persistent damage of the system due to the overheating caused by a high current short-circuit. Hence, the power supply shall be immediately cut off after the failure.

Total ionizing dose effect:

Although a single low energetic ionizing radiation may cause a slight damage in the semiconductor structure, after a long exposition to radiation, a cumulative sum of small damages may turn into severe risk of damage due to a semiconductor degradation.

There are two ways to avoid or minimise any system behaviour degradation caused by ionizing dose effects: using a hardened chip or shielding the electronics.

2.3.4.2 Pressure

Space is a vacuum environment and this condition has to be considered throughout the design phase. The void in space is related to some relevant issues in space engineering.

Outgassing:

Outgassing is defined by ECSS as *"the release of gaseous species from a specimen under high vacuum condition"* [33]. This effect occurs mainly to material that can absorb a relevant amount of gas on it, which –once in space– is released outside. Outgassing may induce the material to break up.

According to outgassing criteria not all materials are suitable for space. For this reason, ESA maintains a database of materials that have been tested and accepted for space application because of their low outgassing [34]. In addition, any European space mission shall pass a Thermal VACuum (TVAC) to obtain a space qualification [33].

Heat convection:

The absence of matter will affect directly on-board system heat dissipation. In vacuum the only way to transfer energy is through heat radiation, and the classic heat convection techniques will not work in this case. Thus, thermal design techniques in electronics shall be addressed to achieve a correct heat treatment and to avoid circuit overheating.

2.3.4.3 Temperature

In space –as mentioned in Subsection 2.3.4.2– the energy transfer is carried out uniquely by radiation. This means that a spacecraft in space will behave as a radiation emitter –due to the heat produced by the systems– and as a radiation absorber –of incident space radiation– until it reaches its thermal equilibrium.

The radiation emission or absorption event will prevail according to the relative position of the satellite with respect to Earth and Sun. During a day orbit position, the body radiation absorption behaviour will predominate and the spacecraft temperature will rise, as opposed to what happens during a night orbit position. Since in LEO orbit the Cubesat will orbit the Earth several times in 24 h, the cycle of temperature is expected to present a periodical behaviour.

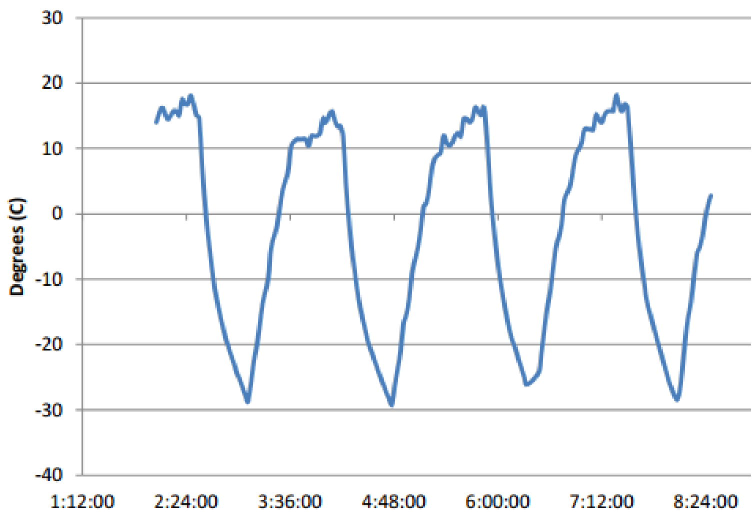


Figure 2.18 – *External temperature cycle for* ***CP3*** *Cubesat. Source: [35]*

Following the thermal analysis carried out by former Cubesat missions –**CP3** [35] and **OUFTI-1** [36]– the expected external temperature can vary from −30 °C to 55 °C [36]. A typical cycle of external temperature is depicted in Figure 2.18. The specific shape of the chart –peak-to-peak temperature and periodicity– will be based on the Cubesat orbital elements, thermal design, payload, etc. [35].

Although building a correct system thermal behaviour is a task for thermal engineers, electronics engineers shall keep in mind the extreme temperature that its electronic design must bear and, therefore, choose the adequate components based on the temperature range for a nominal working.

2.3.4.4 Corrosion in Space

Corrosion in space can occur because of the Atomic Oxygen (ATOX) present in the upper atmosphere. For an altitude between 200 km and 700 km, corrosion by ATOX is considered one of the most serious hazards for a spacecraft in orbit [37].

The typical oxidation product is either a volatile oxide or a layer of oxide, as shown in Figure 2.19. In both cases, the chemical process may cause an erosion in the material surface. For some metals such as aluminium, copper or steel, the oxide foil remains on the surface and it works as an ATOX corrosion protection for the inner material [37].

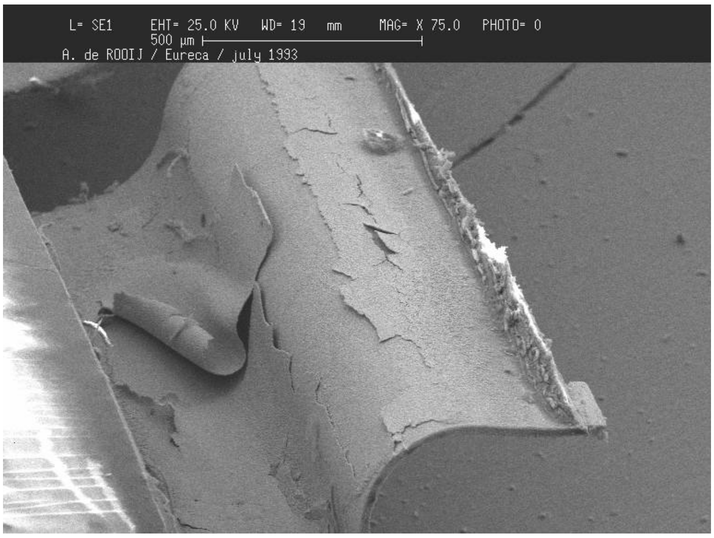


Figure 2.19 – *Silver interconnector oxidised by ATOX corrosion. Source: [37]*

2.4 Radio regulation

Since satellite systems use radio waves –to transmit and receive information– and the radio espectrum is a limited medium, the likelihood of hazardous interference among different systems is quite high. For this reason it becomes necessary to regulate the applications and the use that not only satellite systems but all radio-frequency systems make of the radio espectrum.

2.4.1 ITU – International Telecommunication Union

The radio regulation is carried out by national laws and is coordinated internationally by the International Telecommunication Union (ITU) [38]. Figure 2.20 shows the ITU logo.

To avoid different users of applications interfering with each other, several characteristics of the transmitted radio waves, such as the carrier frequency, bandwidth, and transmission power, are strongly regulated. The *ITU-Radio Regulations* document –consisting of four volumes– itemizes the applicable regulation in this field [39].

Figure 2.20 – *ITU logo*

Since the market of nano-satellites and pico-satellites –where Cubesats are included– has grown up, ITU has also summarised the radio regulation and restrictions involving their use.

2.4.2 IARU – International Amateur Radio Union

The ITU allows other administrations to manage and coordinate some particular tasks, such the use of frequency bands. One of these administrations is the International Amateur Radio Union (IARU), officially accredited as a representative of the amateur service and amateur-satellite service at ITU.

The IARU was born in 1925 with the aim of watching over all the frequency allocations that the amateur-satellite service and the amateur service are formed by. The IARU logo is shown in Figure 2.21.

Usually, frequency allocations inside the radio espectrum are shared by many different services, resulting in a more than possible interference among themselves if the transmission frequencies are not properly selected and managed. The IARU offers assistance during the planning and operation of frequencies to achieve the best performance of the amateur-satellite service by taking into account any other amateur satellites and terrestrial operators and their frequency planning.

Figure 2.21 – *IARU logo*

Besides the frequency planning, this administration also offers many recommendations derived from ITU regulation. Some of these will be mentioned throughout the next subsection (2.4.3).

2.4.3 Radio Regulation Summary

Since the radio regulation is an extensive set of rules applied to the whole radio espectrum, it is hard to fit in this work a complete and exhaustive study of those rules concerning satellite communications or Cubesats in particular. For this reason, it was decided to select the most relevant and restrictive rules within the radio regulation related to amateur-satellite service, where Cubesats missions are included.

In addition, in the following paragraphs herein this subsection, a brief explanation of the regulation background is given to provide a solid basis of knowledge related to the concerned points. For better understanding, a complete list of radio regulations involved in an amateur-satellite service is detailed in Appendix A. This list has been obtained from ITU's document *ITU-Radio Regulations*, article 25 [39].

Amateur Satellite Service – ISM Bands

The use of any part of the radio espectrum shall be done with legal permission, which is usually a paid license –an example of this could be the use of broadcast television stations or cellular base stations–, but an exception is contemplated when using some frequency bands regulated in a less restricted way. These *free* frequency bands are called Industrial, Scientific, Medical (ISM) bands, and were defined by ITU in its document *ITU-Radio Regulations* by the points **RR 5.138**[2] and **RR 5.150**[3] [39].

[2]**RR 5.138:** *"The following bands: 6 765-6 795 kHz (centre frequency 6 780 kHz), 433.05-434.79 MHz (centre frequency 433.92 MHz) in Region 1 except in the countries mentioned in No. 5.280, 61-61.5 GHz (centre frequency 61.25 GHz), 122-123 GHz (centre frequency 122.5 GHz), and 244-246 GHz (centre frequency 245 GHz) are designated for industrial, scientific and medical (ISM) applications. The use of these frequency bands for ISM applications shall be subject to special authorization by the administration concerned, in agreement with other administrations whose radio communication services might be affected. In applying this provision, administrations shall have due regard to the latest relevant ITU-R Recommendations."*

[3]**RR 5.150:** *"The following bands: 13 553-13 567 kHz (centre frequency 13 560 kHz), 26 957-27 283 kHz (centre frequency 27 120 kHz), 40.66-40.70 MHz (centre frequency 40.68 MHz), 902-928 MHz (centre frequency 915 MHz) in Region 2, 2 400-2 500 MHz (centre frequency 2 450 MHz), 5 725-5 875 MHz (centre frequency 5 800 MHz), and 24-24.25 GHz (centre frequency 24 125 GHz), are also designated for industrial, scientific and medical (ISM) applications. Radiocommunications services operating within these bands must accept harmful interference*

Selecting frequency bands allocated for amateur-satellite service inside the ISM bands is often the preferred procedure for universities when obtaining a license for their Cubesat. That is the reason why, for all the Cubesats analysed in Section 2.2, the dominant transmission frequency is the **UHF** and **X band**, leaving other bands such as the **VHF band** and **S band** as negligible Communication System (COMM).

2

Following the point **RR 5.282**[4] from the *ITU-Radio Regulations* document [39], an amateur-satellite service can operate in any of the following bands: 435-438 MHz, 1.26-1.27 GHz, 2.40- 2.45 GHz, 3.40-3.41 GHz and 5.65-5.67 GHz; under the condition that, in accordance with **RR 5.43**[5], they must not cause any harmful interference to other services already operating. The administrations authorising the use of such bands shall ensure that any undesired interference from the amateur-satellite service is stopped straight away in accordance with **RR 25.11**[6] [39].

Harmful interference contingency plan

The accomplishment of **RR 25.11** is one of the few requirements that ITU imposes to any amateur-satellite service, and it compels mission operator to be able to turn off immediately –both Earth and/or space station transmitter– in case of harmful interference. The word *immediately* is used in a wide sense, which means that the time period since the interference is detected until the transceiver is turned off might last a couple of minutes –for interferences to safety services– or a few hours –for non-critical services [40].

The **RR 25.11** requirement encourages to have several procedures able to turn off the transmitter in case of interference. Some recommendations are provided by IARU [40]:

(1) The space station should use an independent receiver for turn-off control commands.

(2) A network of Ground Stations is highly desirable to minimise the turn-off control command sending time.

(3) The implementation of a time-out timer in the transmitter.

which may be caused by these applications. ISM equipment operating in these bands is subject to the provisions of No. 15.13."

[4]**RR 5.282:** *"In the bands 435-438 MHz, 1 260-1 270 MHz, 2 400-2 450 MHz, 3 400-3 410 MHz (in Regions 2 and 3 only) and 5 650-5 670 MHz, the amateur-satellite service may operate subject to not causing harmful interference to other services operating in accordance with the Table (see No. 5.43). Administrations authorizing such use shall ensure that any harmful interference caused by emissions from a station in the amateur-satellite service is immediately eliminated in accordance with the provisions of No. 25.11 . The use of the bands 1 260-1 270 MHz and 5 650-5 670 MHz by the amateur-satellite service is limited to the Earth-to-space direction."*

[5]**RR 5.43:** *"Where it is indicated in these Regulations that a service or stations in a service may operate in a specific frequency band subject to not causing harmful interference to another service or to another station in the same service, this means also that the service which is subject to not causing harmful interference cannot claim protection from harmful interference caused by the other service or other station in the same service."*

[6]**RR 25.11:** *"Administrations authorising space stations in the amateur-satellite service shall ensure that sufficient Earth command stations are established before launch to insure that any harmful interference caused by emissions from a station in the amateur-satellite service can be terminated immediately."*

(4) Limitation of the power budget available for the COMM System, to limit therefore the time of transmission.

Frequency Allocation

Asking IARU for a frequency allocation will minimise the risk of either receiving harmful interference from any other source or becoming a source of interference for other services. To achieve a successful frequency allocation, many band plans have been drawn up by grouping projects with similar nature and technical requirements. Thus, regulating and setting the radio frequency emission parameters may be done easier than mixing many sources with different settings without any kind of arrangement.

Typically, the amateur-satellite service and the amateur service in general are included in ITU's frequency band and have their own space in the radio espectrum in some frequency allocation plans. Due to the different uses of services and needs across the world, ITU adapts the frequency allocation work according to different regions worldwide [40]. Figure 2.22 depicts a world map showing these regions.

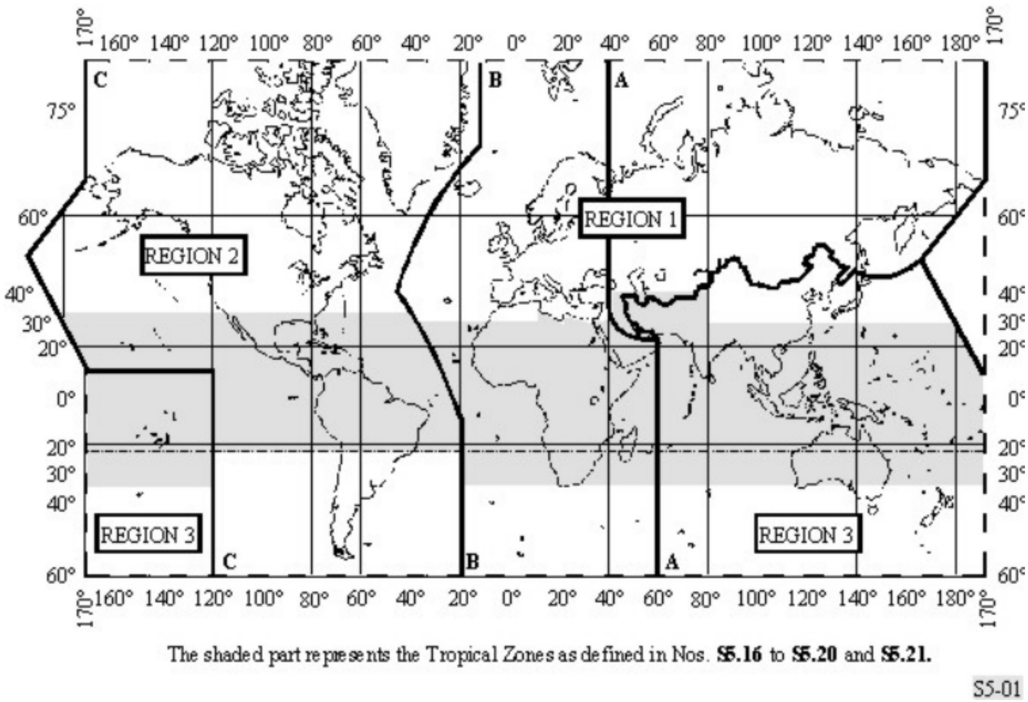


Figure 2.22 – *World map of regions for ITU's frequency allocation. Source: [40]*

The world is split up into three regions:

- Region 1: Europe, Africa, Middle East and North Asia
- Region 2: North America and South America
- Region 3: Asia-Pacific

Since this document explores the frequency regulation for a Spanish amateur-satellite service, the focus will be in Region 1 –and worldwide area– specifications. A frequency bandplan has been summarised in Table 2.4. *Maximum bandwidth* column determines the maximum spectral width – -6 dB points – of all emissions allowed in each frequency band [41] [42].

2

Frequency band	Maximum Bandwidth	Area	Details
7.00 - 7.10 MHz	Not Specified	Worldwide	Primary
14.00 - 14.25 MHz	Not Specified	Worldwide	Primary
18.068 - 18.168 MHz	Not Specified	Worldwide	Primary
21.00 - 21.45 MHz	Not Specified	Worldwide	Primary
24.89 - 24.99 MHz	Not Specified	Worldwide	Primary
28.00 - 29.70 MHz	Not Specified	Worldwide	Primary
145.80 - 146.00 MHz	12 KHz	Worldwide	Primary
435.00 - 438.00 MHz	20 KHz	Worldwide	Non-Interference basis
1.26 - 1.27 GHz	National Regulation	Worldwide	Non-Interference basis Earth-to-space (Uplink)
2.40 - 2.45 GHz	Not Specified	Worldwide	Secondary
3.40 - 3.41 GHz	Not Specified	Region 2 Region 3	Non-Interference basis
5.65 - 5.67 GHz	2700 Hz	Worldwide	Non-Interference basis Earth-to-space (Uplink)
5.83 - 5.85 GHz	Not Specified	Worldwide	Secondary Space-to-Earth (Downlink)
10.45 - 10.50 GHz	Not Specified	Worldwide	Secondary
24.00 - 24.05 GHz	2700 Hz	Worldwide	Primary
47.00 - 47.20 GHz	2700 Hz	Worldwide	Primary
75.50 - 76.00 GHz	2700 Hz	Worldwide	Primary
77.50 - 81.50 GHz	2700 Hz	Worldwide	Secondary
134.00 - 136.00 GHz	Not Specified	Worldwide	Primary
136.00 - 141.00 GHz	Not Specified	Worldwide	Secondary
241.00 - 248.00 GHz	Not Specified	Worldwide	Secondary
248.00 - 250.00 GHz	Not Specified	Worldwide	Primary

Table 2.4 – *Official IARU Region 1 bandplan for amateur-satellite service [42]*

Satellite Operational Modes

Thanks to this frequency allocation in several bands of the radio espectrum, the designers of the amateur-satellite service are able to select the frequency band that better suits the technical constraints of the project. Thus, this also makes possible to carry a communication system that enables an uplink and downlink set in different frequencies. A procedure that is called *Operational Mode*.

Mode		Uplink (MHz)	Downlink (MHz)
Original	Modern		
A	V/T	145.80 - 146.00	29.30 - 29.50
B	U/V	435.00 - 438.00	145.8 - 146.00
J	V/U	145.80 - 146.00	435.00 - 438.00
K	H/T	21.26 - 21.30	29.30 - 29.50
L	L/U	1260.00 - 1270.00	435.00 - 438.00
S	U/S	435.00 - 438.00	2400.00 - 2450.00
T	H/V	21.26 - 21.30	145.80 - 146.00

Table 2.5 – *Satellite Transponder Designators [42]*

The use of different frequencies is flexible, but designers choose some operational modes more frequently than others. Some of the most popular operational modes are summarized in Table 2.5 [42]. The mission requirements, together with the radio equipment already available at GranaSAT facilities (see Chapter 3), will determinate the factors that will decide the most suitable operational mode for the GranaSAT-I Cubesat.

Radio Amateur Community

Apart from the radio espectrum use or the frequency allocation, the ITU is also concerned about the use and nature of the amateur-satellite service: every amateur-satellite service shall be accessible worldwide for the radio amateur community, the educational community included as well [40].

To allow any radio amateur have free access to the amateur-satellite service regardless of where they are located, the ITU has included **RR 25.2**[7] and **RR 25.2A**[8] to its *ITU-Radio Regulations* document. Therefore, the amateur-satellite service technical details –such as coding format, modulation scheme, packet format, etc.– must be **public** and **available** to any licensed radio amateur, in such a way that operating the service

[7]**RR 25.2:** *"Transmissions between amateur stations of different countries shall be limited to communications incidental to the purposes of the amateur service, as defined in No. 1.56 and to remarks of a personal character."*

[8]**RR 25.2A:** *"Transmissions between amateur stations of different countries shall not be encoded for the purposes of obscuring their meaning, except for control signals exchanged between Earth command stations and space stations in the amateur-satellite service."*

2

should be feasible and reasonably easy for a competent operator. Satellite operation commands are excluded from this requirement [40].

Figure 2.23 – *Radio operator managing an amateur Ground Station. Source: Satnogs.org*

For example, Figure 2.23 shows a radio operator controlling an amateur Ground Station (GS) integrated at SatNOGS Network. **SatNOGS** is an open source project aiming to provide all the technical documentation and the SW needed to create and operate a Cubesat Ground Station, integrating it into a GS network as well [43].

Obviously, this kind of initiatives can only be feasible if a wide number of Cubesat missions are open and if it is easy to obtain their communication link details.

Chapter 3

Ground Station

As specified in subsection 2.3.2, a satellite link is made up of an Earth station –or Ground Station (GS)– and the satellite itself, where both must operate as a transmitter and as a receiver. In this master's thesis a Cubesat's Communication System is designed, and for this very reason, it is crucial to keep in mind the relevance of the Ground Station, considering that it bears the half of the communication success.

The author of this project has been involved in the building of two Cubesat GS. The first one has been the Ground Station of the GranaSAT group. The second one has been a Ground Station for the European Space Astronomy Centre (ESAC) in Madrid during a student traineeship programme. The advantage of the know-how acquired throughout the building process may be translated into quick and satisfactory COMM system's requirement phase and design phase performances.

3.1 Link Budget

As it was introduced in Chapter 2, to establish a communication link between a transmitter and a receiver it is required that the radio wave coming at the reception chain has a minimum of power, and this must be higher than the system's noise (see Carrier-to-Noise rate eq. 2.3.18). The $\left(\frac{C}{N}\right)$ parameter offers an excellent way to measure the quality of the link, however, in a digital communication system the performance criteria shall contemplate the Base Band (BB) signal quality, as it does the *energy per bit noise density ratio* $\left(\frac{E_b}{N_0}\right)$ in the BB channel at the reception chain.

Since the carrier power is a function of bit energy and bit duration (or equivalently to bit rate) $c = E_b r_b$, and the thermal power noise is a function of the noise bandwidth and the noise power density $n = n_0 b_N$, by substituting in eq. 2.3.18 we express [30]:

$$\left(\frac{E_b}{n_0}\right) = \left(\frac{c}{n}\right)\left(\frac{b_N}{r_b}\right) = \frac{p_T\ g_T\ g_R\left(\frac{1}{l_{FSPL}\ l_O}\right)}{k\ t_S\ r_b} \tag{3.1.1}$$

If we take the elements in dB and rearrange them adequately:

$$\left(\frac{E_b}{N_0}\right) = \text{EIRP} + \left(\frac{G}{T}\right) - L_{FSPL} - L_O - R_b - K \qquad [\text{dB}] \tag{3.1.2}$$

Where:

EIRP = transmitter Equivalent Isotropic Radiated Power [dBW]
$(\frac{G}{T}) = G_R - T_S$ = receptor Figure Of Merit [dB/K]
L_{FSPL} = free space path loss [dB]
L_O = other losses in the system [dB]
R_b = Base Band signal bit-rate [dBHz]
$K = -228.60$ [dBW/Hz/K] = Boltzmann's constant

3

The process of calculating the value of the expression 3.1.1 for the communication link is the calculation known as **Link Budget**. As stated above, different values of parameters may exist for the transmitters and the receiver within both the Cubesat and the Ground Station, an **uplink budget** and a **dowlink budget** must be addressed to get to know the overall communication system performance.

In addition, designers must not forget that the digital BB signal will require a minimum *energy per bit noise density ratio* E_b/N_0 margin in order to be demodulated with a fixed probability of bit error (see 2.3.3). The theoretical E_b/N_0 margin will depend on the modulation scheme chosen. This value, plus a demodulation implementation margin error, shall be contemplated within the link budget calculation as well.

In summary, a link budget calculation will imply the following steps:

(1) To calculate the overall output power P_T and antenna gain G_T at the transmitter.

(2) To obtain the transmitter EIRP$= P_T + G_T$

(3) To calculate the Free Space Path Loss L_{FSPL} for the orbit slant range distance and carrier frequency (see eq. 2.3.7).

(4) To calculate any other losses L_O within the system, such as atmospheric losses, polarization losses, pointing losses, etc.

(5) To calculate the overall power losses at the receiver L_R and the receiver antenna gain G_R

(6) To calculate the overall system's equivalent temperature noise T_S at the receiver. Use the available NF values and calculate the total NF for a cascade system when required (see 2.3.15). Use general values of Sky noise if required (see [25]).

(7) To obtain the receiver Figure Of Merit $(\frac{G}{T}) = G_R - L_R - T_S$

(8) To obtain the carrier-to-noise density ratio $C/N_0 = \text{EIRP} - L_{FSPL} - L_O + (\frac{G}{T}) - K$

(9) To obtain the energy per bit noise density ratio E_b/N_0 margin before demodulation. Use the bit-rate R_B of the digital communication employed. $E_b/N_0 = C/N_0 - R_B$

(10) To subtract the E_b/N_0 margin required for the demodulation process M_D

(11) To obtain the final Base Band E_b/N_0 margin after demodulation at the receiver.

For better understanding, steps listed above have been summarised in Figure 3.1. A downlink case was considered in this figure –that is, the Ground Station is the receptor and the Cubesat acts as a transmitter. Nevertheless, for an uplink calculation, the process remains symmetric and just the transmission and reception roles are swapped.

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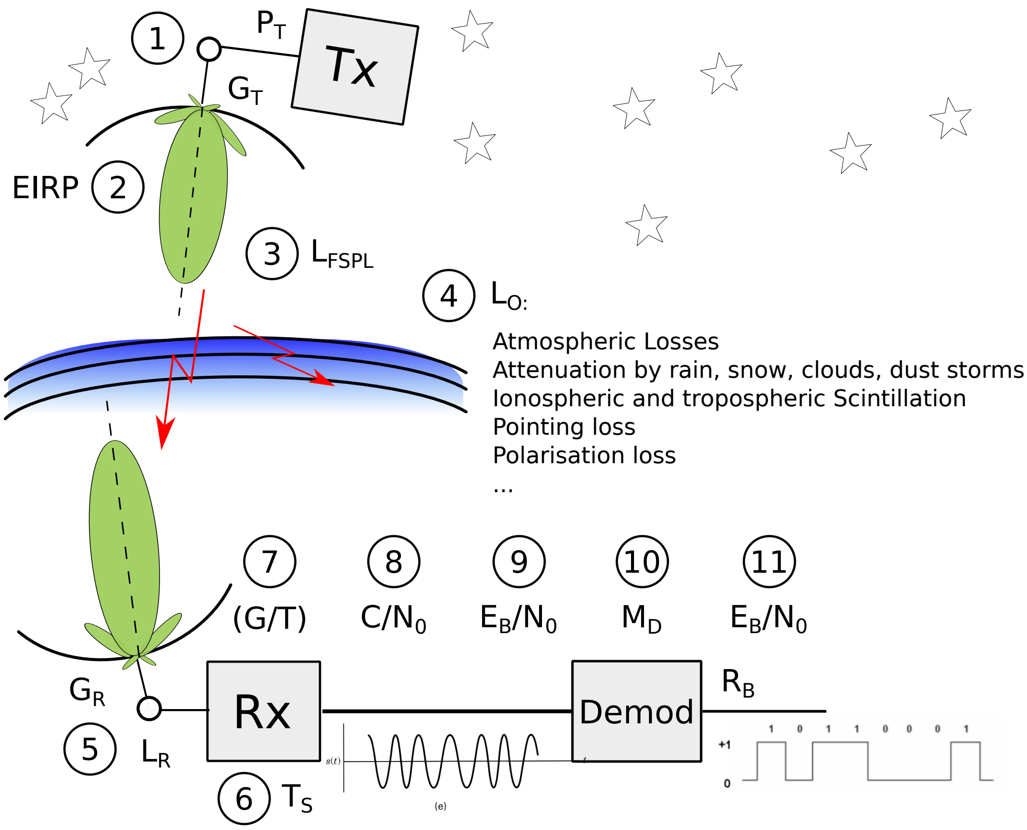


Figure 3.1 – *Downlink budget calculation summary*

By comparing the resulting signal power –once the wavefront has gone through the whole system– against the receptor's power noise density, it is possible to design an efficient communication system on a signal quality basis.

To close a communication link and guarantee a good quality of the signal, a minimum E_b/N_0 margin is required. A positive *energy per bit noise density ratio* value implies a closed communication link because the energy contained per bit is higher than the noise energy introduced by the system. Therefore, the receiver is able to decode correctly the bit stream. Negative ratio means the noise energy is predominant, and therefore the communication link will not be closed.

Proper values may vary from +10 dB for an amateur Ground Station, +6 dB for professional facilities, and +3 dB for a deep-space Ground Station [30]. Very high values for a link budget result implies that the communication system has been over-dimensioned and, therefore, resources, time and money have been invested into facilities for no reason.

For this work, a calculation for two link budgets has been performed: for the GranaSAT Ground Station (see 3.2) and for the ESAC Ground Station (see 3.3). Calculation details can be consulted in Appendix B.

3.1.1 Relevant and useful considerations

3

Noise contribution

It can be noticed that for an overall noise density estimation, only noise temperature contribution at the receiver is considered. For a reception chain whose elements are connected in a cascade mode, the noise contribution of first elements –sky noise and *other types*– has a critical impact to the overall system, being convenient here to apply the principle *the less noise, the better*. In addition, gain value from those different elements in the reception chain will affect system performance (see eq. 2.3.15).

Since the sky noise cannot be reduced, the strategy adopted is to place a high gain Low Noise Amplifier in second position right after the antenna. This way the overall system noise figure will be reduced and, therefore, the performance will boost.

Avoiding the LNA placement at the receiver chain will cause difficulties to close the communication link. A clear example of this fact is the one experienced by the *PolySat Team* with their Cubesat missions and their difficulty to close the uplink because of harmful and undesired noise at the reception chain in their pico-satellites. For the first design of their COMM System they required at their GS a transmission power $P_T = 100\ W$ ($+20$ dBW) to close the uplink. This means a poor design at the reception chain, which has been improved throughout subsequent system design revisions by adding a LNA and optimizing the PCB layout, among other changes. Just including a LNA to the receiver, the system sensibility boosted up to $+10$ dB, that is, went from $P_T = 100\ W$ ($+20$ dBW) to $P_T = 10\ W$ ($+10$ dBW), which is a great improvement. See [44] and [45] for further details.

In summary, noise at the receiver is a big constraint that must be correctly addressed if a reliable communication link is desired for the Cubesat mission.

LNA – Low Noise Amplifier

The importance of using a LNA has been remarked and now its role must be understood as critical. But a common mistake is to think that the system performance is directly related to the LNA gain. Although gain is important to the overall system performance, it is the combination of Noise Figure, gain and other sources of noise what will determine the receiver performance 2.3.15. For example, by increasing $+10$ dB the LNA gain of the GranaSAT GS, it will only improve the E_b/N_0 ratio up to $+0.2$ dB.

In summary, it is pointless to seek the highest LNA gain in the market. For a typical amateur GS, the typical LNA should be enough: low NF (around 1 dB or lower) and a high but modest gain (around +20 dB).

Link budget reliability

At this point we are already aware of the importance of the link budget calculation. That is quite true, but a link budget does not have the final say. Regardless of how complete and accurate the link budget is, many of its fields are mere estimations, whereas other noise sources, such as frequency harmonics, intermodulation noise, crosstalk, image frequency, or clock frequency shifting, may have been wrongly ignored or neglected.

3

In summary, it is the duty of an engineer to check if the link budget calculation meets the actual system performance. Thus, proper and meticulous testing, as well as good design practises, are more than welcome in RF engineering.

Uplink-Downlink budget *interchangeability*

Due to several physical phenomena (such as antenna reciprocity theory, that the L_{FSPL} is symmetrical, and the LNA features in both sides are similar), the theoretical EIRP to stablish a communication link between space and Earth must be quite similar to the required to close an Earth to space link.

A rule of thumb often used by amateur Ground Station operators within the Cubesat framework is the following: the EIRP that the Cubesat presents is the transmission EIRP needed in the Ground Station side to reach the Cubesat.

Although this fact shall not be understood as an universal true, it is normally valid for a typical Cubesat and amateur Ground Stations, as long as both sides present nominal states, that is to say, they are neither malfunctioning nor broken.

3.2 GranaSAT Ground Station

The development of the amateur Ground Station (GS) for the GranaSAT-I mission was the first project performed by the GranaSAT team. Because this work is carried out by students during their free time, the GS features have been updated gradually by several students throughout the last years.

Since the GS development begun in 2014 by David Aguilera (See *Ground Station design and deployment for the GranaSAT-I* [24]) the GranaSAT Ground Station has had two major improvements: the first one in 2015 by the author of this document, and the second one in 2016 by Miguel Ángel del Río (see *Design, development and testing for low cost systems for satellite image reception* [46]). Thus, this section focuses on the work performed by the author.

3.2.1 Architecture

Previous state

The first operational version of the GS (see [24]) was built with a limited budget and partially equipped with old analogue ham radio instrumentation, which made it difficult for crossing sides into a digital work. The use of an available old TNC equipment was very limiting and tedious. This circumstance pushed us to mainly work with an USB SDR dongle, given that all Cubesat missions operate digitally. An architecture diagram for this first operation version is depicted in Figure 3.2.

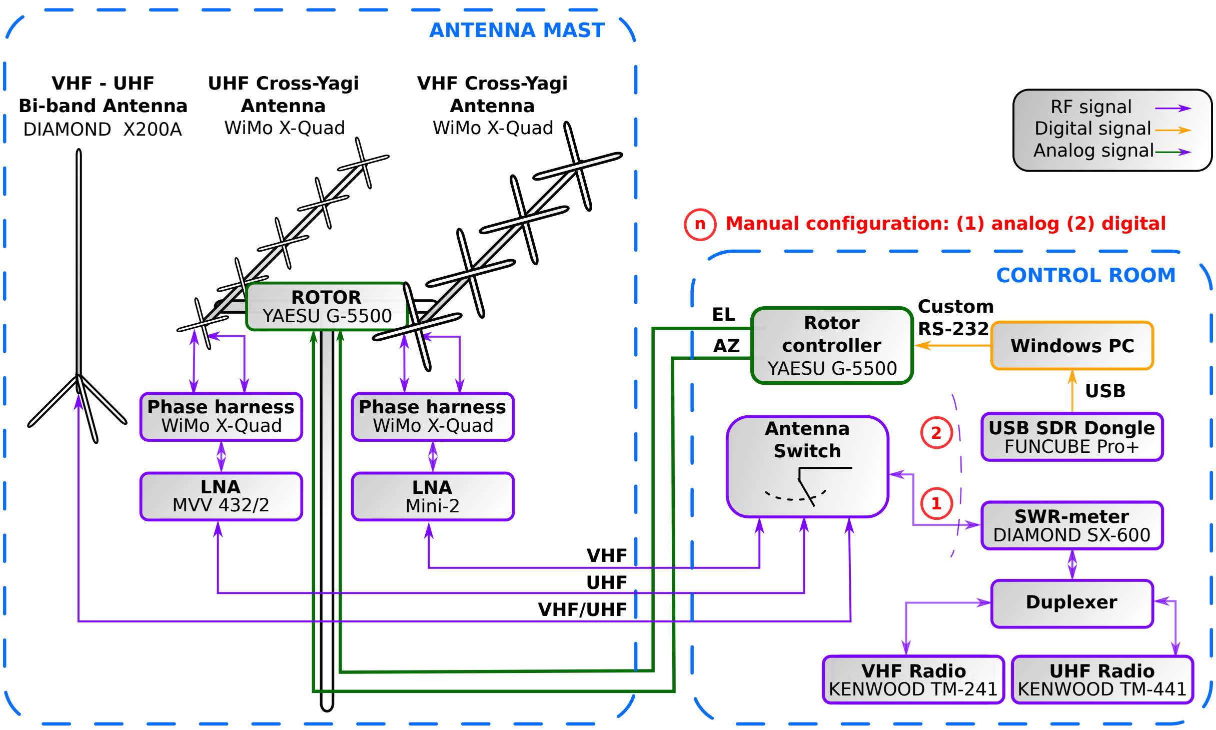
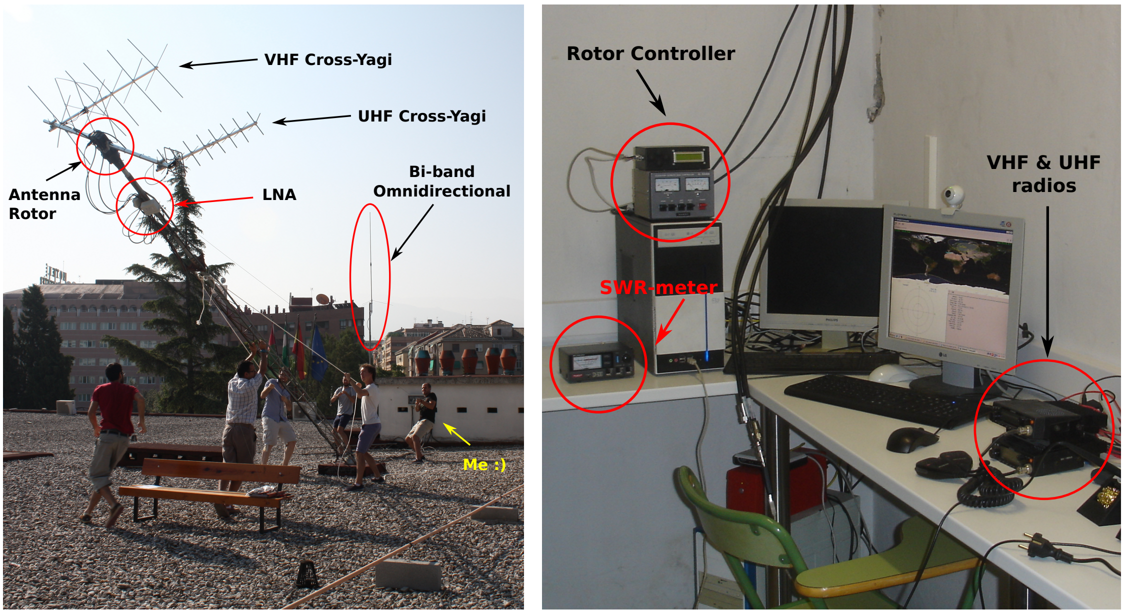


Figure 3.2 – *GranaSAT Ground Station v1 – Block diagram*

A couple of steerable directive antennas, plus an omnidirectional antenna, were placed on the top of the roof of the Faculty of Sciences of the University of Granada. Those antennas make use of VHF and UHF ISM bands. A couple of LNA –one per frequency band– is placed on the *Antenna Mast*, as close as possible to the antennas. The rotor is a compact instrument controlled from the *Control Room*, that is made up of an *elevation* rotor and an *azimuth* rotor. All these elements shape the external facilities of the Ground Station, also known as *Antenna Mast* (see Figure 3.3a).

On the other hand, those elements intended to control and manage the Ground Station, together with the radio equipment, are known as *Control Room* (see Figure 3.3b). For this first operational version of the GranaSAT Ground Station, this part consists of the minimal equipment required to track a satellite and establish a theoretical communication with it: an USB SDR dongle, an analogue ham radio –for VHF and UHF bands– equipment, a rotor controller and a computer.



(a) *Antenna Mast* **(b)** *Control Room*

Figure 3.3 – *GranaSAT Ground Station v.1 parts*

For further details of the first operational GranaSAT Ground Station, such as detailed equipment list, software used, closed satellite communication links, or any other achievements, please check Aguilera's work in [24].

Improvements and final state

Although this first operative version was functional and communication tests were carried out satisfactorily, it presented a clear lack of operability in digital transmission.

Once aware of this limitation, the objective of the work was to adapt the current Ground Station in order to allow a flexible digital processing for both reception and transmission signals. To achieve it, old ham radio equipment had to be updated for a new one, which shall have, of course, some kind of digital interface.

3

Numerous suitable radio transceivers are available in the market, however, only a couple of models are popular among amateur satellite operators. Those radio handsets are the *Kenwood TS-2000* and the *ICOM-9100* (see Figure 3.4). Both models have two individual multi-band transceivers, a feature that allows a satellite communication mode, which enables some *operational modes* (see Table 2.5). In addition, they offer digital interfaces to establish a communication with a computer, mounting for example a built-in TNC or allowing an audio streaming to the computer. Moreover, they can be controlled from a computer using these interfaces.

(a) *ICOM-9100*

(b) *Kenwood TS-2000*

Figure 3.4 – *New GranaSAT Ground Station transceivers*

These ham radio transceivers, while presenting an excellent performance, have a moderate price. Both were acquired to test their features and then choose the most suitable for our activities, although only the *ICOM-9100* has been tested so far. The *Kenwood TS-2000* was kept as a back-up transceiver.

GranaSAT transceivers	**Older models**		**Newer models**	
Model	*Kenwood TM-241*	*Kenwood TM-441*	*ICOM 9100*	*Kenwood TS-2000*
Freq. coverage [MHz]	144.0 - 148.0	430.0 - 440.0	1.8 - 29.7 50.0 - 54.0 136.0 - 174.0 420.0 - 480.0	0.5 - 30.0 50.0 - 54.0 144.0 - 146.0 430.0 - 440.0
Modulation Modes	FM	FM	USB LSB CW RTTY FM AM DV	USB LSB CW AM FM FSK
Antenna Impedance [Ω]	50	50	50	50
Freq. estability [±ppm]	< 10	< 10	0.5	0.5

Table 3.1 – *GranaSAT transceiver comparison*

Table 3.1 outlines the general features of transceivers available at GranaSAT group. As these transceivers can be easily obtained, newer models have undoubtledly better features than the older ones.

Continuing with the work related to the equipment updating, the omnidirectional bi-band antenna was replaced by another omnidirectional tri-band antenna (see Figure 3.5). With this upgrade, the SHF band was added to the frequency band range available at the GranaSAT Ground Station.

Numerous radio services operate within the SHF band –such as WiMAX networks, *Bluetooth*, Amateur Television (ATV), professional spacecraft communication systems, etc.– and now GranaSAT will be able to experiment with them.

Figure 3.5 – *Tri-band antenna Diamond X-7000 placement*

Table 3.2 shows key specifications for both multibands antennas. As previously remarked, an extra band may be operated after the installation of this new tri-band antenna. Other specifications are similar to the previous antenna, but the key aspect for this antenna is the SHF band incorporation.

GranaSAT multiband antennas	**Diamond X-2000**		**Diamond X-7000**		
Bands	VHF	UHF	VHF	UHF	SHF
Gain [dB]	6.0	8.0	8.3	11.7	13.7
SWR	$< 1.5:1$		$< 1.5:1$		
Length [m]	2.5		5		

Table 3.2 – *GranaSAT multiband antenna comparison*

Moreover, a new arrangement of the radio equipment was made within the *Control Room* (see Figure 3.6). In order to provide a correct placement of the equipment, a rack structure was incorporated to our Ground Station facilities. The different handsets where positioned in such a way that can be used comfortably throughout the communication operations.

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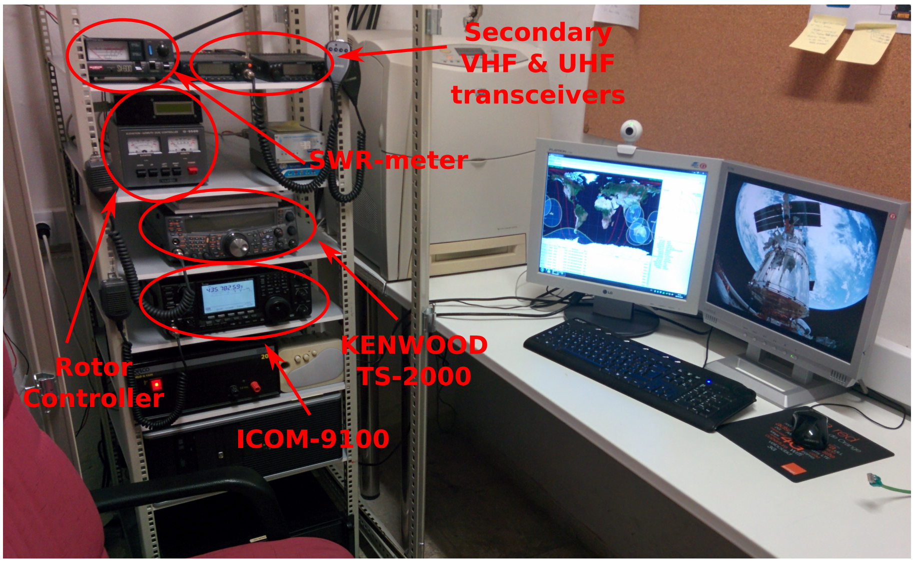

Figure 3.6 – *GranaSAT Ground Station v.2 – Control Room*

After these improvements and new features were added to the GranaSAT Ground Station, the system architecture was significantly modified, mostly at the *Control Room*. A block diagram of the second operative version of the GranaSAT Ground Station is shown in Figure 3.7.

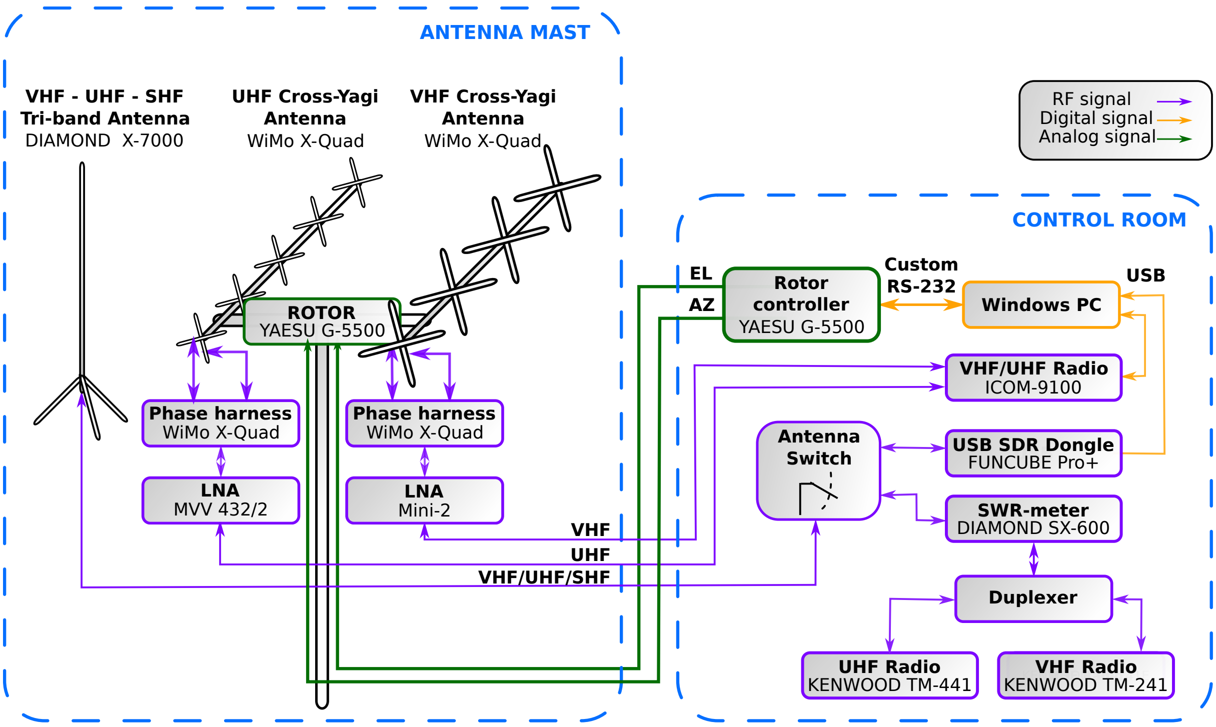

Figure 3.7 – *GranaSAT Ground Station v.2 – Block diagram*

Old *Kenwood* transceivers are now used as a secondary link, whereas the new *ICOM-9100* transceiver has become the main radio equipment and the *Keenwood TS-2000* its back-up. On the other hand, the USB SDR dongle is connected to the tri-band antenna in order to carry out diverse experimental work with those services operating in the frequency bands.

Digital communication between the *ICOM-9100* and the computer is done through a USB cable. The transceiver creates a virtual sound card that is able to stream an audio flow of the incoming Base Band signal –that is, after demodulation– for a computer digital signal processing. This feature requires a new work flow approach, which will be specified in subsection 3.2.3.

3.2.2 Link Budget

Once the elements from the Ground Station are known, it is possible to carry out the link budget of the mission: the couple GranaSAT Ground Station & GranaSAT-I Cubesat.

It is important to remark that the GranaSAT Ground Station was built to establish a communication link with a Cubesat that has not been designed so far. However, satellite parameters within the link budget may set up a series of approximative values that the communication link must achieve to address a successful communication link. Indeed, some of the parameters outlined here will define several requirements for the COMM System design. See *System Requirements and Constraints* (chapter 4) for further details regarding this topic.

In order to achieve a complete link budget calculation, an AMSAT and IARU tool was employed [47]. It is a spreadsheet that collects numerous expressions and is preconfigured to fill in a set of key fields and automatically return the result for the link budget calculation for both uplink and downlink. This spreadsheet has been applied by many Cubesat missions and it is supported by these two prestigious organizations, which makes it a trustworthy tool.

Key values for the link budget were summarised in Table 3.3. The column Step refers to the link budget summary figure – Figure 3.1. To check out a detailed GranaSAT Ground Station link budget, see Appendix B.1.

An acceptable level for the energy per bit noise density ratio (E_b/N_0) for an amateur GS is around 6 dB to 10 dB. Higher results are not desirable because that would mean an over-performed system. For our calculation, a level of +8.2 dB for uplink and +6.1 dB for downlink was obtained. The obtained link budget calculation was the result of the experimentation with values on the Cubesat side in order to get to know the minimum required for those elements within the system, such as EIRP, antenna gain, reception Noise Figure or modulation scheme, among others. See Table 3.3 for more details.

GranaSAT Link Budget				
	Step		**Uplink**[1]	**Downlink**[2]
1+2	**EIRP**	[dBW]	8.9	−1.9*
3+4	**Path losses and others** [3, 4]	[dB]	141.4	152.8
5+6+7	**Receiver (G/T)** [5]	[dB/K]	−33.5*	−12.5
8	$(\mathbf{C/N_o})$	[dBHz]	60.6	61.5
9a	**Bitrate** [6, 7]	[dBHz]	36.8*	39.8*
9b	$(\mathbf{E_b/N_o})$ **before demodulation**	[dB]	23.8	21.7
10	**Modulation threshold** [8, 9, 10]	[dB]	15.6*	15.6*
11	**OVERALL** $(\mathbf{E_b/N_o})$	[dB]	+8.2	+6.1

Table 3.3 – *GranaSAT Link Budget*

* To confirm after verification phase
[1] From GranaSAT Ground Station towards GranaSAT-I Cubesat – 145.8 MHz
[2] From GranaSAT-I Cubesat towards GranaSAT Ground Station – 437.5 MHz
[3] *AAUSAT3* LEO orbit properties
[4] Minimum elevation angle for the GS is $10°$ and pointing angle error is $< \pm 7°$
[5] Chain reception loss – BPF Filter, and other elements included
[6] Uplink bitrate of 4800 bps
[7] Downlink bitrate of 9600 bps
[8] Modulation scheme GMSK, $P_B = 10^{-5}$
[9] No coding techniques applied
[10] Demodulation implementation loss of 6 dB

As some of the parameters are suggested minimal values for the GranaSAT-I Cubesat, this link budget calculation shall be updated once the actual values for the COMM System of the pico-satellite are measured and verified in laboratory.

3.2.3 Signal and data work flow

Satellite communication link involves a wide variety of techniques and specific tools that shall be dominated by the Ground Station operator. In relation to the satellite communication field, many specialised software is available in the market. Some of them are professional, whereas others were developed by the amateur community and shared to anybody interested.

As part of the amateur and educational community, GranaSAT supports the *open source* initiative. Also, the team uses the software and encourages the community to do the same. Contrary to what one may think, these tools are quite complete, allowing various possible options and configuration. In addition they usually show a nice professional look.

Tools employed may communicate between them through an UDP port, permitting to combine single functionality in order to create a complex operation for the GS facilities. Figure 3.8 depicts the interconnection between tools and the equipment and it shows the pass of signal and data among applications.

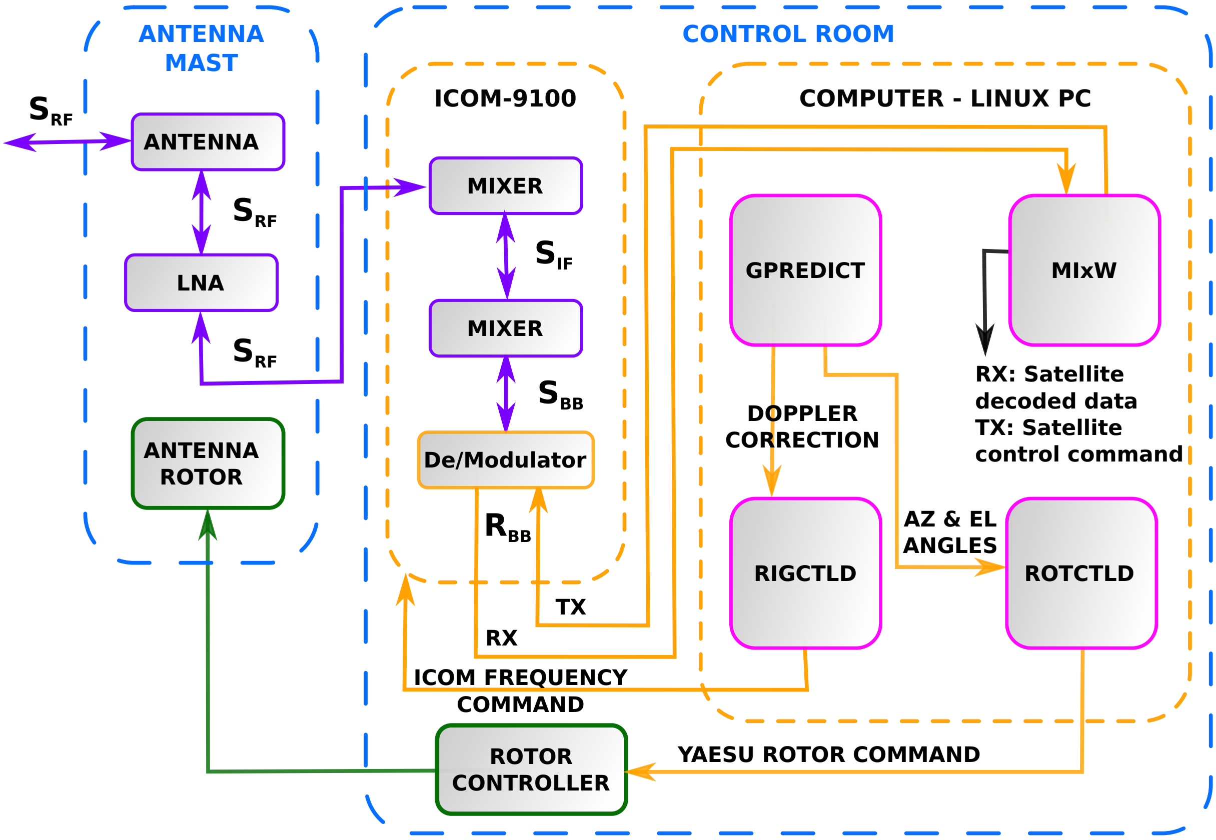

Figure 3.8 – *GranaSAT Ground Station – Signal and data work flow*

Software installed at the GranaSAT Ground Station and its main function is:

- **Gpredict** — By Alexandru Csete, OZ9AEC [48]:

  It allows the calculation of the expected position of a satellite at any time from its TLE file –see 2.3.1. By knowing the orbit calculation and the Ground Station placement coordinates, it is possible to obtain the theoretical *azimuth* and *elevation* angles. These angles are necessary for the antenna tracking of the satellite when it is passing over the Ground Station.

  The software allows to manage a big database of available satellites, to update its TLE files, to schedule passes over the GS, to calculate important information of a satellite pass, etc.

  In addition, *Gpredict* can calculate the *Doppler shift* that the communication link carrier signal is experiencing due to the relative speed among the spacecraft and the Ground Station. By estimating a value of the frequency shifting, the transceiver at the GS will be able to adjust its frequency settings to successfully close a communication link with the satellite and to minimise the frequency shifting effects.

For the GranaSAT Ground Station, *Grepedict* is configured to communicate to:

  - *rotctld*: Gpredict sends the *azimuth* and *elevation* angles required for the antenna tracking of the satellite
  - *rigctld*: Gpredict sends an estimated value of the carrier frequency after applying Doppler shifting corrections

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- **MixW** — By Nick Fedoseev, UT2UZ; and Denis Nechitailov, UU9JDR [49]:

  It is a software that works as a digital TNC. It receives –usually from a sound card– a Base Band analog signal and it is able to decode the signal stream to any desired representation codification format, such as ASCII. *MixW* is able to process many modulation schemas, such as GMSK, MFSK, QPSK, QAM, OOK, etc., in an automated way.

  The hard part of using *MixW* to decode the telemetry of an amateur-satellite service is getting to know how the mission data is coded within the data frames, information not always public or easy to find.

  This piece of software has been configured in the GranaSAT GS in such a way that it receives the satellite BB signal through the *ICOM-9100* radio handset.

- **Hamlib** — By Frank Singleton and Stephane Fillod [50]:

  Hamlib is a set of tools –developed by amateur ham radio operators– that offers an universal tool capable of communicating with the majority of the ham radio equipment regardless of its brand or model. There are tools for controlling both rotors and transceivers. The following tools are used in the GranaSAT Ground Station facilities:

  - **rotctld**: It allows the communication between the computer and the antenna rotor controller. *Rotctld* is a daemon that opens an UDP port that is continuously listening to any update in the *azimuth* and *elevation* angles. Then, it translates these angles into an adequate frame format that the rotor controller needs to perform the antenna tracking.
  - **rigctld**: It has the same behaviour than *rotctld*. In our case, the tool takes care of receiving any new frequency value, to send it immediately to the radio equipment with the correct format. By using *rigctld* it is possible to fit the carrier frequency to the actual shifted frequency value. This task is performed in real time throughout the satellite pass, which allows the establishment of a communication link avoiding a mismatching frequency caused by the Doppler shift.

3.2.4 Ground Station trial

After the radio equipment upgrade was performed within the GranaSAT Ground Station, an overall system evaluation was followed. Some tries of data satellite reception were carried out to verify that the GS could close a satellite downlink path successfully. The procedure was not a formal testing, but rather a verification procedure that lets us know if the system works properly and evaluate the quality of the signal at reception, if there was any anomaly in the behaviour of the system, etc.

Here are two examples out of a dozen of successful downlink satellite communications performed at the GranaSAT GS. Although samples were successfully gathered of either payload or telemetry data, this was dummy data, as the coding format was unknown, and therefore data could not be properly decoded. Two videos below show the Ground Station front end and how carrier frequency at the transceiver is corrected –*Doppler shifting* correction– during the satellite pass in real time.

3

CASE 1: SPROUT

A Japanese 1U Cubesat –see 2.2– from the Tokyo Institute of Technology, in Japan. The communication trial was performed throughout a pass on the 16th of March 2015 at 15:23 UTC, over the Iberian Peninsula, Europe.

The downlink configuration is a 1200 baudrate link, AFSK modulated, and carrier frequency centred at 437.525 MHz. As it can be seen in Figure 3.9, the fact that the frames were continuously downloading indicates that the Cubesat was demanded at some point of the pass by another Ground Station to download the data stored.

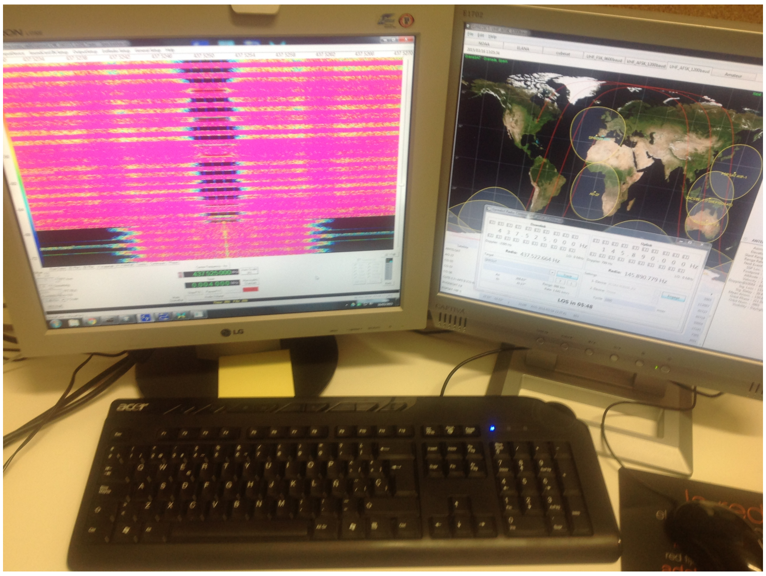

Figure 3.9 – *GranaSAT Ground Station – Listening to SPROUT Cubesat*

It is also interesting to notice how the communication downlink is made of a train of audible bursts, which is a peculiar characteristic of the Audio Frequency-Shift Keying (AFSK) modulation scheme.

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CASE 2: International Space Station – ISS

From an amateur perspective, the ISS is an interesting spacecraft worth trying to communicate with. Apart from the professional radio equipment –intended for the establishment of a reliable communication between the Earth and the on board astronauts within the ISS– it contains some amateur radio equipment open to any licensed ham radio operator around the globe interested in using them.

Ham radio activities are taken seriously by the astronaut crew and their use in space dates back to the early years of the Russian Space Station, MIR. Within the ISS, the Amateur Radio on the International Space Station (ARISS) organization is the responsible for managing the radio equipment and the services available. These services are: an Automatic Packet Reporting System (APRS) digipeater, a Slow Scan Television (SSTV) broadcast service, a cross-band FM voice repeater, and a VHF/UHF FM voice service. The callsign used for any amateur service within the ISS shall be *NA1SS*.

The downlink trial was carried out throughout a pass of the ISS over the GranaSAT Ground Station on the 16th of March 2015 at 14:03 UTC. The received radiowaves were packets of the APRS service, which is a digital messaging protocol designed to broadcast short packets with useful information –weather, traffic, telemetry, position, etc.– in a local area. APRS packets are sent upon demand and/or periodically –typically in periods of several minutes.

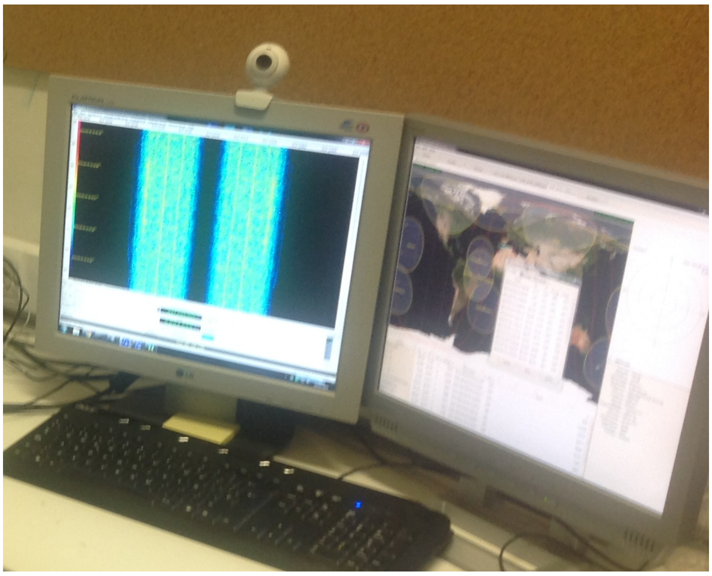


Figure 3.10 – *GranaSAT Ground Station – Listening to ISS' APRS packets*

In Figure 3.10, it can be seen the reception of a few APRS packets from the ISS. The downlink configuration is a 1200 baud link, AFSK modulated, and a frequency carrier centred at 145.825 MHz.

3.3 ESA - ESAC Ground Station

The European Space Astronomy Centre (ESAC) is one out of the seven ESA major establishments. Placed at Villanueva de la Cañada, a village close to Madrid, it is the centre where science operations for all ESA astronomy and planetary missions are conducted. It also hosts archives that they produce and make them accessible to the public.

A student traineeship programme takes place yearly at ESAC, where around 30 science and engineering students from any ESA Member State are selected to join an ESA scientific project for approximately six months. Figure 3.11 shows all ESAC trainees in July 2016.

3

The author of this master's thesis was chosen to work in a Cubesat project leaded by Julio Gallegos, Fernando Martín –both from LISA Pathfinder Science Operations team– and Xavier Dupac –Plank mission Science team. The first objective of the project is to develop a technological demonstrator of a Cubesat platform capable of carrying a set of instrumentation useful for any of the teams within ESAC, that is, for any astronomical or planetary mission. In 2016, for this traineeship project, the duty was to build an amateur VHF and UHF Ground Station for Cubesat missions. In a future upgrade –successive traineeships– this Ground Station must be able to include the X-band within its operative band range.

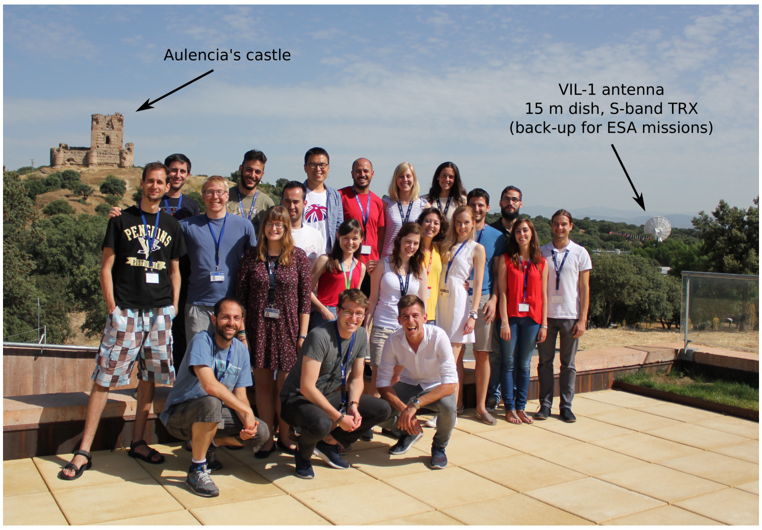


Figure 3.11 – *ESAC trainees in July 2016*

Since the traineeship programme has an educational purpose, the project is expected to be used as a master's thesis or as a part of it. For this reason, the publication of any result, data or design originated during the programme is allowed, as long as this practice doe not go against any specific policy. Due to some similarities between the ESAC traineeship and this master's thesis, numerous key features from the ESAC amateur Ground Station might be useful for this master's thesis research. For this reason, it was decided to include in this document a summary of the ESAC amateur Ground Station project details.

3.3.1 Ground Station Requirements and Constraints

The fact that this project was incipient gave a certain freedom for the design and a low number of requirements or constraints were stated:

- Functionality Requirements
  - F.1 The Ground Station shall operate within the VHF band and the UHF band
  - F.2 The system shall track satellite orbits
  - F.3 The system shall communicate with LEO Cubesat
  - F.4 The signal processing shall be performed by using SDR technology
- Constraints
  - C.1 The system design shall fulfil ESAC security rules
  - C.2 The *Antenna Mast* shall be placed on the **Building A** roof
  - C.3 The *Antenna Mast* structure shall be a portable structure
  - C.4 The *Antenna Mast* shall shall have height between 2 m and 4 m
  - C.5 The *Control Room* shall be placed at **CESAR room**, in Building A
  - C.6 The system shall offer an educational approach and use
  - C.7 The system shall avoid the use of privative SW

3

3.3.2 Mechanical Design

The design of the structure of the *Antenna Mast* shall fulfil the requirements **F.1** and **F.2**, and the constraints **C.1**, **C.2**, **C.3** and **C.4**. This set of requirements and constraints states that the structure shall allow the placement of an antenna rotor and several antennas and shall be portable.

The specific area for the placement of the *Antenna Mast* was not known at the beginning of the design of the structure, and the way it was going to be fixed to the ground was a detail impossible to confirm until the design was advanced. Therefore, throughout the structure design, two fixation procedures were contemplated: one by using bolts and nuts, and another one by placing concrete weights on the *Antenna Mast* base.

In addition, because the Ground Station operator would be alone during the assembly phase, it was highly desirable to design a structure that could be installed by only one person. Although it was not a requirement in itself, it was a feature nice to have.

Bearing in mind this set of ideas for the *Antenna Mast* structure, a 3D model was created by using *Google Sketch-up* (see Figure 3.12). The structure is made up of a squared base of 140 cm length and a stabilizer structure of 150 cm height, which is fixed by four turnbuckles to the base.

The total height of the structure may vary from a minimum of 1.5 m up to any desired height, as long as guy wires are used. The 3D model in Figure 3.12 does not show them, but the use of guy wires must be considered if the mast height is equal or higher than 2.5 m.

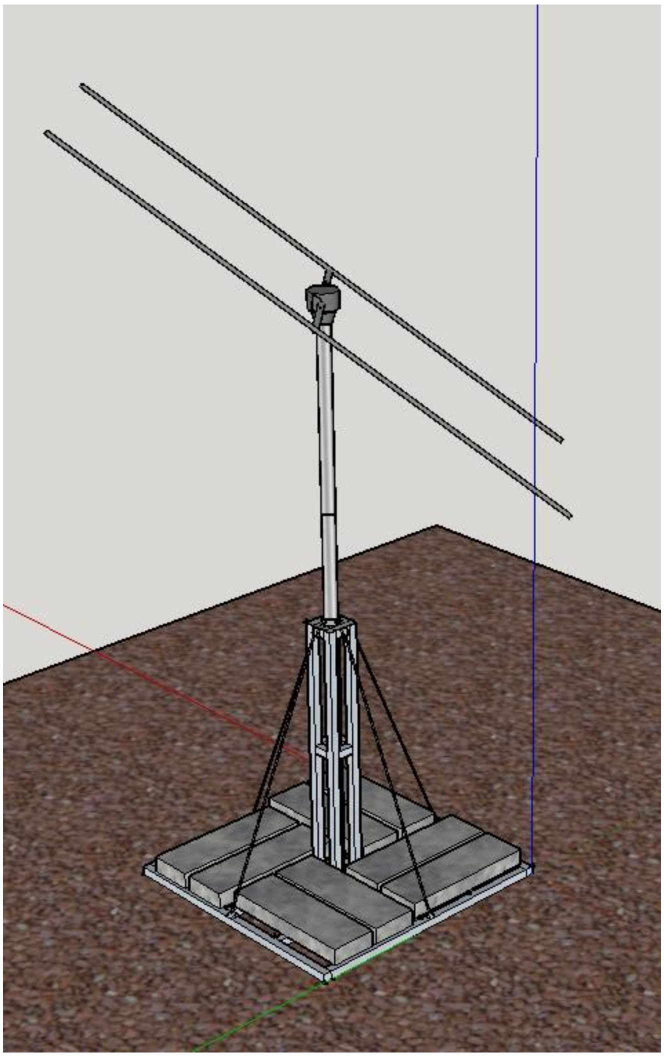


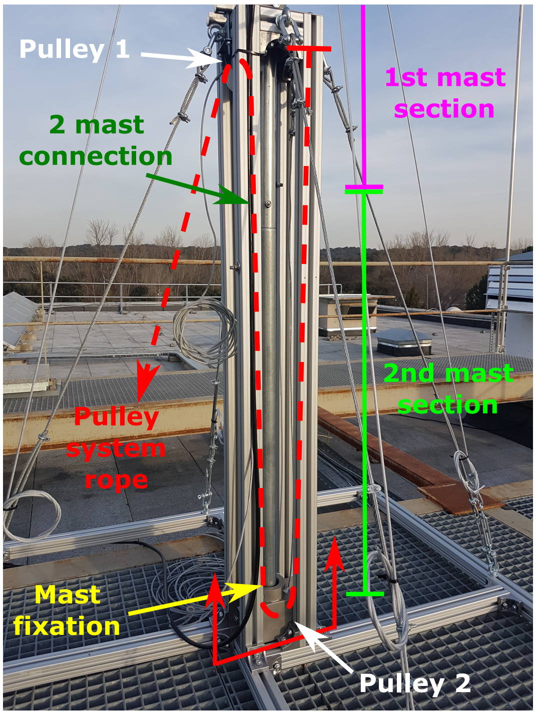
Figure 3.12 – *ESAC amateur Ground Station structure – 3D model*

The material chosen to build the structure is known as *Bosch profiles* (see 3.14c). These profiles are made of aluminium, a material that allows a light but strong structure. In addition, thanks to the profile shape, no special tools or fixation techniques are required for the *Antenna Mast* assembly, wich makes it possible to complete the whole structure very quickly. The only material required are gussets, that may be acquired together with the *Bosch* profile (see 3.14d).

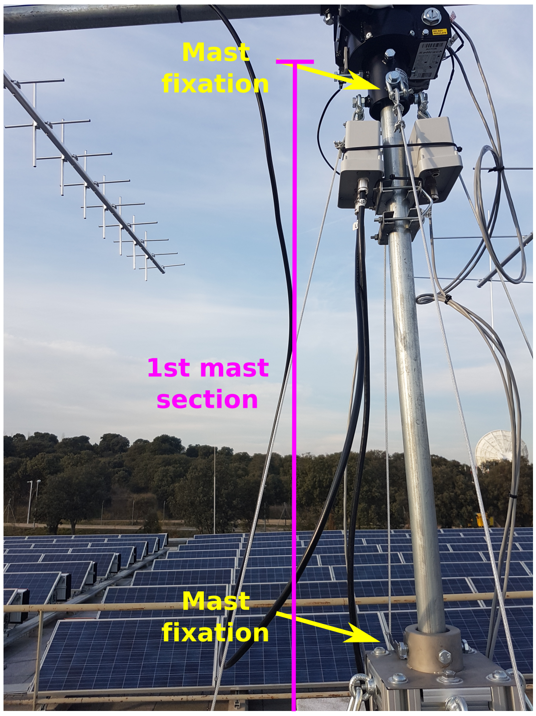
Pulley system

The design includes a **pulley system** that allows an individual and **autonomous deployment** of the *Antenna Mast*. Instead of using a single long mast, which requires more than one person for its deployment, several short mast sections are connected successively among them to create a long mast. The mechanism is simple: when the first mast section –with the rotor and the antennas– is placed, everything is lifted up around 1.2 m with the help of the pulley system. Then, the second mast section is placed at the bottom right after the first section and, afterwards, both are joined each other. More sections can be added if a longer mast is required. Finally, the resulting long mast has to be attached to the main structure.

The pulley mechanism is made up of two pulleys: one is fixed on the top, and the second one is placed in a movable piece at the bottom part (see Figure 3.13c and 3.13d). These pulleys are connected by a steel rope that passes through them –see Figure 3.13a– and, when this rope is pulled up, the movable pulley will rise, lifting up therefore the mast and rest of elements attached to it. The system demonstrated an adequate behaviour during the GS assembling, allowing the author to completely deploy the antennas and the rotor in a quick and safe way only on its own.

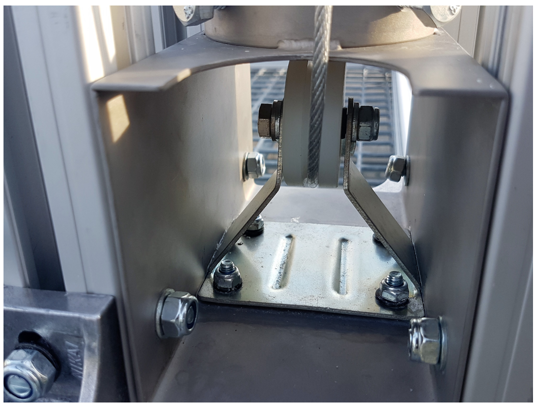


(a) *Pulley system and mast sections marked*



(b) *Detail of the first mast section and fixation points marked*

(c) *Pulley 1 – Fixed*



(d) *Pulley 2 – Movable*

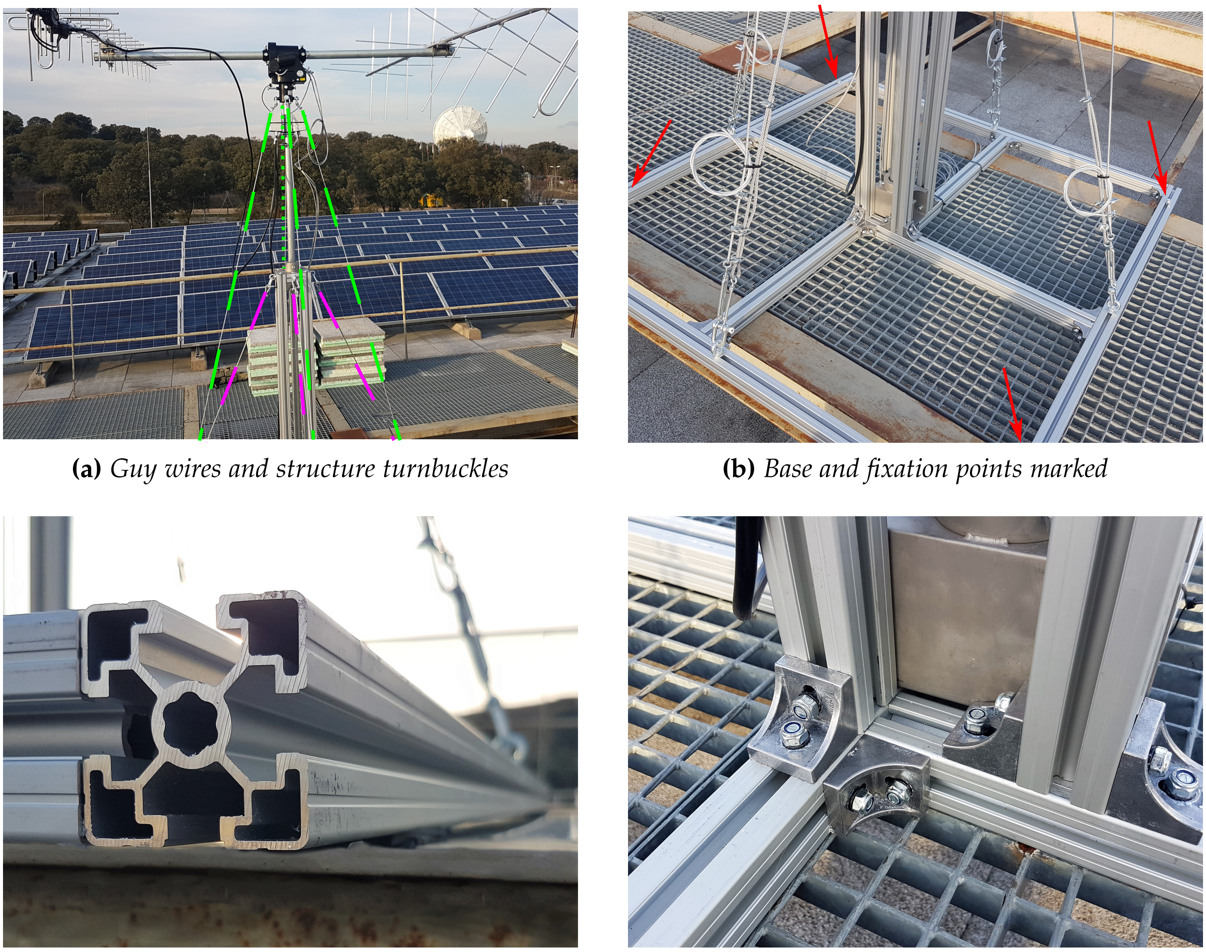
Figure 3.13 – *ESAC amateur Ground Station – Antenna Mast details*

In Figure 3.13a, with a red line, the pulley system rope route is shown, in white the pulley placement, in green and pink the different mast sections, in dark green the inter-section mast fixation, and in yellow the points where the mast is fixed to the main structure. Figure 3.13b shows a detail of the first mast section.

Placement and final arrangement

The antenna structure was eventually placed on the top of the roof at building A of the ESAC centre. It was fixed to a metallic structure by four bolts, as shown in Figure 3.14b.

The final height of the *Antenna Mast* was 2.5 m, made up of two mast sections, one of 1 m lenght and another of 1.5 m length. As the mast height was 2.5 m, guy wires were placed and fixed at the top of the mast. In Figure 3.14a the guy wires are marked in green and the structure turnbuckles in pink.



(a) *Guy wires and structure turnbuckles*

(b) *Base and fixation points marked*

(c) *Bosch profile detail*

(d) *Bosch profile junction detail*

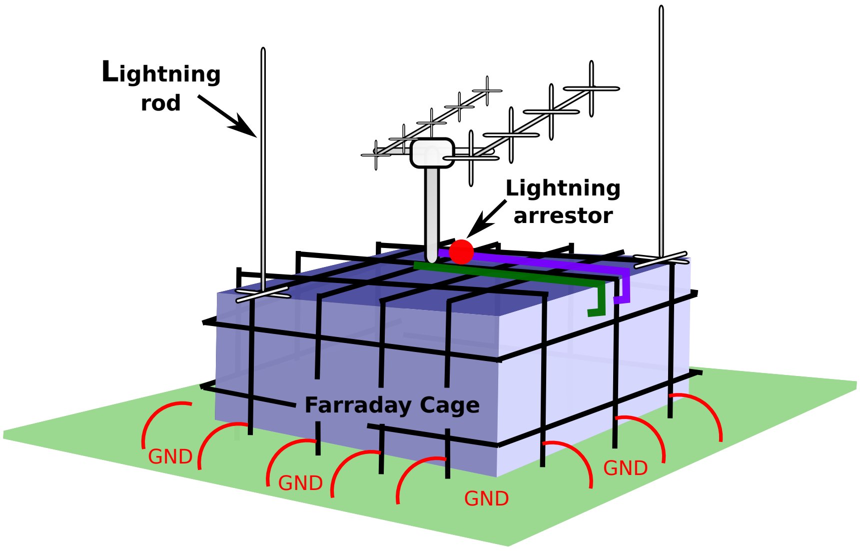
Figure 3.14 – *ESAC amateur Ground Station – Antenna Mast details*

Figure 3.14c shows the shape of the *Bosch* profile used for the assembly. Thanks to the rails inside the metallic profile it is possible to place and screw on it a *T-bolt*, which is useful for attaching any compatible element. Two *Bosch* profiles can be joined by using a right angle, as it is shown in Figure 3.14d.

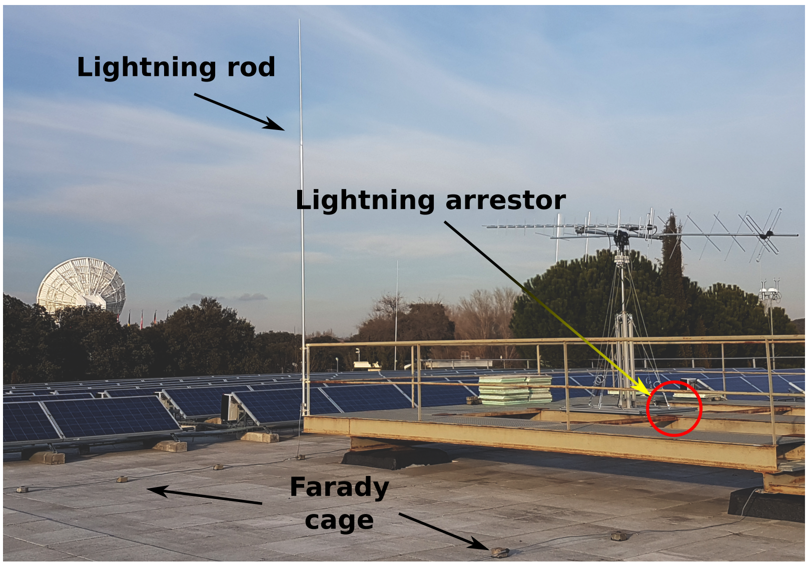
3

Lightning protection

The structure was connected to an Earth point –low resistance path to ground– in order to protect the Ground Station equipment and prevent its damage in case of a lightning strike over the antennas or in a surrounding area. This protection was easy to obtain since all buildings at the ESAC centre are protected against this natural phenomena: numerous lighting rods are placed on the roof and the building structure is surrounded with a metallic wire mesh that works as a *Faraday Cage*. Figure 3.15 depicts how the Ground Station lightning protection is achieved.



(a) *Faraday cage diagram of an ESAC building*



(b) *ESAC amateur Ground Station – Lightning protection*

Figure 3.15 – *ESAC amateur Ground Station – Lightning protection*

In addition, a pair of coaxial lightning arrestors were connected to the Earth point to achieve a higher protection for the overall system. Placing a lighting arrestor in the coaxial cables will avoid a potential damage of the radio equipment at the *Control Room* if a high voltage is applied on the coaxial cable in case of a lightning strike. When this happens, the lightning arrestor provides a low resistance path to ground, at the same time that it creates a high impedance path over the coaxial cable if an extremely high voltage tries to go through it.

3.3.3 Architechture

The first operational version for the ESAC amateur Ground Station may be split up in two main set of elements: the *Antenna Mast* and the *Control Room*. A block diagram for the ESAC amateur Ground Station is depicted in Figure 3.16.

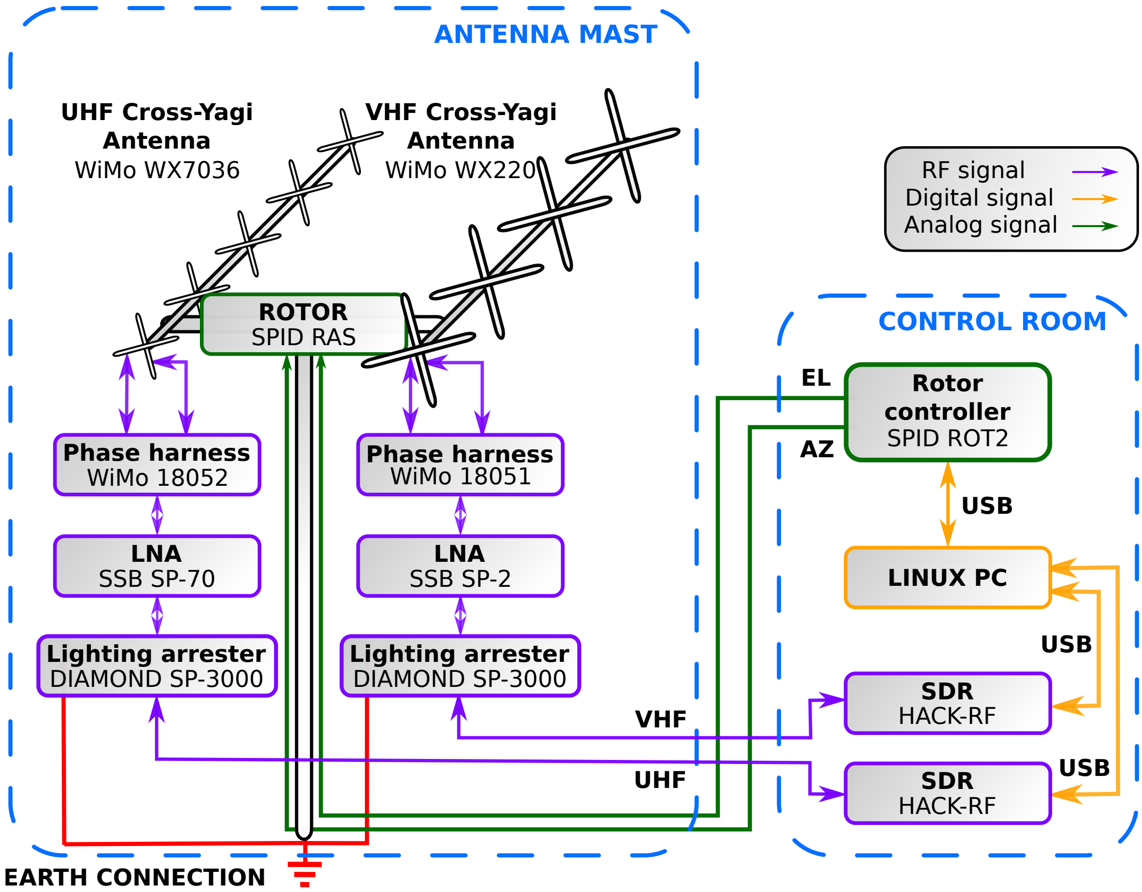


Figure 3.16 – *ESAC Ground Station – Block diagram*

The *Antenna Mast*, which has been thoroughly described from a mechanical perspective in subsection 3.3.2, contains all elements placed in the outside. It contains the elements stated in the list below (detailed technical information is provided in 3.3.5). An overview of the *Antenna Mast* is shown in Figure 3.17.

- A high directivity, RHCP polarised, *Cross-Yagi* UHF antenna; and a 20 dB LNA
- A high directivity, RHCP polarised, *Cross-Yagi* VHF antenna; and a 20 dB LNA
- A pair of lightning arrestors (one per band)
- An *elevation* and an *azimuth* rotor combined into an unitary block

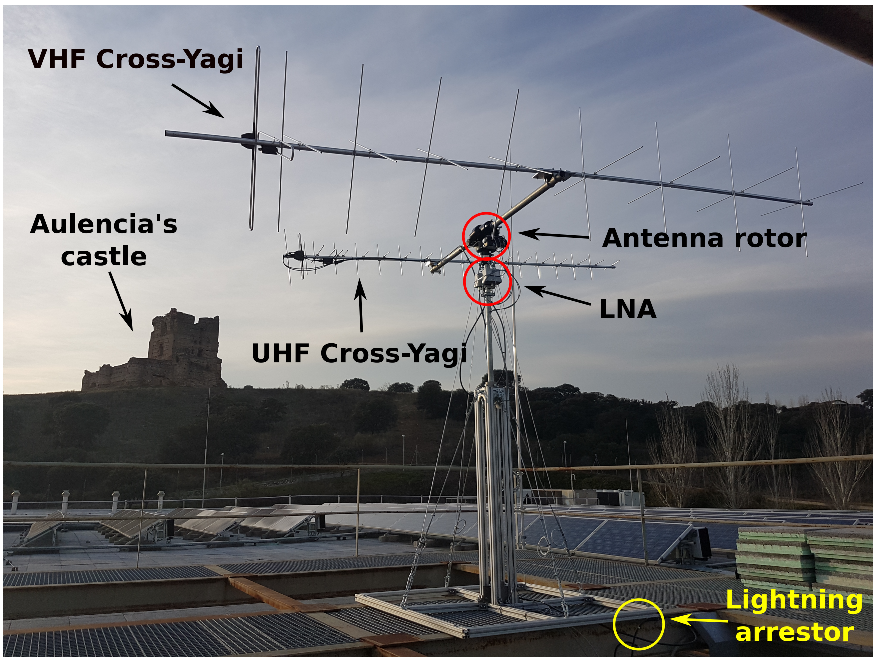


Figure 3.17 – *ESAC Ground Station – Antenna Mast*

The second part that forms the Ground Station is the *Control Room*, which is located inside the CESAR room –see Figure 3.18. It includes all the digital and radio equipment required to establish a communication link with the spacecraft, as well as a *GNU/Linux* computer to centralise its control –see 3.3.6 for further information.

Imposed by the requirement **C.4**, the Software Defined Radio (SDR) technology was the selected to process the radio signal. By using SDR transceivers, the Ground Station capabilities are enhanced in comparison with those Ground Stations using a specialized radio equipment or a regular ham radio handset. A huge number of parameters can be set and modified, such as the operating frequency up to 6 GHz, the modulation and demodulation schema, the signal bandwidth, the signal coding, etc.

One SDR half-duplex transceiver is used per each antenna, which means that both **U/V** and **V/U** operational modes –see 2.4.3– are supported by the ESAC amateur Ground Station and, therefore, it is possible to close a communication link with almost all amateur satellites.

The last element that completes the *Control Room* is the rotor controller. As it has been previously explained, it allows the orbit prediction software to control the pointing angles of the antennas, as stated by requirement **F.2**.

Finally, all the equipment within the *Control Room* is controlled and managed with several radio software utilities. Further details for each hardware element of the ESAC amateur Ground Station are summarised in subsection 3.3.5. A brief description for the software elements employed can be found in subsection 3.3.6.

Figure 3.18 – *ESAC amateur Ground Station – Control Room*

As demanded by constraint **C.5**, the *Control Room* is located at CESAR room. This name comes from the acronym of the education programme at ESAC called Cooperation through Education in Science and Astronomy Research [51]. CESAR project facilities include several solar and star telescopes from ESAC and INTA, a former ESAC 15 m dish S-band antenna –see Figure 3.11–, and the amateur Ground Station. These facilities are operated remotely from the CESAR room, which is in fact the *Control Room* for all of them.

With this initiative, the ESAC centre aims to divulge the results of the research conducted at the centre, as well as to get closer to educational centres all over Spain. Numerous visits of students coming from schools, high schools and universities are scheduled weekly. During these visits, some ESAC facilities and ESA spacecraft scaled models are shown. Also visitors can use and control remotely the CESAR facilities, while professional researchers from ESAC explain the basic theoretical fundamentals and how instruments work.

3.3.4 Link Budget

As it was thoroughly detailed in Section 3.1, a link budget analysis is required when any space mission or Communication System is being designed, as it allows designers to check and set all parameters defining the communication link between the spacecraft and the Earth.

All calculations leading to the results in this subsection have been carried out in a manner similar to the GranaSAT Ground Station link budget –see 3.2.2. To better understan the details of the link budget procedure, refer to Section 3.1.

The main values are summarised in Table 3.4, where the numeration of the column Step refers to the link budget summary figure –Figure 3.1. A full Link Budget for the ESAC amateur Ground Station can be found in Appendix B.2.

As it happens with the GranaSAT GS, to complete the link budget, estimated value for the parameters of the Cubesat has been used, such as the downlink EIRP or the receiver *Figure of Merit*, $\left(\frac{G}{T}\right)$. In order to validate the link budget, these values shall be confirmed or modified according to the results obtained after the verification phase.

ESAC Link Budget

Step			Uplink[1]	Downlink[2]
1+2	**EIRP**	[dBW]	10.8	-1.9^*
3+4	**Path losses and others** [3, 4]	[dB]	143.3	152.3
5+6+7	**Receiver** $(\mathbf{G/T})$ [5]	[dB/K]	-33.5^*	-12.7
8	$(\mathbf{C/N_0})$	[dBHz]	62.3	61.2
9a	**Bitrate** [6, 7]	[dBHz]	36.8^*	39.8^*
9b	$(\mathbf{E_b/N_0})$ **before demodulation**	[dB]	25.5	21.4
10	**Modulation threshold** [8, 9, 10]	[dB]	15.6^*	15.6^*
11	**OVERALL** $(\mathbf{E_b/N_0})$	[dB]	$+9.9$	$+5.8$

Table 3.4 – *ESAC Link Budget*

* To confirm after verification phase
[1] From ESAC amateur Ground Station towards GranaSAT-I Cubesat – 145.8 MHz
[2] From GranaSAT-I Cubesat towards ESAC amateur Ground Station – 437.5 MHz
[3] *AAUSAT3* LEO orbit properties
[4] Minimum elevation angle for the GS is 10° and pointing angle error is $< \pm 7°$
[5] Chain reception loss – BPF Filter, and other elements included
[6] Uplink bitrate of 4800 bps
[7] Downlink bitrate of 9600 bps
[8] Modulation scheme GMSK, $P_B = 10^{-5}$
[9] No coding techniques applied
[10] Demodulation implementation loss of 6 dB

The link budget states that both uplink and downlink paths can be achieved successfully: the uplink will close with +9.9 dB of margin, and the downlink with +5.8 dB.

According to the resulting link budget parameters, the uplink RF chain may reduce the power output up to 0.5 *W* without experiencing a performance impairment, achieving this way a result of +6.9 dB of margin. On the other hand, the downlink link budget results does not leave much room for improvement.

3.3.5 Equipment

This section details the most relevant parameters of the hardware elements that conform the ESAC amateur Ground Station.

Antennas

The antennas chosen for the GS were models ***WX220*** and ***WX7036***, by ***WiMo***. There is one antenna per band – VHF and UHF. Both antennas are *Cross-Yagi* high directive and they also support circular polarization, which is recommended for space communication.

The polarization configuration is set thanks to a phase harness, which splits the signal in two paths and sets a difference of phase of 90° between them. When the antenna is fed through this phase harness it is possible to get either a RHCP or a LHCP configuration. For the ESAC amateur GS, a fixed RHCP polarisation was set.

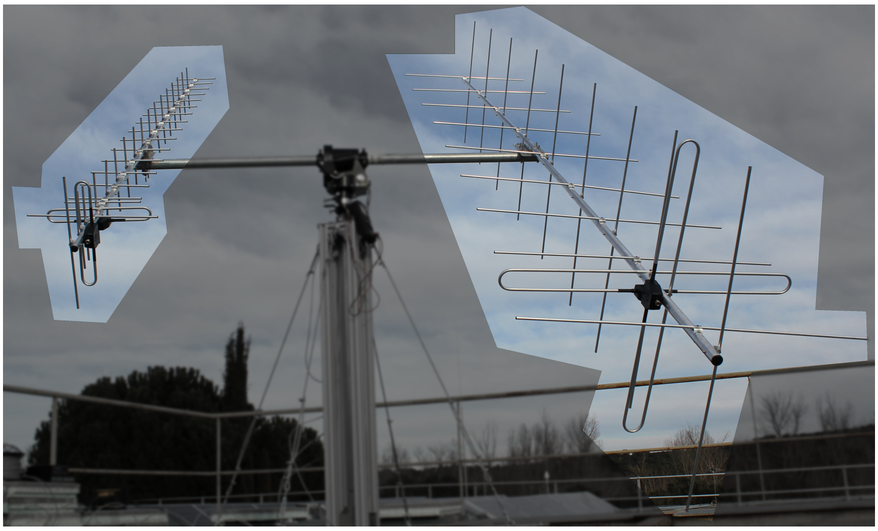


Figure 3.19 – *ESAC amateur Ground Station – Cross-Yagi antennas*

WiMo *Crossed-Yagi*		WX7036	WX220
Frequency band	-	70 cm – UHF	2 m – VHF
Elements	-	2 x 18	2 x 10
Gain	[dBi]	16.15	14.45
Front-back ratio	[dB]	> 20	> 25
SWR	-	< 1.6	< 1.6
HPBW	[degrees]	36	35
Max. power handled	[W]	200	2000
Length	[m]	3.4	4.6
Weight	[kg]	3.1	4.2

Table 3.5 – *ESAC amateur Ground Station – Antenna specifications*

Antenna Rotor

Antennas should be steerable and able to track satellite orbits. For this reason both *azimuth* and *elevation* rotors shall be employed. The selected rotor is a ***SPID RAS***, which includes in a single block *elevation* and *azimuth* rotors. This model also incorporates a rotor controller that allows to control the rotor from a computer.

The entire system works with a DC power supply and each rotor is activated when the DC voltage is applied on their electrical terminals – the direction of rotation is given by the DC polarization. Moreover, a rotary encoder is installed inside the rotors and sends an impulse signal for each turned angle.

Regarding the rotor controller, it allows to control the rotor manually and automatically from a computer. It is able to set the DC polarisation (to set the direction of rotation), to read the impulse signals coming from the rotor to control the tracking angles, and to show in a couple of displays the current position for both rotors.

(a) *SPID RAS Antenna Rotor* **(b)** *SPID RAS Rotor controller*

Figure 3.20 – *ESAC amateur Ground Station – Antenna rotor*

SPID RAS		
Turning torque	[Nm]	158 - 366
Brake torque	[Nm]	1582
Max. load	[kg]	250
Rotation speed	[rpm]	1
Rotation precision	[degrees]	1
azimuth max. angle	[degrees]	360
elevation max. angle	[degrees]	180
Operating voltage	[V]	12 - 24
Weight	[kg]	13

Table 3.6 – *ESAC amateur Ground Station – Antenna rotor specifications*

Pre-amplifier

The overall reception performance is highly dependent on the strength of the incoming signal and the noise system. As pointed before on the Eq. 2.3.15, the receptor noise is delimited by the very first elements in the signal chain. Placing a low noise and a high gain device at the receiver front end increases the reception performance.

A Low Noise Amplifier from ***SSB*** was chosen because of its low Noise Figure value and a reasonably high gain value. While for the *2 meter* band a model ***SSB SP-200*** model is used, for the *70 centimeter* band a ***SSB SP-70*** is employed.

(a) *VHF pre-amplifier SP-200* **(b)** *UHF pre-amplifier SP-70*

Figure 3.21 – *ESAC amateur Ground Station – LNA pre-amplifier*

SSB Amplifier		**SP-200**	**SP-70**
Frequency range	[MHz]	144 - 146	430 - 440
Noise Figure	[dB]	0.5	0.7
Gain	[dB]	10 - 20	12 - 22
Max. power handle	[W]	100	100
Insertion Loss	[dB]	0.04	0.15
Operating voltage	[V]	12 - 14	12 - 14
Current Consumption	[mA]	250	320
DC-Feed connector	-	PL	PL
RF connector	-	N	N

Table 3.7 – *ESAC amateur GS – LNA pre-amplifier specifications*

SDR

A Software Defined Radio (SDR) device is an embedded system that performs in software some tasks that have traditionally been carried out in hardware. Commonly, a SDR transceiver is made up of a wideband RF front end that translates the RF signal into a Base Band (BB) signal, a high-speed ADC that samples the BB signal, and finally, a FPGA that processes the digital BB signal, performing tasks such as filtering, demodulation, data coding, protocol implementation, etc.

This architecture provides a high flexibility in the design of any communication system. This is possible because a single device may be used for a broad range of communication scenarios: a wide number of frequency bands can be selected, may handle numerous modulation schemes, may manage virtually any protocol of communication, etc.

For the ESAC amateur GS, a couple of ***HackRF One*** devices, from ***Great Scott Gadgets***, were acquired. This device is popular among the radio amateur community because it was launched after a really successful crowdfounding campaign. In addition, it is an *Open Hardware* and *Open Software* project, which means that the source code and the electronics design are available for anyone interested. It is also compatible with other *Open Source* projects, such as *GNU Radio*.

Figure 3.22 – *ESAC amateur Ground Station – SDR Transceiver*

HACKRF One		
Frequency range	[MHz]	1 – 6000
Max. bandwidth	[MHz]	20
Max. output power	[dBm]	22
Sampling rate	[Msps]	8 – 20
Quadrature Samples (I/Q) length	[bit]	8
Communication configuration	–	Half duplex
Data interface	–	USB 2.0

Table 3.8 – *ESAC amateur Ground Station – SDR Transceiver specifications*

Lightning arrestor

As explained in section 3.3.2, a lightning arrestor is placed in the coaxial lines. This element avoids damage in the radio equipment within the *Control Room* in the event of a lightning strike in the surroundings of the antenna. The model selected for the Ground Station was a ***SP-3000***, from ***Diamond***.

Figure 3.23 – *ESAC amateur Ground Station – Lighting arrestor*

DIAMOND SP-3000		
Max. frequency	[MHz]	2500
Max. power handle	[W]	400
Insertion Loss	[dB]	0.1
Breakthrough voltage	[V]	230

Table 3.9 – *ESAC amateur Ground Station – Lightning arrestor specifications*

Coaxial cable

Finally, the last component that makes up the Ground Station is the coaxial line. This element provides a suitable path for the RF signal to connect diverse elements whitin the RF chain. Like any lossy transmission line, the coaxial cable presents a negligible attenuation level, which will weak the RF signal going through it.

Since the distance to cover between the *Antenna Mast* and the *Control Room* was considered long enough –around 70 m– for the transmission line to decrease several orders of magnitude the incoming signal, it was decided to utilize a high class coaxial cable. The chosen one for the Ground Station was the model ***Broad Pro 50*** from ***Messi & Paolini***, which offers one of the lowest attenuation rates in the market, as well as an excellent behaviour in a wide variety of parameters.

Figure 3.24 – *ESAC amateur Ground Station – Coaxial cable specifications*

M&P Broad-Pro 50		
Attenuation	[dB/100m]	1.08 @ 7.0 MHz
		2.5 @ 50 MHz
		4.4 @ 140 MHz
		7.8 @ 430 MHz
		14.1 @ 1296 MHz
		19.8 @ 2400 MHz
		34.1 @ 6000 MHz
Impedance	[Ω]	50 @ 200MHz
Screening Efficiency	[dB]	> 105
Exterior diameter	[mm]	10.3
Dielectric diameter	[mm]	7.3
Inner conductor diameter	[mm]	2.76

Table 3.10 – *ESAC amateur Ground Station – Coaxial cable specifications*

3.3.6 Signal and data work flow

As previously explained in Subsection 3.2.3, in a Ground Station the incoming RF signal goes through several blocks that transform it to obtain the information codified on it. These blocks may be either hardware parts or software utilities. Figure 3.25 depicts the blocks the ESAC amateur Ground Station is made of, and how they communicate among themselves.

In compared with GranaSAT Ground Station, the radiowave signal is treated slightly different in the ESAC amateur Ground Station. While for the first one, the demodulated digital signal is provided directly by the ham radio handset, the ESAC amateur GS provides –through the SDR transceiver– a digital I/Q signal sampled from the still modulated Base Band signal. Immediately after, this I/Q signal is processed by the software *GNU Radio*, which demodulates and processes digitally the signal until it obtains the data encoded on it.

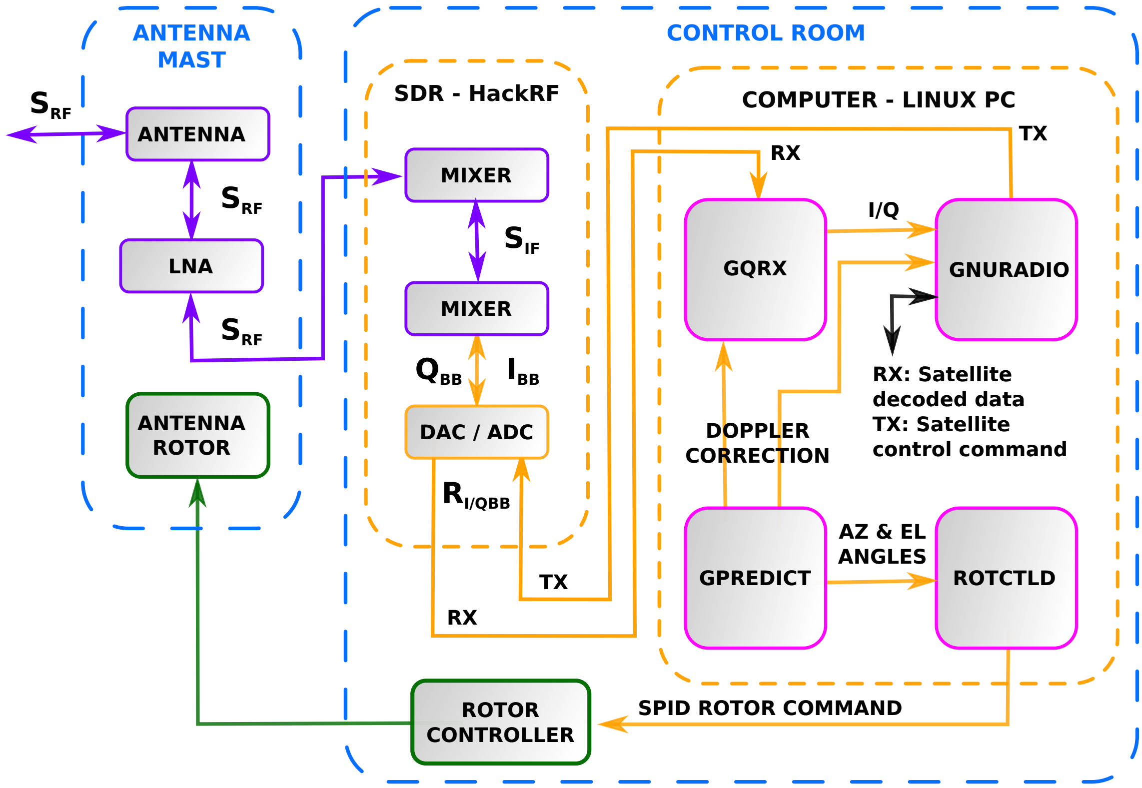


Figure 3.25 – *ESAC amateur Ground Station – Signal and data work flow*

The software installed at the ESAC amateur GS is:

- **gqrx** — By Alexandru Csete, OZ9AEC [52]:

  It is a SDR receiver that provides numerous functionalities useful for the radio operator, such as FFT plot and waterfall, digital filtering, I/Q balance, signal demodulation, etc.

  During the reception, *gqrx* receives a digital I/Q Base Band signal directly from the SDR transceiver and plots useful information of the communication link.

Afterwards –without performing any other operation to the signal– the software sends the very same I/Q Base Band signal to *GNU Radio* for its processing.

Like other applications described in Subsection 3.2.3, it also accepts to stablish a communication among other processes within the Ground Station by an UDP port. This allows *Gpredict* to send to *gqrx* the Doppler corrections to avoid its effects throughout the satellite pass. See Subsection 3.2.3 for further information about this mechanism.

- **GNU Radio** – Supported by a wide community [53]:

  This *Open Source*software is a development toolkit for signal processing for a communication system based on the SDR technology. The toolkit provides blocks of coding to carry out a wide variety of functionalities, such as demodulation, encoding, filtering, equalisation, etc. *GNU Radio* also allows to manage the data flow during the signal processing task, which makes possible to show, store or send the outcoming data at any time.

  For the ESAC amateur GS, the data flow varies acoridng to whether the communication path is *downlink* or *uplink*:

  - For a **reception** –RX– process, *GNU Radio* will receive a digital I/Q signal flow coming from *gqrx*, will process it and store the outcoming data in a text file for a later interpretation from the Ground Station operator.
  - For a **transmission** –TX– process, *GNU Radio* receives a satellite control command that the software is able to translate into a data bit stream. This bit stream is processed until it gets the desired modulated Base Band signal, which is immediately sent to the SDR transceiver, that translates it into the RF domain.

- **Gpredict** and **rotctld**

  A detailed description of what these software products can perform within the Ground Station is provided in Subsection 3.2.3.

3.3.7 Ground Station trial

Once the radio equipment has been set and calibrated, and the software tools have been configured, it is time to check if a reception link can be closed with a standard Cubesat in a LEO orbit.

CubeBug-2 (MANOLITO)

CubeBug-2 –also known as *Manolito*– is a 2U Cubesat supported by the Argentinian Ministry of Science, Technology and Productive Innovation. The pico-satellite carries an UHF *digipeater* as a technology demonstrator, as well as several custom designs on-board that have been tested in orbit.

The communication trial was performed during a pass over the Iberian Peninsula, Europe, on the 27th of January 2017 at 09:44 UTC. The signal caught was a periodical beacon broadcast in the UHF band. The link configuration is 9600 bps, FSK modulation, and a carrier frequency centred at 437.445 MHz –without applying the Doppler correction.

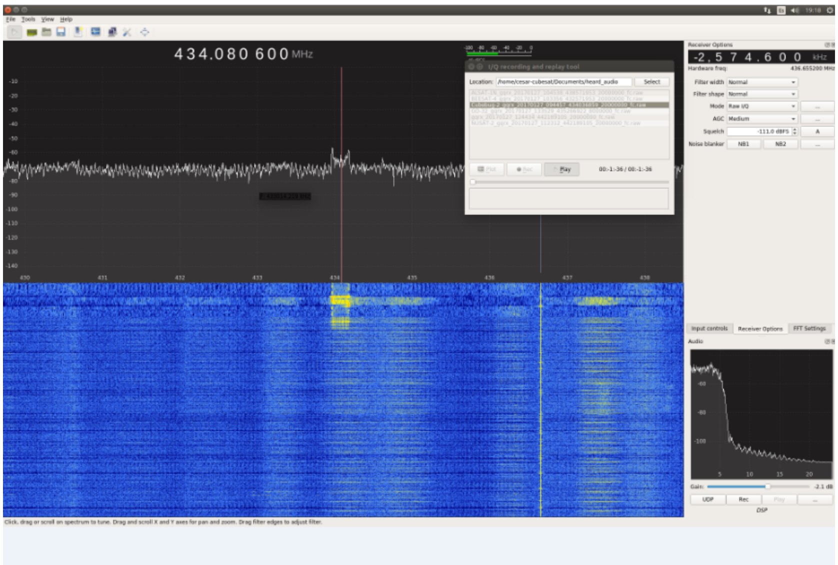


Figure 3.26 – *gqrx ESAC amateur GS – Listening to CubeBug-2 Cubesat*

Figure 3.26 is a screenshot of *gqrx* and it shows the waterfall plot throughout the reception of the signal. In this image appears how the frequency had been adjusted to correct the Doppler shift. Also, it is possible to perceive the characteristic shape of a 2-FSK signal on the frequency spectrum. Another relevant aspect is the resulting *carrier-to-noise rate*, $\frac{C}{N}$, of approximately 10 dB; a tight margin for a successful posterior demodulation.

3

Chapter 4

System requirements and constraints

Once the project technical background is known –and before starting with the design phase– it is necessary to identify, decide, and set those parts of the system that may integrate the project. In this chapter, the objectives, requirements, and constraints of the system will be set for the overall project.

This chapter will also show a review of space standards in order to identify recommendations and procedures that will help us accomplish an efficient work throughout the engineering process. Following professional recommendations since the very beginning will increase the likelihood of project success.

4.1 Space Standards and Recommendations

As in many other industries, it is mandatory the presence of committees working on the standardization of the space technology, ensuring thus the interoperability between agencies and companies. In this work, some of the recommendations suggested by the European Cooperation for Space Standardization (ECSS) [54] and Consultative Committee for Space Data Systems (CCSDS) [55] will be followed.

Following standard recommendations provides several benefits during the development phase of a space mission or product, cutting down costs and test periods or reducing mission risk. Thus, it is highly recommended to follow point by point all these recommendations.

At this point, it is important to remark that, due to time constraints, following closely all the recommendations guided by ECSS and CCSDS is out of the scope of this work and will be pointed out as future work in Chapter 8.

4.1.1 European Cooperation for Space Standardization – ECSS

The ECSS is a joint initiative of the ESA, national space agencies and European industry associations with the purpose of developing and maintaining common standards for space applications. It was established in 1993 and currently it is formed by the following national agencies: ASI, UKSA, CNES, DLR, ESA, NSO, NSC, the European industry represented by Eurospace and the CSA as associated member [54].

Numerous ECSS standards have been released with the aim to be applied altogether for the management, engineering and product assurance. Standards and recommendations for the development of the space technology are split up in four disciplines: *Space project management branch* (M), *Space product assurance branch* (Q), *Space engineering branch* (E), and *Space sustainability branch* (U) [56].

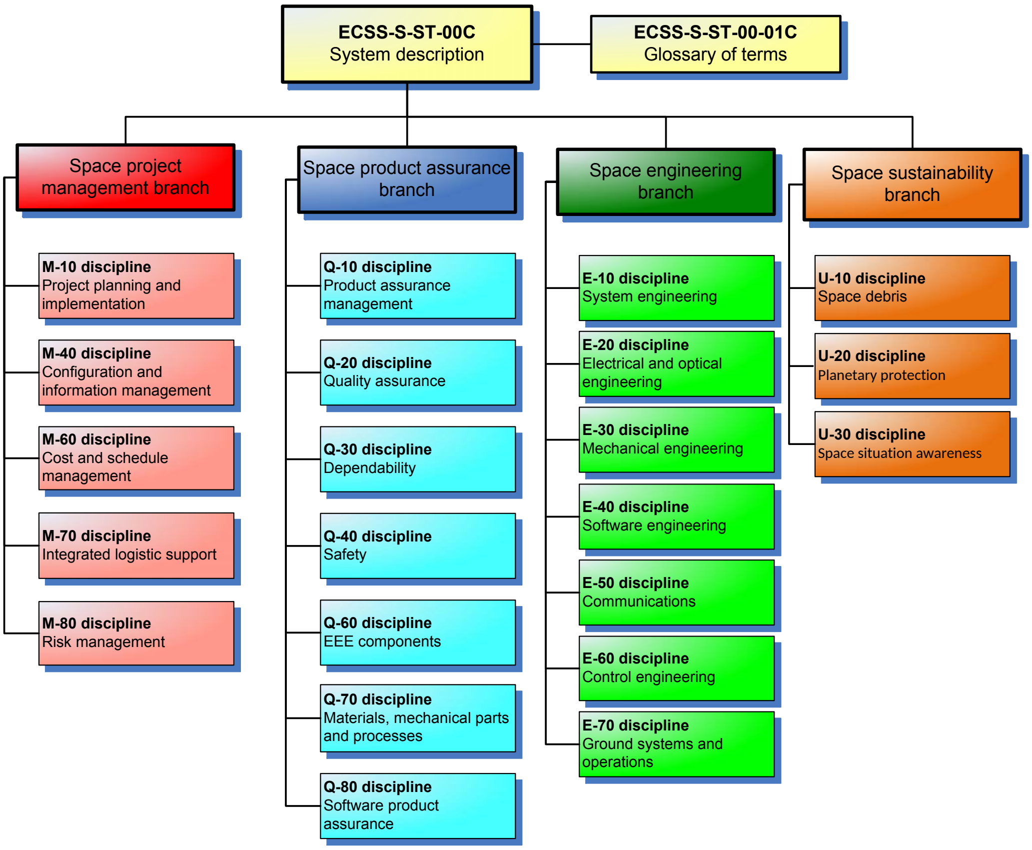


Figure 4.1 – *ECSS disciplines. Source: [57]*

These recommendations are periodically revised, and new discipline standards are still being published frequently by ECSS. Also several discipline handbooks have been published by ECSS to facilitate the understanding and application of the recommendations for the engineering community. Current disciplines related to an ECSS recommendation are shown in Figure 4.1. Furthermore, in order to increase the reliability of the products manufactured, those contractors working for ESA must follow the ECSS standards and recommendations.

4.1.2 Consultative Committee for Space Data Systems – CCSDS

The CCSDS [55] is a consortium created in 1982 by the world-leading space agencies. It was established to develop standards and recommendations for data and information systems in order to promote interoperability among space agencies and simplify the cooperation amongst them.

It is formed by many national agencies: ASI, CSA, CNES, CNSA, DLR, ESA, INPE, JAXA, NASA, RFSA and UKSA. Furthermore, other national agencies participate as observer members and more than one hundred of industrial companies as associates.

Standards are split up in several books whose names are based on colours, where each colour is related to a level of development of the standard [55]. This system helps distinguish those recommendations that must be followed from those non-restrictive ones: Blue book for Recommended standards, Magenta book for Recommended practices, Green book for Informational reports, Orange book for Experimental, Yellow book for Record Files, and Silver book for Historical recommendations.

In addition, documents at CCSDS are sorted into different areas of work within the communication and data system filed, as it can be seen in Figure 4.2 [55].

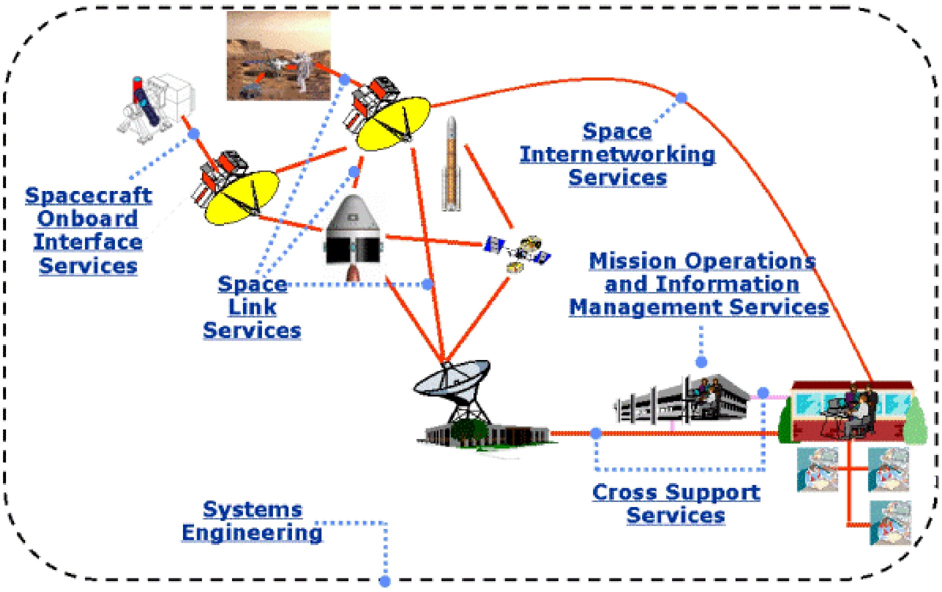


Figure 4.2 – *CCSDS area references. Source: [55]*

4.1.3 Standards and recommendations followed in this project

This master's thesis work was carefully developed following closely ECSS recommendations related to engineering disciplines involved in this project. It is important to mention that, despite the effort made, it was not always possible to design and implement the project following these recommendations point by point due to time, budget or facilities constraints.

The next list of ECSS recommendations have been used throughout the development of this master's thesis:

- Space engineering:

  ECSS-E-ST-10C: System engineering general requirements [58].

  ECSS-E-ST-10-06C: Technical requirements specification [59].

  ECSS-E-ST-20C: Electrical and electronic [60].

  ECSS-E-ST-50C: Communications [61].

  ECSS-E-ST-50-05C-Rev.2: Radio frequency and modulation [62].

- Space project management:

  ECSS-M-ST-10C: Project planning and implementation [63].

- Space product assurance:

  ECSS-Q-ST-70-08C: Manual soldering of high-reliability electrical connections [64].

  ECSS-Q-ST-70-12C: Design rules for printed circuit boards [65].

  ECSS-Q-ST-70-28C: Repair and modification of printed circuits board assemblies for space use [66].

  ECSS-Q-ST-70-38C: High-reliability soldering for surface-mount and mixed technology [67].

In addition, ECSS standard is consistent with other standards (CCSDS or ISO) and regulations (ITU-RR). Therefore, ECSS embraces CCSDS recommendations when appropriate –for example, recommendations related to Radio Communication discipline:

CCSDS-401.0-B-20: Radio Frequency and Modulation systems. Earth Stations and Spacecraft, Blue book. [68]

4.2 System Requirements and Constraints

Objectives, requirements and constraints will show engineers involved throughout the design, verification and test processes what the system must do and must not do. This way time and resources will be saved as it avoids an over-design or underestimation of any part of the system.

Due to their nature, requirements are simple statements that must be unambiguous, unique, and verifiable. Requirements that are compounded of several statements must be avoided because their verification is more complex than if they are written individually.

In addition, requirements must have a reason to exist, which is in origin either a system objective or an external factor. This fact forces requirements to be traceable in high-to-low and low-to-high levels in order to ensure consistency between requirements. Thus, any requirement without a parent shall be removed.

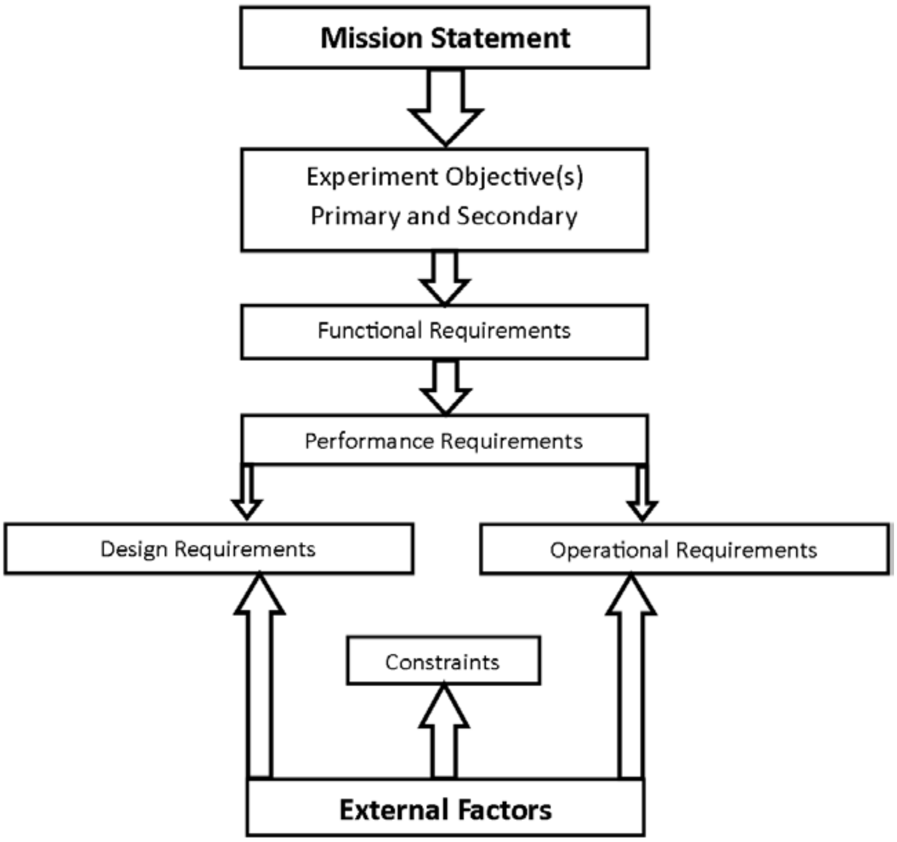


Figure 4.3 – *Requirement flow chart. Source: [69]*

Figure 4.3 depicts a typical requirement flow chart. From the *Mission statement* is obtained a first batch of requirements stating the objectives of the experiment. Then, a second batch of requirements, known as *functional requirements*, must detail the expected functionality of the experiment that allows achieving the *experiment objectives*. From these general requirements, engineers and managers must obtain gradually more detailed requirements, until reaching such a level that it is possible to describe unambiguously the expected behaviour of the system and its features.

External factors and *constraints* will identify any factor that can restrict the development of the experiment somehow, for example: environment conditions, time resources, customer's budget, available facilities and technology, etc.

4.2.1 System Objectives

System Objectives is a simple list of broad objectives of what the system must do. It will specify as *Primary Objectives* those objectives that the system shall fulfil in order to achieve a minimum of success. *Secondary Objectives* are other additional objectives that will complement the primary list.

Primary Objectives

4

Obj.1 To allow GranaSAT operators to communicate with the GranaSAT-I Cubesat

Obj.2 To allow GranaSAT-I to send telemetry and payload data to ground segment

Obj.3 To allow GranaSAT-I to receive control commands from ground segment

Secondary Objectives

Obj.4 To avoid potential damages due to environmental conditions

Obj.5 To be an Engineering Model: to allow PCB modifications and measurements

4.2.2 Functional Requirements

Requirements that define the functionality that the system shall perform in order to conform to the experiment objectives [59].

F.1 The system shall establish a radio link between satellite and Earth segment

F.2 The system shall be able to broadcast a data beacon

F.3 The system shall establish a radio link between Earth segment and satellite

F.4 The system shall be able to communicate to other systems within the Cubesat

F.5 The system shall limit the load current in a module level

F.6 The system shall cut off the power supply to modules if a short circuit is detected

F.7 The system shall monitor voltage level in a module level

F.8 The system shall switch off critical components if voltage level is out of range

F.9 The system shall monitor the temperature of critical components when they are active

F.10 The system shall switch off overheated critical components

F.11 The system shall be reprogrammable and debuggable by using an external device

F.12 The system shall be able to communicate to a *PC*

F.13 The system shall allow to do PCB modifications

4.2.3 Performance Requirements

Requirements that quantify to what level the *Functional Requirements* have to be fulfilled. This set of requirements will define the quality of the measurements, operations, and the overall system [59].

4

P.1 The transmission EIRP shall be higher than +28 dBm

P.2 The transmission adjacent channel power shall be lesser than −50 dBc

P.3 The transmission spurious emissions shall be lesser than −50 dBm

P.4 The transmission chain SWR shall be equal or lesser than 1.8

P.5 The transmission bit-rate shall be equal or higher than 4.8 kbps

P.6 The reception chain's first element Noise Figure shall be lesser than 1.0 dB

P.7 The reception chain's first element gain shall be higher than 15 dB

P.8 The receiver Noise Figure shall be lesser than 10 dB

P.9 The reception chain's losses shall be lesser than 10 dB

P.10 The reception chain's SWR shall be equal or lesser than 1.8

P.11 The reception bit-rate shall be equal or higher than 4.8 kbps

P.12 The reception demodulation E_b/N_0 required threshold shall be lesser than 16 dB

P.13 The communication bit-rate between systems within the Cubesat shall be higher than 100 kbps

P.14 Other systems within the Cubesat shall communicate to the COMM System with a frequency equal or lesser than 20 Hz

P.15 The COMM System shall communicate to other systems within the Cubesat with a frequency equal or lesser than 20 Hz

P.16 The microcontroller shall allow communication with other systems within the Cubesat at any time

P.17 The load current limit for each monitored module of the system shall be 1 A

P.18 The load current limit for system high power demanding modules shall be 2.5 A

P.19 The module power supply cutting off since maximum current load is detected shall be performed faster than 1 ms

P.20 The module power supply cutting off since short circuit is detected shall be performed faster than 10 µs

P.21 The nominal voltage range shall be 2.8 V to 3.7 V

P.22 The critical component switching off since out of range voltage is detected shall be performed faster than 20 µs

P.23 The temperature monitor range shall be −30 °C to +85 °C

4

P.24 The temperature monitor accuracy shall be equal or higher than 4 °C

P.25 The temperature monitor frequency shall be equal or higher than 10 KHz

P.26 The maximum working temperature for monitored components shall be +80 °C

P.27 The component switching off since overheating is detected shall be performed faster than 1 ms

P.28 The frequency band for an amateur-satellite service operating within the VHF band shall be from 145.8 MHz to 146.0 MHz [39]

P.29 The maximum bandwidth used within the VHF band shall be 12 KHz [39]

P.30 The frequency band for an amateur-satellite service operating within the UHF band shall be from 435.0 MHz to 438.0 MHz [39]

P.31 The maximum bandwidth used within the UHF band shall be 20 KHz [39]

4.2.4 Interface Requirements

Those requirements that are relevant to satisfy an interconnection between the system and any other system from Cubesat or from the outside [59].

I.1 The system shall be compatible with GranaSAT-I antenna subsystem interface

I.2 The system shall be compatible with GranaSAT-I bus

I.3 The system shall be compatible with *PC-104* physical interface

I.4 The system shall offer a microcontroller programming and debugging port

I.5 The system shall offer a serial port for external connection

4.2.5 Constraints

Constraints are mandatory singularities that the system must adhere to. They may be imposed by other system requirement or by the mission nature itself [59].

C.1 The system shall be compatible with GranaSAT *Ground Station*

C.2 The system shall follow the GranaSAT-I system specifications

C.3 The system shall follow the Cubesat specifications

C.4 The system shall follow the ITU-RR rules

C.5 The system shall follow the ECSS standards and recommendations

C.6 The Cubesat will be placed into a LEO orbit

C.7 Development costs are not supported by University – Budget shall be under €300

C.8 GranaSAT-I project has no testing facilities

4

4.2.6 Environmental Requirements

Requirements related to the environment that the system shall fulfil in order to operate in safety conditions. Both natural environments and induced environments are included, such as heat, electromagnetism, radiation, vibration, contamination, etc. [59].

E.1 The system shall operate in the temperature range from $-35\,^{\circ}\mathrm{C}$ to $+70\,^{\circ}\mathrm{C}$

E.2 The system shall operate in a low pressure environment equal or lesser than $10^{-5}\,\mathrm{hPa}$

E.3 The system shall operate in an environment of high-ionizing radiation dose

4.2.7 Design Requirements

Requirements related to the design topic resulting from any previous function, requirement (Performance R., Environmental R., Interface R.), constraint, related standard or any other decision linked to the behaviour of the system [59].

D.1 The system shall have a *High Power Amplifier* unit

D.2 The system shall have a band pass filter centred at carrier frequency in the transmission chain

D.3 The system shall have tuned matching networks

D.4 The system shall include a RF shielding

D.5 The system shall have a *Low Noise Amplifier* unit at the reception chain

D.6 The system shall implement a QPSK modulation scheme

D.7 The system shall implement a CW modulation scheme

D.8 The microcontroller shall allow interruption events

D.9 A single current limit for the *High Power Amplifier* shall be used

D.10 The system short circuit protection shall be a hardware solution

D.11 The nominal voltage required for components shall be 3.3 V

D.12 The system voltage monitoring shall be a hardware solution

D.13 The microcontroller temperature shall be monitored

D.14 The receiver temperature shall be monitored

D.15 The transmitter temperature shall be monitored

D.16 The *High Power Amplifier* temperature shall be monitored

D.17 The microcontroller temperature measurement shall be calibrated

D.18 The receiver temperature measurement shall be calibrated

D.19 The transmitter temperature measurement shall be calibrated

D.20 The *High Power Amplifier* temperature measurement shall be calibrated

D.21 The system shall have, as a transmission chain main front-end, a SMA connector

D.22 The characteristic impedance of the main front-end at the transmission chain shall be 50 Ω

D.23 The system shall have, as a transmission chain secondary front-end, two balanced RF paths

D.24 The system shall have, as a transmission chain secondary front-end, two balanced 90° phased RF paths

D.25 The system shall have, as a reception chain main front-end, a SMA connector

D.26 The characteristic impedance of the main front-end at the reception chain shall be 50 Ω

D.27 The system shall have, as a reception chain secondary front-end, two balanced RF paths

D.28 The system shall have, as a reception chain secondary front-end, two balanced 90° phased RF paths

D.29 The system shall use I^2C to communicate with other systems within the Cubesat

D.30 The system shall have a hard reset line

D.31 The system shall be powered by 3.3 V

D.32 The system shall be compatible with *PC-104* GND pines

D.33 The system shall be compatible with *PC-104* V_{cc} pines

D.34 The system shall be compatible with *PC-104* I^2C bus pines

D.35 The debugging protocol used shall be the ARM Serial Wire Debug (SWD)

D.36 The debugging port shall be a separate port

D.37 The serial protocol used shall be UART

D.38 The UART port shall be a separate port

D.39 The system shall allow easy access to instrumentation probes

D.40 The system shall allow the option of soldering external wires

D.41 The system shall allow to redistribute tracks reaching the microcontroller pines

D.42 The system shall show the component designator on the PCB

D.43 The system shall allow manual soldering of components

D.44 The system shall allow different topologies of adaptation network in RF chains

D.45 The system shall use for communication any ISM band allocated within either UHF or VHF bands

D.46 The system shall allocate the downlink and uplink frequencies in the UHF band for half-duplex and simplex operations

D.47 The system shall allocate the downlink frequency in the UHF band and the uplink frequency in the VHF band for full-duplex operations

D.48 The system physical dimensions shall be the specified for GranaSAT-I

D.49 The system shall weigh less than 150 *gr*

D.50 The system power consumption during transmission shall be lower than 9 *W*

D.51 The system power consumption during reception shall be lower than 3 *W*

D.52 The system shall follow *Cubesat Design Specification, Rev. 13*: 3.3.5 [6]

D.53 The system shall follow *Cubesat Design Specification, Rev. 13*: 3.3.9 [6]

D.54 The system shall follow *ITU – Radio Regulations*: RR 5.282 [39]

D.55 The system shall follow, when applicable, *Space Engineering: Electrical and electronic*: 7.3 RF Power (ECSS-E-ST-20C) [60]

D.56 The system shall follow, when applicable, *Space Engineering: Communications*: 5.3 Space Communication System (ECSS-E-ST-50C) [61]

D.57 The system shall follow, when applicable, *Space Engineering: Communications*: 5.5 Space Link (ECSS-E-ST-50C) [61]

D.58 The system shall follow, when applicable, *Space Engineering: Radio frequency and modulation*: 6.2 Suppressed carrier modulation (ECSS-E-ST-50-05C) [62]

D.59 The system shall follow, when applicable, *Space Engineering: Radio frequency and modulation*: 8.3 Link budget tables (ECSS-E-ST-50-05C) [62]

4

D.60 The system shall follow, when applicable, *Space product assurance: Design rules for printed circuit boards*: 7.4 Track width and spacing (ECSS-Q-ST-70-12C) [65]

D.61 The system shall follow, when applicable, *Space product assurance: Design rules for printed circuit boards*: 7.8 PCB surface finish (ECSS-Q-ST-70-12C) [65]

D.62 The system shall follow, when applicable, *Space product assurance: Manual soldering of high-reliability electrical connections* (ECSS-Q-ST-70-08C) [64]

D.63 The system shall follow, when applicable, *Space product assurance: Repair and modification of printed circuits board assemblies for space use* (ECSS-Q-ST-70-28C) [66]

D.64 The system shall follow, when applicable, *Space product assurance: High-reliability soldering for surface-mount and mixed technology* (ECSS-Q-ST-70-38C) [67]

D.65 The system components shall offer an operative work temperature range equal or wider than $-35\ ^{\circ}\mathrm{C}$ to $+60\ ^{\circ}\mathrm{C}$

D.66 The system components shall be suitable to function under a low pressure environment, equal or lesser than $10^{-5}\ \mathrm{hPa}$

D.67 The system shall allow the placement of an electromagnetic shielding

D.68 The system shall only use COTS components

D.69 Any in-house test or verification process shall not require facilities out of the GranaSAT reach

4.2.8 Operational Requirements

Those requirements that define the system operability, from operation behaviour to control or contingency [59].

O.1 The system shall operate in multi-band full-duplex mode

O.2 The system shall be able to operate in single-band half-duplex mode

O.3 The system shall establish the downlink after an Earth control requirement

O.4 The system shall perform a periodical CW beacon when idle status

O.5 The system shall establish the uplink when idle status

O.6 The system shall be manageable by Cubesat's OBC system

O.7 The system shall cease any communication and switch to failure state if overload occurs

O.8 The system shall cease any communication and switch to failure state if voltage out of range occurs

O.9 The system shall cease any communication and switch to failure state if overheating occurs

O.10 *Cubesat Design Specification, Rev. 13*: 3.4.1 [6]

O.11 *Cubesat Design Specification, Rev. 13*: 3.4.2 [6]

O.12 *Cubesat Design Specification, Rev. 13*: 3.4.5 [6]

O.13 *ITU – Radio Regulations*: RR 25.11 [39]

O.14 *ITU – Radio Regulations*: RR 25.2A [39]

4.3 Requirement Traceability

When the requirement identification phase is being performed, more statements than those originally required are normally taken into account and added to the project for no apparent reason. In the same way, other requirements may be unperceived or not properly treated.

In order to achieve a consistent requirement work, it is necessary to ensure that requirements are traceable in both forward and backward directions. Thus, we will be able to ensure that any requirement is parented by either a high-level requirement, a objective or a constraint.

In addition, traceability helps to understand how objectives and functionality mould the system into low-level details.

To check requirement traceability, all high-level and low-level requirements broken down in the previous section (4.2) have been gathered and depicted in two tables –table 4.1 for system objectives and table 4.2 for system constraints.

<table>
<tr><th colspan="7">COMM System - Requirements Traceability</th></tr>
<tr><th>Objective</th><th>Functional Requirement</th><th>Performance Requirement</th><th>Interface Requirement</th><th>Environmental Requirement</th><th>Design Requirement</th><th>Operational Requirement</th></tr>
<tr><td rowspan="20">Obj.1</td><td rowspan="13">F.1</td><td>-</td><td>-</td><td>-</td><td>-</td><td>O.1</td></tr>
<tr><td>-</td><td>-</td><td>-</td><td>-</td><td>O.2</td></tr>
<tr><td>-</td><td>-</td><td>-</td><td>-</td><td>O.3</td></tr>
<tr><td>P.1</td><td>-</td><td>-</td><td>D.1</td><td>-</td></tr>
<tr><td>P.2</td><td>-</td><td>-</td><td>D.2</td><td>-</td></tr>
<tr><td>P.3</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>P.4</td><td>-</td><td>-</td><td>D.3</td><td>-</td></tr>
<tr><td>P.5</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>P.12</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>-</td><td rowspan="4">I.1</td><td>-</td><td>D.21</td><td>-</td></tr>
<tr><td>-</td><td>-</td><td>D.22</td><td>-</td></tr>
<tr><td>-</td><td>-</td><td>D.23</td><td>-</td></tr>
<tr><td>-</td><td>-</td><td>D.24</td><td>-</td></tr>
<tr><td rowspan="2">F.2</td><td>-</td><td>-</td><td>-</td><td>-</td><td>O.4</td></tr>
<tr><td>-</td><td>-</td><td>-</td><td>D.7</td><td>-</td></tr>
<tr><td rowspan="5">F.3</td><td>-</td><td>-</td><td>-</td><td>-</td><td>O.1</td></tr>
<tr><td>-</td><td>-</td><td>-</td><td>-</td><td>O.2</td></tr>
<tr><td>-</td><td>-</td><td>-</td><td>-</td><td>O.5</td></tr>
<tr><td rowspan="2">P.6</td><td>-</td><td>-</td><td>D.4</td><td>-</td></tr>
<tr><td>-</td><td>-</td><td>D.5</td><td>-</td></tr>
</table>

... continued

Objective	Functional Requirement	Performance Requirement	Interface Requirement	Environmental Requirement	Design Requirement	Operational Requirement
Obj.1	F.3	P.7	-	-	D.5	-
		P.8	-	-	D.4	-
		P.9	-	-	D.3	-
		P.10	-	-	D.3	-
		P.11	-	-	-	-
		P.12	-	-	D.6	-
		-	I.1	-	D.25	-
		-		-	D.26	-
		-		-	D.27	-
		-		-	D.28	-
Obj.2 Obj.3	F.4	-	-	-	-	O.6
		P.13	-	-	-	-
		P.14	-	-	-	-
		P.15	-	-	-	-
		P.16	-	-	D.8	-
		-	I.2	-	D.29	-
		-		-	D.30	-
		-		-	D.31	-
		-	I.3	-	D.32	-
		-		-	D.33	-
		-		-	D.34	-

. . . continued

Objective	Functional Requirement	Performance Requirement	Interface Requirement	Environmental Requirement	Design Requirement	Operational Requirement
Obj.4	F.5	P.17	-	-	-	-
		P.18	-	-	D.9	-
		P.19	-	-	-	-
	F.6	-	-	-	-	O.7
		P.20	-	-	D.10	-
	F.7	P.21	-	-	D.11	-
	F.8	-	-	-	-	O.8
		P.22	-	-	D.12	-
	F.9	P.23	-	-	D.13	-
			-	-	D.14	-
			-	-	D.15	-
			-	-	D.16	-
		P.24	-	-	D.17	-
			-	-	D.18	-
			-	-	D.19	-
			-	-	D.20	-
		P.25	-	-	-	-
	F.10	-	-	-	-	O.9
		P.26	-	-	-	-
		P.27	-	-	-	-

. . . continued

Objective	Functional Requirement	Performance Requirement	Interface Requirement	Environmental Requirement	Design Requirement	Operational Requirement
Obj.5	F.11	-	I.4	-	D.35	-
		-		-	D.35	-
	F.12	-	I.5	-	D.37	-
		-		-	D.38	-
	F.13	-	-	-	D.39	-
		-	-	-	D.40	-
		-	-	-	D.41	-
		-	-	-	D.42	-
		-	-	-	D.43	-
		-	-	-	D.44	-
High Level	⟶				Low Level	

Table 4.1 – *Requirement Traceability – System Objectives*

COMM System – Requirements Traceability

Constraint	Functional Requirement	Performance Requirement	Interface Requirement	Environmental Requirement	Design Requirement	Operational Requirement
C.1	-	-	-	-	D.45	-
	-	-	-	-	D.46	-
	-	-	-	-	D.47	-
C.2	-	-	-	-	D.48	-
	-	-	-	-	D.49	-
	-	-	-	-	D.50	-
	-	-	-	-	D.51	-
C.3	-	-	-	-	-	O.10
	-	-	-	-	-	O.11
	-	-	-	-	-	O.12
	-	-	-	-	D.52	-
	-	-	-	-	D.53	-
C.4	-	-	-	-	-	O.13
	-	-	-	-	-	O.14
	-	P.28	-	-	-	-
	-	P.29	-	-	-	-
	-	P.30	-	-	-	-
	-	P.31	-	-	-	-
	-	-	-	-	D.54	-
C.5	-	-	-	-	D.55	-

. . . continued

Constraint	Functional Requirement	Performance Requirement	Interface Requirement	Environmental Requirement	Design Requirement	Operational Requirement
C.5	-	-	-	-	D.56	-
	-	-	-	-	D.57	-
	-	-	-	-	D.58	-
	-	-	-	-	D.59	-
	-	-	-	-	D.60	-
	-	-	-	-	D.61	-
	-	-	-	-	D.62	-
	-	-	-	-	D.63	-
	-	-	-	-	D.64	-
C.6	-	-	-	E.1	D.65	-
	-	-	-	E.2	D.66	-
	-	-	-	E.3	D.67	-
C.7	-	-	-	-	D.68	-
C.8	-	-	-	-	D.69	-
High Level	→				Low Level	

Table 4.2 – *Requirement Traceability – System Constraints*

4

Chapter 5

Project Management & Planning

In previous chapters, key aspects for the design of the COMM system have been carried out, such as the study of the science and engineering behind a Cubesat, as well as the design and construction of an amateur Ground Station. Moreover, a closer task related to the COMM system has been performed: the analysis and statement of requirements and constraints.

By gathering the work carried out so far, this chapter will detail those elements that will set up the COMM system, the resources available for this purpose, and the budget assigned to the project.

5.1 Work Breakdown Structure

A Cubesat is a complex system that is made up of an unfixed number of other dedicated systems. The combination of these systems creates a new one, that usually is more complex and has a higher functionality than just the sum of each system separately. This structure is commonly known as a System of Systems (SoS).

In a Cubesat, the Communication System (COMM) is just one among several systems that conform the spacecraft, such as the ADCS, EPS, and OBC system, or the payload itself. Figure 5.1 depicts the flight configuration of the *ESTCube-1* –a 1U Cubesat– and the systems that make it up.

To manage the wide number of systems involved in a big project, as well as to ensure the consistency of the overall solution, it is necessary the incorporation of management tools that help to handle the system in an affordable way. Their use is recommended by ECSS in *"Space project management: Project planning and implementation"*, *ECSS-M-ST-10C* [63].

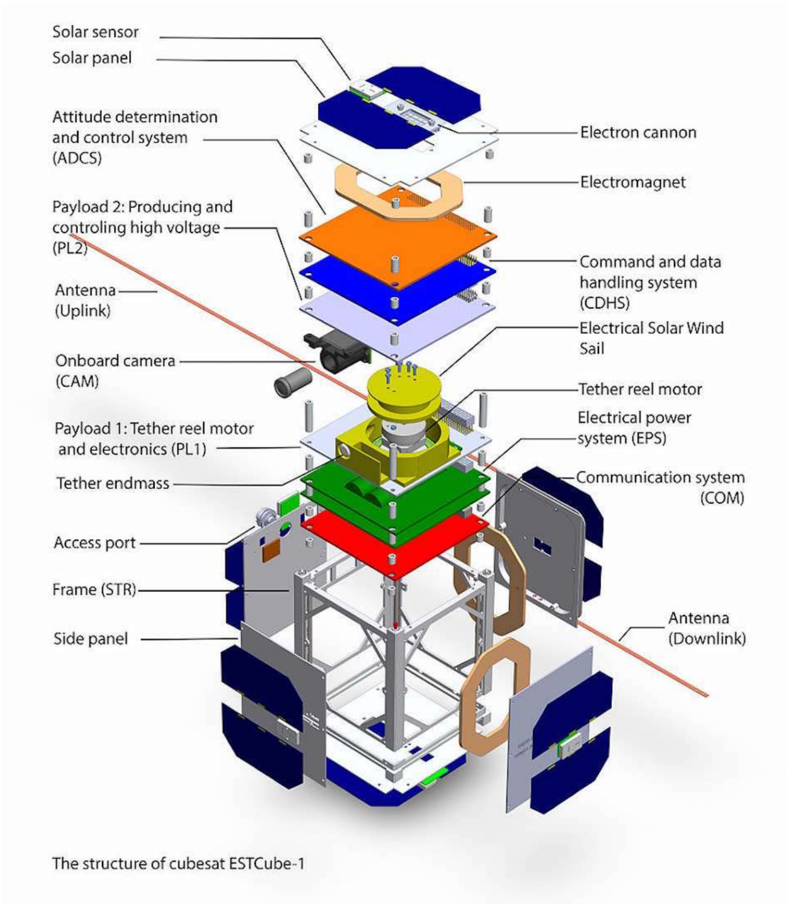


Figure 5.1 – *ESTCube-1 flight configuration. Source: Estcube*

One of these recommended tools is the Work Breakdown Structure (WBS). A WBS is a graphical structure that split up the project into several manageable Work Package (WP), arranged according to the nature of the work. A Work Breakdown Structure is a hierarchical structure that states *what* has to be done, but not *when* nor *how* it must be performed.

It has a hierarchical up-down structure, and can specify as much project details as required. When this is demanded, the lower-level details are itemised in a *tasks* list. In order to get a reliable catalogue of WPs and *tasks*, firstly a thorough list of *requirements* and *constraints* is necessary to state the characteristics of the system. Only after the *requirements* and *constraints* analysis –as it was performed in Chapter 4– it will be feasible to determinate, by using the WBS, *what* is necessary to develop in order to fulfil them.

In Figure 5.2, a WBS for the GranaSAT mission is given. Following the nature of the activities, the mission has been split up into two segments: the *WP 10 – Ground Segment* and the *Space Segment*, which in turn is composed of the *WP 20 – Platform* and the *WP 30 – Payload*.

The *WP 10 – Ground Segment* is broken down into three key areas related to the activities that are necessary to carry out on Earth. These three areas are:

- **WP 11 – Mission Control:**
  To design and elaborate a work route and to manage the Cubesat mission throughout its lifespan. The WP also includes the activities related to the control of the spacecraft by means of sending telecommands.

- **WP 12 – Payload Control:**
  To manage the payload that have been sent to the Cubesat– while it is in space. The objective of this activity is to make the most of the payload as long as the mission is ongoing.

- **WP 13 – Communication System:**
  To design and build the radio equipment that allows to stablish a satellite-Earth communication path. The activity also includes the design and the development of the Ground Station. The development of this WP has been conducted and carefully explained in Chapter 3.

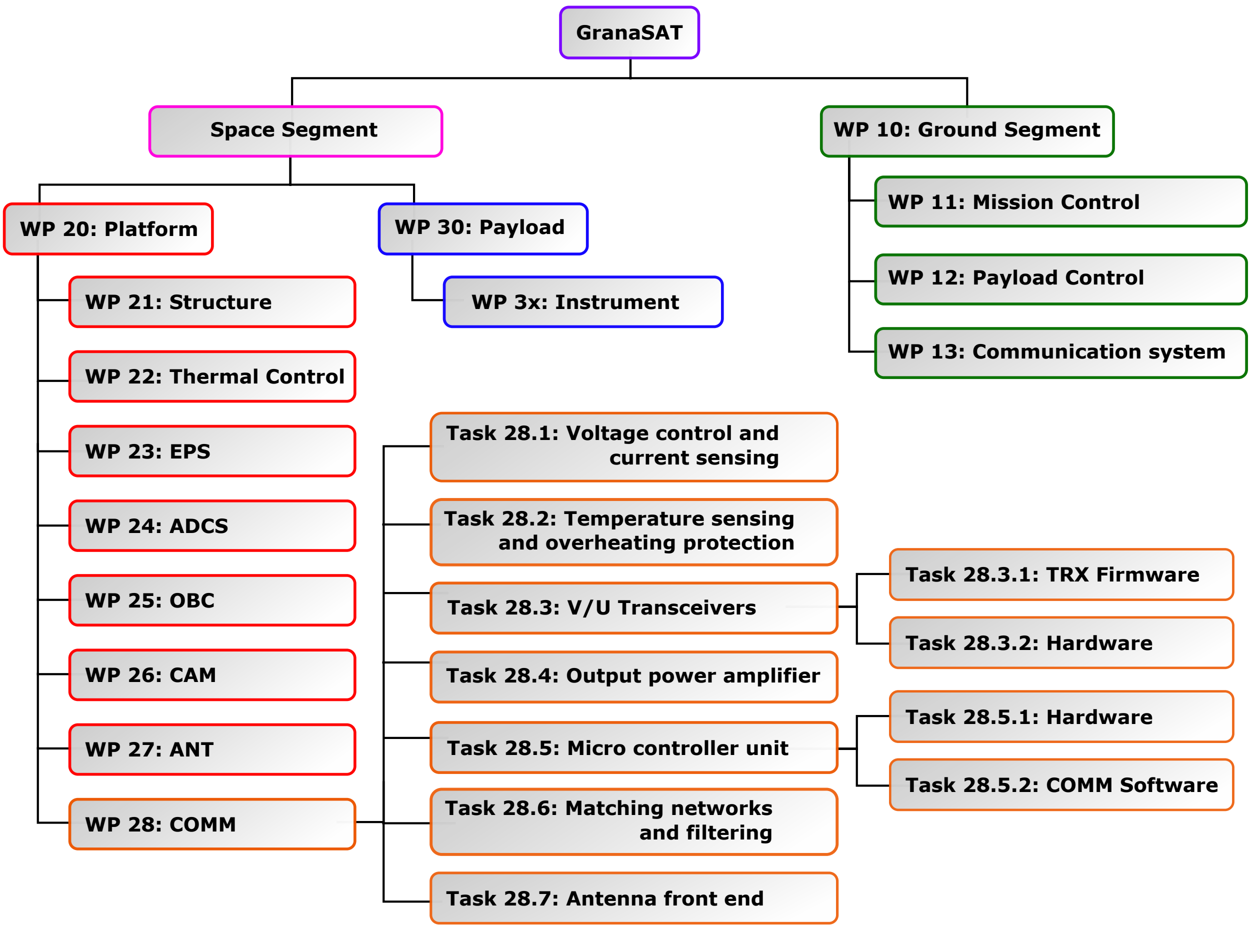


Figure 5.2 – *GranaSAT project – Work Breakdown Structure*

The *WP 20 – Platform* embraces the engineering activities associated with the Cubesat in itself. It comprises the next Work Packages:

- **WP 21 – Structure:**
  To design and build the structure of the Cubesat, as well as any other task related to the mechanical platform.

- **WP 22 – Thermal Control:**
  To design and build the set of sensors, hardware and algorithms that determines an either active or passive thermal control within the Cubesat.

- **WP 23 – Electrical Power System (EPS):**
  To design and build the combination of batteries, solar panels, and control hardware to power the pico-satellite while the mission is taking place.

- **WP 24 – Attitude Determination & Control System (ADCS):**
  To design and develop the set of sensors responsible for determining the attitude of the spacecraft, as well as the actuators in charge of making corrections of the Cubesat attitude when necessary. This WP also embraces the implementation of the required algorithm for this purpose.

- **WP 25 – On-Board Computer (OBC):**
  To design and develop a central unit board to control the spacecraft. This system also shall work as a *"Command and Data handling"* module, which allows to command the different systems in the Cubesat, such as the transmission of telemetry data over the radio system, the configuration of system parameters, the management of the payload, or the verification of the battery charge level, among other tasks.
  This WP also includes the software tasks, such as the development of the routines and functions by using RTOS techniques, as well as the development of the communication protocol among systems in the Cubesat through the internal bus.

5

- **WP 26 – CAM:**
  To design, develop and integrate a camera to take pictures of the space and Earth during the Cubesat mission. These pictures may be used as scientific data or for marketing purposes.

- **WP 27 – ANT:**
  To design, build and integrate the antenna front end of the Cubesat and the COMM system. The antenna deployment mechanism is also included in the WP.

- **WP 28 – Communication System (COMM):**
  To design and develop a communication system able to transmit any data generated by the spacecraft, and to receive data and commands from the *Ground Segment*. Since this system is the one expected to be designed in this master's thesis, the WP will be detailed down-level. The WP is broken down into a list of *tasks* that have been outlined following the list of *requirements* and *constraints* defined in Chapter 4.

  In particular for this master's thesis, software tasks have been performed partially, just to verify that the system functionality was correct, and the hardware components were working properly after the soldering process. Therefore, the tasks concerning the objective of this master's thesis –hardware design– are marked in green, while red tasks have just been initialized as they are software-related.

The tasks of the WP 28 – Communication System are:

– **Task 28.1 - Voltage control and current sensing:** To design and develop a module capable of monitoring the voltage level in the PCB and the current consumption. In case of any anomaly, the module has to protect and power off the components in a safe way.

– **Task 28.2 - Temperature sensing and overheating protection:** To design and develop a module able to measure the temperature in different points of the PCB and, in case of overheating, to power off the affected components immediately.

– **Task 28.3 - V/U Transceivers:** To design and develop a couple of RF transceivers, one suitable for the VHF band and the other one for the VHF band:

  * *Task 28.3.1 - Transceiver firmware:*
    To design and implement the firmware for the transceivers. This is demanded because the transceivers are controlled digitally and, therefore, they require their own custom *firmware* to function correctly.
  * *Task 28.3.2 - Hardware:*
    To design and develop the hardware part of this task.

– **Task 28.4 - Output power amplifier:** To design and develop a RF power amplifier able to fulfil the transmission chain requirements.

– **Task 28.5 - Micro-controller unit:** To design and develop a central unit capable of managing the system, and to communicate with each module of the system and other systems within the Cubesat:

  * *Task 28.5.1 - Hardware:*
    To design and develop the hardware part of this task.
  * *Task 28.5.2 - COMM software:*
    To design and implement the software elements for this WP. Since the micro-controller unit is the only computing component in the system, the whole software work is included in this task.

– **Task 28.6 - Matching networks and filtering:** To design and integrate the adequate signal filters and to match networks in the RF chain when required.

– **Task 28.7 - Antenna front end:** To design and develop an antenna front end suitable for different kinds of antennas and connections.

Finally, the *WP 30 – Payload* is a Work Package reserved for the payload of the Cubesat, which most probably will be a scientific instrumentation or a technological demonstrator. The payload has yet to be defined, and for this reason it appears empty. Ideally, this WP will be filled up by the different instruments defining the payload.

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5.2 Resources

Some facilities available at the Electronics and Computer Technology Department are expected to be utilized by students throughout their master's thesis. This provides access to an electronic laboratory that offers the following elements:

- **SMD rework station:**

  It is a soldering station made up of a soldering iron and a hot-air gun. It is specially created for PCB designs including SMD components.

- **Microscope:**

  When a manual soldering of small footprint components is required, a microscope has to be used to do the soldering work.

- **Oscilloscope:**

  Instrument intended to analyse the signals –normally low frequency– within a PCB. This is useful, for example, to check if the behaviour of a circuit is the expected or to verify if the lines of a communication bus are working properly.

- **Vector Network Analyser (VNA):**

  It is a complex equipment to evaluate RF systems. The instrument is able to analyse the frequency response of a RF device, providing –among others– its Scattering parameters or its Stationary Wave Ratio (SWR) value.

- **Signal Analyser:**

  It is an instrument that analyses an incoming RF signal and provides its key attributes. The features of a signal analyser are useful to check if the outcome signal in a radio system has the expected characteristics and behaviour.

5.2.1 Budget

As any other master's thesis carried out at the University of Granada, this project was assigned with a budget of zero euros by the Electronics and Computer Technology Department. Such amount of money is clearly insufficient to develop any technological project at all.

This sad circumstance pushes the author of this project to support himself all costs related to the development of the project, and therefore to keep the costs of components down for the prototype, evaluation boards and any other necessary expenses to complete the project. The final budget of the project can be check in Appendix G

Note that costs related to the Ground Station activities in Chapter 3 are not considered part of the COMM system labour, therefore they are not included here. Each Ground Station had its respective assigned budget for its development.

Chapter 6

System design

Thanks to the work performed in previous chapters, the project has been completely defined from a system perspective. In chapter, 2 a thorough study of the Cubesat framework, and the background engineering fields associated with space communications was carried out. This study has helped to better understand what kind of features are necessary for the system.

Also, this work shows in Chapter 3 the development of two Ground Stations. The participation in these Ground Station projects allowed the identification of the most important elements within a space communication, both in the ground segment and the space segment.

By combining these two chapters, it was possible to sketch the parts that will conform the COMM System and carry out a quick inspection to identify if the equipment available in the GranaSAT facilities was enough to achieve the objectives –chapter 4. Finally, in chapter 5, an exhaustive analysis of requirements and constraints was carried out. This chapter provides a detailed description of the system, defining *what* and *how* it shall be performed.

Here in this chapter, the design of a system capable of achieving the objectives laid down will be suggested, explained and executed. In the next chapter, the design will be verified and, depending on the verification results, changes will be required.

6.1 System Architecture

To start the design phase, the first step is to suggest an architecture for the system, which will define the system in a high-level and will work as a basis for designing the low-level modules. The system architecture is usually represented by a *block diagram*, a very useful tool that shows the different parts –blocks– that the system is made up of. It also represents the interdependency between the blocks, without defining how the operation of each individual block is.

Usually, the first design is considered a draft, and it will be analysed and modified in order to ensure that it is able to fulfil all the requirement specifications. It is also critical to determine if the design complies exactly with what is being demanded.

The first version of the COMM system block diagram is shown in Figure 6.1. This first sketch contemplates the main features of the system, such as the use of a MCU and the multi-band full duplex operation, the use of a LNA in the RF reception chain, among other capabilities.

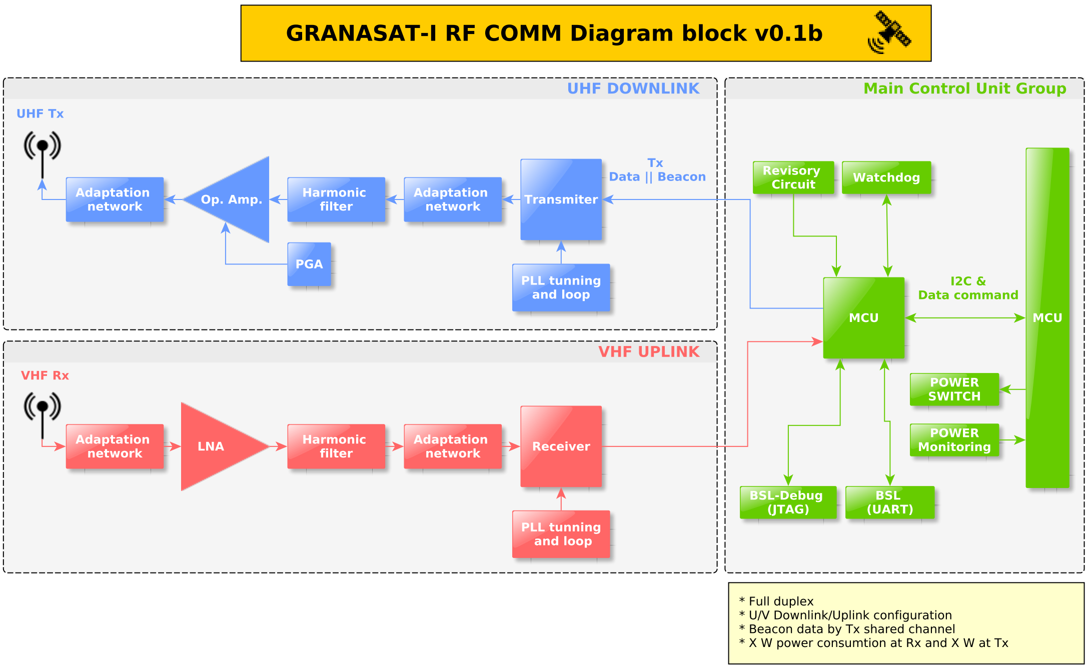

Figure 6.1 – *COMM System – Block diagram V0.1b*

Shortly after releasing the block diagram, it must be meticulously examined in order to identify those features that do not meet the stated requirements and, therefore, should be improved. The process is iterative and will require analysing several times the proposed design until obtaining the one that does *what* we want to do and in such a way that it is exactly *how* we want to.

For the first version of the block diagram, clearly the proposed block diagram cannot accomplish, for instance, the features related to the temperature monitoring, or the ones associated with the power management and the protection against overcurrent events.

For these very reasons, improvements were studied and suggested in the following versions of the COMM System architecture. A total of four iterations were needed to reach a design that could fulfil all the the provided requirements and constraints.

The architecture that was approved by the author of this master's thesis and the coordinator of the GranaSAT-I project is the shown Figure 6.2, numbered as V0.3. This block diagram fulfils every applicable requirement and the modules suggested in the project WBS –see chapter 5.

This suggested design covers all design requirements and provides the room and flexibility necessary for fulfilling the remaining requirements that are only dependent on the block-level design. Hence, the high-level design for the COMM System is set with this block diagram.

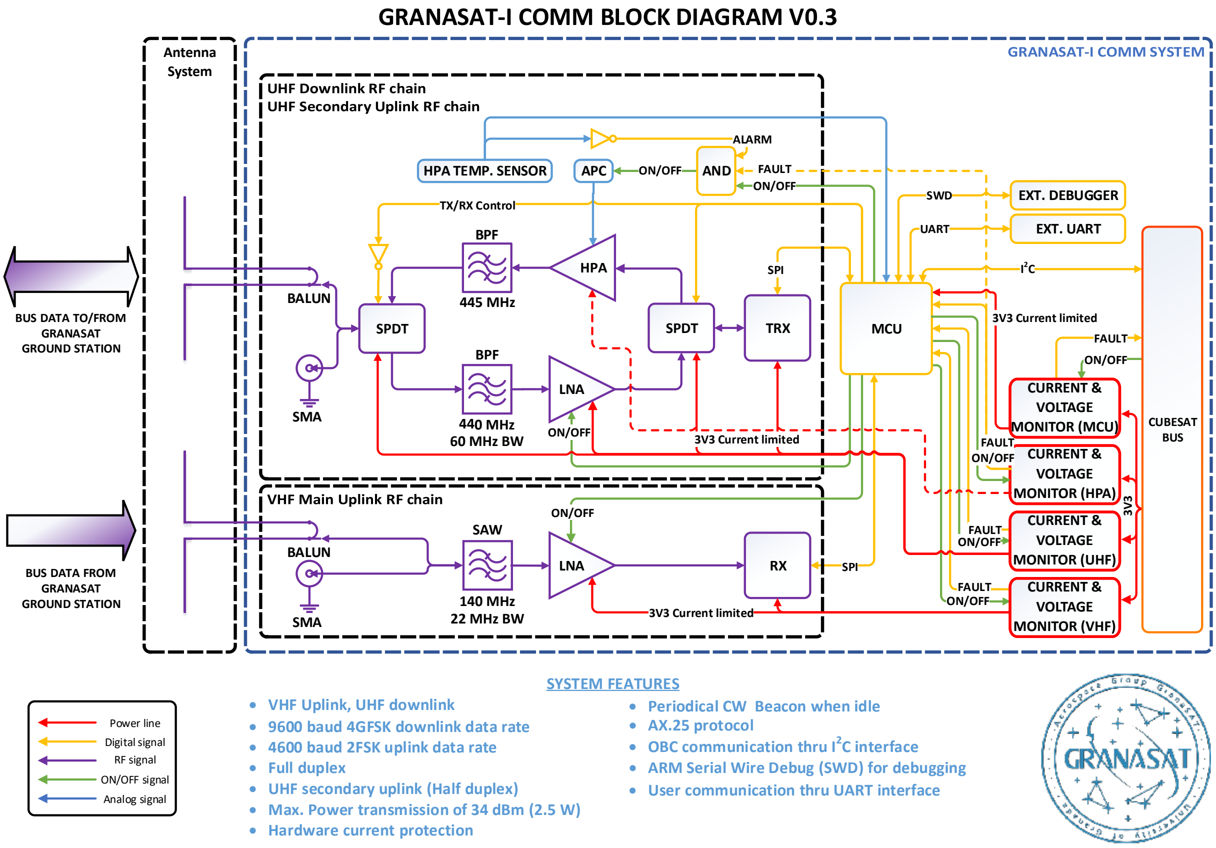

Figure 6.2 – *COMM System – Block diagram V0.3*

This suggested design covers all design requirements and provides the room and flexibility necessary for fulfilling the remaining requirements that are only dependent on the block-level design. Hence, the high-level design for the COMM System is set with this block diagram.

In summary, and following the design specifications –see chapter 4–, the system supports a multi-band V/U full duplex radio, as well as a half-duplex mode in the UHF band. It has a module for monitoring the current and voltage that can protect, in case of overcurrent or voltage anomaly, the affected module. Also a mixed software/hardware temperature monitoring feature is added to the system, which provides an overheating protection. Finally it also includes the required ports for the future development of the software.

Next step will consist in designing the low-level parts of the system, that is, each single module –or block. This task also includes the selection of those components that will make possible the fulfilment of the remaining requirements.

6.2 System dimensions

Normally, Cubesats use the *PC104* standard to define the form factor and the bus data. This standard is also the most commonly employed by the companies that do business with Cubesat systems. Figure 6.3 depicts the physical dimensions of the PCB commercialised by *Pumpkin Inc.*

The GranaSAT project decided to incorporate this standard for the GranaSAT-I Cubesat because it would ensure the compatibility with the commercial products in case it would be necessary to include an external system to the spacecraft.

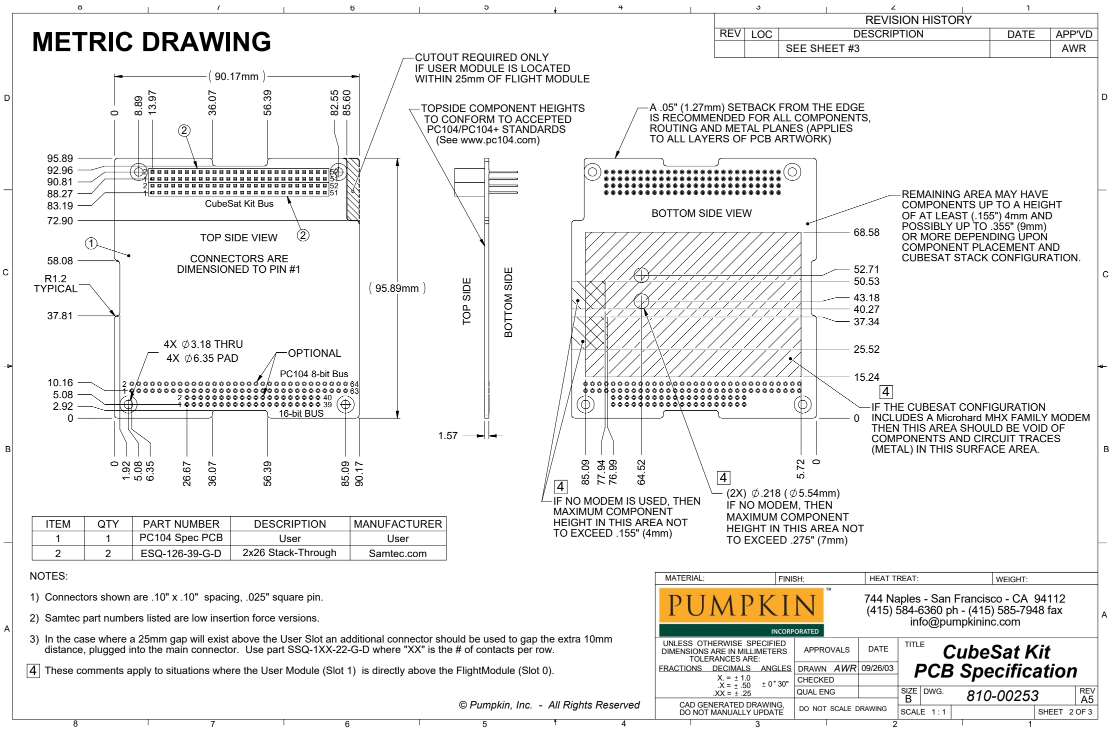

Figure 6.3 – *COMM System – PC104 physical specifications*

In spite of deciding to incorporate the PC104 standard for the overall Cubesat project, for the first version of the COMM System it was decided to slightly modify the dimensions of the PCB for design and manufacture reasons.

As depicted in Figure 6.4, the basic dimensions of the PCB are:

- Length: 95 mm
- Width: 90 mm
- Hole size: ⌀3.2 mm

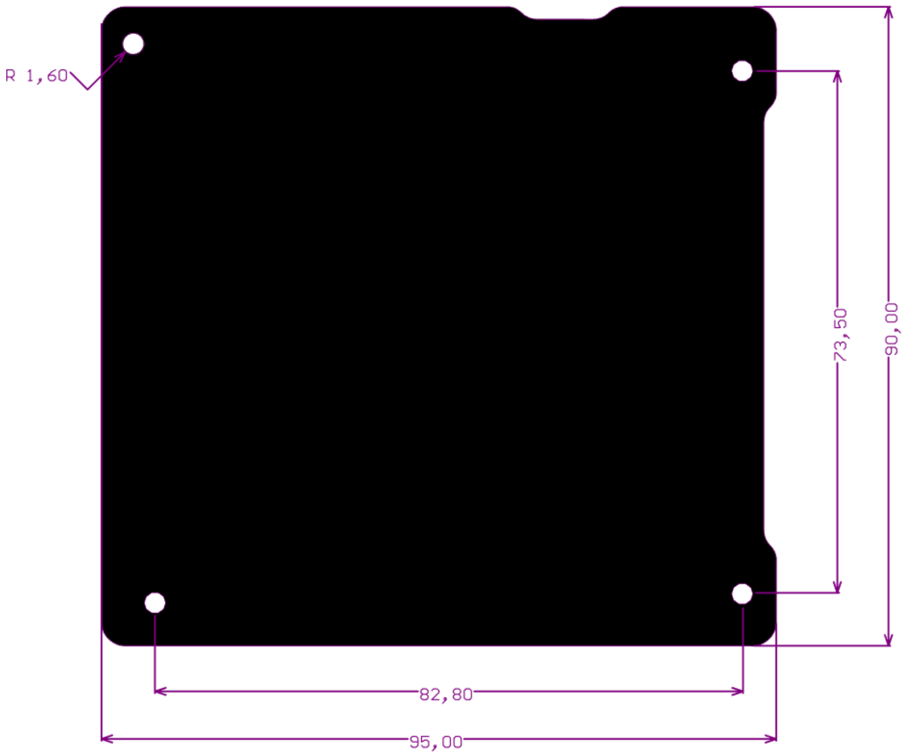

Figure 6.4 – *COMM System – PC104 physical specifications*

6

6.3 System interfaces

6.3.1 Cubesat Bus Data

The PC104 standard also defines the bus data. Since one of the peculiar characteristics of the standard is the self-stacking configuration, the connector employed in the design shall be compatible with it.

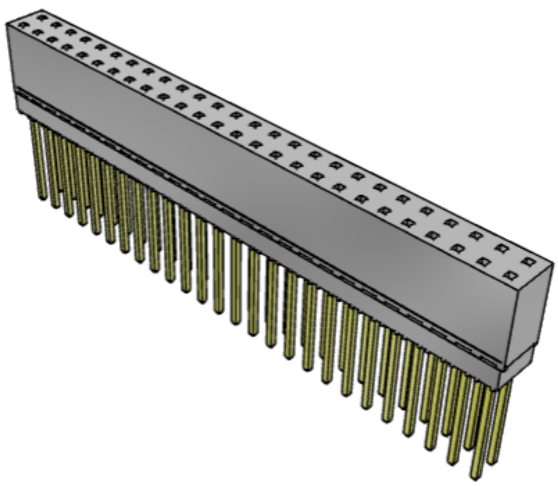

Figure 6.5 – *COMM System – Main bus connector. Source: Samtec*

The main bus is made by of two vertical through-hole connectors, 52 pins each, and a pitch between pins of 2.54 mm. Figure 6.5 shows the 3D model of the connector used for the system, the part number ESQ-126-39-G-D, from *Samtec*. A good particularity of this connector is its gold plated pins, which have the advantage of offering better mechanical and electrical features than a normal tin finished pin.

Electrical connection

The bus data electrical connection has been carried out as shown in Figure 6.6. Again, the placement of the main signals are defined by the PC104 standard, such as the 3.3 V, GND, or I^2C signals, while the rest of these pins are reserved for custom designs –as it is our case. A summary of the pin placements is shown in Table 6.1.

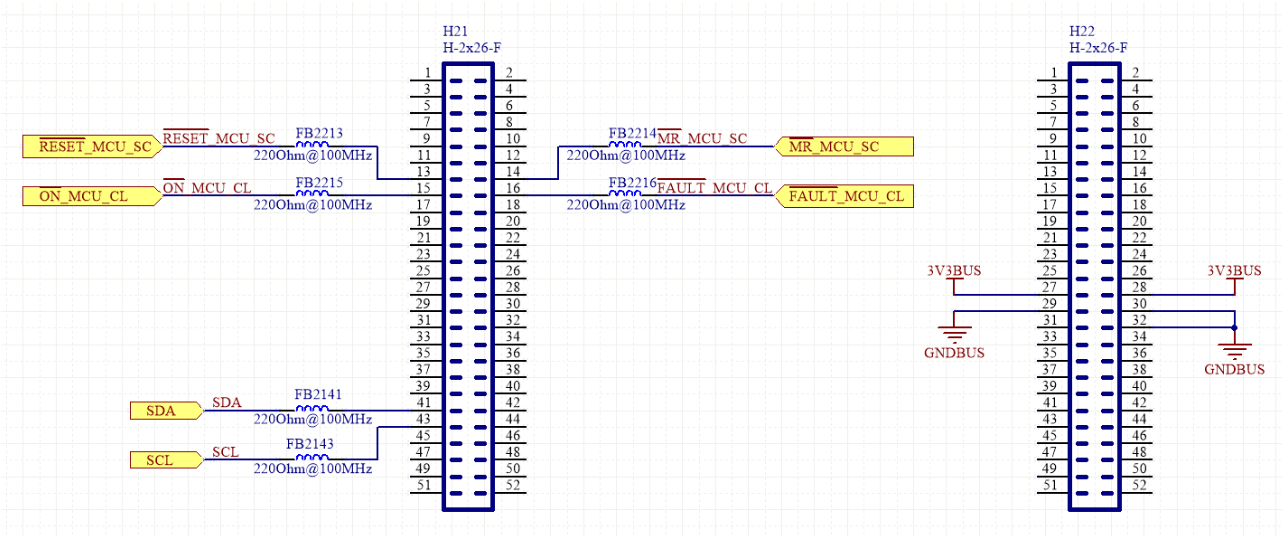

Figure 6.6 – *COMM System – Main bus connector. Electrical connection*

The lines referring to the supervisory circuit ($\overline{\mathrm{RESET}}$_MCU_SC and $\overline{\mathrm{MR}}$_MCU_SC) and the current limiter ($\overline{\mathrm{ON}}$_MCU_CL and $\overline{\mathrm{FAULT}}$_MCU_CL) are signal lines associated with some integrated circuits belonging to the power management module that will be detailed in Section 6.4. In summary, these lines let the OBC System do a MCU hard reset in case it suffers a problem related to a power issue.

SCL and SDA are I^2C lines. This serial data bus is the main bus within the Cubesat and it will be utilised for establishing a communication with the OBC. These lines connect directly to the MCU in the COMM System.

The 3.3 V and GND voltage reference are shared with the rest of the systems in the Cubesat. This means that special actions should be taken in order to avoid the injection of RF noise in the main bus. This action will be discussed in Section 6.4.

Connector	Pin #	Signal	Description
H21	13	$\overline{\text{RESET}}$_MCU_SC	Supervisory circuit $\overline{\text{reset}}$ output line
H21	14	$\overline{\text{MR}}$_MCU_SC	Supervisory circuit $\overline{\text{manual reset}}$ input line
H21	15	$\overline{\text{ON}}$_MCU_CL	Current limiter $\overline{\text{on}}$ input line
H21	16	$\overline{\text{FAULT}}$_MCU_CL	Current limiter $\overline{\text{fault}}$ output line
H21	41	SDA	I^{2}C Signal data
H21	43	SCL	I^{2}C Clock data
H22	27	3V3BUS	3.3 V voltage reference
H22	28	3V3BUS	3.3 V voltage reference
H22	29	GNDBUS	Ground reference
H22	30	GNDBUS	Ground reference
H22	32	GNDBUS	Ground reference

Table 6.1 – *COMM System – Main bus connector. Pin placement*

On the other hand, digital signals have been connected in series with a ferrite bead in order to diminish possible noisy signals coming from the RF circuits, or produced by bounces in the digital signal, or by any other part of the system from internal or external sources. Ferrite beads present an ohmic resistance dependent on the frequency, provoking a suppression of a high-frequency signal.

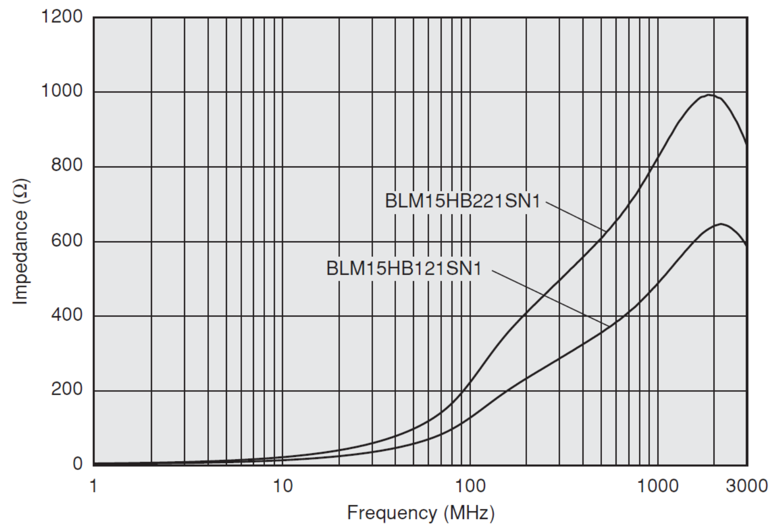

Figure 6.7 – *Murata BLM15 series. Frequency characteristics*

The one placed in these lines is a 0402 Noise Suppression Chip Ferrite Bead, BLM15HB221SN1D from *Murata*. The impedance characteristics of this ferrite bead is shown in Figure 6.7.

6.3.2 Antenna front end

Another important interface in the system is used for sending and receiving the RF signals, respectively, to and from the Antenna System. This interface is commonly known as *antenna front end*.

Figure 6.8 depicts the three different variations designed for the COMM System front end. A better quality image of the schematic can be found in Appendix C. As previously stated, this module considers three possibilities for the antenna assemblies in the Antenna System:

- Main connection: Unbalanced 50 Ω SMA connector
- Secondary connection: Balanced terminals. Room for a differential matching network.
- Secondary connection: 90° phased, 50 Ω balanced terminals.

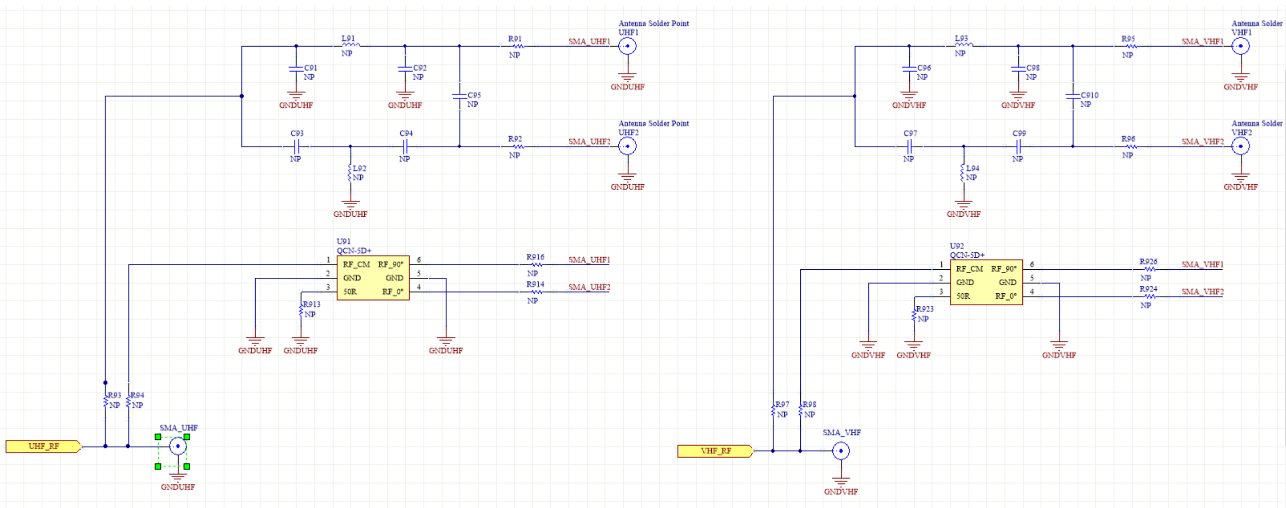

Figure 6.8 – *COMM System – Antenna front end*

Each kind of connection is duplicated to meet the need of the V/U multimode full-duplex operation. That is, one connector will be available for the UHF band and the other one for the VHF band.

Main connection

This configuration is expected to be the main connector to the Antenna System. It is a connector for an unbalanced line with a characteristic impedance of 50 Ω. This termination is one of the most common connectors in RF designs, and therefore, it allows to connect a wide number of commercial antennas, as well as any home-made antenna.

The chosen model has been a *Samtec* SMA-J-P-H-RA-TH1, which is a through-hole, right-angle, 50 Ω impedance jack connector, and it is able to handle frequencies from DC to 20 GHz signals. Figure 6.9 shows a picture of the connector employed in the COMM System.

Figure 6.9 – *COMM System – SMA RF. Source: Samtec*

Secondary front end

Since one of the expected applications for the COMM System PCB in this master's thesis is to enable its use as an Engineering Model, the GranaSAT team found interesting the possibility of connecting directly the antenna front end to the different kinds of antennas. This would admit any future experimentations with the Antenna System, and will make it easier due to a better integration of both systems.

For that reason, an unpopulated circuit has been included for two different antennas: two balanced terminals with a differential matching network, and two 90° phased, 50 Ω balanced terminals.

The most interesting part is the second one, the two 90° phased, 50 Ω balanced terminals. This configuration allows the connection of a Circular Polarisation (CP) antenna, such as a turnstile antenna. The difference of phase between the two terminals is achieved by using a ceramic power splitter, the QCN-5D+ from *Minicircuits*. The component is a Low Temperature Co-fired Ceramics (LTCC) circuit and it is integrated in a 3.2 x 1.6 mm package, as shown in Figure 6.10, which allows an incredibly compact design.

Figure 6.10 – *COMM System – Minicircuits power splitter. Source: Minicircuits*

6.4 Electronics design

In this section the electronic features of the system will be explained from a component selection perspective. For a better understanding of the main design referring to the system schematics in Appendix C is recommended.

6.4.1 Power monitoring

Current limiter

The system shall control the power line in order to avoid overcurrent events and short circuits. Since there are two values to limit, 1 A for each module and 2.5 A for the High Power Amplifier module, there will be two different components.

For the 1 A limitation, a *MAX890* from *MAXIM* was chosen. On the other hand, a *MAX14575*, also from *MAXIM*, was the chosen one for the 2 A limitation. Since both components come from the same manufacturer, the behaviour of both circuits are very similar: they have an output line to indicate events and cut off the power if an overcurrent event happens.

Those components are placed in series with the 3V3BUS line and the new regulated line for each module. A ferrite bead is also placed to ensure a high frequency isolation. Figure 6.11 shows the circuit designed for the MCU, UHF and VHF modules, while 6.12 shows the circuit employed for the HPA module.

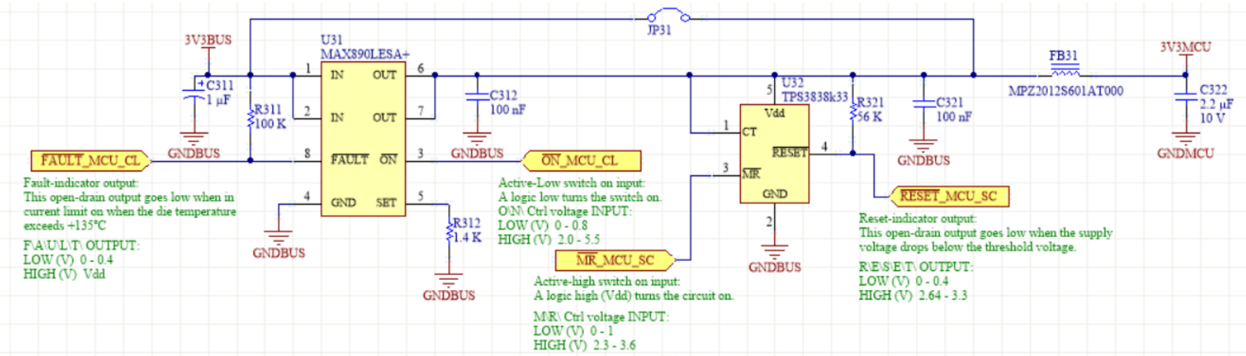

Figure 6.11 – *COMM System – 1 A current limitation and voltage monitoring diagram*

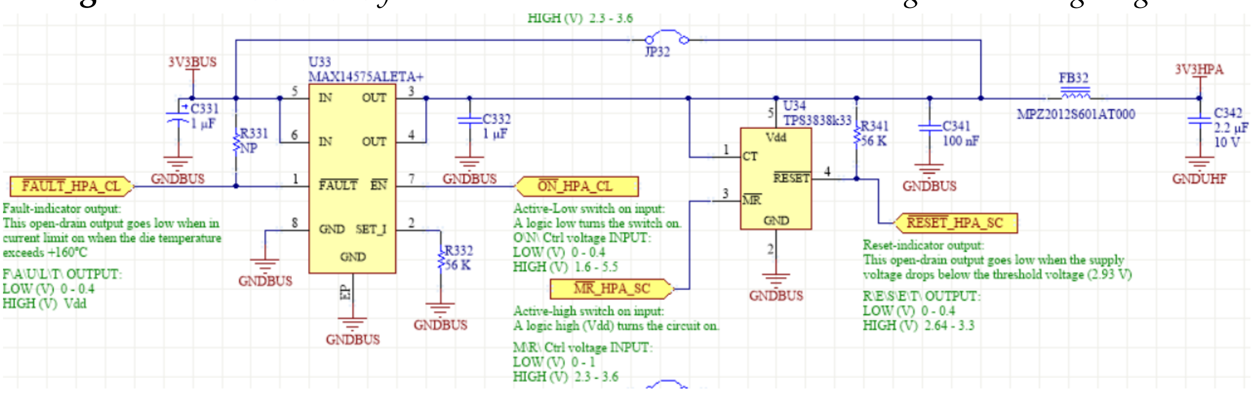

Figure 6.12 – *COMM System – 2.5 A current limitation and voltage monitoring diagram*

Voltage monitoring

The chosen IC is the *TPS3838k* from *Texas Instruments*. It is connected in parallel with the current regulated line. The device will monitor the voltage level and in case this level is out of range, an output line will be triggered. It also has the functionality of temporising the turning on of the device by using the output reset line.

The placement of the chip is shown in Figure 6.11, and the same component in each different module is used.

6.4.2 Micro Controller Unit Module

The chosen MCU is the *XMC1302* from *Infineon*, a 32-bit ARM Cortex M0 processor. A comparative table (see table 6.2) was done in order to choose the most suitable one. In the table, the best component features is marked in green, while the worst ones are in red.

The features of the IC are numerous: it has available I2C, UART and SPI serial interfaces, which ensure a correct communication with other parts of the system. In addition, the component is Automotive graded, which means that a correct behaviour under extreme conditions is ensured by the manufacturer.

In Figure 6.13 and Table 6.3, the pin mapping connection of the MCU is shown. It can be noticed that almost all its terminals have been employed. In addition, a 0Res was placed in each pin, in order to isolate it in case that any modification in the board was required.

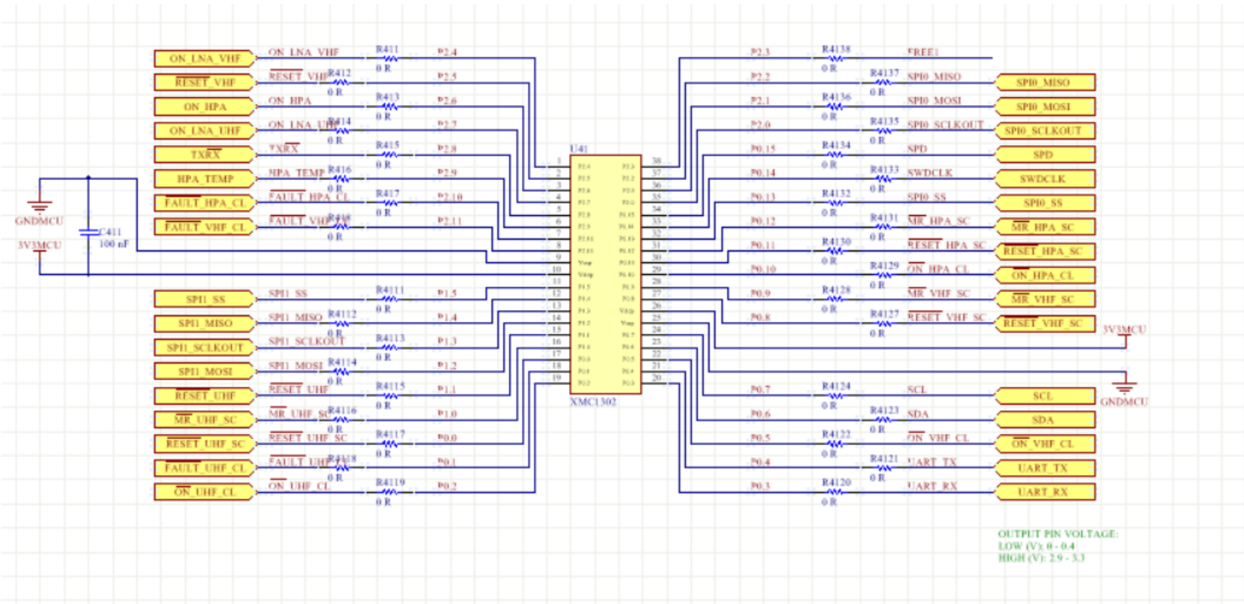

Figure 6.13 – *COMM System – MCU diagram*

Also a nice feature worth mentioning is that the MCU has an internal oscillator, which saves designer the necessity of placing an external oscillator.

Micro Controller Unit				
Feature	**MSP430F1612**	**PIC18LF6720**	**ATMega128A**	**XMC1302**
Manufacturer	Texas Instruments	Microchip	Atmel	Infineon
Used in missions	CubeCat, OSSI, OUFTI	CP2, CP3, CP4, CP5, CP6, CubeCat, CubeStar	CubeStar, AAUSAT3,4,5	Not Identified
Temperature Range [°C]	-40 – $+85$	-55 – $+125$	NA	-40 – $+105$
Max. current consumption [1] [mA]	1	1	5	2
Architecture	16bit RISC	16bit RISC	8bit RISC	32bit RISC ARM CORTEX
Flash memory [KB]	55	128	128	200
SRAM Memory [KB]	5	4	4	16
EEPROM Memory [KB]	1	1	4	8
Watchdog timer [KB]	Yes	Yes	Yes	Yes
USIC	1xI2C, 1xUART, 2xSPI	1xSPI, 1xI2C	1xSPI	2xSPI, 1xI2C, 1xUART
Debug Interface	JTAG	MPLAB	JTAG	SWD
Price Digikey / Mouser [$]	16.9/16.3	10.5/–	14.9/ – .4	3.5/3.8

Table 6.2 – *COMM System – MCU market study*

[1] Max. current consumption at $f_{osc} = 1$ MHz

The pin mapping of the MCU in the system is as follows.

#1	P2.4	ON_LNA_VHF	FREE_1	P2.3	#38
#2	P2.5	$\overline{\text{RESET}}$_VHF	SPI0_MISO	P2.2	#37
#3	P2.6	ON_HPA	SPI0_MOSI	P2.1	#36
#4	P2.7	ON_LNA_UHF	SPI0_SCLK	P2.0	#35
#5	P2.8	TX$\overline{\text{RX}}$	SPD	P0.15	#34
#6	P2.9	HPA_TEMP	SWDCLK	P0.14	#33
#7	P2.10	$\overline{\text{FAULT}}$_HPA_CL	SPI0_SS	P0.13	#32
#8	P2.11	$\overline{\text{FAULT}}$_VHF_CL	$\overline{\text{MR}}$_HPA_SC	P0.12	#31
#9	-	GNDMCU	$\overline{\text{RESET}}$_HPA_SC	P0.11	#30
#10	-	3V3MCU	$\overline{\text{ON}}$_HPA_CL	P0.10	#29
#11	P1.5	SPI1_SS	$\overline{\text{MR}}$_VHF_SC	P0.9	#28
#12	P1.4	SPI1_MISO	$\overline{\text{RESET}}$_VHF_SC	P0.8	#27
#13	P1.3	SPI1_SCLK	3V3MCU	-	#26
#14	P1.2	SPI1_MOSI	GNDMCU	-	#25
#15	P1.1	$\overline{\text{RESET}}$_UHF	SCL	P0.7	#24
#16	P1.0	$\overline{\text{MR}}$_UHF_SC	SDA	P0.6	#23

#17	P0.0	$\overline{\text{RESET}}$_UHF_SC	$\overline{\text{ON}}$_VHF_CL	P0.5	#22
#18	P0.1	$\overline{\text{FAULT}}$_UHF_CL	UART_TX	P0.4	#21
#19	P0.2	$\overline{\text{ON}}$_UHF_CL	UART_RX	P0.3	#20

Table 6.3 – *COMM System – MCU pin mapping*

6.4.3 Receiver RF chain

The VHF RF chain is made up of the transceiver and the Low Noise Amplifier. Since this part is intended for reception purposes, the transceiver will only work as a receiver.

Transceiver

The transceiver is one of the key components in the system. For that reason it has to be carefully selected. Although it is specified here in the VHF module, the transceiver must be able to operate also in the UHF band.

In Table 6.4 are summarised the different features of transceivers in the market. The chosen one was the *CC1125* from *Texas Instruments*. It is able to operate in the ISM bands under 1 GHz and support many modulation schemes, such as FSK and GMSK.

It communicates with the MCU by using a SPI serial interface and several hardware lines that are used to reset the device, for example.

It was not possible to identify if the transceiver has been used in some Cubesat mission, but his predecessor has been used in many missions. Therefore it has *flight heritage* and that is an important feature to take into account.

In addition, the manufacturer provides a circuit application, which makes the design phase much easier. This also includes the design of the discrete elements *balun* or the matching networks.

In Figure 6.14, the circuit employed for the VHF transceiver is shown. It has been included a 40.00 MHZ signal reference TCXO, with a 2.5 ppm deviation, to ensure a correct frequency behaviour during the working time.

Transceiver				
Feature	**ADF7021**	**CC1000**	**CC1125**	**SI4362**
Manufacturer	Analog Devices	Texas Instruments	Texas Instruments	Silicon Labs
Used in missions	OSII, OUFTI	CP2, CP3, CP4, CP5, CP6, CubeCat, CubeStar	Not Identified	Not Identified
Temperature Range [°C]	-40 — $+85$	-40 — $+85$	-40 — $+85$	-40 — $+85$
Current Consumption in RX [mA]	18	29	27	14
Signal modulation	FSK, 4FSK, MSK	FSK, OOK	FSK, 4FSK, MSK, GMSK, ASK, OOK	FSK, 4FSK, MSK, GFSK, ASK, OOK
Bitrate [1] [kbps]	0.15 — 200	0.6 — 76.8	0 — 200	0.1 — 1000
Operating frequencies [MHz]	135 — 650	300 — 1000	136 — 960	142 — 1050
RX Sensibility [1] [dBm]	-114	-116	-123	-110
Price Digikey / Mouser [$]	5.3/5.1	9.4/9.4	5.5/5.4	–/1.9

Table 6.4 – *COMM System – Transceiver market study*

[1] FSK modulation
[2] Measurement conditions: 9.6 kbps, FSK, BER= 10^{-3}, 70 cm band.

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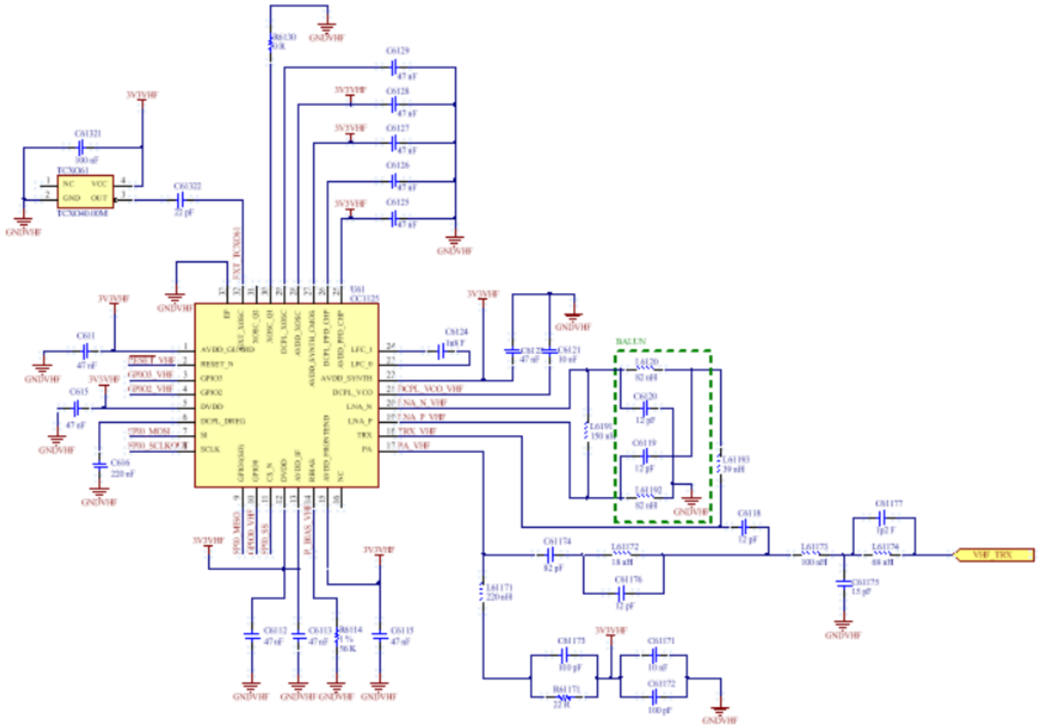


Figure 6.14 – *COMM System – VHF Transceiver diagram*

Low Noise Amplifier

The LNA is the more important element in the reception chain. As it has be done for the other elements, a comparative table (see Table 6.5) has been created in order to choose the most suitable component. Moreover, the LNA must also work in the UHF frequency band.

The chosen one is the *BGU6104* from *NXP*. It is an IC designed for communication applications and has excellent features: gain of 24 dB and Noise Figure of 0.8 dB with only a current consumption of 6 mA.

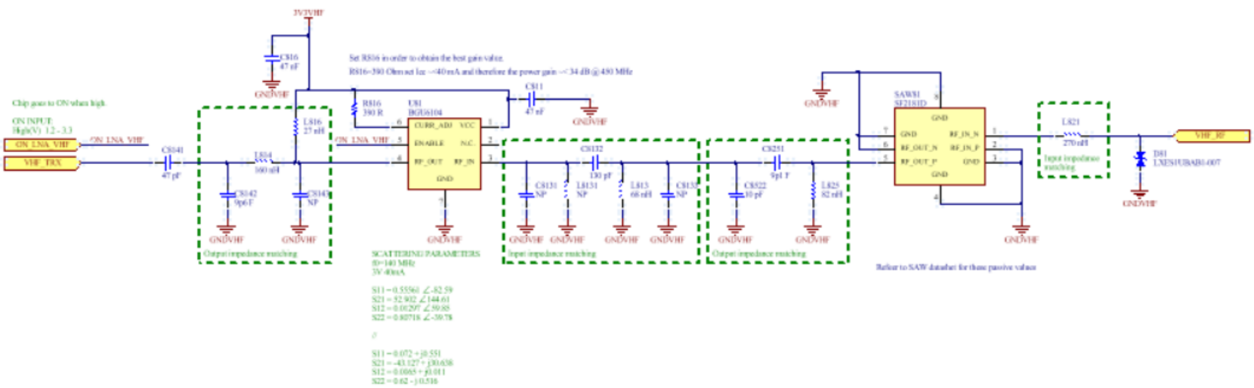


Figure 6.15 – *COMM System – VHF LNA and filter diagram*

The diagram of the receiver chain in the VHF band is shown in Figure 6.15. It is made up of the LNA, a SAW filter centred in 140 MHz, and a discrete element band pass filter.

The SAW filter is the *SF2181D* from *Murata*, and ensures that out of band frequencies coming from the antenna are rejected before going to the LNA.

An ESD suppressor at the SMA connector is also placed in order to avoid any damage due to static discharges. The selected one is the *LXES1UBAB1* from *Murata*, which is designed for high-speed applications and does not introduce relevant parasitic capacitances in the line.

Low Noise Amplifier

Feature	**BGB741L7**	**MAX2373**	**MGA-62563**	**BGU6104**
Manufacturer	Infineon	Maxim	Avago	NXP
Used in missions	Not Identified	Not Identified	Not Identified	Not Identified
Temperature Range [°C]	−40 − +85	−40 − +85	−40 − +85	−40 − +85
Current Consumption [mA]	10	6	62	6
Operating Frequency [MHz]	50 − 5000	100 − 1000	100 − 3500	40 − 4000
Gain [dB]	21	17	23	24
Noise Figure [dB]	1.1	1.8	1.1	0.8
Max. RF power input [dBm]	+20	+5	+21	+12
ON/OFF control	Yes	Yes	No	Yes
Price Digikey / Mouser [$]	0.9/0.9	2.4/2.3	2.7/2.4	−/0.7

Table 6.5 – *COMM System – Low Noise Amplifier (LNA) market study*

6.4.4 Transmitter RF chain

This module is the most complex in the system and with more components. It has to ensure a half-duplex communication when required. Nevertheless, the expected use of this module in a nominal work is as a transmitter.

Since the reception components are the same than those used in the VHF RF chain, in this section only the new components that are just employed for the UHF RF chain will be highlighted.

Transceiver

The transceiver employed in the UHF RF chain is the same than the one used in the VHF RF chain, but with recalculated discrete elements. Therefore, the behaviour and features will be the same. Figure 6.16 shows the diagram designed for this component.

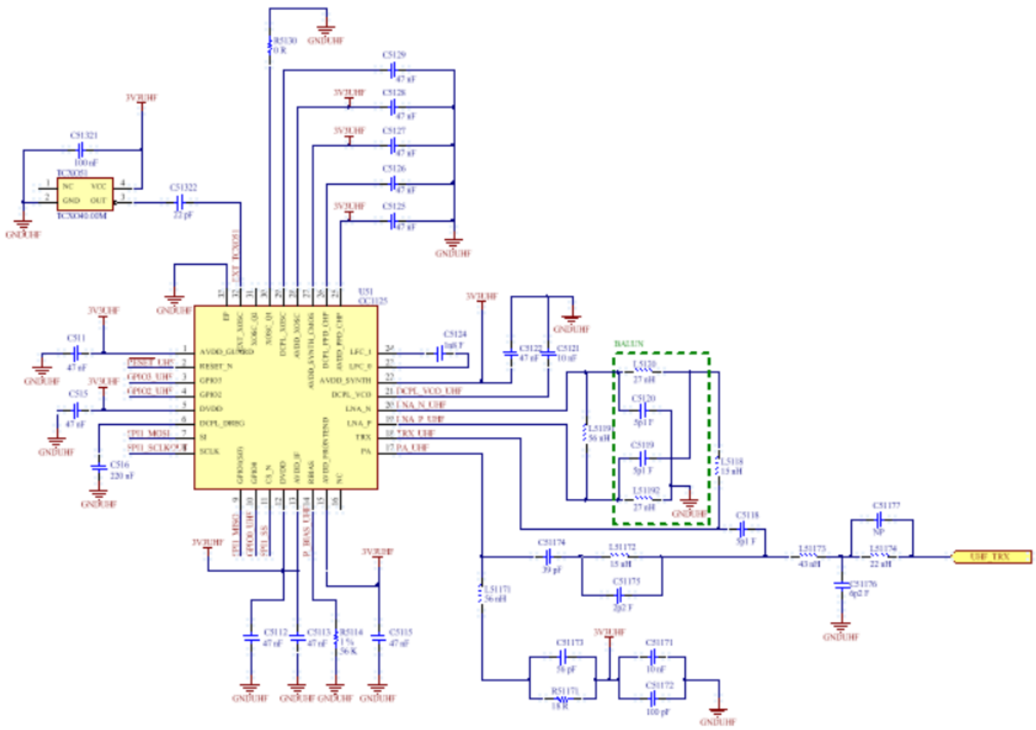


Figure 6.16 – *COMM System – UHF Transceiver diagram*

High Power Amplifier

The HPA element is one of the key component in this module, for this reason a study of the available options in the market has been performed. See Table 6.6. The *RF5110G* from *RF Microdevices* was chosen. It has a great flight heritage from other Cubesat missions and it also has excellent features among the analysed components.

The RF5100G IC is able to work in a wide frequency range and it also offers a high gain value of 33 dB, with a P1dB of +32 dBm, which ensure the expected power level at the system output.

High Power Amplifier				
Feature	**RF5110G**	**HMC453ST89E**	**RF6886**	**SKY65116**
Manufacturer	RF Microdevices	Hittite Microwave Corp.	RF Microdevices	Skyworks
Used in missions	OSII, OUFTI, CubeStar, SwissCube	Not Identified	CubeCat (main)	CubeCat (secondary)
Temperature Range [°C]	−40 − +85	−40 − +85	−40 − +85	−40 − +85
Current Consumption [1] [mA]	2400	725	3100	1300
Power-Added Efficiency (PAE) [2] [%]	51	41	55	42
Operating Frequency [MHz]	150 − 960	400 − 2200	100 − 1000	390 − 500
P1dB [2] [dBm]	+32	+31	+34	+32
Gain [3] [dB]	33	21	33	35
ON/OFF control	Yes	No	No	Yes
Price Digikey / Mouser [$]	7.1/−	17.9/16.9	8.3/−	5.3/5.3

Table 6.6 – *COMM System – High Power Amplifier market study*

[1] Absolute maximum ratings
[2] Measurement conditions: $V_{cc} = 3.3$ V, 430 − 470 MHz

The Figure 6.17 shows the diagram designed for this component. The manufacturer provides a reference design with the value of most of the components, which facilitate the designing task a lot.

It receives the input signal from the left, and after amplifying the signal, it delivers the output signal to the right part of the diagram. The impedance matching networks were designed for the frequency operation of 435 MHz.

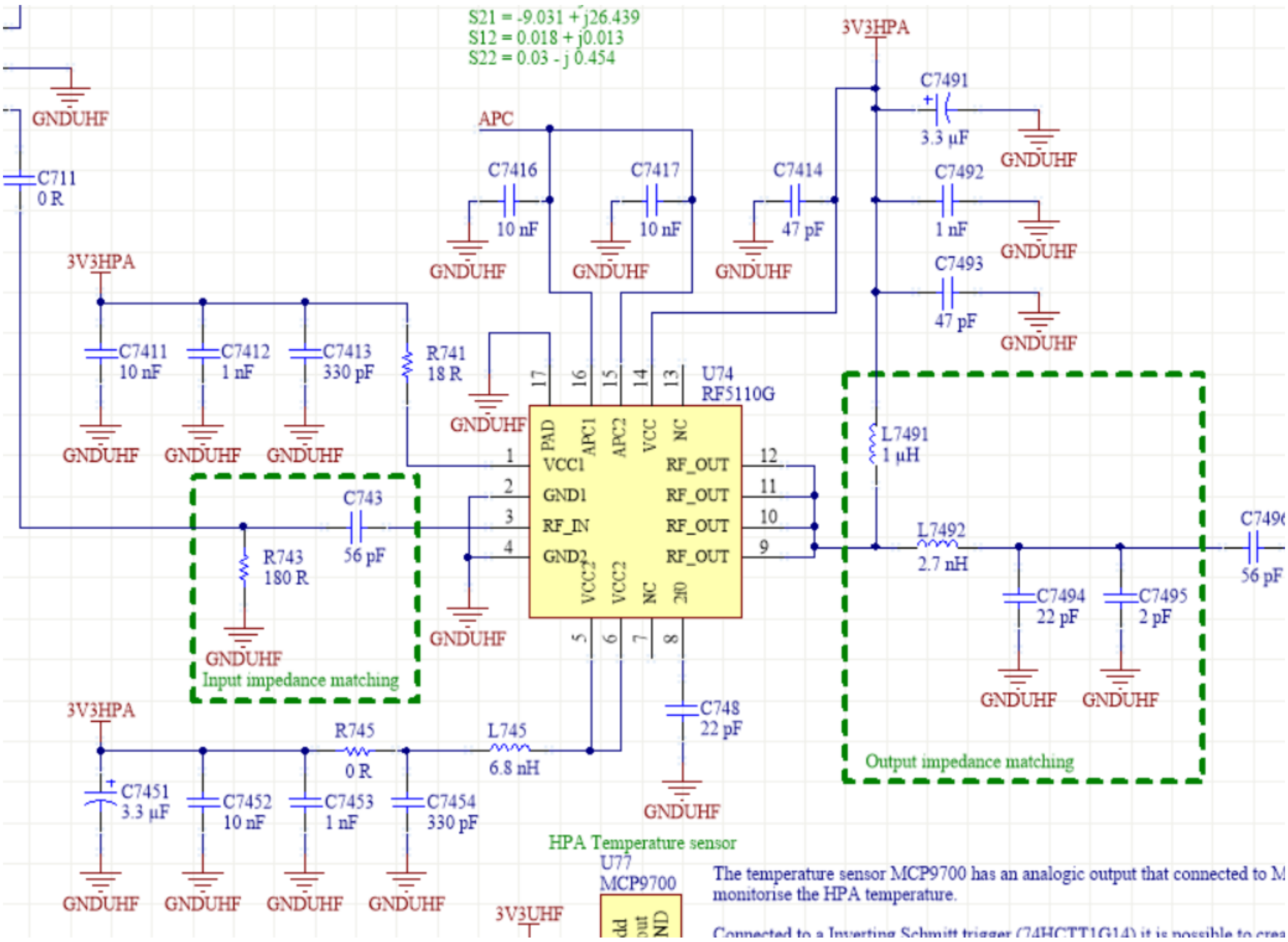


Figure 6.17 – COMM *System* – UHF HPA *diagram*

Single Pole Double Throw (SPDT)

A couple of SPDT have been used to select the path of the signal in the module. This is necessary for the half-duplex operation in the UHF band. It will allow to switch the elements connected between the transceiver and the antenna, or the LNA when receiving signal, or the HPA when transmitting.

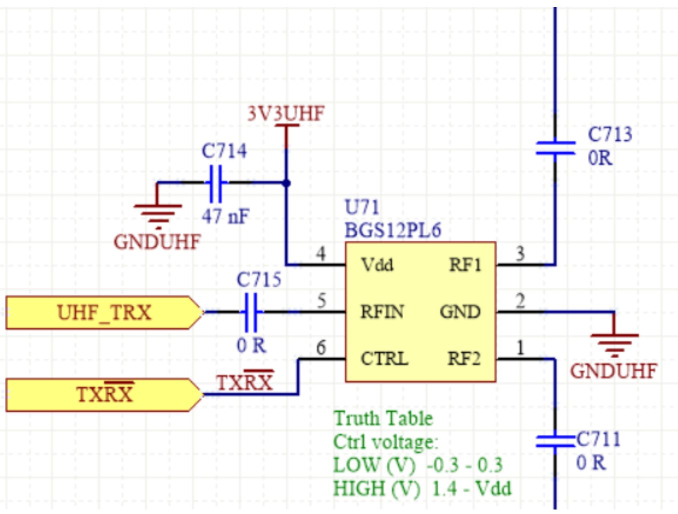


Figure 6.18 – COMM *System* – SPDT *diagram*

As it was considered also as a critical component, a market study was performed in order to choose the most suitable element. This can be seen in Table 6.7. The chosen one has been the *BGS12PL6* form *Infineon*.

It is a wide frequency range SPDT and can handle an input power up to +36 dBm with only an Insertion Loss of 0.3 dB. In addition, it has an internal logic circuitry that is used for switching between lines.

Single-Pole Double-Throw			
Feature	**BGS12PL6**	**HMC536MS8**	**PE42420**
Manufacturer	Infineon	Hittite Microwave Corp.	Peregrine Semiconductor
Used in missions	Not Identified	Not Identified	Not Identified
Temperature Range [°C]	−40 – +85	−40 – +85	−40 – +85
Current Consumption [μA]	200	50	120
Operating Frequency [MHz]	40 – 4000	DC – 6000	100 – 6000
Input P0.1dB [dBm]	+38	+29	+23
Max. RF input power [1] [dBm]	+36	+39	+30
Insertion Loss [dB]	0.3	0.4	0.9
On-chip control logic	Yes	No	No
Price Digikey / Mouser [$]	0.5/–	5.8/5.4	–/–

Table 6.7 – *COMM System – SPDT market study*

[1] Measurement conditions: Frequency : 150 MHz

Temperature sensor

In order to protect the HPA component from overheating when it is transmitting, a temperature sensor was placed close to it. The chosen temperature sensor is the *MCP9700* from *Microchip* and can measure the temperature from $-40°C$ to $150°C$.

The temperature sensor is employed in a small logic circuitry that is shown in Figure 6.19. The sensor provides the temperature readings in an analog line, which is connected to an Inverting Schmitt Trigger that triggers when a determinate value of voltage is surpassed.

The output of the Inverting Schmitt Trigger is connected, together with other controlling logic signals, to an AND gate, that in accordance with the combination of values, will turn off or turn on the HPA component.

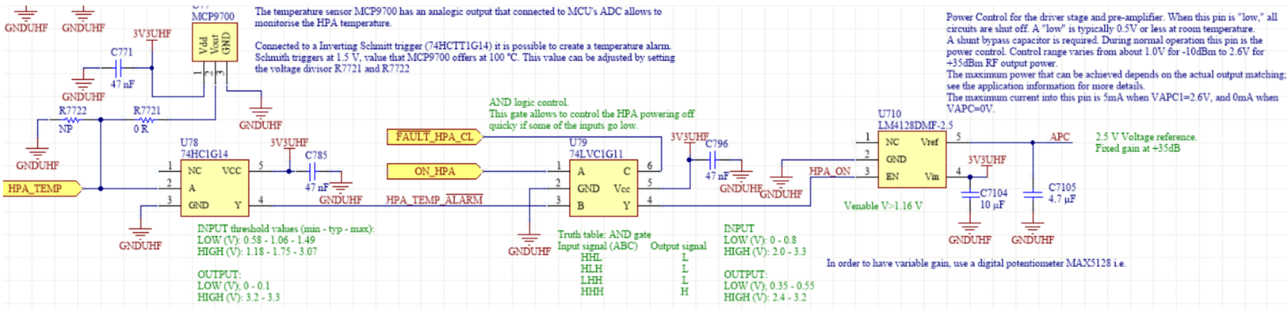


Figure 6.19 – *COMM System – Temperature sensor diagram*

This combination of components will ensure a very fast response for overheating events, ensuring in this way that the component will be protected any time from this risk.

6.4.5 Ground diagram

Defining a correct grounding scheme for the spacecraft is an important task in the spacecraft architecture design. A wrong approach can put at risk the overall mission success, due to a bad grounding work will increase the Electromagnetic Interference (EMI) between systems and, therefore, the likelihood of an Electromagnetic Compatibility (EMC) success will diminish.

The grounding architecture design shall be performed at early stages of the mission design, because some spacecraft systems will depend on the required architecture, although hybrid solutions are allowed. Although the grounding architecture for the GranaSAT-I does not exist, a ground design for the COMM System has been performed following a NASA recommendation: *Electrical grounding architecture for unmanned spacecraft* [70].

When grounding the system, the most important thing is to avoid the creation of ground loops. A ground loop is created when two or more ground references are connected with each other, and there is an electric potential difference among them. The effect is depicted in Figure 6.20. These loops act as an antenna and, in consequence, they radiate and introduce magnetic field noise from and to the circuit. Therefore, it is recommended to avoid this effect at all costs.

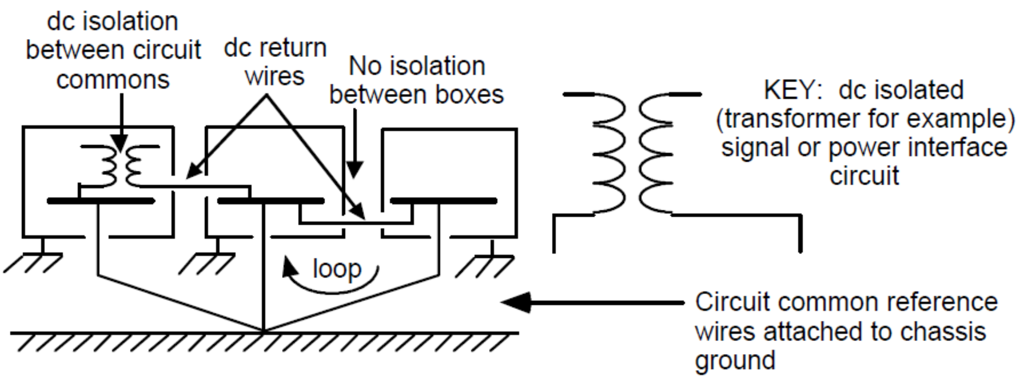
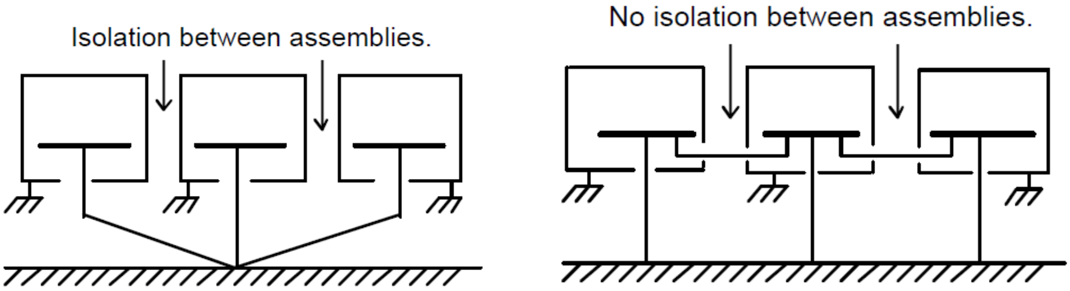


Figure 6.20 – *Grounding diagram. Source: [70]*

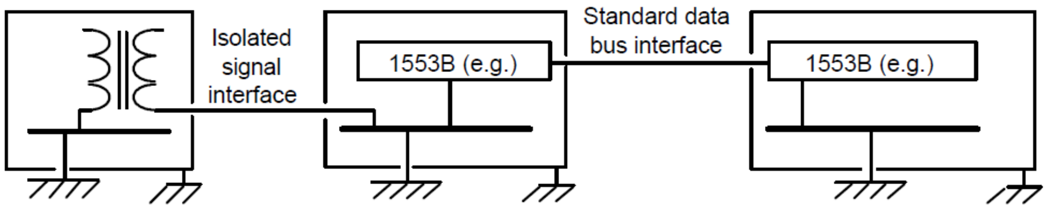
There are several possible topologies for grounding systems. A very common connection is the *single-point ground*, known as *star ground*, shown in Figure 6.21a. This procedure connects all grounds in the system in a single point, ensuring the isolation between assemblies. However, when the wires are very long, they will introduce a parasitic inductance to the ground path that will affect the high frequency signals.



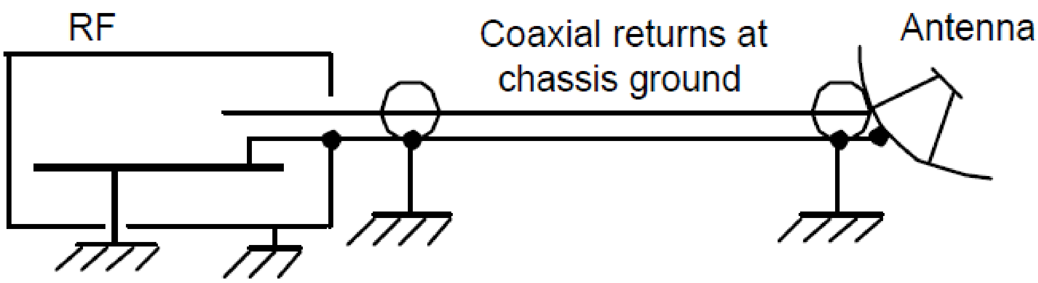
(a) *Single-point 'Star' ground* **(b)** *Multiple-point ground*

Figure 6.21 – *Types of grounding systems. Source: NASA [70]*

Nevertheless, sometimes the direct connection of grounds from different boards will be unavoidable, as shown in Figure 6.21b. This topology is called *multiple-point ground* and is employed, for example, in a RF circuit when a signal is transmitted from the transmitter to the antenna through a coaxial cable. Figure 6.22b depicts a similar scenario to the one explained. This grounding system shall be used in the COMM System when connecting with the Antenna System in the Cubesat.



(a) *Command, signal and data interface grounding*



(b) *RF grounding*

Figure 6.22 – *Hardware ground architecture. Source: NASA [70]*

Another kind of architecture that should be considered in the COMM System is the one shown in Figure 6.22a, which is related to the Cubesat main bus. For the design of the system, it has been assumed that the power lines are properly treated in the Electrical Power System, and both 3.3VBUS and GNDBUS signals have been isolated at the output port of the EPS board.

The grounding connection for the COMM System is shown in Figure 6.23. As it can be seen, the grounds from different modules within the system have been isolated from each other and connected in a single point, creating a star connection inside the board.

By isolating the different parts that can cause harmful interference, the cross-talking between modules and EMI will diminish. For this reason, the board contains four different ground references: GNDUHF is for the RF UHF chain, GNDVHF is for the RF VHF chain, GNDMCU is for the MCU, and GNDBUS is the main ground reference in the system and it is provided by the EPS.

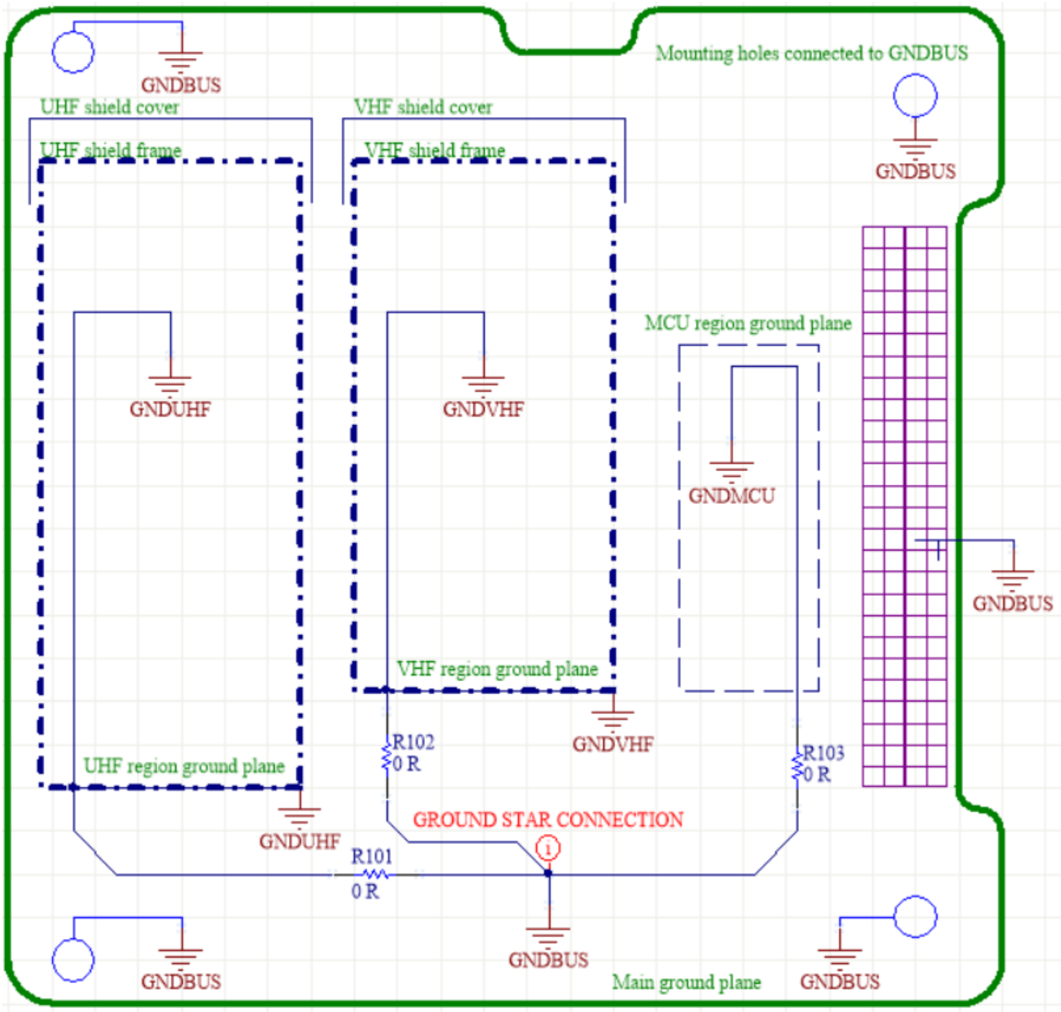


Figure 6.23 – *COMM System – Ground diagram*

In addition, the UHF and VHF RF circuits are individually shielded. The shield, together with the ground plane, will conform a *Faraday Cage* that will increase isolation from external interference, which will improve the overall system performance. The shield is soldered in a designated area within the PCB.

On the other hand, plated pads in the PCB are connected to GNDBUS, connecting therefore the board ground to the spacecraft chassis in order prevent the PCB from having a floating ground with respect to the Cubesat structure.

6.5 Board design

Once the electric design has been done, it is necessary to pass that design from paper to a physical product, where the electrical connections take place and the components are soldered. This is performed in a board that take the name of a Printed Circuit Board (PCB).

The EDA tool that has been employed for the PCB design has been *Altium*, which is one of the most used tools for designing PCB in the world. In addition, the University of Granada has some free student licenses available for its use in the laboratory.

Layer Stack

A PCB is made up of copper layers that are interconnected with each other. The number of layers is variable and it will depend on how complex the design is. In addition, the number of layers will define the manufacturing process and its final price. The higher the number of layers, the more expensive.

There are numerous ways to design and arrange the layers in a PCB. The final application of the circuit will define to a great extent the final arrangement of the layers in the board, also known as the *layer stack*.

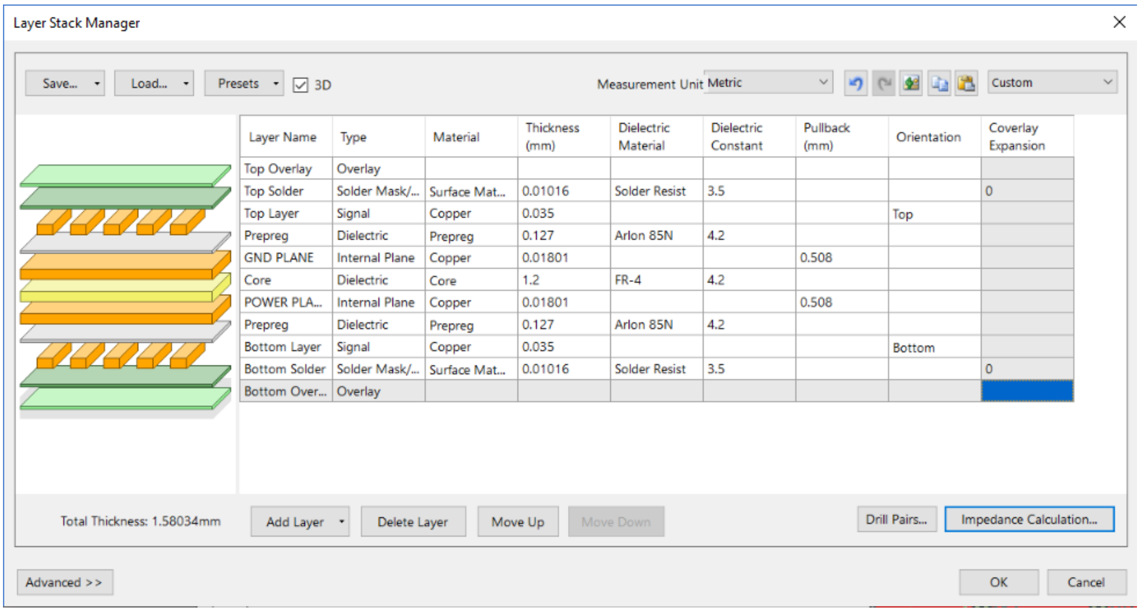


Figure 6.24 – COMM *System – Layer Stack*

As it will be detailed in the next part of this section, micro-strip transmission lines have been included in the design. This circumstance forces the layer stack to have, at least, one ground plane under the RF line. In addition, since the design is make up of numerous digital lines, it will be useful to have an extra layer for digital signal lines. Taking into account these two conditions, and trying always to have a layer stack that is symmetrical and with the smallest possible number of layers, a 4 layer PCB can be suitable for the COMM system.

The chosen layer stack is depicted in Figure 6.24, and it is composed of the next layers:

(1) Signal layer (Mostly RF)

(2) Prepreg

(3) Ground plane

(4) Dielectric core

(5) Power plane

(6) Prepreg

(7) Signal layer (Only digital)

With this layer stack, the top signal layer will have below a ground plane –required for a microstrip transmission line–, and the bottom signal layer will be isolated from the first one thanks to the power plane and the ground plane.

Between each copper layer, a dielectric layer that can be a *prepreg* or a *core* must be placed. The difference between them is their use during the manufacturing process. The core is a dielectric layer with two copper plane in each side, while the prepreg is a dielectric layer impregnated with resin that is used as a bonding agent between the core and other copper layers.

6

Since the PCB layer stack shall be symmetrical, normally the centre will be taken by the core, and the rest of dielectric layers will be prepreg. Nevertheless, complex combinations can be done without problem.

Although there are many available options, for the ordered PCB the manufacturer did not allow to choose the prepreg and core materials because of the low price of the trade. Some prepregs are qualified for space applications and must be used for the Flight Model. One of them is the *Arlon 85N*, which is resistant to high temperatures and also to drill cracking.

Microstrip impedance

For any RF or high-speed circuit, it is very important to have an accurate control of the impedance of the trace. This is only possible when the transmission line fabrication is controlled and the design takes into account this circumstance.

The EDA tool employed for the PCB design has the option of calculating the impedance value of the trace, taking into account the configuration of the layer stack (thickness and dielectric constant of the dielectric).

By using Equations 6.5.1 and 6.5.2, the tool is able to calculate, respectively, the characteristic impedance of the microstip line, and the width required for a microstip line to obtain a demanded impedance. The only values that are necessary to know are the width and height of the microstrip trace, the distance between the trace and the ground plane, and the characteristic impedance of the line.

Figure 6.25 shows a capture from *Altium* and the equations employed for the impedance calculation. These equations in the image are the same than 6.5.1 and 6.5.2.

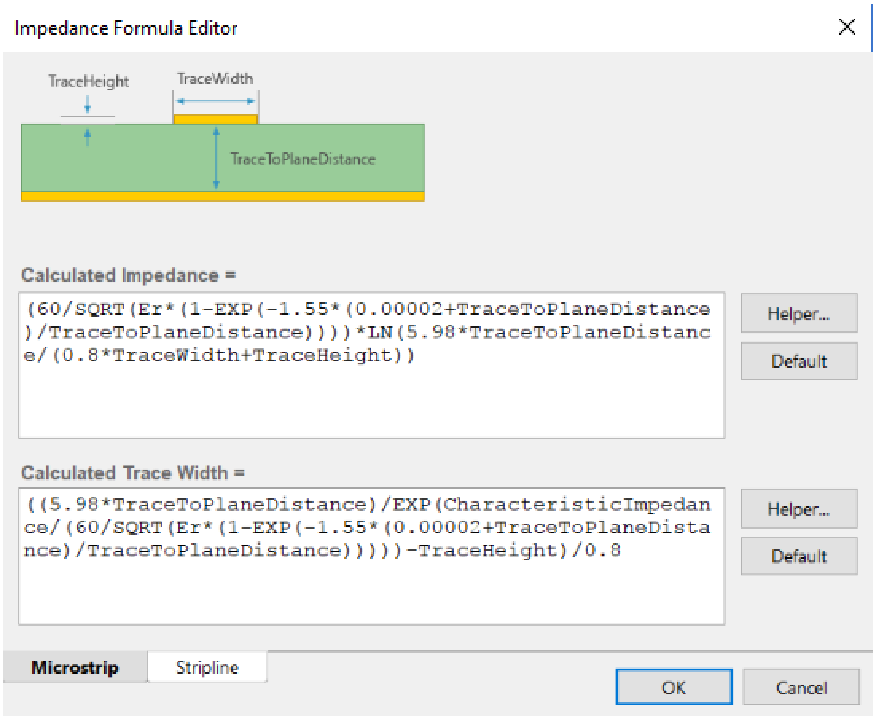


Figure 6.25 – *COMM System – Microstrip impedance control*

To obtain the characteristic impedance, Z_0, from the width and height of the trace and the distance between planes, the next expression is used:

$$Z_0 = 60\left[\epsilon_r\left(1-\exp\left(-1.55\frac{0.00002+d}{d}\right)\right)\right]^{-1/2}\ln\left[\frac{5.98d}{0.8w+h}\right] \qquad (6.5.1)$$

Where:

$d =$ Trace to plane distance [m]
$w =$ Trace width [m]
$h =$ Trace height [m]

On the other hand, to know the width of the trace from the characteristic impedance, the distance between planes and the trace height,the next expression will be used:

$$w = 1.25\left[\frac{5.98d}{\exp\left(\frac{Z_0*\sqrt{\epsilon_r\left[1-\exp\left(-1.55\frac{0.00002+d}{d}\right)\right]}}{60}\right)} - h\right] \qquad (6.5.2)$$

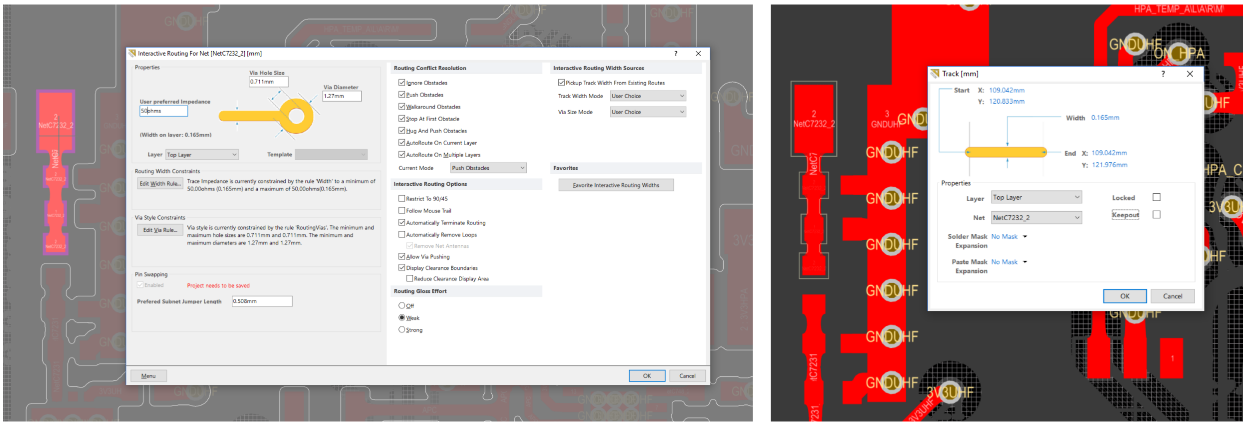
Where:

Z_0 = Characteristic impedance $[\Omega]$
d = Trace to plane distance $[m]$
h = Trace height $[m]$
ϵ_r = Dielectric constant

For the COMM System, Equation 6.5.2 was employed to know the width of the microstrip line to obtain a characteristic impedance of 50 Ω. The conditions are:

- $h = 35\ \mu m$ – Imposed by the manufacturer: 1 oz. characteristic
- $d = 0.127\ mm$ – Chosen by the designer, also it is a manufacturer standard.
- $\epsilon_r = 4.2$ – Chosen by the designer: Arlon 85N prepreg.

The obtained width is: $w = 0.1647\ mm$. The value can be compared with the one provided by *Altium*. Figure 6.26a shows the window used for automatic trace width control, which is set to 50 Ω, and Figure 6.26b shows the width of the trace that has been eventually placed in the PCB. See the trace width in the PCB is $w = 0.165\ mm$.



(a) *Altium automatic trace width control* **(b)** 50 Ω *trace width*

Figure 6.26 – *Altium microstrip impedance control*

Finishing with this section, it would be interesting to recall a common mistake. It is usual to place a ground plane covering all the unused space in the board. This technique is employed a lot in digital designs, as it improves the ground quality and may improve the EMI as well.

The problem arises when a ground plane is placed next to a microstrip line. This decision will ruin the characterization of the trace impedance because it will become a hybrid microstrip/coplanar transmission line.

To avoid this issue, the GND plane must be far from the microstrip trace. At least, 3 times the trace width. Figure 6.27 shows how the RF area has been cleared and any non-required ground planes were removed.

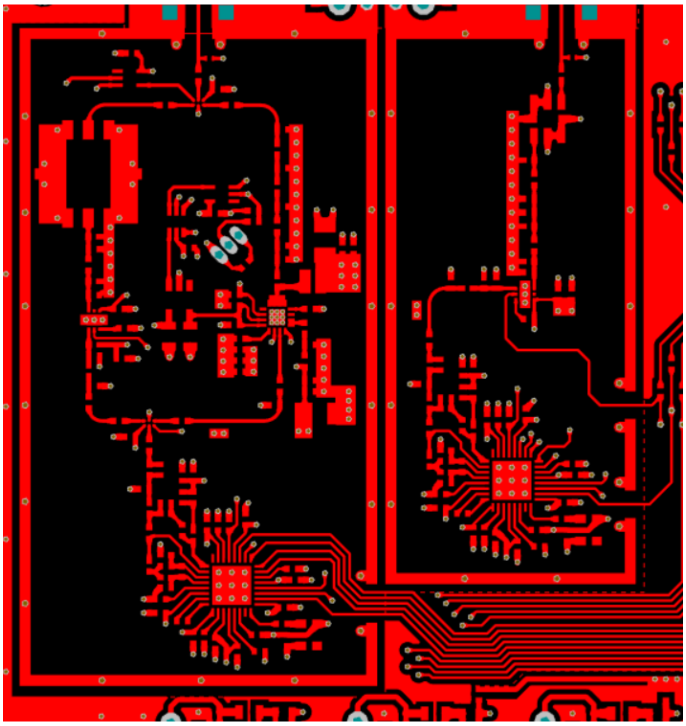


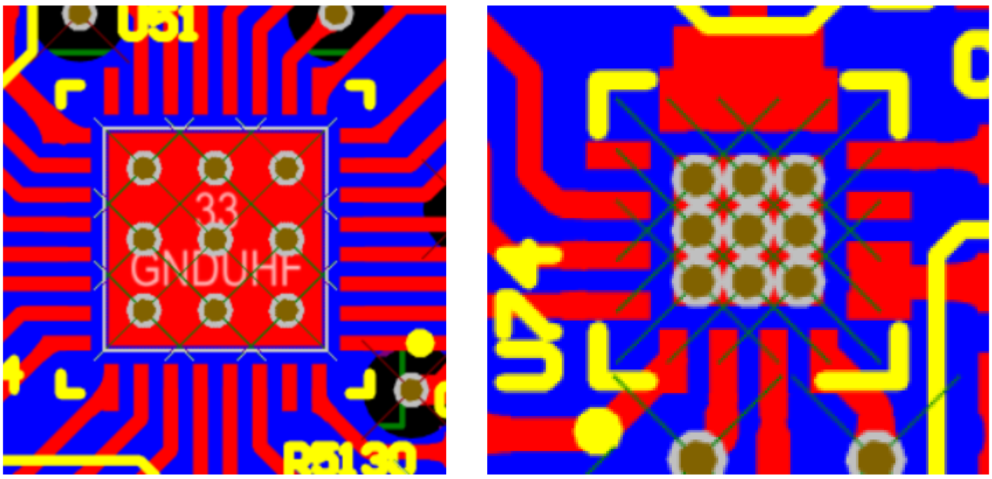
Figure 6.27 – *COMM System – Microstrip lines in RF parts*

Thermal considerations

6

As explained in Chapter 2, the void of air in space changes completely the thermal behaviour of all ICs in the system: air convection does not exist, and therefore, neither does heat dissipation.

The followed strategy is to make the most out of the *thermal conduction* effect, and try to transfer the heat generated by a component to other parts of the board –and even the Cubesat structure also– through the PCB itself. The way to achieve it is by placing numerous through hole vias under the IC connecting with other layers in the board.



(a) *Transceiver CC1125* **(b)** *HPA RF5110G*

Figure 6.28 – *Component thermal pads*

Components compatible with this technique have a squared surface, known as *thermal pad*, that must be soldered to the board. Figure 6.28 shows the thermal pad of two components of the COMM system. The red colour is the thermal pad itself in the top layer, while the blue colour is the bottom layer. Both layers are connected through the vias –shown as gray circles.

Moreover, thermal pads have a double function: one is the one already explained – to offer a low thermal-resistive path to allow heat to go to the copper planes in the board–, while the second one is to ensure a strong GND connection of the component with the ground plane.

Obtained PCB design overview

The different modules that conform the system have been placed in the board as shown in Figure 6.29. The numeration of each module has been done according to the schematic page number where they can be found (see Appendix C):

(1) System architecture

(2) Cubesat main bus

(3) Current and voltage monitoring

(4) Micro Controller Unit (MCU)

(5) UHF transceiver

(6) VHF transceiver

(7) UHF RF chain

(8) VHF RF chain

(9) Antenna front end

(10) GND diagram

The landing place of each module has been figured out bearing in mind two key elements: the use of the space available in the board and the isolation between modules. The MCU module, together with the UHF and VHF RF chains, has been placed in parallel, in such a way that each one has its own monitored supply point very close to them. In addition, system interfaces –SMA, debugger, serial port connectors– are close to the edge of the board, which allow the user an easy access.

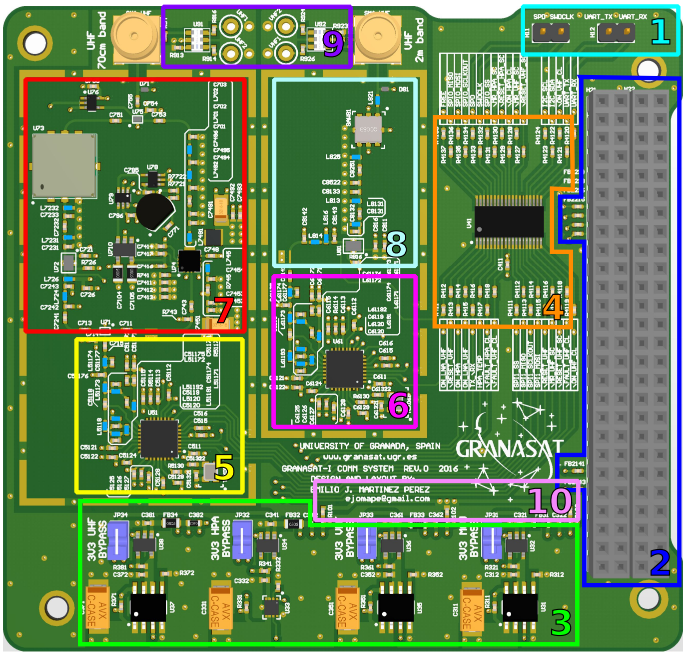


Figure 6.29 – COMM *System – Modules placement in the* PCB

The 3D model rendering is a feature of *Altium*, which allow designers to check the board while the design is ongoing. Nevertheless, a 2D view is the one that is used everyday for completing the board design. In Figure 6.30, a general view of the PCB design is shown. Each layer is represented by a single color. Here in this picture, the red colour represents the top layer, the blue one the bottom layer, the green one is intended for its use as a GND plane, and the dark red is for the PWR plane.

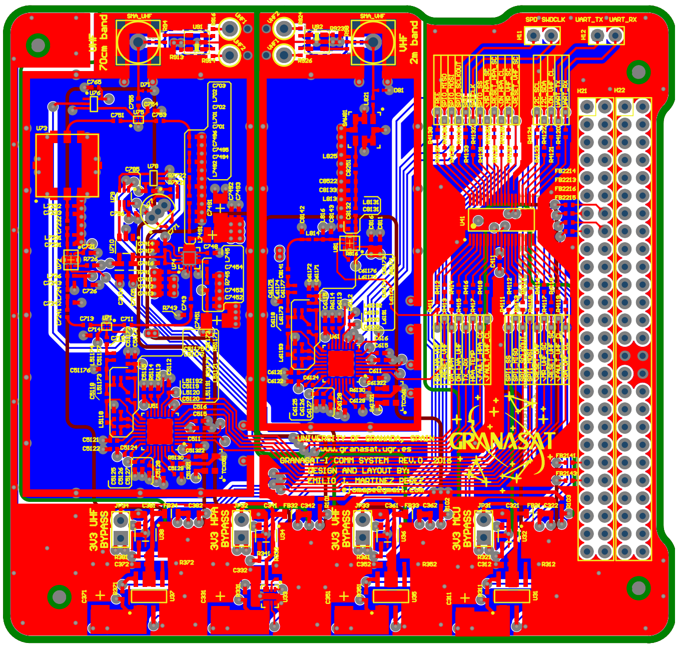


Figure 6.30 – COMM *System –* PCB *design: all system layers*

The top layer is shown in Figure 6.31. It is a mixed signal layer and, therefore, RF and digital signals can be found on it. RF areas are placed on the top-left corner of the board and they are delimited by a via fence, which is intended for allocating the shield. In addition, this is the layer where SMD components are placed and soldered.

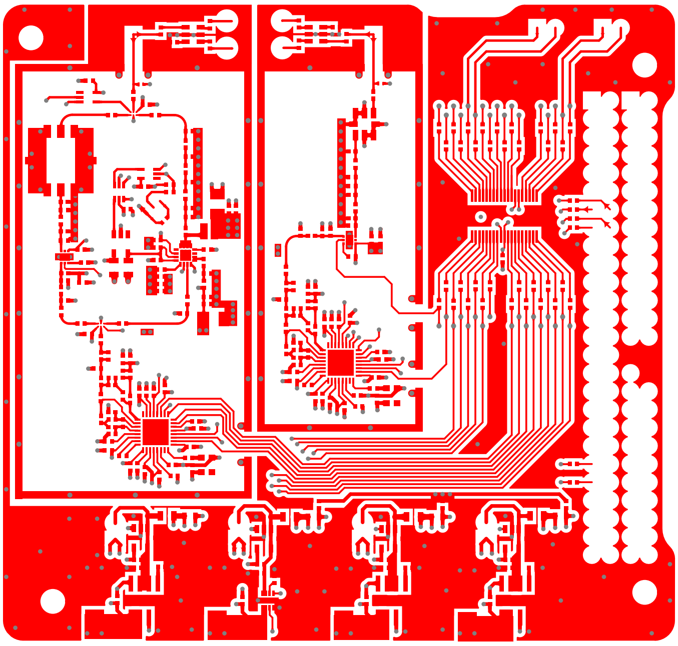


Figure 6.31 – *COMM System – PCB top layer*

The GND plane is shown in Figure 6.32. It has 4 isolated areas, each one for one GND reference in the board: 3V3BUS, 3V3MCU, 3V3UHF and 3V3VHF. These ground references are connected with each other in a star connection on the top layer.

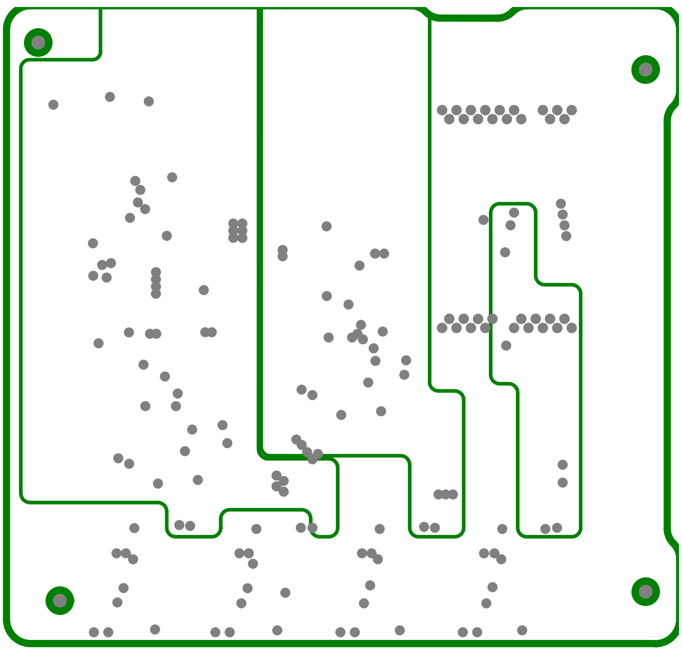


Figure 6.32 – *COMM System – PCB* GND *plane*

In Figure 6.33 the power plane is shown. This plane has 5 differenciated and isolated areas: 3V3UHF, 3V3HPA, 3V3VHF, 3V3MCU and 3V3BUS. The place of origin for these areas is the current limiter output of each one, which means that each power plane area is regulated and monitored, both in current and voltage.

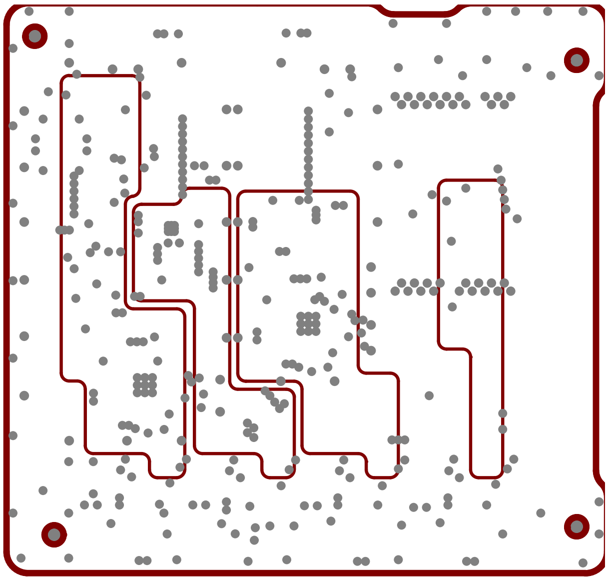


Figure 6.33 – *COMM System – PCB Power plane*

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The bottom layer of the board is shown in Figure 6.34. This is a digital signal layer, which means that digital lines connecting different modules with each other will be routed here. This lines can go freely through the whole board, even in the RF areas also, without worries about affecting other areas of the board.

Moreover, since RF lines in top layer already have a GND plane, it is possible to fill the empty areas with a ground plane. Finally, through-hole components must be soldered in this layer.

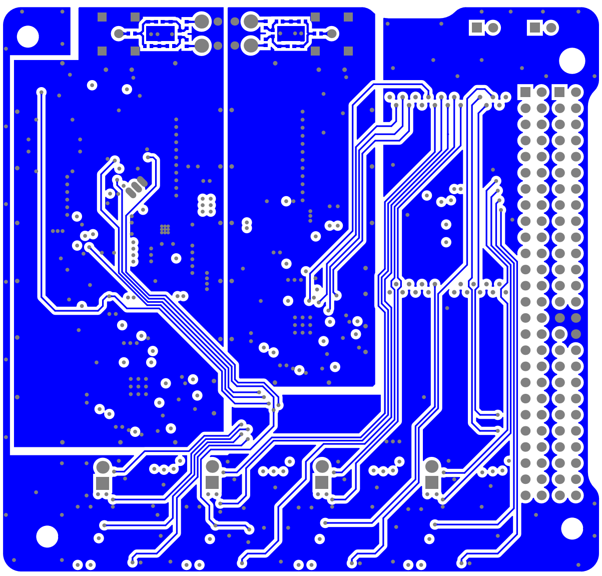

Figure 6.34 – *COMM System – PCB bottom layer*

If a 3D model has been linked to a component when it is placed in the schematic, it will be possible to render a three-dimensional model of the board. This feature is very useful when designing the board because it allows to see the current status of the PCB. In Figure 6.35, the generated 3D model for the system is shown.

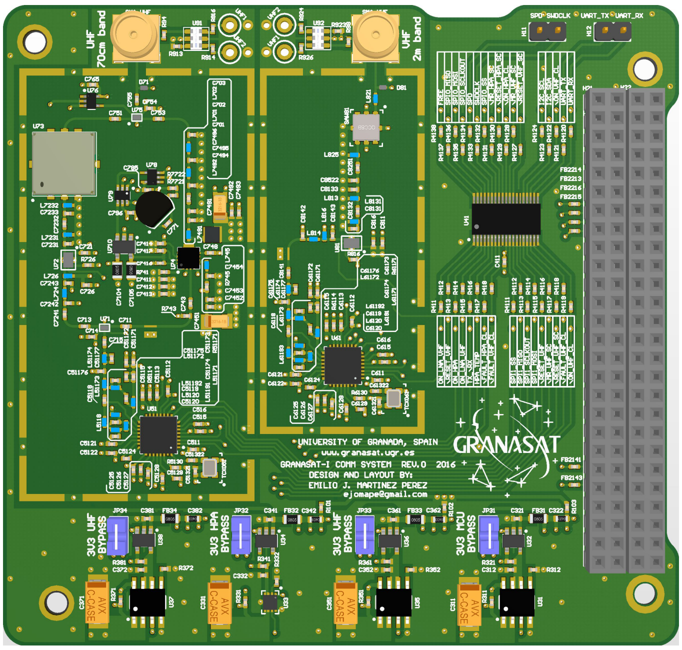

Figure 6.35 – *COMM System – PCB 3D model*

To check the final assembly of this PCB with all components soldered, see Appendix F, where some difficulties that were faced during the component soldering process are explained.

6

Chapter 7

System verification and testing

At this stage of the project, an electronic system has been designed with the objective of solving a defined problem. As it was explained in all previous chapters, the design process of the electronic board has been performed following closely a wide number of requirements that define the characteristics of the design –performance, operational, interface, environment, etc.

When a prototype is built, the next step is to check out whether the proposed design comply with the functionality demanded. Performing a complete design implies that it shall fulfil without exceptions all system requirements. This chapter will specify the verification plan that has been employed in order to verify the requirements. The results obtained and the current status of the procedure will also be included.

There are several verification methods that can be applied to verify if a requirement has been achieved [71]:

- **Examination:** *"An element of verification that is generally nondestructive and typcally includes the use of sight, hearing, smell, touch, and taste; simple physical manipulation; and mechanical and electrical gauging and measurement"* [72].
- **Analysis:** *"An element of verification that uses established technical or mathematical models or simulations, algorithms, charts, graphs, circuit diagrams, or other scientific principles and procedures to provide evidence that stated requirements were met"* [72].
- **Demonstration:** *"An element of verification that involves the actual operation of an item to provide evidence that the required functions were accomplished under specific scenarios. The items may be instrumented and performance monitored"* [72].
- **Test:** *"An element of verification in which scientific principles and procedures are applied to determine the properties or functional capabilities of items"* [72].

It is important to remark that a verification process does not always mean performing a test, which implies the use of more facilities and complex procedures, as well as a more rigorous and expensive verification procedure.

7.1 Verification matrix

A verification matrix is a document that states the verification method that will be executed to confirm the status of every system requirement. This procedure allows engineers to better understand the system verification procedure at a glance.

As presented in Table 7.1, for the GranaSAT-I COMM system, the *examination* and *demonstration* methods have been the preferred verification procedures for almost all the performance and design requirements within the project. All *test* procedures have been defined and scheduled by the time the design is almost complete and a functional or objetive-level verification is required.

COMM System Verification Matrix				
ID	**Examination**	**Analysis**	**Demonstration**	**Test**
F.1				X
F.2				X
F.3				X
F.4				X
F.5				X
F.6				X
F.7				X
F.8				X
F.9				X
F.10				X
F.11			X	
F.12			X	
F.13	X			
P.1			X	
P.2			X	
P.3			X	
P.4			X	
P.5			X	
P.6	X			
P.7			X	
P.8	X			
P.9			X	
P.10			X	

. . . continued

ID	Examination	Analysis	Demonstration	Test
P.11			X	
P.12			X	
P.13			X	
P.14			X	
P.15			X	
P.16			X	
P.17			X	
P.18			X	
P.19			X	
P.20			X	
P.21			X	
P.22			X	
P.23	X			
P.24	X			
P.25			X	
P.26			X	
P.27			X	
P.28			X	
P.29			X	
P.30			X	
P.31			X	
I.1	X			
I.2	X			
I.3	X			
I.4	X			
I.5	X			
E.1				X
E.2				X
E.3				X
D.1	X			
D.2	X			
D.3			X	

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. . . continued

ID	Examination	Analysis	Demonstration	Test
D.4	X			
D.5	X			
D.6	X			
D.7	X			
D.8	X			
D.9	X			
D.10	X			
D.11	X			
D.12	X			
D.13	X			
D.14	X			
D.15	X			
D.16	X			
D.17	X			
D.18	X			
D.19	X			
D.20	X			
D.21	X			
D.22	X			
D.23	X			
D.24	X			
D.25	X			
D.26	X			
D.27	X			
D.28	X			
D.29	X			
D.30	X			
D.31	X			
D.32	X			
D.33	X			
D.34	X			
D.35	X			

. . . continued

ID	Examination	Analysis	Demonstration	Test
D.36	X			
D.37	X			
D.38	X			
D.39	X			
D.40	X			
D.41	X			
D.42	X			
D.43	X			
D.44	X			
D.45	X			
D.46	X			
D.47	X			
D.48	X			
D.49	X			
D.50				X
D.51				X
D.52	X			
D.53	X			
D.54	X			
D.55	X			
D.56	X			
D.57	X			
D.58	X			
D.59	X			
D.60	X			
D.61	X			
D.62	X			
D.63	X			
D.64	X			
D.65	X			
D.66	X			
D.67	X			

. . . continued

ID	Examination	Analysis	Demonstration	Test
D.68	X			
O.1	X			
O.2	X			
O.3				X
O.4				X
O.5				X
O.6				X
O.7	X			
O.8	X			
O.9	X			
O.10			X	
O.11			X	
O.12			X	
O.13			X	
O.14			X	

Table 7.1 – *COMM System – Verification matrix*

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7.2 Verification plan

The verification phase strategy and test campaign are thoroughly designed to pass the verification procedure quickly and satisfactorily. As expected, every test, demonstration procedure or simulation must be carried out to verify a requirement (or a set of requirements) and their existence should be justified. Hence, when a verification procedure is defined, it must state the next five elements: [71]:

- **Objective:** The purpose of the verification procedure.
- **Method:** The verification procedure that will be executed.
- **Environment:** The environmental conditions under which the item will be verified.
- **Special conditions:** Any particular circumstance necessary to carry out the verification process.
- **Success criteria:** The expected result required to consider the verification as accomplished.

In this section, seven test have been performed, which will allow to verify that the functionality of the prototype is in accordance with the expected functionality of the COMM System. Since all tests have been planned as a high-level functionality verification, they must be performed only when the low-level requirements have been successfully verified by examination or demonstration.

The test planning expected to perform to verify the system functionality is as follows:

Test #1: Communication test 1

- *Objective:* To verify if the COMM System is able to communicate with the GranaSAT Ground Station under the conditions of a simulated scenario consisting of a LEO orbit.
- *Method:* Functionality test.
- *Environment:* No special circumstances.
- *Special Conditions:* The system shall be tested together with the *WP: 27 – Antennas*. The GranaSAT Ground Station has to be included in the test.
- *Success Criteria:* The system is able to close a communication link with the Ground Station. It is possible to send telemetry and payload data to the GS, as well as to receive control commands from it.

Test #2: Communication test 2

- *Objective:* To verify if the COMM System is able to communicate with other systems within the GranaSAT-I.
- *Method:* Functional test.
- *Environment:* No special circumstances.
- *Special Conditions:* The system shall be tested together with the *WP: 25 – OBC* through the Cubesat internal data bus.
- *Success Criteria:* Both systems are able to send and receive data frames from each other successfully.

Test #3: Overcurrent test

- *Objective:* To verify if the COMM System is able to detect any over currentevent and the protection actions are carried out satisfactorily.
- *Method:* Functional test.
- *Environment:* No special circumstances.
- Special Conditions: This is a potentially destructive test. It has to be performed in a laboratory, under controlled conditions, and taking all the security measures to ensure that the test equipment is not damaged during its execution.

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- *Success Criteria:* The system is able to protect itself from the overcurrent events, and not a single module suffers any damage.

Test #4: Voltage monitoring test

- *Objective:* To verify if the COMM System is capable of monitoring the incoming voltage level and taking protection actions when the voltage level is out of the nominal range.
- *Method:* Functional test.
- *Environment:* No special circumstances.
- *Special Conditions:* This is a potentially destructive test. It has to be performed in a laboratory, under controlled conditions, and taking all the security measures to ensure that the test equipment is not damaged during its execution.
- *Success Criteria:* The system is able to monitor the voltage level in the board and can react adequately to protect itself when the voltage level is not the correct one.

Test #5: Temperature protection test

- *Objective:* To verify if the system is able to monitor the temperature of the board and protect the components from overheating if necessary.
- *Method:* Functional test.
- *Environment:* No special circumstances.
- *Special Conditions:* This is a potentially destructive test. It has to be performed in a laboratory, under controlled conditions, and taking all the security measures to ensure that the test equipment is not damaged during its execution.
- *Success Criteria:* The system is capable of monitoring the temperature of critical components and turning them off when they reach a temperature limit.

TVAC: Thermal VACuum (TVAC) test

- *Objective:* To verify if the COMM system is able to withstand the extreme temperature and vacuum conditions in space.
- *Method:* Environmental test.
- *Environment:* Non applicable.
- *Special Conditions:* The Cubesat shall be tested to obtain the qualification pass. Therefore, the COMM System will be tested together with the rest of the systems.
- *Success Criteria:* The system survives the thermal-vacuum cycles applied and it is still operative after the test.

TID: Total Ionizing Dose (TID) test

– *Objective:* To verify if the COMM system is capable of working without anomalies in a harsh environment coated with radiation.

– *Method:* Environmental test.

– *Environment:* Non applicable.

– *Special Conditions:* The Cubesat shall be tested to obtain the qualification pass. Therefore, the COMM System will be tested together with the rest of the systems.

– *Success Criteria:* The system survives the received radiation received the test and it is able to work normally once the test is done.

Besides all the tests defined in this section, in the verification plan it is also expected to conduct laboratory demonstrations to verify every single performance and design requirements. Demonstrations are very specific processes and are closely related to the feature to be verified and the hardware involved. For this reason, it is not practical to define them in advance and they will be specified in the next section (7.3) together with the result of the laboratory demonstration itself.

7.3 Verification results

In this section the results of the verification procedures are revealed. Several summary tables –7.3, 7.4, 7.5, 7.6, 7.7, 7.8– show the status of the COMM System verification process at the moment of this writing.

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These tables are very useful to understand what the current status of the design is, since they help to know at a glance those design features that have been already accomplished, and those that still need another design iteration in order to fulfil the requirement.

Verification Status	Color code
The verification has been performed and it was accomplished correctly	**Success**
The verification procedure could not be carried out because: a) a lack of facilities or time b) the system needs to be completely finished or other systems of the Cubesat are required	**Unperformed**
The verification method has been conducted but it was not possible to meet the success criteria	**Fail**

Table 7.2 – *Verification status – Color code*

A colour code has been used for indicating the status of the verification process for each requirement. As shown in Table 7.2, the colour **green** has been employed to mark the accomplished requirement, the **yellow** one for those requirements that have not been evaluated yet. Finally, the **red** colour has been used to mark those requirements that were evaluated but the design does not fulfil completely the expected behaviour or performance.

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COMM System Verification Matrix				
ID	**Description**	**Procedure**	**Status**	**Note**
F.1	The system shall establish a radio link between satellite and Earth segment	Test	**Unperformed**	Test #1
F.2	The system shall be able to broadcast a data beacon	Test	**Unperformed**	Test #1
F.3	The system shall establish a radio link between Earth segment and satellite	Test	**Unperformed**	Test #1
F.4	The system shall be able to communicate to other systems within the Cubesat	Test	**Unperformed**	Test #2
F.5	The system shall limit the load current in a module level	Test	**Unperformed**	Test #3
F.6	The system shall cut off the power supply to modules if a short circuit is detected	Test	**Unperformed**	Test #3
F.7	The system shall monitor voltage level in a module level	Test	**Unperformed**	Test #4
F.8	The system shall switch off critical components if voltage level is out of range	Test	**Unperformed**	Test #4
F.9	The system shall monitor the temperature of critical components when they are active	Test	**Unperformed**	Test #5
F.10	The system shall switch off overheated critical components	Test	**Unperformed**	Test #5
F.11	The system shall be reprogrammable and debuggable by using an external device	Demonstration	**Success**	See Lab. Demo. F.11
F.12	The system shall be able to communicate to a *PC*	Demonstration	**Unperformed**	Task 28.5.2 – SW
F.13	The system shall allow to do PCB modifications	Examination	**Success**	Design feature

Table 7.3 – *COMM Verification Matrix – Functional Requirements*

COMM System Verification Matrix

ID	Description	Procedure	Status	Note
P.1	The transmission EIRP shall be higher than +28 dBm	Demonstration	Unperformed	To perform together with the Antenna System
P.2	The transmission adjacent channel power shall be lesser than −50 dBc	Demonstration	Success	See Lab. Demo. P.2
P.3	The transmission spurious emissions shall be lesser than −50 dBm	Demonstration	Success	See Lab. Demo. P.3
P.4	The transmission chain SWR shall be equal or lesser than 1.8	Demonstration	Fail	See Lab. Demo. P.4
P.5	The transmission bit-rate shall be equal or higher than 4.8 kbps	Demonstration	Unperformed	Task 28.5.2 – SW
P.6	The reception chain's first element Noise Figure shall be lesser than 1.0 dB	Examination	Success	Design feature. See LNA data sheet
P.7	The reception chain's first element gain shall be higher than 15 dB	Demonstration	Success	See Lab. Demo. P.7
P.8	The receiver Noise Figure shall be lesser than 10 dB	Examination	Success	Design feature. See transceiver data sheet
P.9	The reception chain's losses shall be lesser than 10 dB	Demonstration	Unperformed	To perform together with the Antenna System
P.10	The reception chain's SWR shall be equal or lesser than 1.8	Demonstration	Fail	See Lab. Demo. P.10
P.11	The reception bit-rate shall be equal or higher than 4.8 kbps	Demonstration	Unperformed	Task 28.5.2 – SW
P.12	The reception demodulation E_b/N_0 required threshold shall be lesser than 16 dB	Demonstration	Unperformed	To perform together with the Antenna System

...continued

ID	Description	Procedure	Status	Note
P.13	The communication bit-rate between systems within the Cubesat shall be higher than 100 kbps	Demonstration	Unperformed	Task 28.5.2 – SW
P.14	Other systems within the Cubesat shall communicate to the COMM System with a frequency equal or lesser than 20 Hz	Demonstration	Unperformed	Task 28.5.2 – SW
P.15	The COMM System shall communicate to other systems within the Cubesat with a frequency equal or lesser than 20 Hz	Demonstration	Unperformed	Task 28.5.2 – SW
P.16	The microcontroller shall allow communication with other systems within the Cubesat at any time	Demonstration	Unperformed	Task 28.5.2 – SW
P.17	The load current limit for each monitored module of the system shall be 1 A	Demonstration	Success	See Lab. Demo. P.17
P.18	The load current limit for system high power demanding modules shall be 2.5 A	Demonstration	Success	See Lab. Demo. P.18
P.19	The module power supply cutting off since maximum current load is detected shall be performed faster than 1 ms	Demonstration	Fail	Partial success. See Lab. Demo. P.19
P.20	The module power supply cutting off since short circuit is detected shall be performed faster than 10 µs	Demonstration	Fail	Partial success. See Lab. Demo. P.20
P.21	The nominal voltage range shall be 2.8 V to 3.7 V	Demonstration	Success	See Lab. Demo. P.21
P.22	The critical component switching off since out of range voltage is detected shall be performed faster than 20 µs	Demonstration	Fail	Partial success. See Lab. Demo. P.22
P.23	The temperature monitor range shall be −30 °C to +85 °C	Examination	Success	Design feature
P.24	The temperature monitor accuracy shall be equal or higher than 4 °C	Examination	Success	Design feature
P.25	The temperature monitor frequency shall be equal or higher than 10 KHz	Demonstration	Unperformed	Task 28.5.2 – SW

...continued

ID	Description	Procedure	Status	Note
P.26	The maximum working temperature for monitored components shall be +80 °C	Demonstration	**Unperformed**	Task 28.5.2 – SW
P.27	The component switching off since overheating is detected shall be performed faster than 1 ms	Demonstration	**Unperformed**	Task 28.5.2 – SW
P.28	The frequency band for an amateur-satellite service operating within the VHF band shall be from 145.8 MHz to 146.0 MHz [39]	Demonstration	**Unperformed**	To perform together with the Antenna System
P.29	The maximum bandwidth used within the VHF band shall be 12 KHz [39]	Demonstration	**Unperformed**	To perform together with the Antenna System
P.30	The frequency band for an amateur-satellite service operating within the UHF band shall be from 435.0 MHz to 438.0 MHz [39]	Demonstration	**Unperformed**	To perform together with the Antenna System
P.31	The maximum bandwidth used within the UHF band shall be 20 KHz [39]	Demonstration	**Unperformed**	To perform together with the Antenna System

Table 7.4 – *COMM Verification Matrix – Performance Requirements*

COMM System Verification Matrix

ID	Description	Procedure	Status	Note
I.1	The system shall be compatible with GranaSAT-I antenna subsystem interface	Examination	**Success**	Design feature
I.2	The system shall be compatible with GranaSAT-I bus	Examination	**Success**	Design feature
I.3	The system shall be compatible with *PC-104* physical interface	Examination	**Success**	Design feature

…continued

ID	Description	Procedure	Status	Note
I.4	The system shall offer a microcontroller programming and debugging port	Examination	**Success**	Design feature
I.5	The system shall offer a serial port for external connection	Examination	**Success**	Design feature

Table 7.5 – *COMM Verification Matrix – Interface Requirements*

COMM System Verification Matrix

ID	Description	Procedure	Status	Note
E.1	The system shall operate in the temperature range from −35 °C to +70 °C	Test	**Unperformed**	TVAC
E.2	The system shall operate in a low pressure environment equal or lesser than 10^{-5} hPa	Test	**Unperformed**	TVAC
E.3	The system shall operate in an environment of high-ionizing radiation dose	Test	**Unperformed**	TID

Table 7.6 – *COMM Verification Matrix – Environmental Requirements*

COMM System Verification Matrix

ID	Description	Procedure	Status	Note
D.1	The system shall have a *High Power Amplifier* unit	Examination	**Success**	Design feature
D.2	The system shall have a band pass filter centred at carrier frequency in the transmission chain	Examination	**Success**	Design feature
D.3	The system shall have tuned matching networks	Demonstration	**Fail**	Partial success. See Lab. Demo. P.4 and P.10

...continued

ID	Description	Procedure	Status	Note
D.4	The system shall include a RF shielding	Examination	Fail	Partial success. The PCB has room for the shielding, but this has not been designed yet
D.5	The system shall have a *Low Noise Amplifier* unit at the reception chain	Examination	Success	Design feature
D.6	The system shall implement a QPSK modulation scheme	Examination	Success	Design feature
D.7	The system shall implement a CW modulation scheme	Examination	Success	Design feature
D.8	The microcontroller shall allow interruption events	Examination	Success	Design feature
D.9	A single current limit for the *High Power Amplifier* shall be used	Examination	Success	Design feature
D.10	The system short circuit protection shall be a hardware solution	Examination	Success	Design feature
D.11	The nominal voltage required for components shall be 3.3 V	Examination	Success	Design feature
D.12	The system voltage monitoring shall be a hardware solution	Examination	Success	Design feature
D.13	The microcontroller temperature shall be monitored	Examination	Unperformed	Task 28.5.2 – SW
D.14	The receiver temperature shall be monitored	Examination	Unperformed	Task 28.5.2 – SW
D.15	The transmitter temperature shall be monitored	Examination	Unperformed	Task 28.5.2 – SW
D.16	The *High Power Amplifier* temperature shall be monitored	Examination	Unperformed	Task 28.5.2 – SW
D.17	The microcontroller temperature measurement shall be calibrated	Examination	Unperformed	Task 28.5.2 – SW
D.18	The receiver temperature measurement shall be calibrated	Examination	Unperformed	Task 28.5.2 – SW
D.19	The transmitter temperature measurement shall be calibrated	Examination	Unperformed	Task 28.5.2 – SW

...continued

ID	Description	Procedure	Status	Note
D.20	The *High Power Amplifier* temperature measurement shall be calibrated	Examination	Unperformed	Task 28.5.2 – SW
D.21	The system shall have, as a transmission chain main front-end, a SMA connector	Examination	Success	Design feature
D.22	The characteristic impedance of the main front-end at the transmission chain shall be 50 Ω	Examination	Success	Design feature
D.23	The system shall have, as a transmission chain secondary front-end, two balanced RF paths	Examination	Success	Design feature
D.24	The system shall have, as a transmission chain secondary front-end, two balanced 90° phased RF paths	Examination	Success	Design feature
D.25	The system shall have, as a reception chain main front-end, a SMA connector	Examination	Success	Design feature
D.26	The characteristic impedance of the main front-end at the reception chain shall be 50 Ω	Examination	Success	Design feature
D.27	The system shall have, as a reception chain secondary front-end, two balanced RF paths	Examination	Success	Design feature
D.28	The system shall have, as a reception chain secondary front-end, two balanced 90° phased RF paths	Examination	Success	Design feature
D.29	The system shall use I^2C to communicate with other systems within the Cubesat	Examination	Unperformed	Task 28.5.2 – SW
D.30	The system shall have a hard reset line	Examination	Success	Design feature
D.31	The system shall be powered by 3.3 V	Examination	Success	Design feature
D.32	The system shall be compatible with *PC-104* GND pines	Examination	Success	Design feature
D.33	The system shall be compatible with *PC-104* V_{cc} pines	Examination	Success	Design feature

...continued

ID	Description	Procedure	Status	Note
D.34	The system shall be compatible with *PC-104* I^2C bus pines	Examination	**Success**	Design feature
D.35	The debugging protocol used shall be the ARM Serial Wire Debug (SWD)	Examination	**Success**	Design feature
D.36	The debugging port shall be a separate port	Examination	**Success**	Design feature
D.37	The serial protocol used shall be UART	Examination	**Success**	Design feature
D.38	The UART port shall be a separate port	Examination	**Success**	Design feature
D.39	The system shall allow easy access to instrumentation probes	Examination	**Success**	Design feature
D.40	The system shall allow the option of soldering external wires	Examination	**Success**	Design feature
D.41	The system shall allow to redistribute tracks reaching the microcontroller pines	Examination	**Success**	Design feature
D.42	The system shall show the component designator on the PCB	Examination	**Success**	Design feature
D.43	The system shall allow manual soldering of components	Examination	**Success**	Design feature
D.44	The system shall allow different topologies of adaptation network in RF chains	Examination	**Success**	Design feature
D.45	The system shall use for communication any ISM band allocated within either UHF or VHF bands	Examination	**Success**	Design feature
D.46	The system shall allocate the downlink and uplink frequencies in the UHF band for half-duplex and simplex operations	Examination	**Success**	Design feature
D.47	The system shall allocate the downlink frequency in the UHF band and the uplink frequency in the VHF band for full-duplex operations	Examination	**Success**	Design feature
D.48	The system physical dimensions shall be the specified for GranaSAT-I	Examination	**Success**	Design feature

. . . continued

ID	Description	Procedure	Status	Note
D.49	The system shall weigh less than 150 grams	Examination	**Success**	Total weigh of the system is 53 ± 1 grams
D.50	The system power consumption during transmission shall be lower than 9 *W*	Test	**Unperformed**	Test #1
D.51	The system power consumption during reception shall be lower than 3 *W*	Test	**Unperformed**	Test #1
D.52	The system shall follow *Cubesat Design Specification, Rev. 13*: 3.3.5 [6]	Examination	**Success**	Design feature
D.53	The system shall follow *Cubesat Design Specification, Rev. 13*: 3.3.9 [6]	Examination	**Success**	Design feature
D.54	The system shall follow *ITU – Radio Regulations*: RR 5.282 [39]	Examination	**Success**	Design feature
D.55	The system shall follow, when applicable, *Space Engineering: Electrical and electronic*: 7.3 RF Power (ECSS-E-ST-20C)	Examination	**Success**	Design feature
D.56	The system shall follow, when applicable, *Space Engineering: Communications*: 5.3 Space Communication System (ECSS-E-ST-50C)	Examination	**Success**	Design feature
D.57	The system shall follow, when applicable, *Space Engineering: Communications*: 5.5 Space Link (ECSS-E-ST-50C)	Examination	**Success**	Design feature
D.58	The system shall follow, when applicable, *Space Engineering: Radio frequency and modulation*: 6.2 Suppressed carrier modulation (ECSS-E-ST-50-05C)	Examination	**Success**	Design feature
D.59	The system shall follow, when applicable, *Space Engineering: Radio frequency and modulation*: 8.3 Link budget tables (ECSS-E-ST-50-05C)	Examination	**Success**	Design feature

...continued

ID	Description	Procedure	Status	Note
D.60	The system shall follow, when applicable, *Space product assurance: Design rules for printed circuit boards*: 7.4 Track width and spacing (ECSS-Q-ST-70-12C)	Examination	Success	Design feature
D.61	The system shall follow, when applicable, *Space product assurance: Design rules for printed circuit boards*: 7.8 PCB surface finish (ECSS-Q-ST-70-12C)	Examination	Success	Design feature
D.62	The system shall follow, when applicable, *Space product assurance: Manual soldering of high-reliability electrical connections* (ECSS-Q-ST-70-08C)	Examination	Success	Design feature
D.63	The system shall follow, when applicable, *Space product assurance: Repair and modification of printed circuits board assemblies for space use* (ECSS-Q-ST-70-28C)	Examination	Success	Design feature
D.64	The system shall follow, when applicable, *Space product assurance: High-reliability soldering for surface-mount and mixed technology* (ECSS-Q-ST-70-38C)	Examination	Success	Design feature
D.65	The system components shall offer an operative work temperature range equal or wider than $-35\ ^{\circ}\mathrm{C}$ to $+60\ ^{\circ}\mathrm{C}$	Examination	Success	Design feature
D.66	The system components shall be suitable to function under a low pressure environment, equal or lesser than 10^{-5} hPa	Examination	Success	Design feature
D.67	The system shall allow the placement of an electromagnetic shielding	Examination	Success	Design feature
D.68	The system shall only use COTS components	Examination	Success	Design feature
D.69	Any in-house test or verification process shall not require facilities out of the GranaSAT reach	Examination	Success	Design feature

Table 7.7 – *COMM Verification Matrix – Design Requirements*

COMM System Verification Matrix				
ID	**Description**	**Procedure**	**Status**	**Note**
O.1	The system shall operate in multi-band full-duplex mode	Examination	**Success**	Design feature
O.2	The system shall be able to operate in single-band half-duplex mode	Examination	**Success**	Design feature
O.3	The system shall establish the downlink after an Earth control requirement	Test	**Unperformed**	Test #1
O.4	The system shall perform a periodical CW beacon when idle status	Test	**Unperformed**	Test #1
O.5	The system shall establish the uplink when idle status	Test	**Unperformed**	Test #1
O.6	The system shall be manageable by Cubesat's OBC system	Test	**Unperformed**	Test #2
O.7	The system shall cease any communication and switch to failure state if overload occurs	Examination	**Unperformed**	Task 28.5.2 – SW
O.8	The system shall cease any communication and switch to failure state if voltage out of range occurs	Examination	**Unperformed**	Task 28.5.2 – SW
O.9	The system shall cease any communication and switch to failure state if overheating occurs	Examination	**Unperformed**	Task 28.5.2 – SW
O.10	*Cubesat Design Specification, Rev. 13*: 3.4.1	Examination	**Unperformed**	This must be performed by the project manager
O.11	*Cubesat Design Specification, Rev. 13*: 3.4.2	Demonstration	**Unperformed**	-
O.12	*Cubesat Design Specification, Rev. 13*: 3.4.5	Demonstration	**Unperformed**	Task 28.5.2 – SW
O.13	*ITU – Radio Regulations*: RR 25.11	Demonstration	**Unperformed**	Task 28.5.2 – SW
O.14	*ITU – Radio Regulations*: RR 25.2A	Demonstration	**Unperformed**	Task 28.5.2 – SW

Table 7.8 – *COMM Verification Matrix – Operational Requirements*

Laboratory demonstration: F.11

- *Description:* The system shall be reprogrammable and debuggable by using an external device.
- *Procedure:* To connect the Infineon *XMC1300 Boot Kit* to the COMM System MCU and load a dummy code into it.

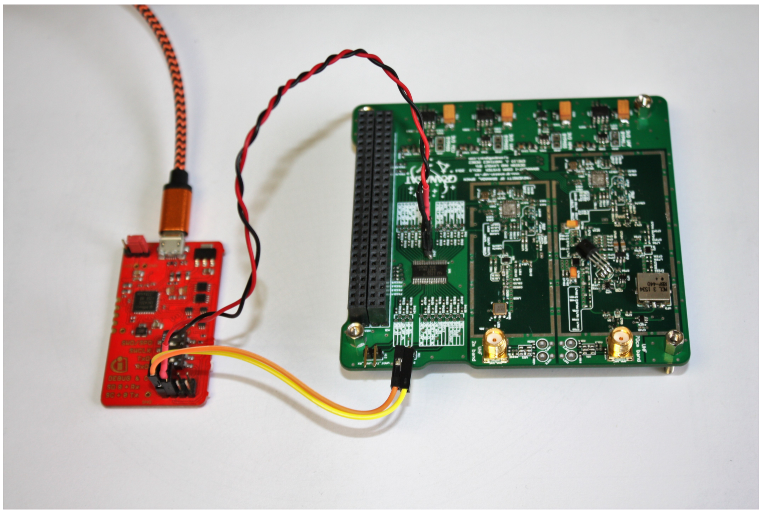


Figure 7.1 – *Lab. Demo. F.11 – Demonstration Setup*

- *Result:* It is possible to load the code into the MCU successfully.
- *Status:* **Success**.
- *Future actions:* None.

7

Laboratory demonstration: P.2 and P.3

- *Description:*
  - The transmission adjacent channel power shall be lesser than −50 dBc.
  - The transmission spurious emissions shall be lesser than −50 dBm.
- *Procedure:* To connect the HPA output to a signal analyser and measure the frequency spectrum adjacent to the carrier frequency and spurious emissions.
- *Result:* As shown in Figure 7.2, the power level of the carrier signal is +27.79 dBm, while the adjacent frequencies are always under −30 dBm. This confirms the required value of −50 dBc. None spurious emission higher than −50 dBc has been measured.
- *Status:* **Success**.
- *Future actions:* None.

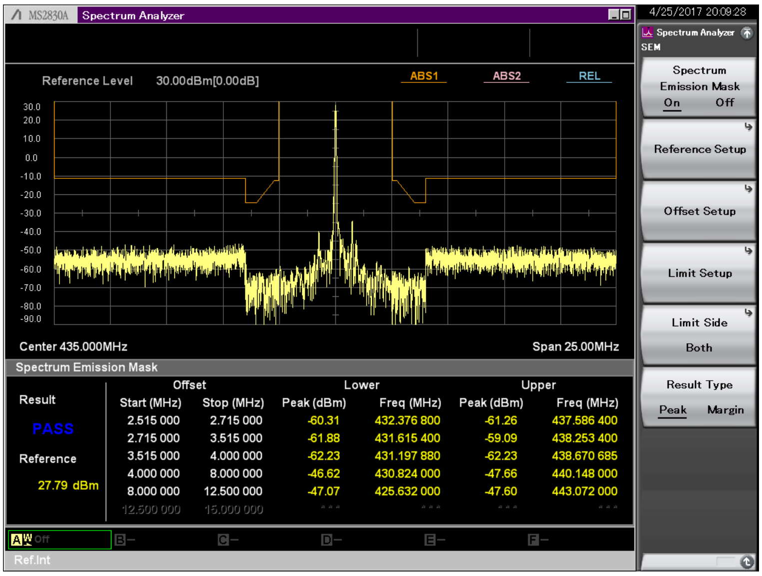


Figure 7.2 – *Lab. Demo. P.2 – Demonstration result*

Laboratory demonstration: P.4

- *Description:* The transmission chain SWR shall be equal or lesser than 1.8.
- *Procedure:* To solder a coaxial cable at the input and output of the transmission chain and measure the SWR value in the VNA. Figure 7.3 shows the board utilised for the verification procedure and the wires and coaxial cables soldered on it. It is important to remark that the measurements have been performed after calibrating the VNA taking into account the soldered coaxial cables.

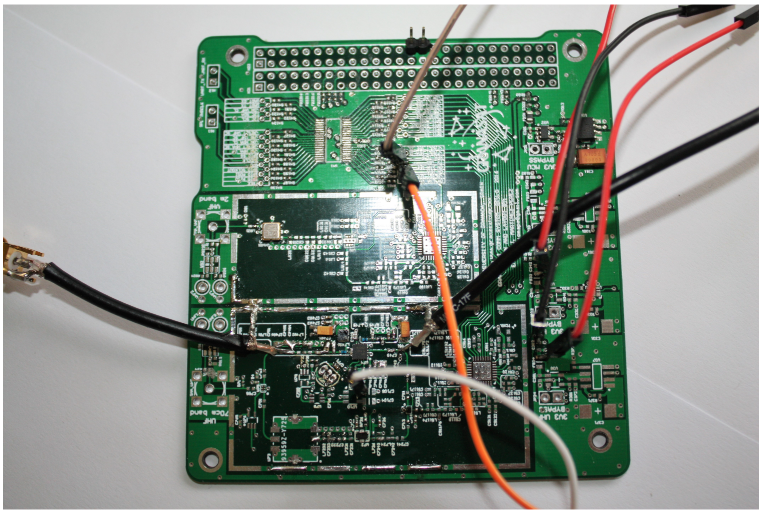


Figure 7.3 – *Lab. Demo. P.4 – Demonstration Setup*

- *Result:* The obtained SWR value for the transmission chain input at the centred frequency of 436.5 MHz is around 10. This value is clearly higher than the desired 1.8. Results can be seen in Figure 7.4.

7

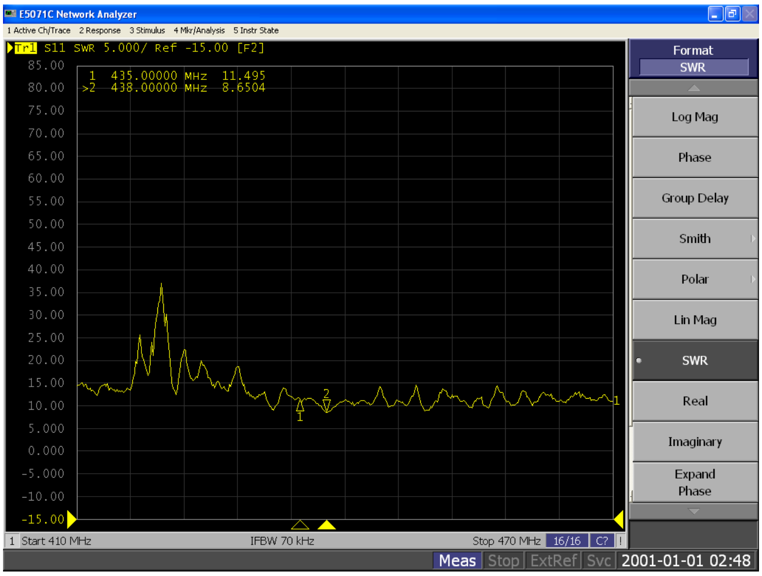


Figure 7.4 – *Lab. Demo. P.4 – Demonstration result*

– *Status:* **Fail**.

– *Future actions:* Transmission chain matching networks must be reviewed and verified again one by one.

Laboratory demonstration: P.7

– *Description:* The reception chain's first element gain shall be higher than 15 dB.

– *Procedure:* To solder a coaxial cable at the input and output of the reception chain LNA and measure the parameter S21 in the VNA. It is important to remark that the measurements have been performed after calibrating the VNA taking into account the soldered coaxial cables.

– *Result:* The obtained gain value for the centred frequency 145.5 MHz is around +30.7 dB. Figure 7.5 shows parameters S11, S12, S21 and S22 for the VHF LNA. Figure 7.6 shows a detailed scale for the S21 parameter.

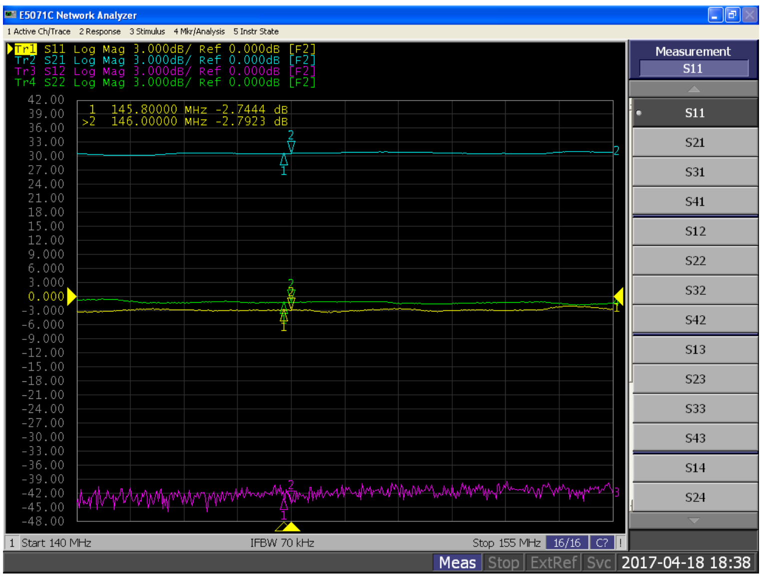


Figure 7.5 – *Lab. Demo. P.7 – Demonstration result*

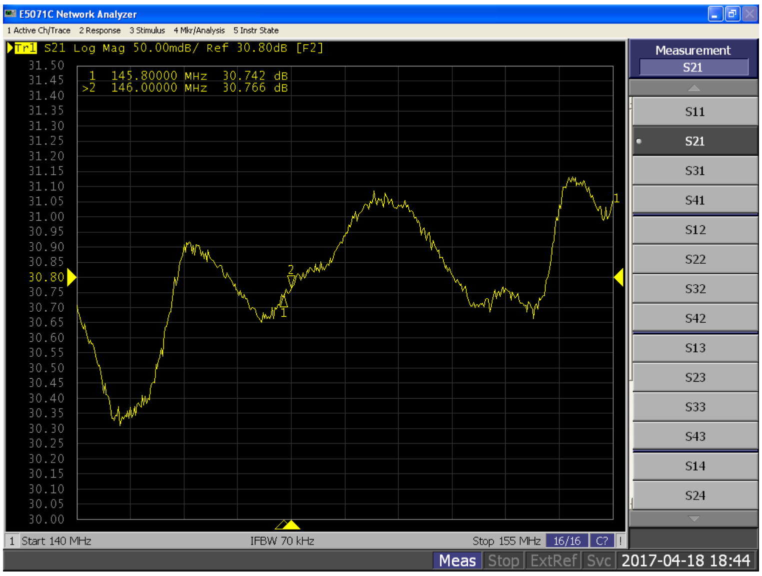


Figure 7.6 – *Lab. Demo. P.7 – Demonstration result detail*

- *Status:* **Success**.
- *Future actions:* None.

Laboratory demonstration: P.10

- *Description:* The reception chain SWR shall be equal or lesser than 1.8.
- *Procedure:* To solder a coaxial cable at the input and output of the reception chain and measure the SWR value in the VNA. It is important to remark that the measurements have been performed after calibrating the VNA taking into account the soldered coaxial cables.
- *Result:* The obtained SWR value for the reception chain input at the centred frequency of 145.5 MHz is around 6.4. This value is clearly higher than the desired 1.8. Results can be seen in Figure 7.7.

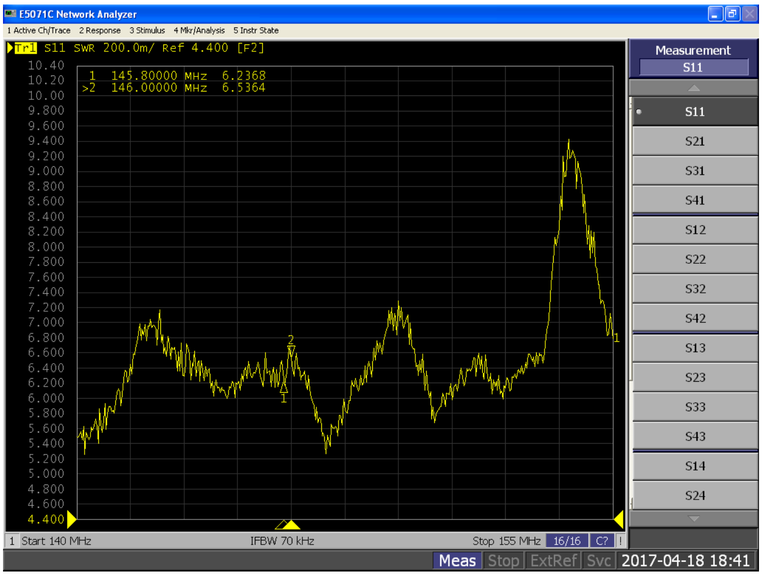


Figure 7.7 – *Lab. Demo. P.10 – Demonstration result*

7

– *Status:* **Fail**.
– *Future actions:* Reception chain matching networks must be reviewed and verified again one by one.

Laboratory demonstration: P.17

– *Description:* The load current limit for each monitored module of the system shall be 1 A.
– *Procedure:* To connect a variable load directly in the voltage output of the switch circuit (*MAX890*) and gradually demand more current until reaching the value that triggers the integrated circuit.
– *Result:* Figure 7.8 depicts the behaviour of the *MAX890* throughout the demonstration procedure. The green line is the */FAULT* signal, the purple line is the *3.3 VBUS* and the yellow line is the regulated *3.3 V* output line.
The current consumption of the load is increased gradually and, at 0.98 *A*, the */FAULT* signal drops to zero and the output line is cut off. When the demand of current is again under the maximum level, the */FAULT* signal goes back to 3.3 V and the output line is restored again to 3.3 V.

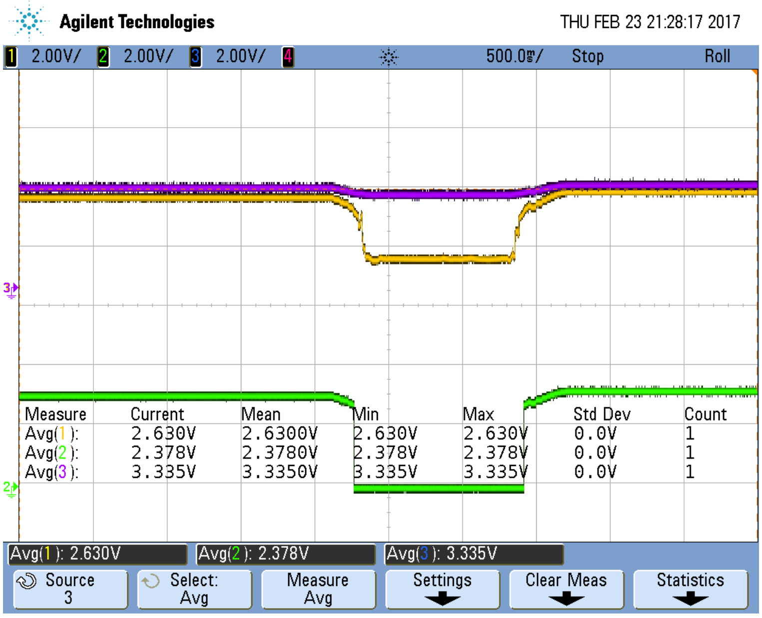


Figure 7.8 – *Lab. Demo. P.17 – Demonstration result*

– *Status:* **Success**.
– *Future actions:* None.

Laboratory demonstration: P.18

– *Description:* The load current limit for system high power demanding modules shall be 2.5 *A*.
– *Procedure:* To connect a variable load directly in the voltage output of the switch circuit (*MAX14575*) and gradually demand more current until reaching the value that triggers the integrated circuit.

- *Result:* The behaviour of the *MAX14575* is identical to the *MAX890*. In this case, the current consumption of the load is increased gradually until reaching the value of 2.43 A. With this value, the */FAULT* signal drops to zero and the output line is cut off. When the demanding of current is again under the maximum level, the */FAULT* signal goes back to 3.3 V and the output line is restored again to 3.3 V.
- *Status:* **Success**.
- *Future actions:* None.

Laboratory demonstration: P.19

- *Description:* The module power supply cutting off since maximum current load is detected shall be performed faster than 1 ms.
- *Procedure:* This demonstration procedure is carried out at the same time as the Laboratory demonstration P.17. For this demonstration, the aim is to measure the time required for the integrated circuit to cut off the output signal when it identifies an overcurrent event.
- *Result:* The behaviour is the expected and, apparently, the time required for the *MAX890* to cut off the output signal is sufficient to accomplish the requirement. The inconvenience is that the measurement procedure is not the adequate to provide a response time number. For this reason the demonstration is considered unsuccessful.
- *Status:* **Fail**.
- *Future actions:* To develop a demonstration procedure suitable for measuring the response time of the integrated circuit.

7

Laboratory demonstration: P.20

- *Description:* The module power supply cutting off since short circuit is detected shall be performed faster than 10 μs.
- *Procedure:* The same than the Laboratory demonstration P.19.
- *Result:* The same than the Laboratory demonstration P.19.
- *Status:* **Fail**.
- *Future actions:* To develop a demonstration procedure suitable for measuring the response time of the integrated circuit.

Laboratory demonstration: P.21

- *Description:* The nominal voltage range shall be between 2.8 V and 3.7 V.
- *Procedure:* To supply the PCB and modify slightly 3.3 V line. While the */RESET* output of the monitoring circuit *TPS3838* is analysed with an oscilloscope.

– *Result:* The supervisory circuit is able to detect when the voltage signal goes lower than 2.9 V. When this happens the */RESET* signal drops to zero. This sequence of events is depicted in Figure 7.9.

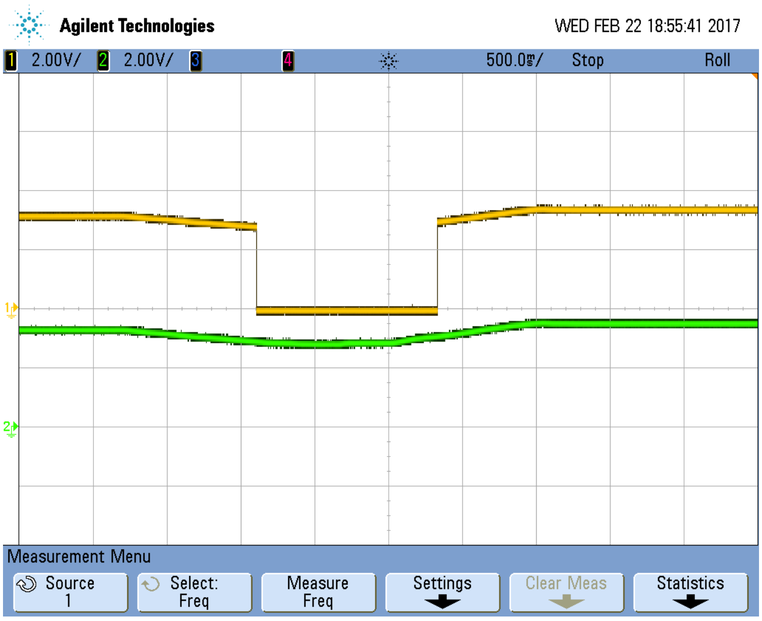


Figure 7.9 – *Lab. Demo. P.21 – Demonstration result*

– *Status:* **Success**.

– *Future actions:* None.

Laboratory demonstration: P.22

– *Description:* The critical component switching off since out of range voltage is detected shall be performed faster than 20 µs.

– *Procedure:* The same than the Laboratory demonstration P.21.

– *Result:* The behaviour of the *TPS3838* monitoring circuit is the adequate, but there is no way of switching off the components via hardware – however it is possible via software.

– *Status:* **Fail**.

– *Future actions:* To modify the circuitry to allow an adequate hardware behaviour. One option can be to connect the output */RESET* line of the monitoring circuit to the input */ON* line of the load switch.

7

Chapter 8

Conclusions, future work and lessons learned

8.1 Conclusions

Throughout the development of the project, numerous key elements associated to satellite communications have been carried out. While some of them were properly studied previously in academic courses, others have been completely new for the author.

Fields of science involved somehow in this project have been: space standardization and regulatory laws, satellite communication engineering, radio wave propagation, digital communications, systems engineering, RF electronics, digital electronics, PCB design, manufacturing, component soldering, PCB rework, verification process and planning of a test campaign.

Also it is important to recall those skills acquired that are related to the satellite and radio operation, and the laboratory instrumentation –such as the use of the oscilloscope, the network analyser, the spectrum analyser or the signal analyser.

After concluding this project, solid skills and knowledge were garnered, which will be for sure a great asset in a near future when seeking a job in a leading space technology company.

In summary, the author is highly satisfied with the work accomplished and the results presented. Indeed, he considers that the work handled is complete, rigorous, self-reliant, and appropriately cited when needed. In case the reader feels a lack of information in some section of this document, any text of the referenced literature may be a good starting point.

8.2 Future work

This project was born already bearing in mind that it would not be possible to finish it completely. The nature of the remaining work is varied. While the actions unable to perform are minimal, other remaining tasks may well be large enough to conduct a related master's thesis. For example:

- Electronics:
  - To design a second version of the board, where the identified mistakes and inaccuracies are corrected.
  - To carry out the verification process for this new PCB design.
  - To develop the antenna system and the test procedures in order to verify both systems altogether.
  - To gather capacitors and inductors in buckets in order to properly tune –without material restrictions– all matching networks and filters.
- Software:
  - To design all the functions and routines for the whole system.
  - To develop the microcontroller firmware: SPI protocol, hardware interruptions, external hardware interface, Cubesat bus protocol, etc.
  - To specify an optimal CC1125 register setup.
  - To develop and integrate an implementation of the AX.25 protocol.
- Testing and qualification:
  - To finish all those verifications that were unable to perform.
  - To develop and fulfil all the tests listed in order to get a qualified board.

8

8.3 Lessons learned

The mere opportunity to perform a project like this pushes engineers to work beyond their own knowledge, and to think out of the box. Therefore, a list of the lessons learned would be infinite. This is a brief summary of most enriching ones:

- Applicable *space standards* and *recommendations* are vast and hard to apply for a project, but their use ensure a correct behaviour of the system.
- Legal regulations may restrict the development of the project, for that reason it is recommended to check them throughout the very first design phase.
- Definition of the system requirements demands a deep knowledge of extensive engineering fields and a clear picture of the project itself.

- A precise estimation of the time required for the project development is hard to make. It is easy to undervalue risky delays or to estimate them in a very optimistic manner.
- Fabrication and implementation phase is much more slow and laborious than expected, even though it was expected to be slow.
  - Hofstadter's Law: *It always takes longer than you expect, even when you take into account Hofstadter's Law.*
- Selection of components is a slow and arduous task that should be done simultaneously during the schematics and PCB design.
- Even when many system elements are considered in the first version of the system, there will be some characteristics that had not been taken into account at first.
- A proper RF design forces us to be rigorous and meticulous throughout its development.
- Matching networks tunning is a very hard task. It is almost certain that a theoretical value for the passive components will not match the actual required value because of the board parasitic values.
- Verification and test planning cannot wait until the first version of the design is finished, but it needs to be done during the very first stages of the project.
- Handling and having a good control of the laboratory instrumentation is a slow task.

8

Appendix A

Radio Regulations for Satellite-Amateur Services

For better understanding, a complete list of Radio Regulations involved in amateur-satellite service and amateur service is provided in this Appendix. This list has been obtained from ITU's document *ITU-Radio Regulations* [39].

ARTICLE 25

Amateur services

Section I – Amateur service

25.1 § 1 Radiocommunications between amateur stations of different countries shall be permitted unless the administration of one of the countries concerned has notified that it objects to such radiocommunications.

25.2 § 2 1)Transmissions between amateur stations of different countries shall be limited to communications incidental to the purposes of the amateur service, as defined in No. 1.56 and to remarks of a personal character.

25.2A 1 bis) Transmissions between amateur stations of different countries shall not be encoded for the purposes of obscuring their meaning, except for control signals exchanged between Earth command stations and space stations in the amateur-satellite service.

25.3 2) Amateur stations may be used for transmitting international communications on behalf of third parties only in case of emergencies or disaster relief. An administration may determine the applicability of this provision to amateur stations under its jurisdiction.

25.4 SUP

A

25.5 § 3 1) Administrations shall determine whether or not a person seeking a license to operate an amateur station shall demonstrate the ability to send and receive texts in Morse code signals.

25.6 2) Administrations shall verify the operational and technical qualifications of any person wishing to operate an amateur station. Guidance for standards of competence may be found in the most recent version of Recommendation ITU-R M.1544.

25.7 § 4 The maximum power of amateur stations shall be fixed by the administrations concerned.

25.8 § 5 1) All pertinent articles and provisions of the Constitution, the Convention and of these Regulations shall apply to amateur stations.

25.9 2) During the course of their transmissions, amateur stations shall transmit their call sign at short intervals.

25.9A Administrations are encouraged to take the necessary steps to allow amateur stations to prepare for and meet communication needs in support of disaster relief.

25.9B An administration may determine whether or not to permit a person who has been granted a license to operate an amateur station by another administration, to operate an amateur station while that person is temporarily in its territory, subject to such conditions or restrictions as it may impose.

Section II – Amateur-satellite service

25.10 § 6 The provisions of Section I of this Article shall apply equally, as appropriate, to the amateur-satellite service.

25.11 § 7 Administrations authorising space stations in the amateur-satellite service shall ensure that sufficient Earth command stations are established before launch to insure that any harmful interference caused by emissions from a station in the amateur-satellite service can be terminated immediately (See No. 22.1).

Appendix B

Link budget

As specified in Section 3.1, a link budget is the calculation of the overall *energy per bit* and *noise density* ratio of the system. It is employed to know the system behaviour. Figure B.1 is recalled from Chapter 3 (see Figure 3.1), where the steps involved in the budget calculation are summarised. In this appendix, unlike in Chapter 3, the detailed data regarding the Ground Station and the Cubesat specifications is provided.

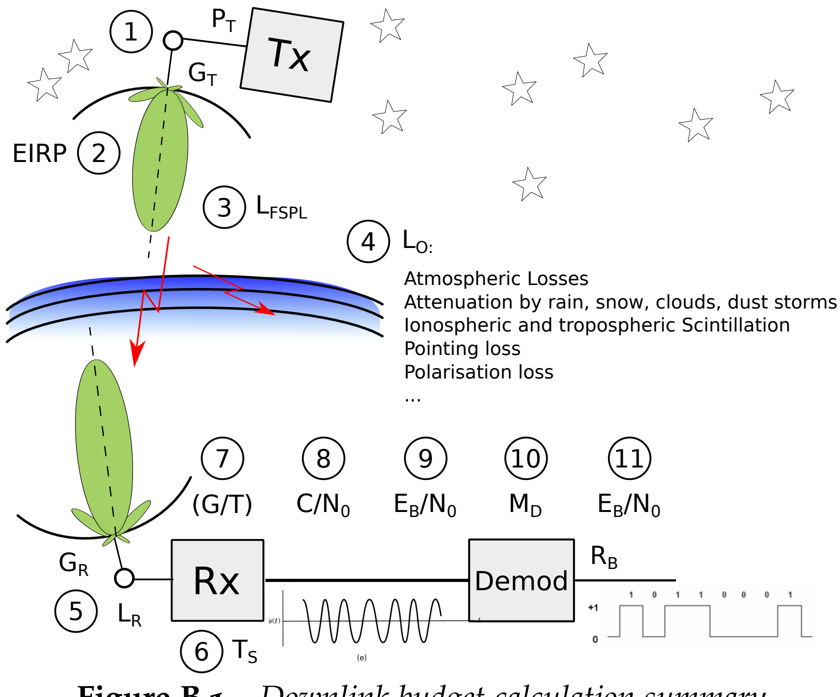


Figure B.1 – *Downlink budget calculation summary*

Calculations were done by using the AMSAT and IARU link budget tool [47] available in http://www.amsatuk.me.uk/iaru/spreadsheet.htm.

B.1 GranaSAT Ground Station

GranaSAT Ground Station — 37°18 41 N 3°36 3 W
Spacecraft orbit: LEO — Slant range: 1831 km
Uplink frequency: 145.800 MHz — Dowlink frequency: 437.500 MHz

B

Parameter		*UPLINK*	*DOWNLINK*
TX		**Ground Station**	**Cubesat**
Transmitter power output	[dBW]	0	−3.5
Total transmission line losses	[dB]	3.7	0.6
Antenna gain	[dBi]	12.6	2.2
EIRP	[dBW]	8.9	−1.9
FSPL and other losses		**Uplink path**	**Downlink path**
TX antenna pointing loss	[dB]	0.3	0.3
Antenna polarisation loss	[dB]	0.1	0.1
Path loss	[dB]	141.0	150.5
Atmospheric losses	[dB]	1.1	1.1
Ionospheric losses	[dB]	0.7	0.4
Isotropic power at RX	[dBW]	−134.2	−154.2
RX		**Cubesat**	**Ground Station**
Antenna pointing loss	[dB]	0.3	0.4
Antenna gain	[dBi]	2.2	14.9
Total reception line losses	[dB]	9.3	1.4
Effective Noise Temperature	[K]	433	392
Figure of Merit (G/T)	[dB/K]	−33.5	−12.5
Carrier-to-noise density (C/N_0)	[dBHz]	+60.6	+61.5
Data rate	[dBHz]	36.8	39.8
(E_b/N_0)	[dB]	+23.8	+21.7
Modulation Scheme		**GMSK**	**GMSK**
Probability of bit error		$P_B = 10^{-5}$	$P_B = 10^{-5}$
Required (E_b/N_0)	[dB]	9.6	9.6
Demodulator implementation loss	[dB]	6	6
SYSTEM LINK MARGIN	[dB]	+8.2	+6.1

Table B.1 – *GranaSAT Ground Station Link Budget*

B.2 ESAC Ground Station

ESAC Ground Station — 40°44 4 N 3°95 3 W
Spacecraft orbit: LEO — Slant range: 1831 km
Uplink frequency: 145.800 MHz — Dowlink frequency: 437.500 MHz

Parameter		*UPLINK*	*DOWNLINK*
TX		**Ground Station**	**Cubesat**
Transmitter power output	[dBW]	0.0	−3.5
Total transmission line losses	[dB]	3.7	0.6
Antenna gain	[dBi]	14.5	2.2
EIRP	[dBW]	10.8	−1.9
FSPL and other losses		**Uplink path**	**Downlink path**
TX antenna pointing loss	[dB]	0.5	0.3
Antenna polarisation loss	[dB]	0.1	0.1
Path loss	[dB]	141.0	150.5
Atmospheric losses	[dB]	1.1	1.1
Ionospheric losses	[dB]	0.7	0.4
Isotropic power at RX	[dBW]	−132.5	−154.2
RX		**Cubesat**	**Ground Station**
Antenna pointing loss	[dB]	0.3	0.4
Antenna gain	[dBi]	2.2	16.2
Total reception line losses	[dB]	9.3	2.1
Effective Noise Temperature	[K]	433	475
Figure of Merit (G/T)	[dB/K]	−33.5	−12.7
Carrier-to-noise density (C/N_0)	[dBHz]	+62.3	+61.2
Data rate	[dBHz]	36.8	39.8
(E_b/N_0)	[dB]	+25.5	+21.4
Modulation Scheme		**GMSK**	**GMSK**
Probability of bit error		$P_B = 10^{-5}$	$P_B = 10^{-5}$
Required (E_b/N_0)	[dB]	9.6	9.6
Demodulator implementation loss	[dB]	6	6
SYSTEM LINK MARGIN	[dB]	+9.9	+5.8

Table B.2 – *ESAC Ground Station Link Budget*

B

Appendix C

Electronics schematics

In this appendix, the electronic schematics from the GRANASAT-COMM-pcb-revo board are provided.

Further details about these documents can be found in Chapter 6, where it is explained the functionality of the circuitry shown here. Documents provided are, in order of appearance, the following:

(1) System architecture

(2) Cubesat main bus

(3) Current and voltage monitoring

(4) Micro Controller Unit (MCU)

(5) UHF transceiver

(6) VHF transceiver

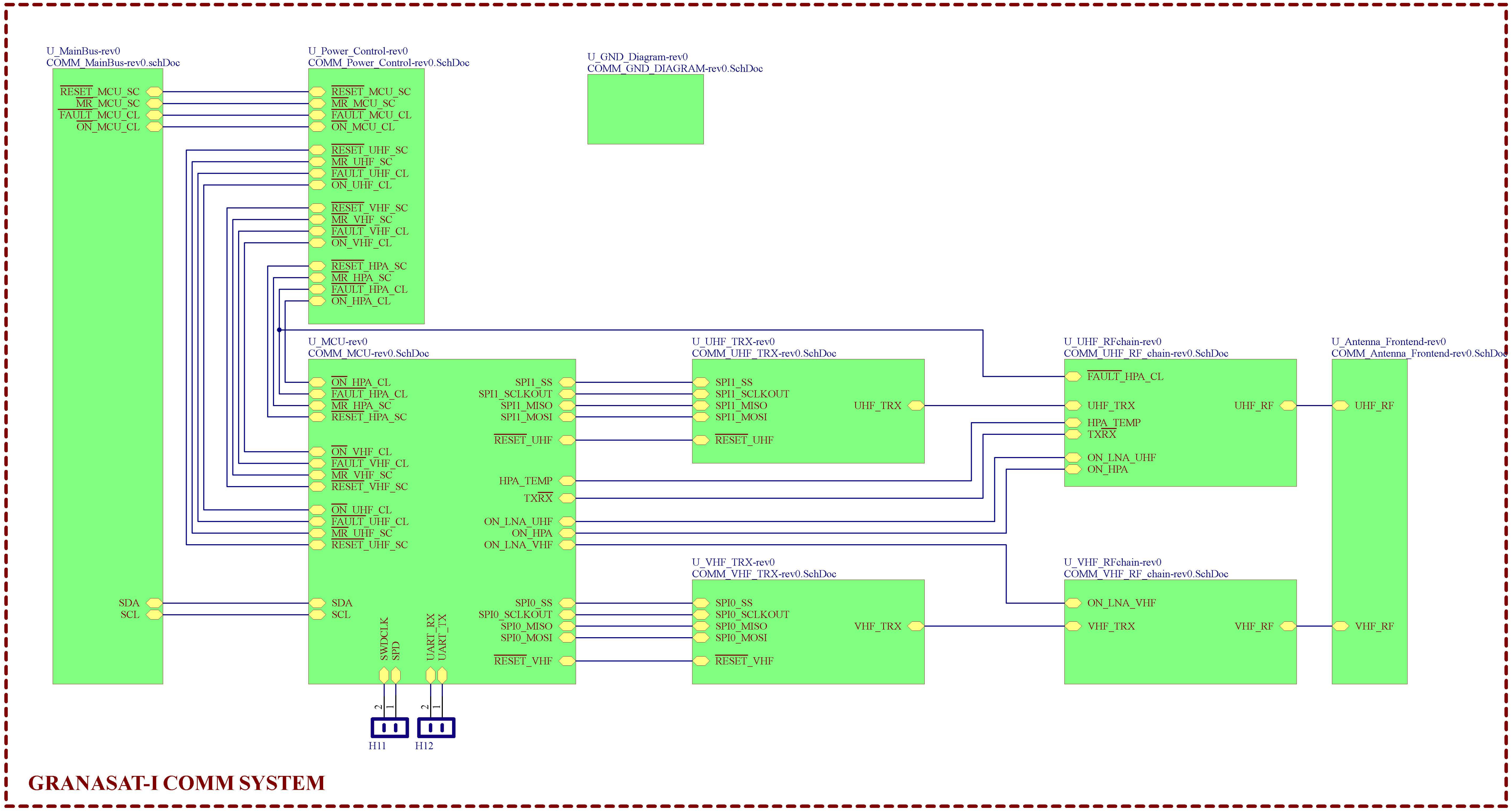
(7) UHF RF chain

(8) VHF RF chain

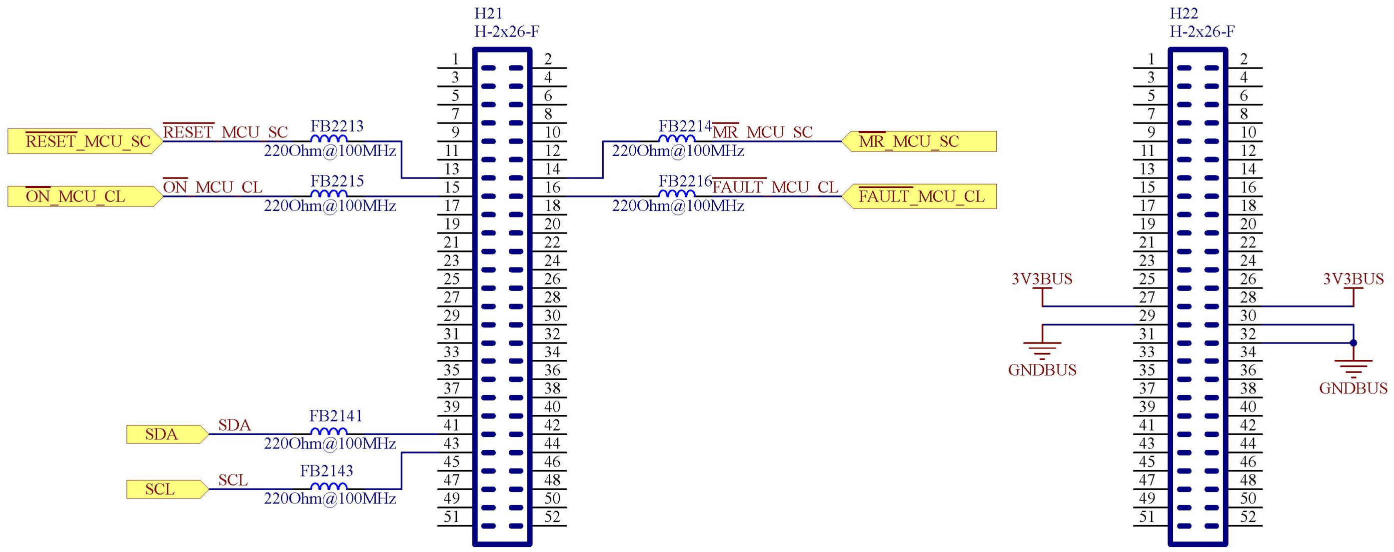
(9) Antenna front end

(10) GND diagram

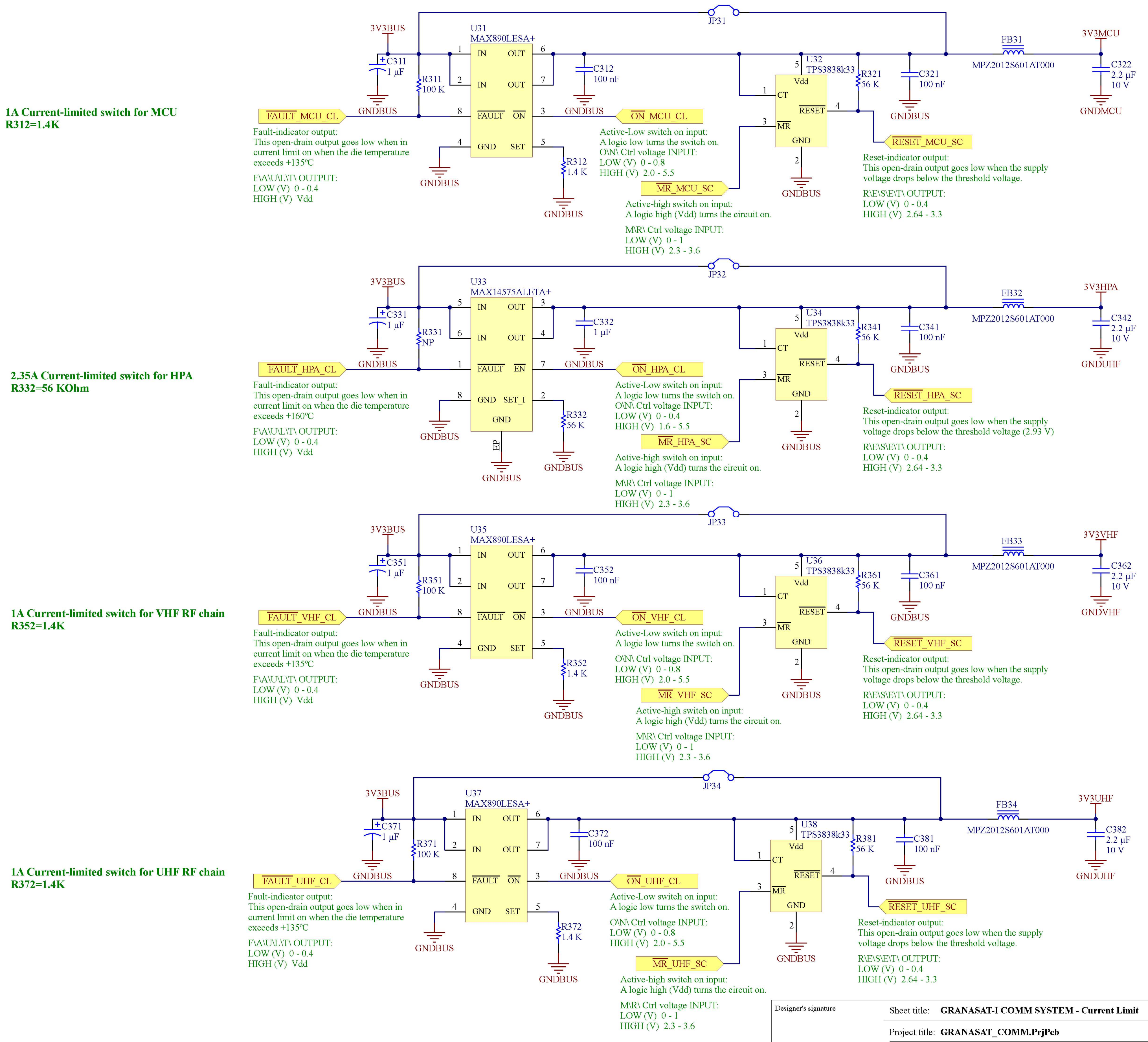
C



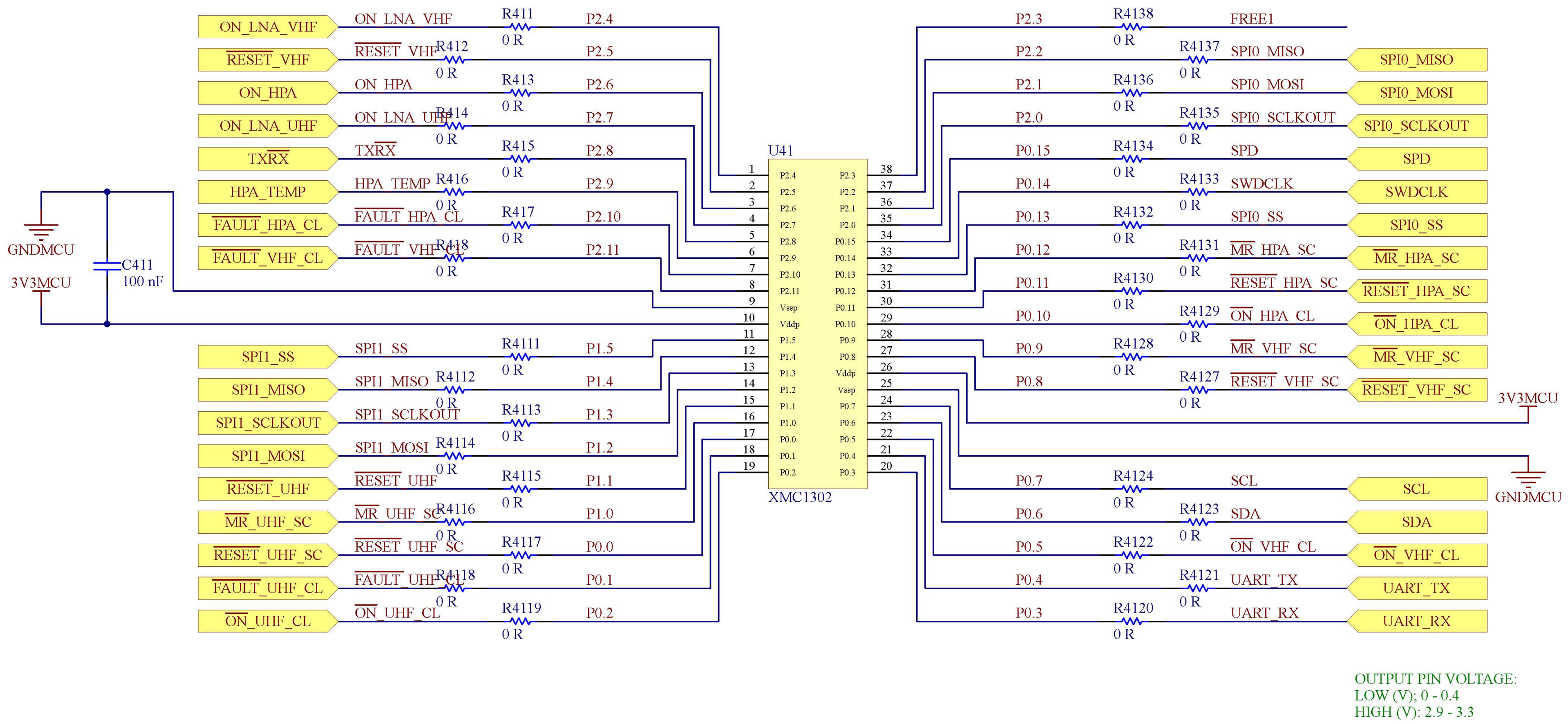
Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM**	Dpto. Electrónica y Tecnología de Computadores
	Project title: **GRANASAT_COMM.PrjPcb**	University of Granada
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**	*C/ Fuente Nueva s/n, 18001 Granada, Spain*
	Date: **09-09-2017** Revision: **0** Sheet **1** of **10**	*Sr. Andrés Roldán Aranda*



Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM - Cubesat Main Bus**	Dpto. Electrónica y Tecnología de Computadores
	Project title: **GRANASAT_COMM.PrjPcb**	University of Granada
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**	*C/ Fuente Nueva s/n, 18001 Granada, Spain*
	Date: **09-09-2017** Revision: **0** Sheet **2** of **10**	*Sr. Andrés Roldán Aranda*



Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM - Current Limit**	Dpto. Electrónica y Tecnología de Computadores
	Project title: **GRANASAT_COMM.PrjPcb**	University of Granada
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**	*C/ Fuente Nueva s/n, 18001* *Granada, Spain*
	Date: **09-09-2017** Revision: **0** Sheet **3** of **10**	*Sr. Andrés Roldán Aranda*



Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM - Main Controller Unit**
	Project title: **GRANASAT_COMM.PrjPcb**
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**
	Date: **09-09-2017** Revision: **0** Sheet **4** of **10**

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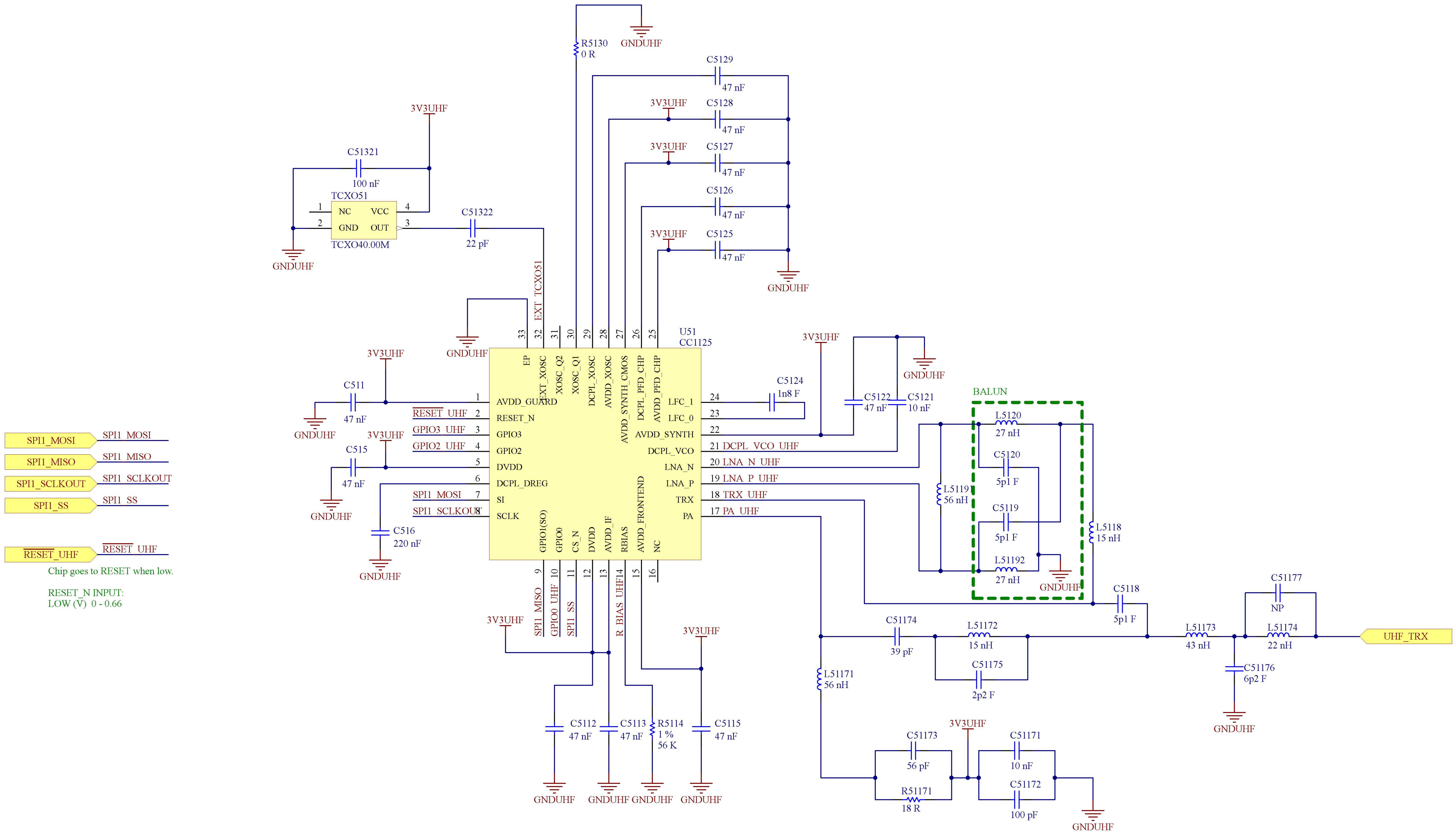

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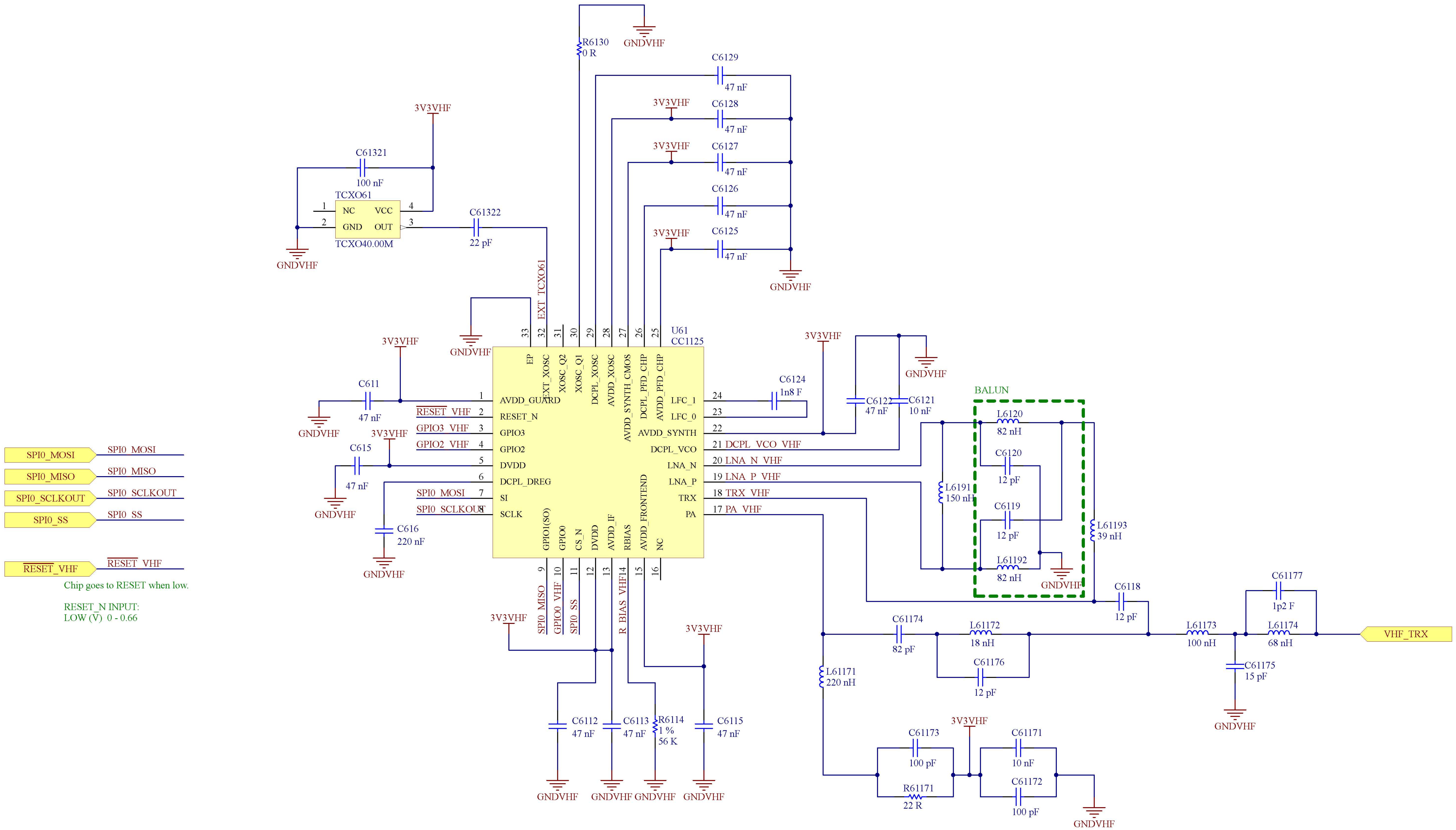
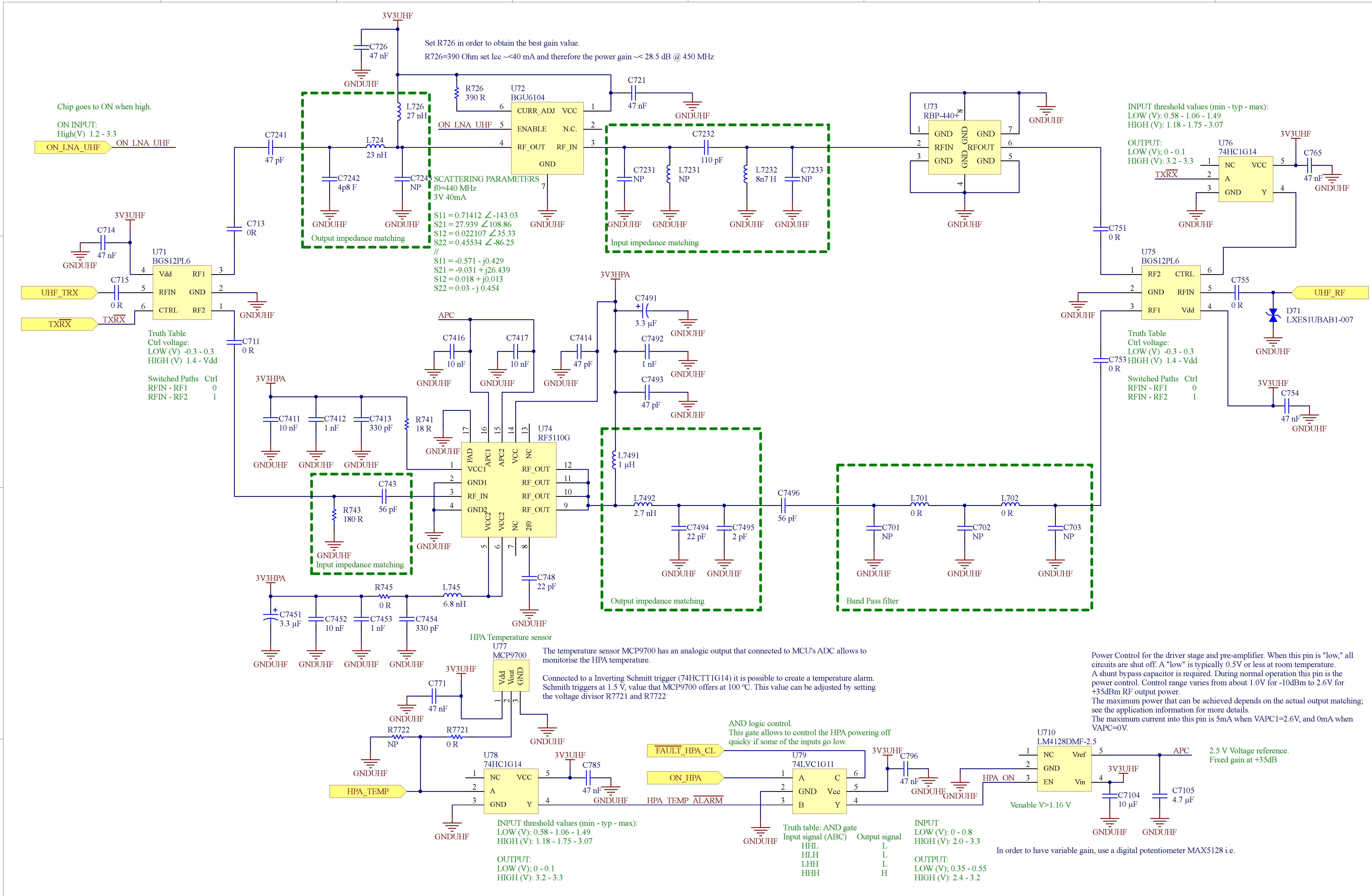
	Project title: **GRANASAT_COMM.PrjPcb**	University of Granada
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**	C/ Fuente Nueva s/n, 18001 Granada, Spain
	Date: **09-09-2017** Revision: **0** Sheet **5** of **10**	Sr. Andrés Roldán Aranda



Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM - VHF Transceiver**	Dpto. Electrónica y Tecnología de Computadores
	Project title: **GRANASAT_COMM.PrjPcb**	University of Granada
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**	*C/ Fuente Nueva s/n, 18001 Granada, Spain*
	Date: **09-09-2017** Revision: **0** Sheet **6** of **10**	*Sr. Andrés Roldán Aranda*



Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM - UHF RF Chain**
	Project title: **GRANASAT_COMM.PrjPcb**
Supervisor's signature	Designer: **Emilio J. Martinez Perez**
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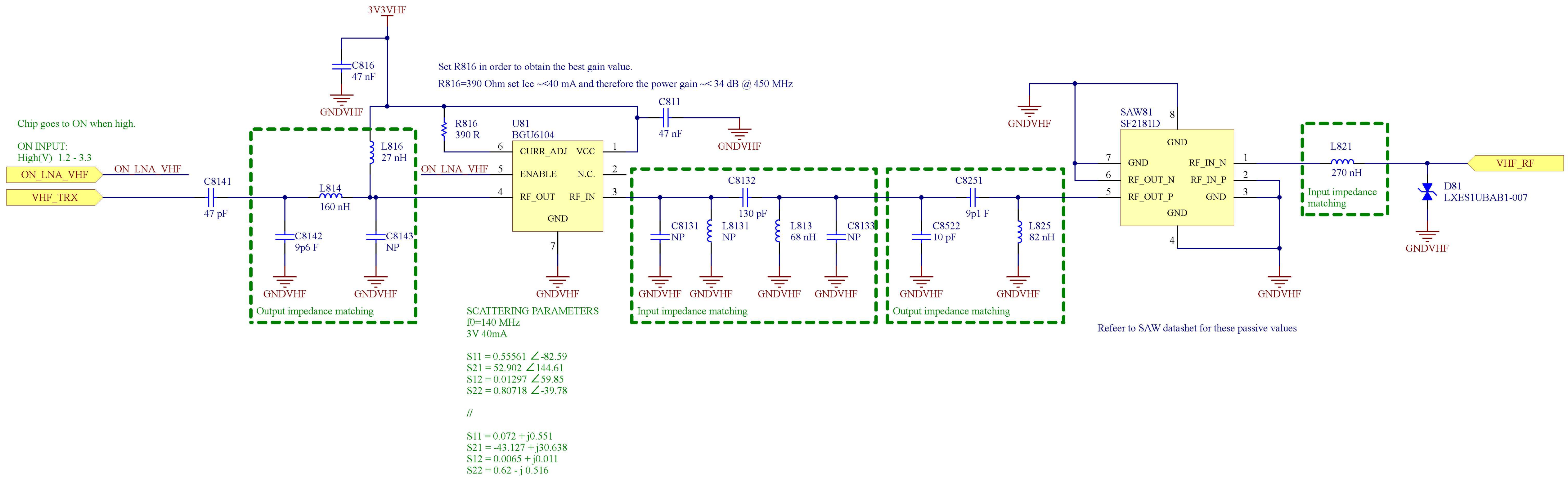
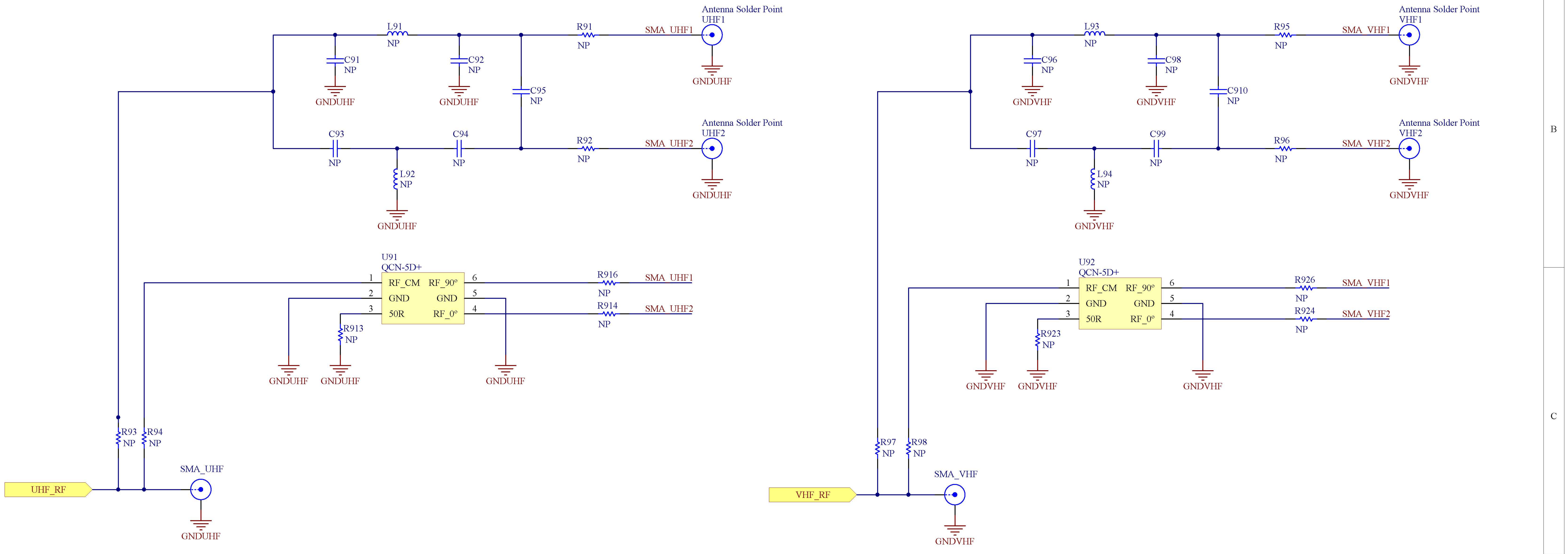


Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM - VHF RF Chain**	Dpto. Electrónica y Tecnología de Computadores
	Project title: **GRANASAT_COMM.PrjPcb**	University of Granada
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**	*C/ Fuente Nueva s/n, 18001 Granada, Spain*
	Date: **09-09-2017** Revision: **0** Sheet **8** of **10**	*Sr. Andrés Roldán Aranda*



Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM - Antenna Frontend**
	Project title: **GRANASAT_COMM.PrjPcb**
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**
	Date: **09-09-2017** Revision: **0** Sheet **9** of **10**

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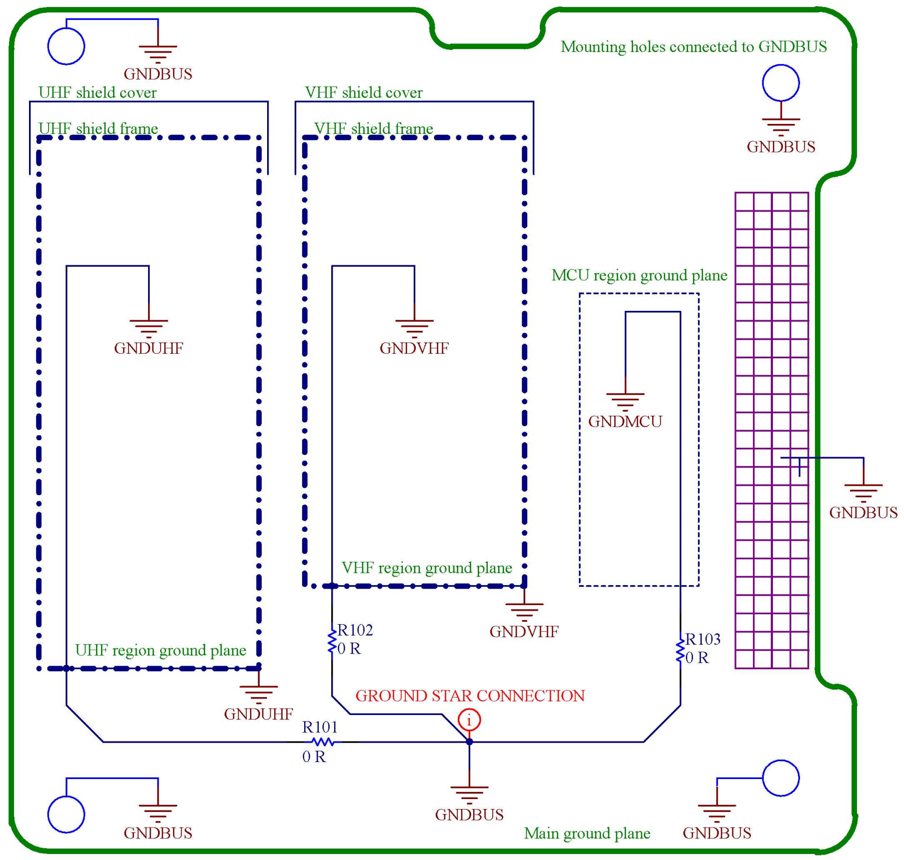


Designer's signature	Sheet title: **GRANASAT-I COMM SYSTEM - GND Diagram**	Dpto. Electrónica y Tecnología de Computadores
	Project title: **GRANASAT_COMM.PrjPcb**	University of Granada
Supervisor's signature	Desginer: **Emilio J. Martinez Perez**	*C/ Fuente Nueva s/n, 18001 Granada, Spain*
	Date: **09-09-2017** Revision: **0** Sheet **10** of **10**	*Sr. Andrés Roldán Aranda*

Appendix D

Electronics BOM

The development of an electronics project implies not only the PCB design but also the selection of the components. When a design has been finalised, a Bill Of Material (BOM) file is generated. This document contains a list of all chosen components in the electronic design and also provides useful information about them. Together with the *Gerber* files (see Apendix E), the BOM file is the only document required to manufacture and produce a complete and functional PCB.

During the course of this project, the components have been named in accordance to the module numeration depicted in Figure D.1. Therefore, in order to know the module a component belongs to, only the **first number of the component** is needed. For example, C322 and L745 belong, respectively, to module 3 and 7.

This is the complete list of modules that conform the system:

(1) External interface

(2) GranaSAT-I PC-104 bus

(3) Power monitoring, control and current protection

(4) Microcontroller module

(5) UHF transceiver

(6) VHF transceiver

(7) UHF transmission and reception chain

(8) VHF reception chain

(9) Experimental antenna sub-system interface

(10) Ground signal management

D

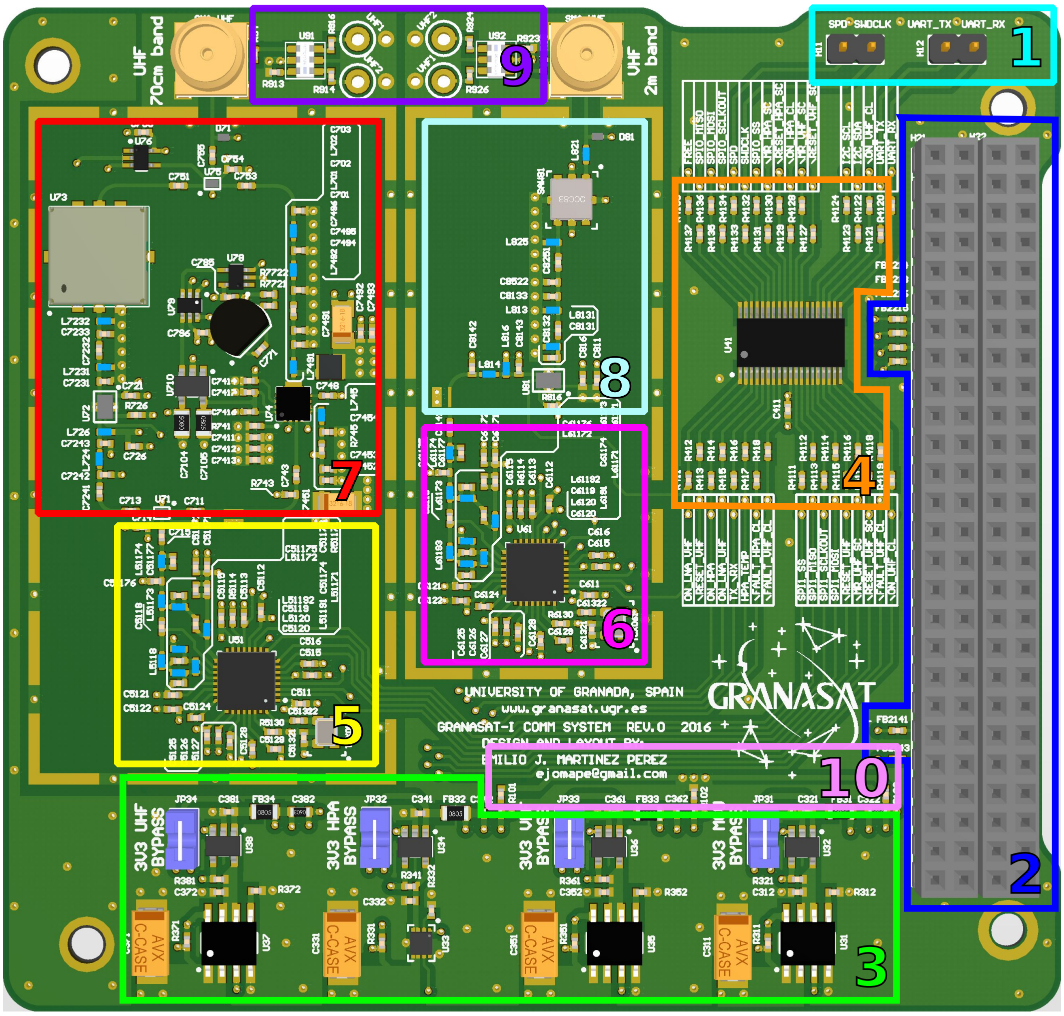


Figure D.1 – *Modules highlighted in 3D model of the COMM system PCB*

Designator	#	Value	Rate	Toler.	Footprint	Manufact.	Part Number	Description
C91, C92, C93, C94, C95, C96, C97, C98, C99, C701, C702, C703, C711, C713, C715, C751, C753, C755, C910, C7231, C7233, C7243, C8131, C8133, C8143, C51177, R321, R331, R341, R361, R381, R7722	32	NP	NA	NA	0402	NP	NP	Not placed
C311, C331, C351, C371	4	1 µF	63 V	±20 %	C Case	AVX	TCJC105M063R0300	Polarized Capacitor
C312, C321, C341, C352, C361, C372, C381, C411, C51321, C61321	10	100 nF	16 V	±10 %	0402	Murata	GRM155R71C104KA	Capacitor
C511, C515, C611, C615, C714, C721, C726, C754, C765, C771, C785, C796, C811, C816, C5112, C5113, C5115, C5122, C5125, C5126, C5127, C5128, C5129, C6112, C6113, C6115, C6122, C6125, C6126, C6127, C6128, C6129	32	47 nF	25 V	±10 %	0402	Murata	GRM155R71E473KA	Capacitor
C332	1	1 µF	10 V	±10 %	0402	Murata	GCM155C71A105KE	Capacitor
C322, C342, C362, C382	4	2.2 µF	10 V	±10 %	0603	Murata	GRM188R71A225KE	Capacitor

Designator	#	Value	Rate	Toler.	Footprint	Manufact.	Part Number	Description
C516, C616	2	220 nF	10 V	±10 %	0402	Murata	GRM155R61A224KE	Capacitor
C51172, C61172, C61173	3	100 pF	50 V	±5 %	0402	Murata	GRM1555C1H101JA	Capacitor
C51174	1	39 pF	50 V	±5 %	0402	Murata	GRM1555C1H390JA	Capacitor
C51175	1	2p2 F	50 V	±0.25 pF	0402	Murata	GRM1555C1H2R2CA	Capacitor
C51176	1	6p2 F	50 V	±0.25 pF	0402	Murata	GRM1555C1H6R2CA	Capacitor
C5118, C5119, C5120	3	5p1 F	50 V	±0.25 pF	0402	Murata	GRM1555C1H5R1CA	Capacitor
C5121, C6121, C7411, C7416, C7417, C7452, C51171, C61171	8	10 nF	25 V	±10 %	0402	Murata	GRM155R71E103KA	Capacitor
C5124, C6124	2	1n8 F	10 V	±5 %	0402	Murata	GRM1557U1A182JA	Capacitor
C51322, C61322	2	22 pF	50 V	±5 %	0402	Murata	GRM1555C1H220JA	Capacitor
C61174	1	82 pF	50 V	±5 %	0402	Murata	GRM1555C1H820JA	Capacitor
C61175	1	15 pF	50 V	±5 %	0402	Murata	GRM1555C1H150JA	Capacitor
C61177	1	1p2 F	50 V	±0.5 pF	0402	Murata	GJM1555C1H1R2BB	Capacitor
C6118, C6119, C6120, C61176	4	12 pF	50 V	±5 %	0402	Murata	GRM1555C1H120JA	Capacitor
C743, C7496, C51173	3	56 pF	50 V	±5 %	0402	Murata	GRM1555C1H560JA	Capacitor
C748, C7494	2	22 pF	50 V	±1 %	0402	Murata	GRM1555C1H220FA	Capacitor
C7104	1	10 µF	10 V	±10 %	0805	Murata	GCM21BR71A106KE	Capacitor
C7105	1	4.7 µF	16 V	±10 %	0805	Murata	GCM21BR71C475KA	Capacitor
C7232	1	110 pF	50 V	±2 %	0402	Murata	GRM1555C1H111GA	Capacitor
C7241, C7414, C7493, C8141	4	47 pF	50 V	±1 %	0402	Murata	GRM1555C1H470FA	Capacitor

Designator	#	Value	Rate	Toler.	Footprint	Manufact.	Part Number	Description
C7242	1	4p8 F	50 V	±0.1 pF	0402	Murata	GJM1555C1H4R8BB	Capacitor
C7412, C7453, C7492	3	1 nF	50 V	±10 %	0402	Murata	GCM155R71H102KA	Capacitor
C7413, C7454	2	330 pF	50 V	±5 %	0402	Murata	GCM1555C1H331JA	Capacitor
C7451, C7491	2	3.3 µF	25 V	±10 %	A Case	AVX	TAJA335K025RNJ	Polarized Capacitor
C7495	1	2 pF	50 V	±0.1 pF	0402	Murata	GJM1555C1H2R0BB	Capacitor
C8132	1	130 pF	50 V	±2 %	0402	Murata	GRM1555C1H131GA	Capacitor
C8142	1	9p6 F	50 V	±0.25 pF	0402	Murata	GJM1555C1H9R6CB	Capacitor
C8251	1	9p1 F	50 V	±0.25 pF	0402	Murata	GJM1555C1H9R1CB	Capacitor
C8522	1	10 pF	50 V	±5 %	0402	Murata	GJM1555C1H100JB	Capacitor
D71, D81	2	-	15 V	-	DFN1006	Murata	LXES1UBAB1-007	Diode ESD Protection
FB31, FB32, FB33, FB34	4	-	2 A	±25 %	0805	TDK	MPZ2012S601AT000	EMI Ferrite Bead
FB2141, FB2143, FB2213, FB2214, FB2215, FB2216	6	-	250 mA	±25 %	0402	Murata	BLM15HB221SN1D	EMI Ferrite bead
H11, H12	2	-	-	-	-	-	-	Header 2-Pin
H21, H22	2	-	-	-	PC104	Samtec	ESQ-126-39-G-D	PC104 connector
L701, L702	2	0 R	3 A	<20 mR	0402	Vishay	RCS04020000Z0ED	0 Res
L724	1	23 nH	310 mA	±2 %	0402	Murata	LQW15AN23NG00D	Wire-wound inductor

Designator	#	Value	Rate	Toler.	Footprint	Manufact.	Part Number	Description
L726, L816, L5120, L51192	4	27 nH	280 mA	±5 %	0402	Murata	LQW15AN27NJ00D	Wire-wound inductor
L745	1	6.8 nH	1.45 A	±2 %	0402	Murata	LQW15AN6N8G80D	Wire-wound inductor
L51171, L51191	2	56 nH	-	±5 %	0402	Murata	LQW15AN56NJ00D	Wire-wound inductor
L51173	1	43 nH	-	±5 %	0402	Murata	LQW15AN43NJ00D	Wire-wound inductor
L51174	1	22 nH	-	±5 %	0402	Murata	LQW15AN22NJ00D	Wire-wound inductor
L5118, L51172	2	15 nH	-	±5 %	0402	Murata	LQW15AN15NJ00D	Wire-wound inductor
L61171	1	220 nH	-	±5 %	0402	Murata	LQG15HSR22J02D	Wire-wound inductor
L61172	1	18 nH	-	±5 %	0402	Murata	LQW15AN18NJ00D	Wire-wound inductor
L61173	1	100 nH	-	±5 %	0402	Murata	LQW15ANR10J00D	Wire-wound inductor

Designator	#	Value	Rate	Toler.	Footprint	Manufact.	Part Number	Description
L61174	1	68 nH	-	±5 %	0402	Murata	LQW15AN68NJ00D	Wire-wound inductor
L61193	1	39 nH	-	±5 %	0402	Murata	LQW15AN39NJ00D	Wire-wound inductor
L6191	1	150 nH	-	±5 %	0402	Murata	LQG15HSR15J02D	Wire-wound inductor
L7232	1	8n7 H	540 mA	±2 %	0402	Murata	LQW15AN8N7G00D	Wire-wound inductor
L7491	1	1 µFH	1.8 A	±20 %	XPL2010	Coilcraft	XPL2010102ML	Inductor
L7492	1	2.7 nH	1.5 A	±0.1 nH	0402	Murata	LQW15AN2N7B80D	Wire-wound inductor
L813	1	68 nH	320 mA	±5 %	0402	Murata	LQW15AN68NJ80D	Wire-wound inductor
L814	1	160 nH	480 mA	±5 %	0402	Murata	LQW15CNR16J00D	Wire-wound inductor
L821	1	270 nH	420 mA	±5 %	0402	Murata	LQW15CNR27J10D	Wire-wound inductor

Designator	#	Value	Rate	Toler.	Footprint	Manufact.	Part Number	Description
L825, L6120, L61192	3	82 nH	130 mA	±5 %	0402	Murata	LQW15AN82NJ00D	Wire-wound inductor
L91, L92, L93, L94, L7231, L8131	6	NP	NP	NP	0402	NP	NP	Not placed
R411, R412, R413, R414, R415, R416, R417, R418, R4111, R4112, R4113, R4114, R4115, R4116, R4117, R4118, R4119, R4120, R4121, R4122, R4123, R4124, R4127, R4128, R4129, R4130, R4131, R4132, R4133, R4134, R4135, R4136, R4137, R4138, R5130, R6130, R7721	37	0 R	2 A	<0.05 R	0402	Yageo	RC0402FR-070RL	0 Res
R311, R351, R371	3	100 K	-	±1 %	0402	Yageo	RC0402FR-07100KL	Resistor
R312, R352, R372	3	1.4 K	-	±1 %	0402	Yageo	RC0402FR-071K4L	Resistor
R332, R5114, R6114	3	56 K	-	±1 %	0402	Koa	RK73H1ETTP5602F	Resistor
R61171	1	22 R	-	±1 %	0402	Yageo	RC0402FR-0722RL	Resistor
R726, R816	2	390 R	100 mW	±1 %	0402	Panasonic	ERJ-2RKF3900X	Resistor
R741, R51171	2	18 R	-	±1 %	0402	Yageo	RC0402FR-0718RL	Resistor
R743	1	180 R	-	±1 %	0402	Yageo	RC0402FR-07180RL	Resistor
R913, R923	2	50 R	-	±1 %	0402	Yageo	AC0402JR-0750RL	Resistor

Designator	#	Value	Rate	Toler.	Footprint	Manufact.	Part Number	Description
R91, R92, R93, R94, R95, R96, R97, R98, R101, R102, R103, R745, R914, R916, R924, R926	16	0 R	3 A	<20 mR	0402	Vishay	RCS04020000Z0ED	0 Res
SAW81	1	-	-	-	SM3838-8	Murata	SF2181D	140MHz SAW filter
SMA-UHF, SMA-VHF	2	-	-	-	-	Samtec	SMA-J-P-H-RA-TH1	SMA RF connector
TCXO51, TCXO61	2	40 MHz	-	$\pm$5 ppm	2.5x2 mm	CTS	520L15IA40M0000	TCXO
U31, U35, U37	3	-	-	-	SO8-N	Maxim	MAX890LESA+	1.2 A current limited switch
U32, U34, U36, U38	4	-	-	-	SOT-23-5	TI	TPS3838K33	Voltage supervisory circuit
U33	1	-	-	-	TDFN	Maxim	MAX14575ALETA+	2.5 A current limited switch
U41	1	-	-	-	TSSOP-38	Infineon	XMC1302T038X0200	ARM Cortex $M0+\mu C$
U51, U61	2	-	-	-	RHB32-N	TI	CC1125RHBT	<1 GHz RF Transceiver

Designator	#	Value	Rate	Toler.	Footprint	Manufact.	Part Number	Description
U71, U75	2	-	-	-	TSLP-6-4	NXP	BGS12PL6	RF SPDT switch
U72, U81	2	-	-	-	HXSON-6	NXP	BGU6104,147	VHF & UHF LNA
U73	1	-	-	-	PL-176	Mini-Circuits	RBP-440+	440 MHz BPF
U74	1	-	-	-	QFN-16	RFMD	RF5110GTR7	UHF HPA
U76, U78	2	-	-	-	TSSOP-5	NXP	74HC1G14GW,125	CMOS Logic inverter
U77	1	-	-	-	TO-92A	Microchip	MCP9700A-E/TO	Analog output temperature sensor
U79	1	-	-	-	SOT-363	NXP	74LVC1G11GW,125	3 inputs AND gate
U710	1	-	-	-	SOT-23-5	TI	LM4128DMF-2.5	2.5 V Voltage Reference
U91, U92	2	-	-	-	FV1206	Mini-Circuits	QCN-5D+	Power Splitter & Combiner

Table D.1 – *Bill Of Material (BOM) for GRANASAT-COMM-pcb-rev0 board*

Appendix E

Manufacturing Gerber drawings

In this appendix, Gerber drawings from the GRANASAT-COMM-pcb-rev0 board are provided.

Gerber files are manufacturing files originated in the 80's, and are used by PCB manufacturers to know the placement and physical dimensions of tracks, vias, pads, or any other element inside the board. Therefore, with these pictures and the BOM file (see Appendix D) the replication and manufacture of the COMM System PCB would be possible.

Actual PCB dimensions are 95 x 90 mm. Gerber **drawings are scaled**. Dimensions should be checked before printing.

The set of Gerber Drawings herein offered are:

- Gerber Top Layer (GTL) – Tracks, vias, pads in top layer
- Gerber inner Plane 1 (GP1) – Tracks, vias, pads in first intermediate layer
- Gerber inner Plane 2 (GP2) – Tracks, vias, pads in second intermediate layer
- Gerber Bottom Layer (GBL) – Tracks, vias, pads in bottom layer
- Gerber Top Overlay (GTO) – Silkscreen information for top layer
- Gerber Bottom Overlay (GBO) – Silkscreen information for bottom layer
- Gerber Top Solder (GTS) – Mask solder for top layer
- Gerber Bottom Solder (GBS) – Mask solder for bottom layer
- Gerber Keep Out (GKO) – Board outline of the PCB

E

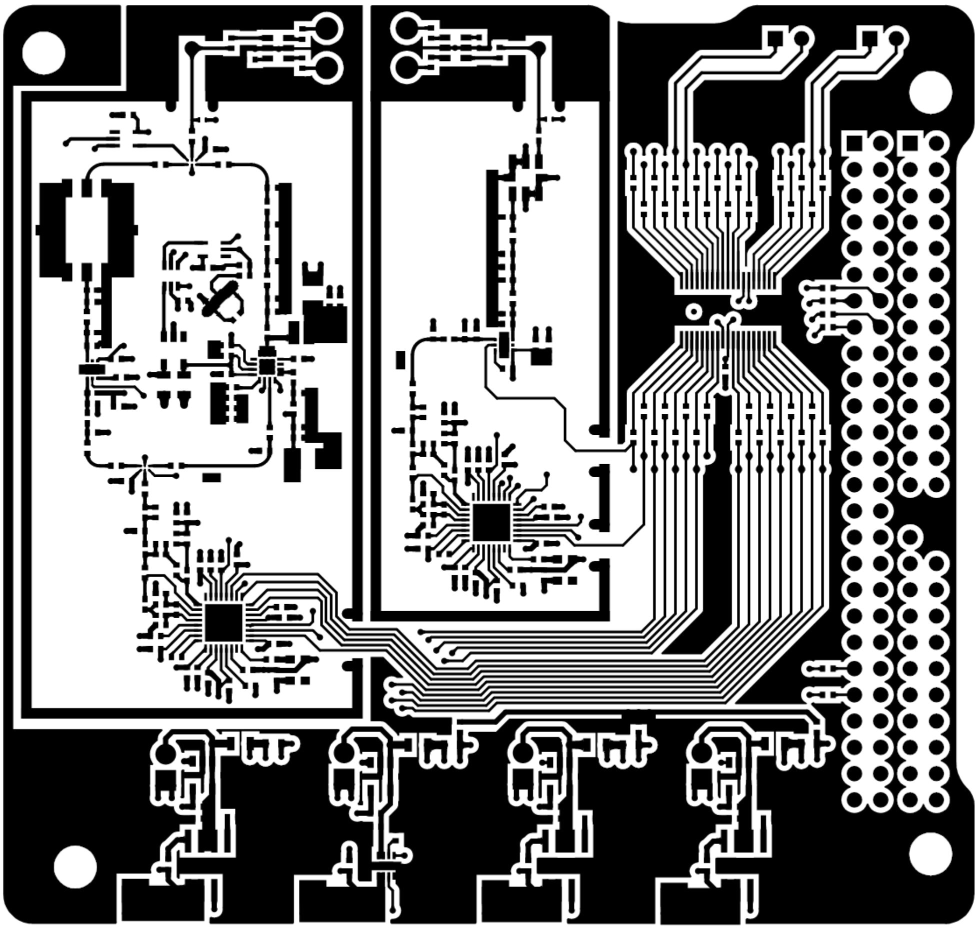


Figure E.1 – *Gerber Top Layer – Image is scaled. Dimensions should be checked before printing*

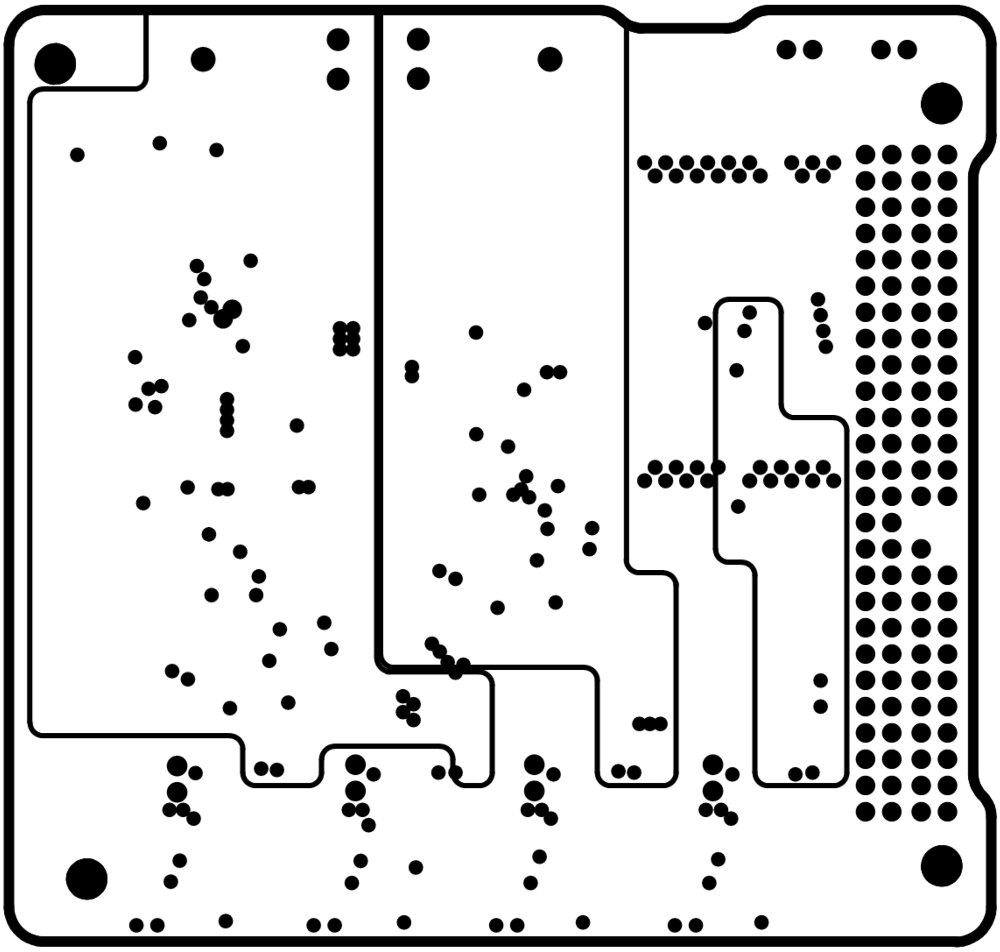


Figure E.2 – Gerber inner Plane 1 – *Image is scaled. Dimensions should be checked before printing*

E

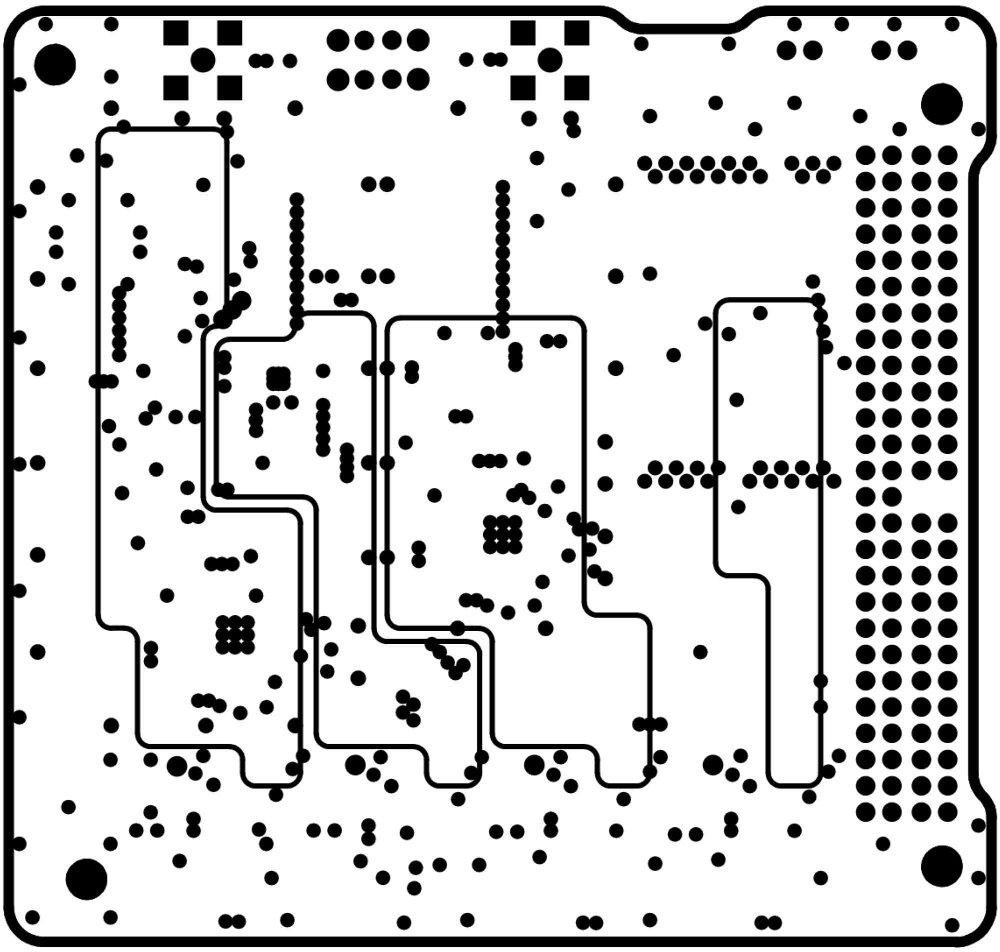


Figure E.3 – Gerber inner Plane 2 – *Image is scaled. Dimensions should be checked before printing*

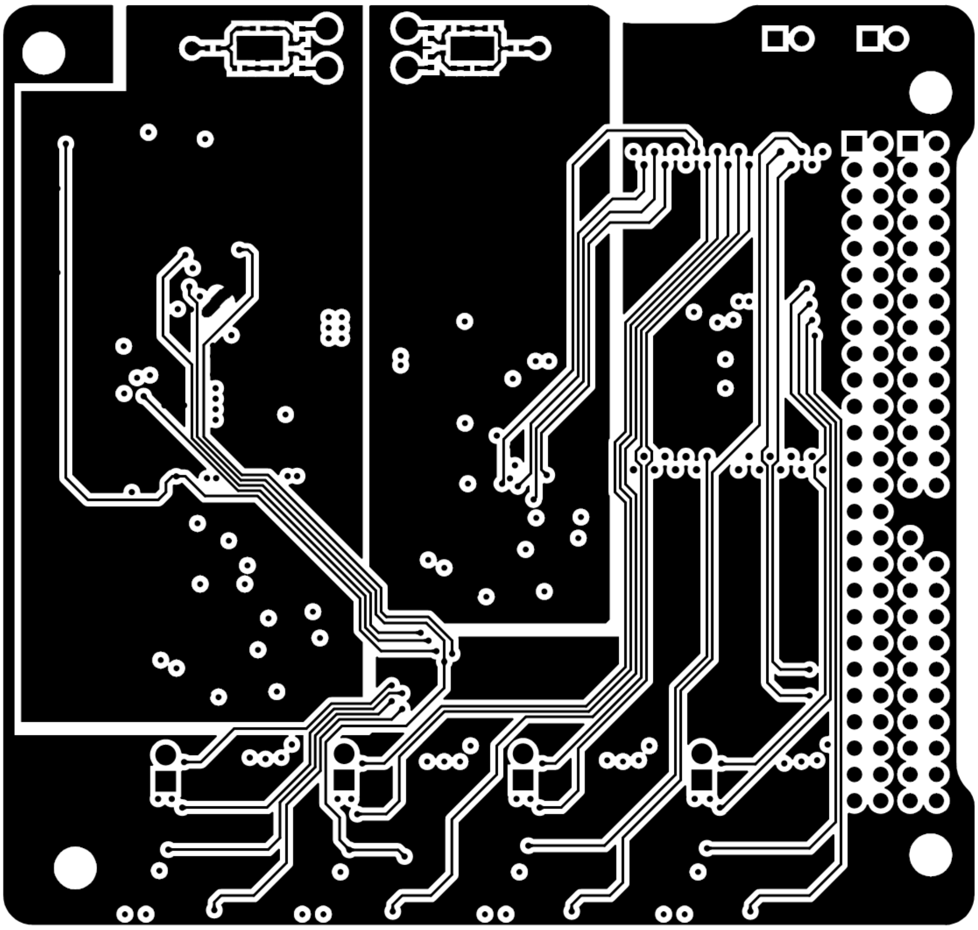


Figure E.4 – Gerber Bottom Layer – *Image is scaled. Dimensions should be checked before printing*

E

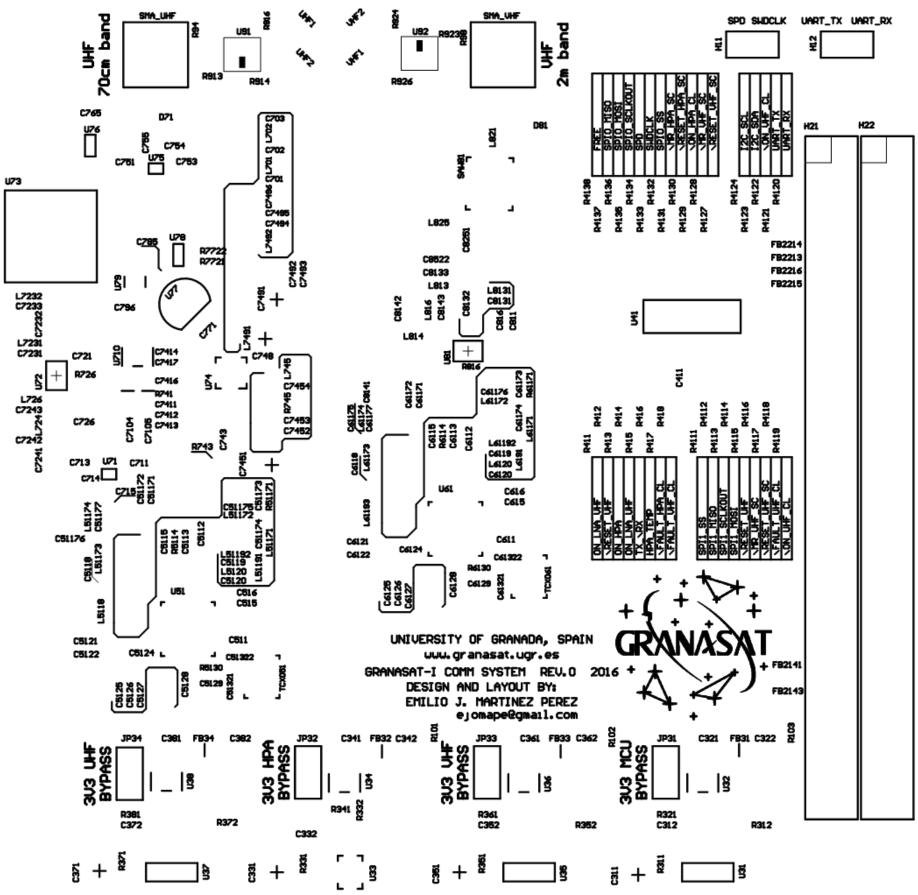


Figure E.5 – *Gerber Top Overlay – Image is scaled. Dimensions should be checked before printing*

E

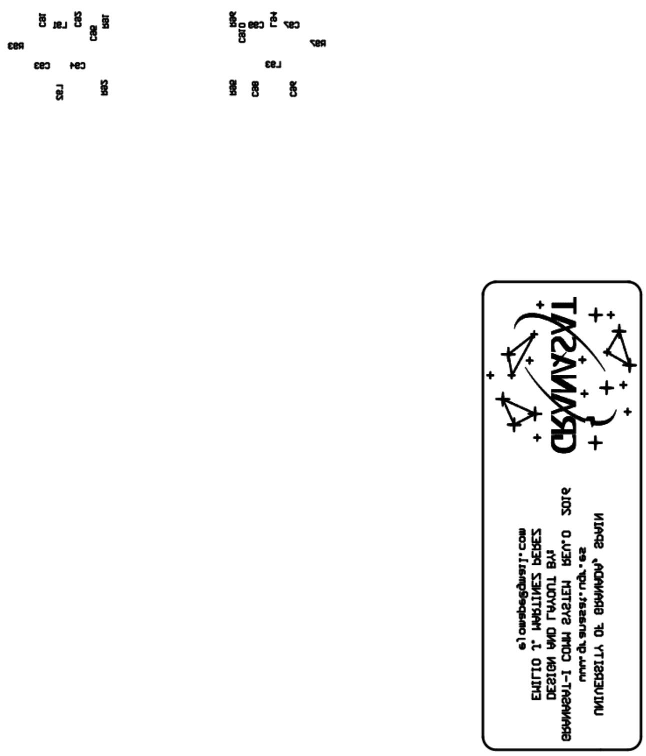


Figure E.6 – Gerber Bottom Overlay – *Image is scaled. Dimensions should be checked before printing*

E

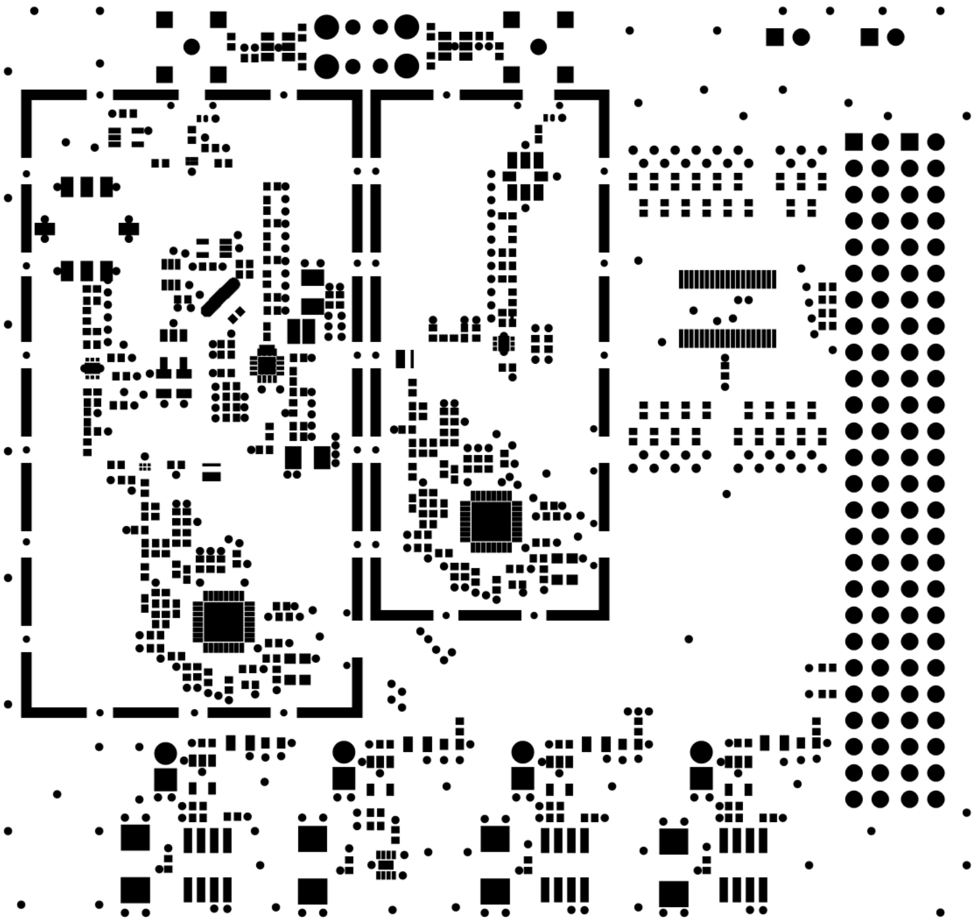


Figure E.7 – Gerber Top Solder – *Image is scaled. Dimensions should be checked before printing*

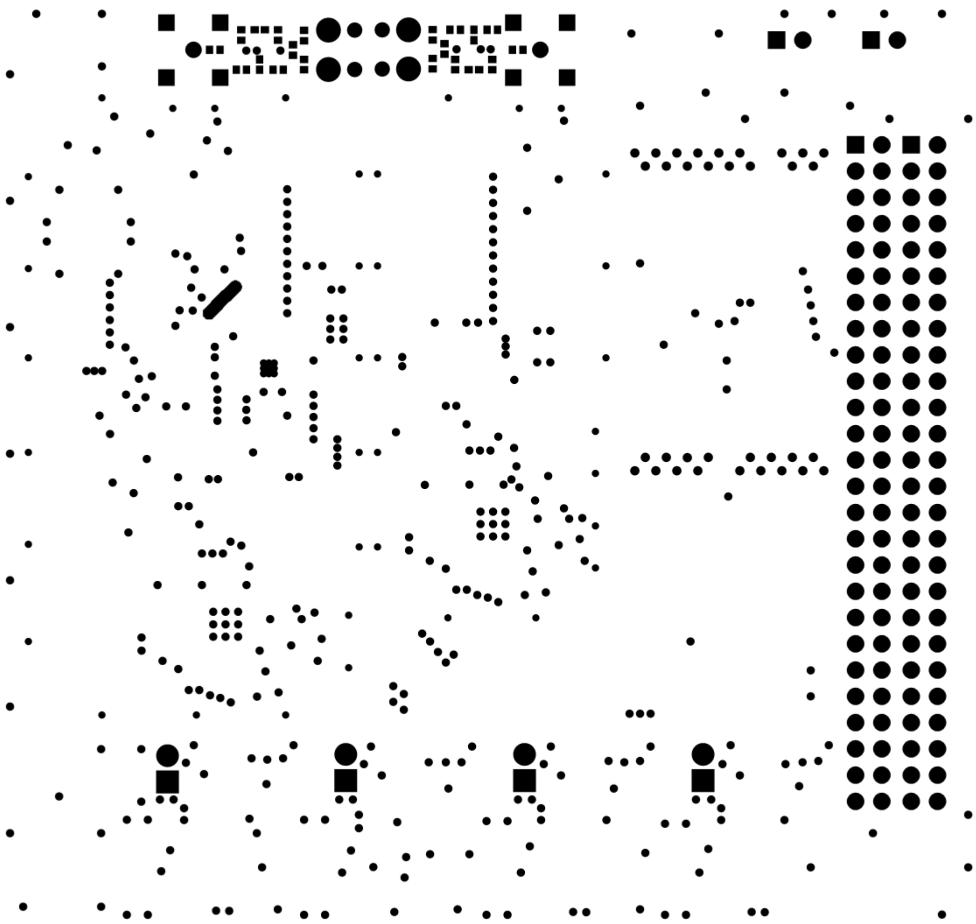


Figure E.8 – Gerber Bottom Solder – *Image is scaled. Dimensions should be checked before printing*

E

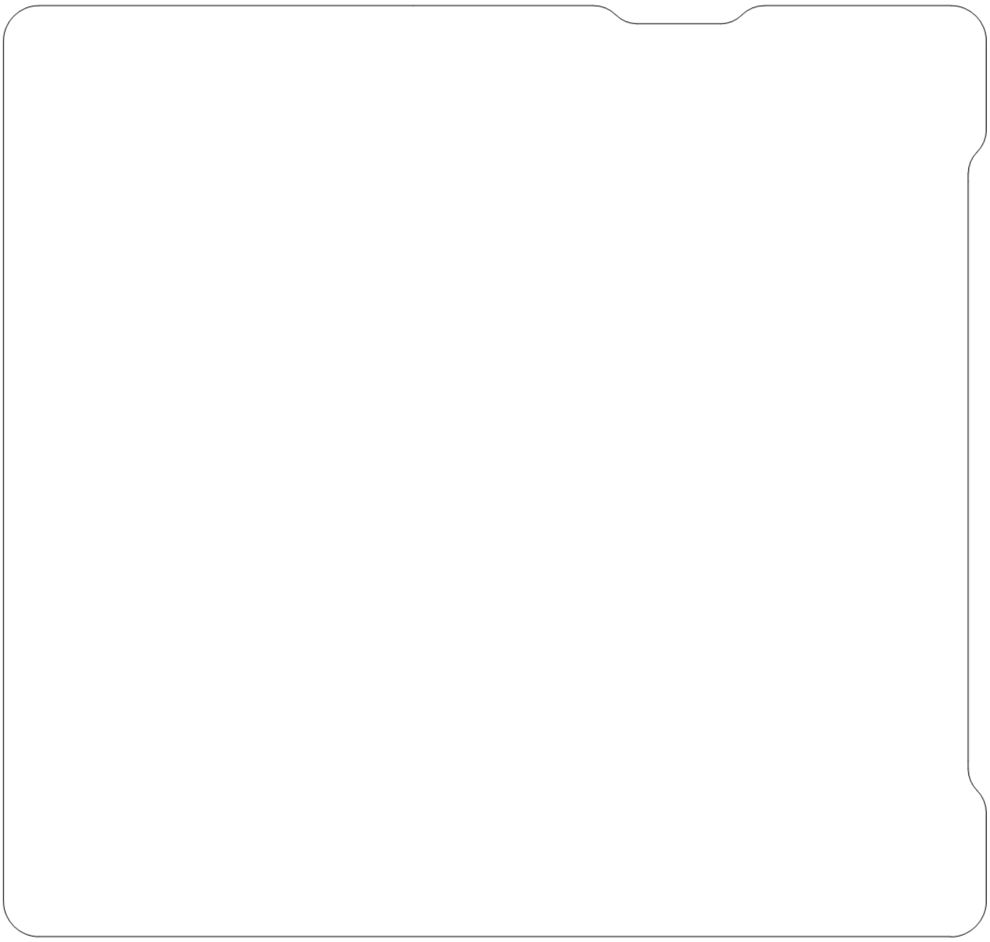


Figure E.9 – *Gerber Keep Out / Board Outline – Image is scaled. Dimensions should be checked before printing*

Appendix F

Electronics assembly

This appendix shows some pictures and comments related to the assembly of the PCB of the COMM System Engineering Model. The aim is to provide information about the challenges, difficulties and problems that have arisen throughout the soldering work, and how they have been solved.

Solder Stencil and solder paste

The procedure followed for soldering SMD components in the PCB starts with the placement of a small amount of solder paste in the board pads. Solder paste is made of tiny balls of tin and other metals, mixed up with *flux*, a chemical component that facilitates the soldering operation.

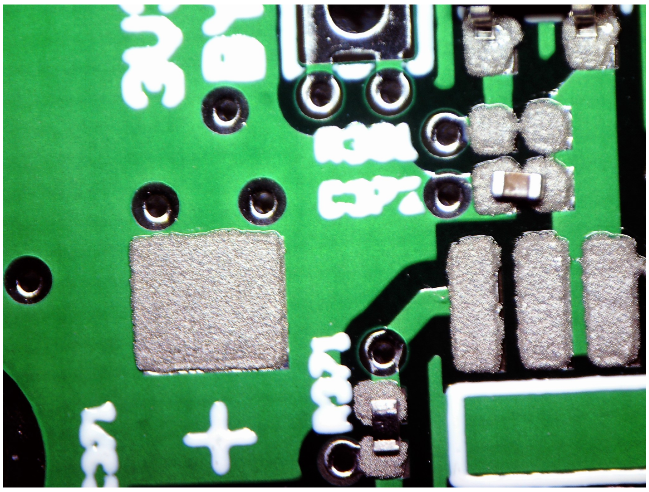


Figure F.1 – *Solder paste – Magnified view of the PCB*

When the solder paste is distributed all over the board pads, the SMD components are placed in the pads and fixed because of the viscosity of the paste. Then, the entire board is heated and the solder paste melted, soldering the components to the PCB. In Figure F.1, a detail of the COMM board with the solder paste applied in some of its pads is shown.

The placement of the solder paste is carried out by means of a *solder stencil*, an aluminium foil –although sometimes is made of polyamide– that has been perforated in accordance with the position and size of the different pads of the PCB. In Figure F.3a, on the left, it is possible to see the solder stencil employed.

When the solder stencil has been placed and fixed appropriately on top of the PCB, a gentle quantity of solder paste is applied and carefully spread over the entire surface of the board. Solder stencils are often about 100 μm thick, which implies that only a small amount of solder past is enough.

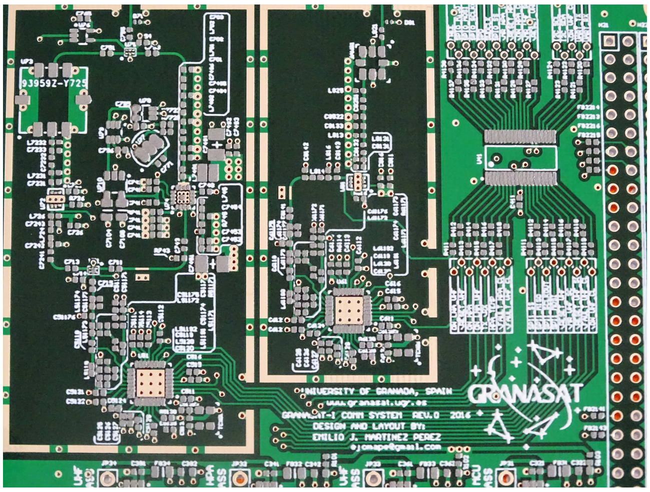
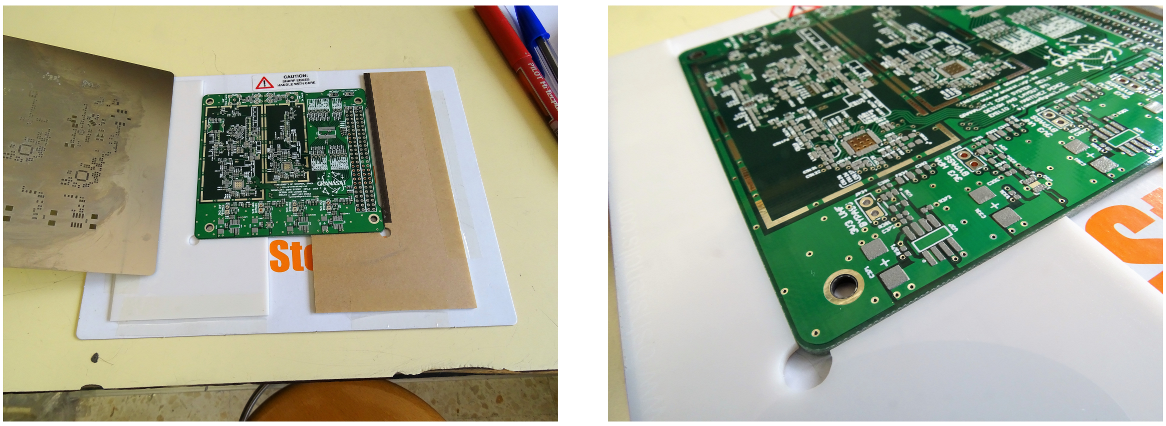


Figure F.2 – *Solder paste applied in excess*

If the stencil procedure is new for the operator, probably the solder paste will be applied in excess, which will provoke short circuits during the soldering process. Figure F.2 shows the board with a slight excess of solder paste. If this happens, the paste must be cleaned from the PCB and the procedure has to be started again. As a reference, throughout the development of this work, it was required to apply the solder paste up to six times in order to obtain the appropriate quantity of solder paste in the board.

Figure F.3 shows the solder paste set-up used during the procedure (F.3a) and a detail of the PCB with the solder paste successfully applied (F.3b).



(a) *Stencil and board* **(b)** *Detail of solder paste*

Figure F.3 – *Setup of board and stencil*

Board population

Once the solder paste has been applied, the next step is to place the SMD components. In the electronic industry, the procedure is automatically carried out by a *pick-and-place* machine, which is able to place thousands of components per minute. For this work, the procedure had to be performed manually and it took 9 hours to get the board ready for the soldering process.

Since there are hundreds of different components, it is necessary to follow a meticulous method able to ensure that components do not mix up and they are placed in their correct pad. For this work, the procedure that has been followed is the next one:

1. A top view of the 3D model of the PCB is printed – Preferably a zoomed-in image.
2. Following the schematic document, a component is cut from the paper/plastic tape and glued to the board image in its proper place. This is done for every single component in the board.
3. When all components have been glued in the paper image, each component is taken one by one from the paper, and carefully placed in the PCB.

This procedure may seem slow, but it ensures that the different component tape cuts do not mix up. A slow but reliable method is worth more than a fast one but that cannot ensure an assembly free of errors. Figure F.4 shows the employed setup for this step in the manufacturing process.

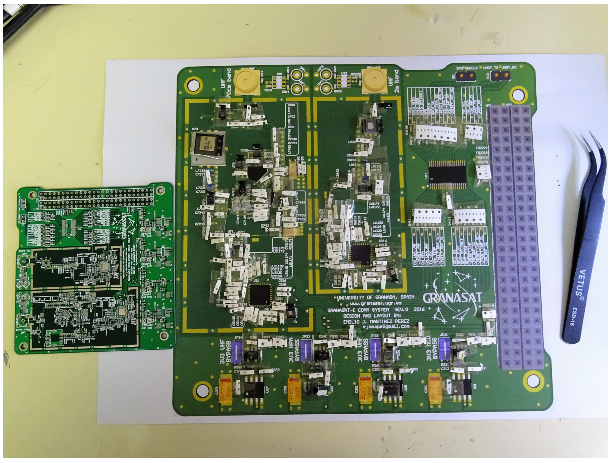


Figure F.4 – *Component population – Final arrangement*

In addition, the size of passive SMD components is 0402, which is very small: a size of only 1 mm x 0.5 mm. This fact forces to use special tweezers and a microscope, as the one shown in Figure F.5, when working with PCB that contains this kind of components.

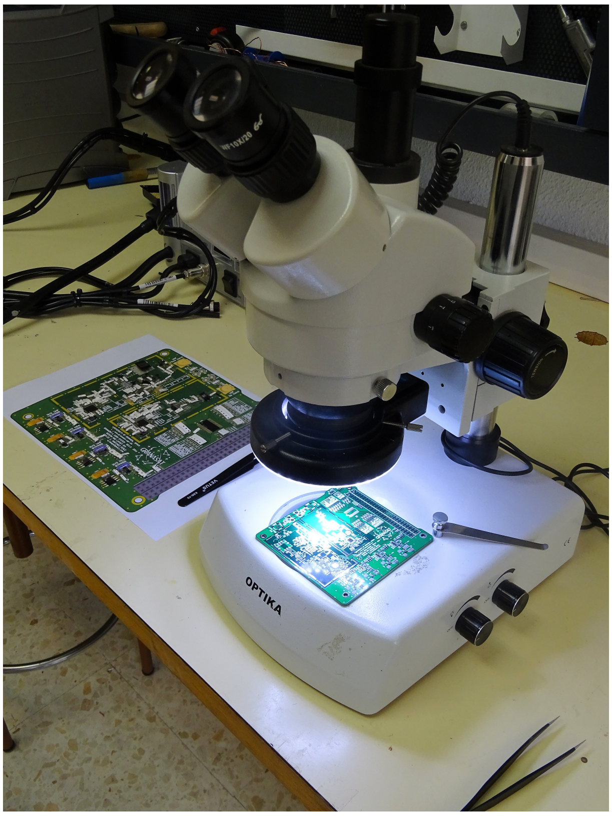


Figure F.5 – *Component population – Microscope*

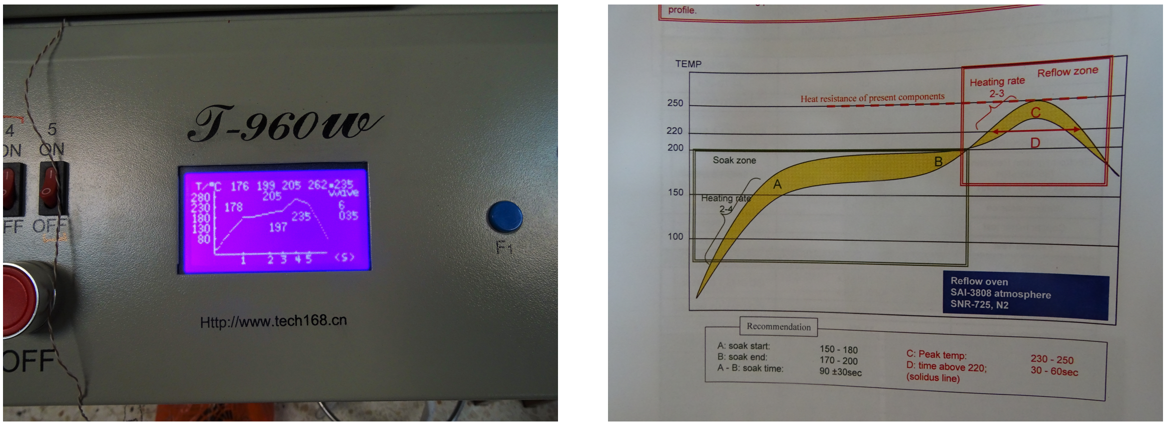
F

Reflow Soldering

When the manufacturing work was in progress, the department acquired a reflow oven (shown in Figure F.6) to allow students to develop their electronic projects in a faster way. A reflow oven heats the PCB by means of infrared heaters.

Figure F.6 – *Reflow oven at the GranaSAT facilities*

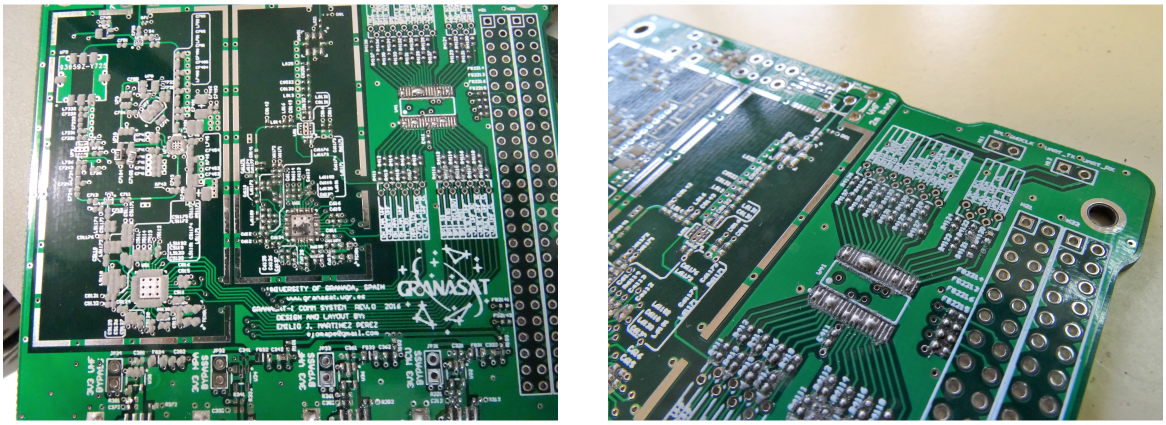
The solder paste has a specific *solder profile*, also known as *curve of temperature*, which has a shape as shown in Figure F.7. The solder profile specifies how the board must be heated to ensure a successful soldering process.



(a) *Solder profile configured in the reflow oven* **(b)** *Solder profile recommended for the solder paste*

Figure F.7 – *Solder profiles*

A soldering test was performed with an unpopulated PCB, in order to check if the solder paste was able to melt with the applied solder profile. Two kinds of solder paste were tested. In Figure F.8, the result of the experiment is shown: only one of the solder paste placed melted (the one on the right), while the other one (on the left) remained without any change.



(a) *Two solder pastes are used* **(b)** *Detail of the melted solder paste*

Figure F.8 – *Final state of two solder pastes after going through the reflow oven*

Given that the solder paste did not melt, the board was introduced several times in a row into the reflow oven, with such bad luck that the board began to burn. The recovered PCB is shown in Figure F.9. After this incident, it was decided to proceed with a manual soldering while the reflow oven was not completely operational.

Clearly a big mistake was made: the configured solder profile in the reflow oven is given for a room temperature board, and not for one that was already hot. Luckily the board was extinguished quickly and neither the oven nor any other facility was damaged. By the way, if the solder paste melted during this last time in the oven remains unknown.

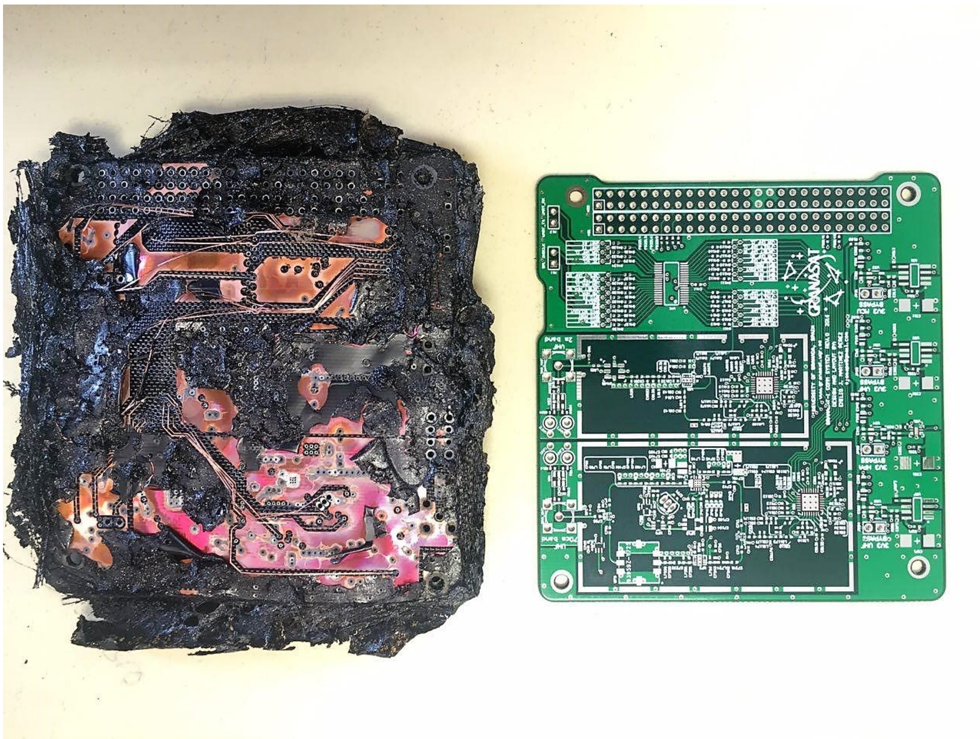


Figure F.9 – *Burnt PCB due to board overheating*

F

Manual soldering & Rework

A special soldering station, as the one shown in Figure F.10, is recommended when manually soldering or reworking the PCB is desired. The soldering station must have a hot-air gun and a soldering iron with a fine tip.

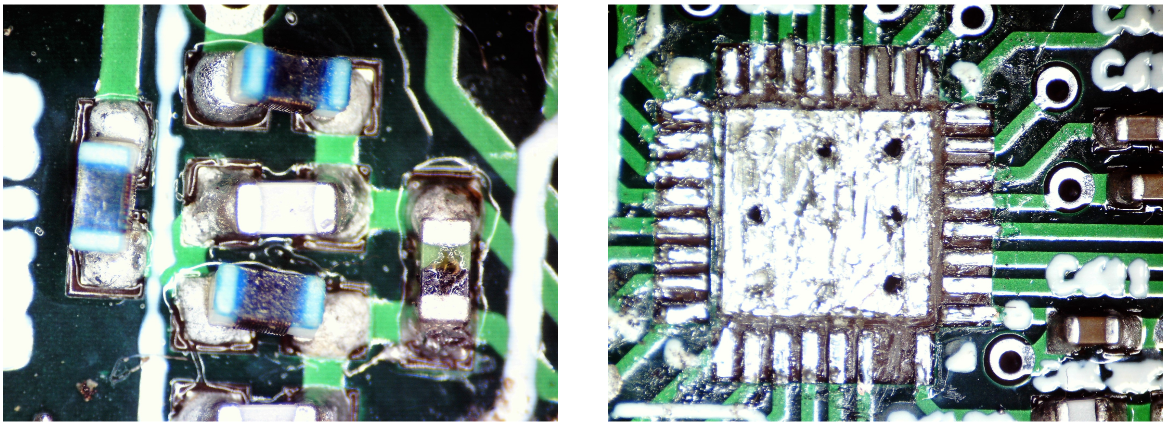
Figure F.10 – *Soldering station at the GranaSAT facilities*

There are no relevant comments to make regarding the manual soldering work. The process has to be done patiently and trying to not overheat the component of the board, because that may cause its rupture.

Moreover, when the soldering work is done, it is a must to check out thoroughly if all components were properly soldered. Again, the use of a microscope is essential to identify the very small imperfections such as the ones that will be specified.

Solder excess is a problem when soldering. The surface tension of the component causes always the component to move, and when there is more solder than the necessary, components can be shifted in strange positions, as it can be seen in Figure F.11a. Note how small balls of solder are created behind the wire-wound inductors.

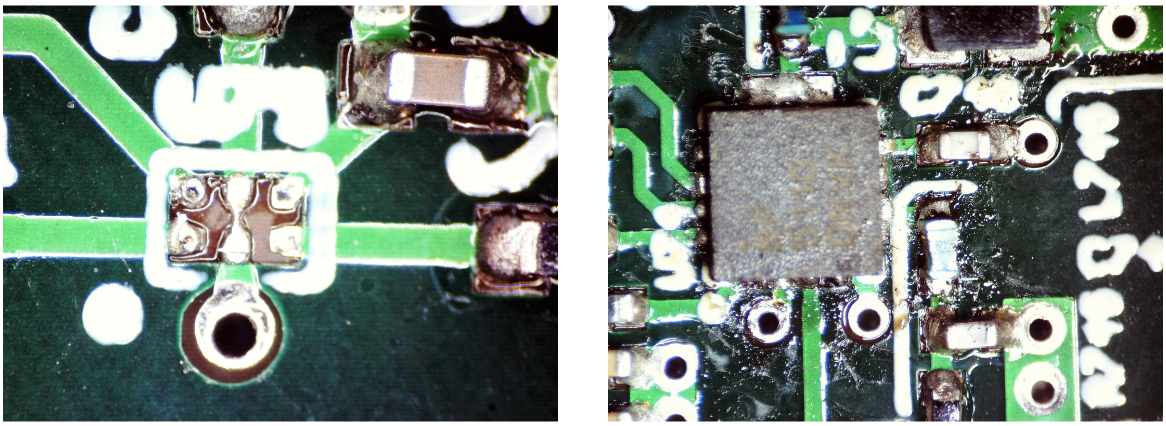
Another trouble with solder excess may arise when an IC is soldered. Sometimes there are short circuits that are hidden by the component itself and it is not possible to figure out what the exact problem is. For that reason it is necessary to remove the component, clean the area, and solder a new component again. This had to be done for the transceiver CC1125 (Figure F.11b) and for the SPDT BGS12PL6 (Figure F.12a).



(a) *Wire-wound inductors with solder excess* **(b)** *GND pad with solder excess and cold soldering*

Figure F.11 – *Solder excess imperfection*

Cleanliness is also important in electronics. When soldering, rests of flux will remain in the PCB, generating a small layer that will make it hard to solder again in the same area. For this reason, after every soldering it is recommended to clean the surface with a brush and Isopropyl Alcohol (IPA). Figure F.12b shows a very dirty area around the High Power Amplifier RF5110G that was cleaned up after taking the picture.



(a) *SPDT pads short circuited* **(b)** *Dirty RF5110G*

Figure F.12 – *Component soldering imperfections*

Final assembly

Finally, several pictures of the final assembly of the functional COMM System Engineering Model presented in this master's thesis are shown in this section.

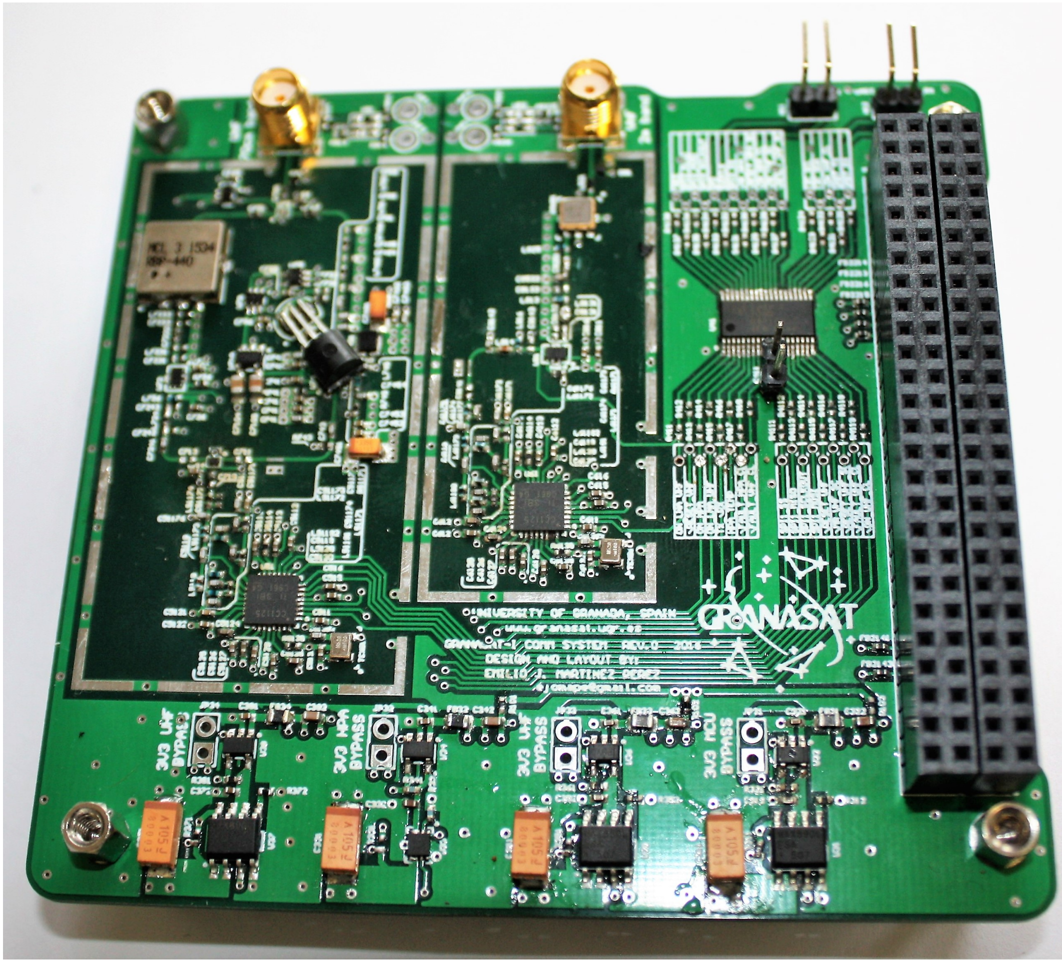


Figure F.13 – *COMM System – Final assembly: top*

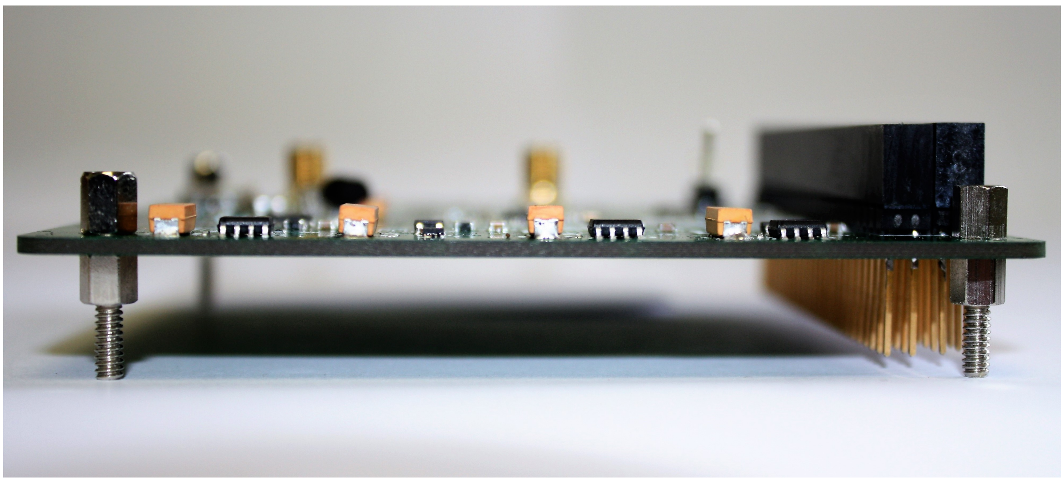


Figure F.14 – *COMM System – Final assembly: side*

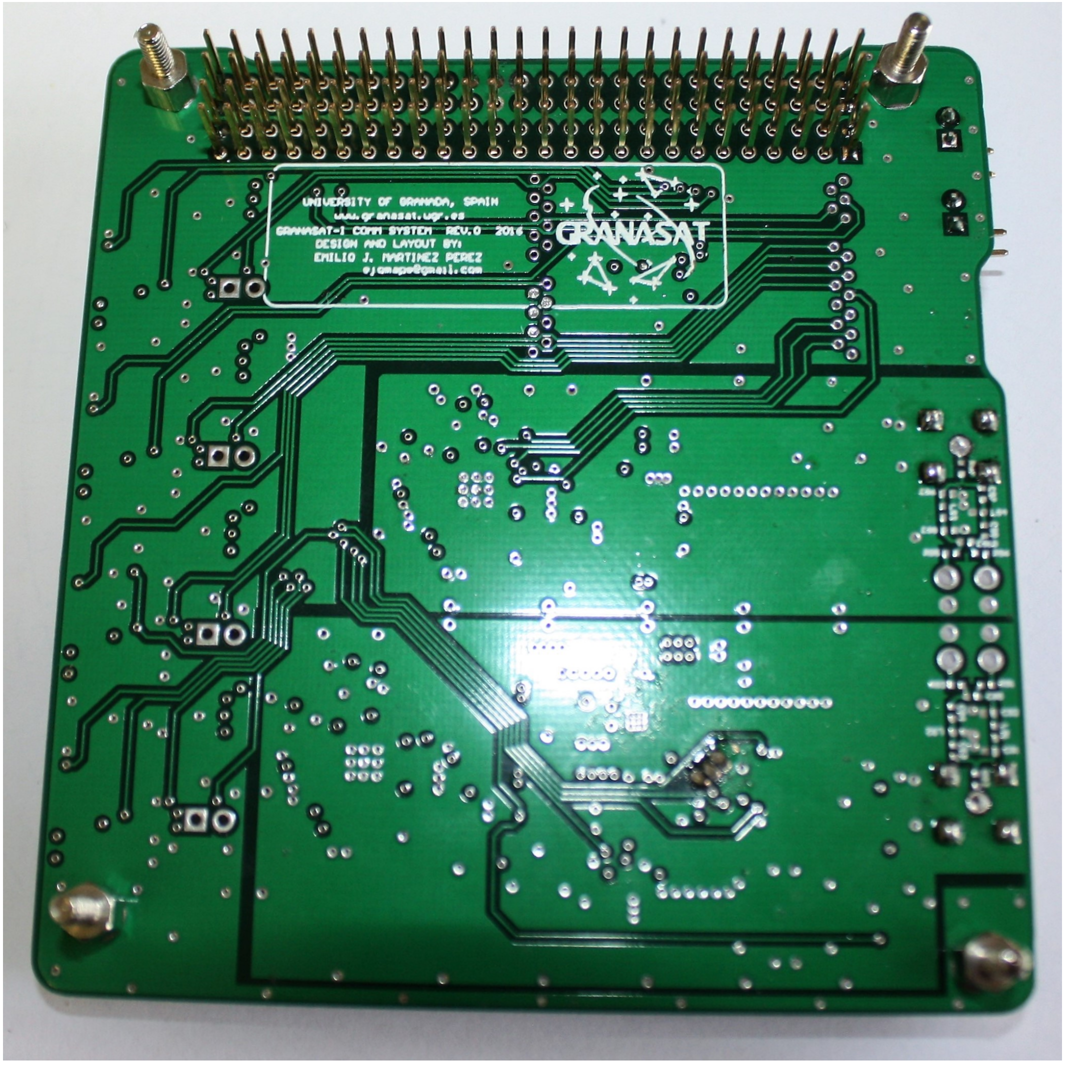


Figure F.15 – *COMM System – Final assembly: bottom*

F

A general overview of the board from another perspective:

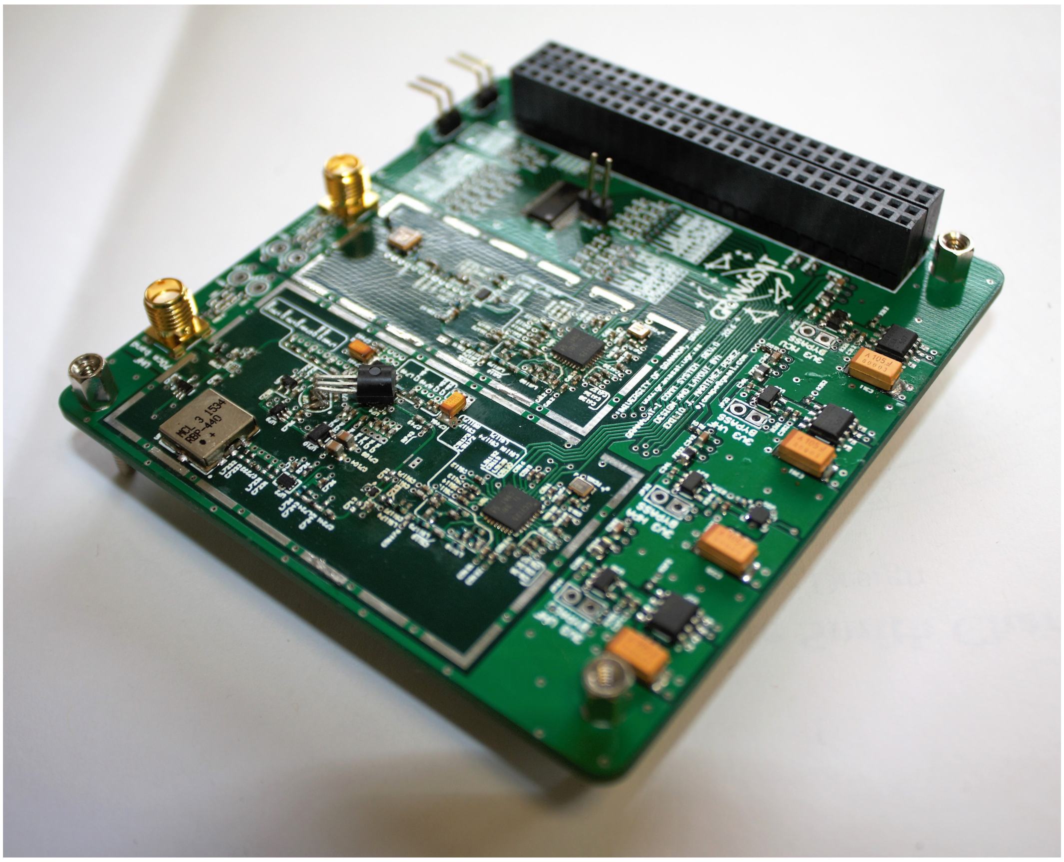


Figure F.16 – COMM *System – Final assembly: general overview*

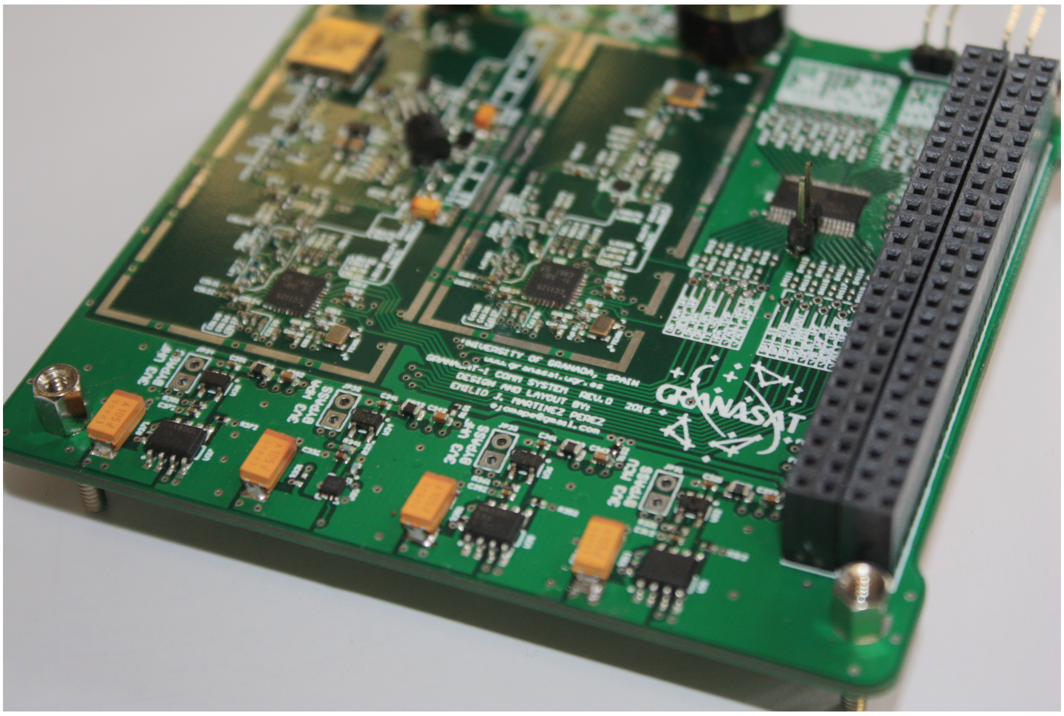


Figure F.17 – COMM *System – Final assembly: detail*

Antennas can be incorporated to the COMM System to perform the communication test or to connect with the Antenna System:

Figure F.18 – *COMM System – Final assembly with antennas*

The system was placed in a 3D printed Cubesat structure to check dimensions and physical aspects of the board:

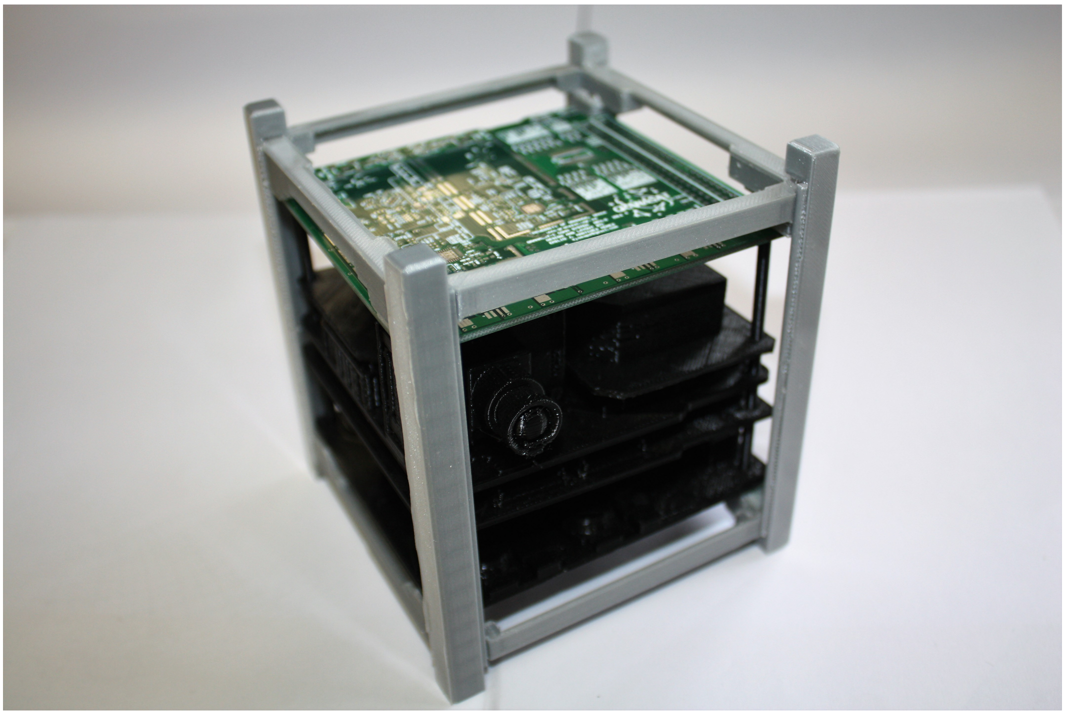


Figure F.19 – *COMM System – Final assembly in the Cubesat structure*

F

Appendix G

Project budget

This appendix will analyse the investment made in terms of costs of material and manpower that has been required in order to perform this master's thesis. This estimation should give an idea of how much it could cost to carry out the same project in an actual engineering company.

Following the nature of the work, the estimation has been split up in three parts:

- Improvements in the GranaSAT Ground Station
- Development of the ESAC amateur Ground Station
- Design and implementation of the GranaSAT-I Communication System

For each individual item in the appendix, the price of the goods before taxes has been considered. In addition, they have been rounded to the nearest ten. Moreover, manpower has been calculated based on a gross rate of €20 per hour of work, except for the ESAC amateur Ground Station, in which case the actual fee received during the traineeship has been applied.

Sub-project	Budget [€]
GranaSAT Ground Station improvement	13,220
ESAC amateur Ground Station development	18,370
Communication System design and implementation	26,040
TOTAL BUDGET	57,610

Table G.1 – *Total costs for the development of the project*

In total, taking into account the three budgets broken down in Table G.2, G.3 and G.4, the total expenses for the manpower and the material required exclusively for the development of this project has been €57,610. This is shown in Table G.1.

Costs related to the work executed for the improvement of capabilities of the GranaSAT Ground Station are shown in Table G.2.

GranaSAT Ground Station improvement	
Item	**Total cost [€]**
Ham radio transceivers - Kenwood TS200 and ICOM 9100	5,090
Coaxial cable	510
Antenna - Diamond X-7000	280
Electronic and laboratory goods	140
Gpredict license	0
Hamlib license	0
MixW	0
Manpower – 360 hours	7,200
BUDGET	13,220

Table G.2 – *GranaSAT Ground Station – Improvement expenses*

Costs related to the design and development from scratch of the ESAC amateur Ground Station are shown in Table G.3.

ESAC amateur Ground Station development	
Item	**Total cost [€]**
Structure material - BOSCH profiles and other steel goods	1,290
Ham radio equipment - Antennas, rotor and coaxial cable	3,290
SDR Transceivers - HackRF	690
Laboratory goods and measuring equipment	1,100
Desk computer	1,200
Gpredict license	0
Hamlib license	0
GNURadio	0
Manpower – 1280 hours	4,800
BUDGET	18,370

Table G.3 – *ESAC amateur Ground Station – Development expenses*

G

Costs related to material and manpower invested during the design and implementation of the GranaSAT-I COMM System are shown in Table G.4.

Communication System design and implementation	
Item	**Total cost [€]**
4 layer PCB	80
PCB Stencil	50
Soldering tools	20
Soldering goods	30
SMD components	260
Altium License	0
DAVE IDE License	0
Manpower – 1280 hours	25,600
BUDGET	26,040

Table G.4 – *Communication System – Design and implementation expenses*

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Glossary

Allocation	*"(of a frequency band) Entry in the Table of Frequency Allocations of a given frequency band for the purpose of its use by one or more terrestrial or space radiocommunication services or the radio astronomy service under specified conditions. This term shall also be applied to the frequency band concerned."* **ITU-RR 1.16** [39]
Amateur Service	*"A radiocommunication service for the purpose of self-training, intercommunication and technical investigations carried out by amateurs, that is, by duly authorized persons interested in radio technique solely with a personal aim and without pecuniary interest."* **ITU-RR 1.56** [39]
Amateur-satellite Service	*"A radiocommunication service using space stations on earth satellites for the same purposes as those of the amateur service."* **ITU-RR 1.57** [39]
Cubesat	A type of miniaturized satellite for space research that is made up of multiples cubic units of 10×10×11.35 cm. Cubeats have a mass of no more than 1.33 kilograms per unit [73]
Eurospace	Created in 1961, it is a non-profit organization which works as a trade association of the European Space Industry. Website: http://www.eurospace.org/
GranaSAT	An aerospace development group from the University of Granada. Formed entirely by students, it is conducting research on aerospace-related projects, such as a Cubesat mission or space instrumentation. Website: http://granasat.ugr.es

GranaSAT-I — The first satellite of the University of Granada. It is a 1U Cubesat completely designed and implemented by students. The design phase started in 2014. Website: http://granasat.ugr.es

International Space Station — *"It is a space station, or a habitable artificial satellite, in low Earth orbit. The ISS consists of pressurised modules, external trusses, solar arrays, and other components. The ISS programme is a joint project among five participating space agencies: NASA, Roscosmos, JAXA, ESA, and CSA."* [74]

ISM — Name of a radio band reserved internationally for Industrial, Scientific and Medical applications. It is defined by the ITU Radio Regulations in **5.138**, **5.150**, and **5.280** footnotes [39]

Keep It Simple and Stupid — *"The KISS principle states that most systems work best if they are kept simple rather than made complicated; therefore simplicity should be a key goal in design and unnecessary complexity should be avoided. The phrase has been associated with aircraft engineer Kelly Johnson (1910–1990)."* [75]

Radio Spectrum — Part of the electromagnetic spectrum which includes the group of frequencies from 1 Hz to 3000 GHz

Soyuz — A family of expendable launch systems developed and manufactured in Russia. The Soyuz launch vehicle is the most frequently used and reliable launch vehicle in the world. After the U.S. Space Shuttle program ended in 2011, Soyuz rockets became the only launch vehicle able to transport astronauts to the International Space Station [76]

Van-Allen Belts — *"The Van Allen belts are a collection of charged particles, gathered in place by Earth's magnetic field. They can wax and wane in response to incoming energy from the sun, sometimes swelling up enough to expose satellites in low-Earth orbit to damaging radiation."* [77]

Acronyms

A-ACDS	Active Attitude Determination and Control System
ADC	Analog-to-Digital Converter
ADCS	Attitude Determination & Control System
ADS	Attitude Determination System
AFSK	Audio Frequency-Shift Keying
AIS	Automated Identification System
AMSAT	Radio Amateur Satellite Corporation
APRS	Automatic Packet Reporting System
ARISS	Amateur Radio on the International Space Station
ASCII	American Standard Code for Information Interchange
ASI	Agenzia Spaziale Italiana
ASK	Amplitude-Shift Keying
ATOX	Atomic Oxygen
ATV	Amateur Television
AWGN	Additive White Gaussian Noise
BB	Base Band
BER	Bit Error Rate
BEXUS	Balloon EXperiments for University Students
BFSK	Binary Frequency-Shift Keying
BOM	Bill Of Material
BPF	Band Pass Filter
BPSK	Binary Phase-Shift Keying
CCSDS	Consultative Committee for Space Data Systems

CESAR	Cooperation through Education in Science and Astronomy Research
CNES	Centre National d'Études Spatiales
CNSA	China National Space Administration
COMM	Communication System
COTS	Commercial-Off-The Shelf
CP	Circular Polarisation
CSA	Canadian Space Agency
CW	Continuous Wave
D-STAR	Digital Smart Technology for Amateur Radio
DLR	German Aerospace Center
DOA	Dead-On-Arrival
ECSS	European Cooperation for Space Standardization
ECTD	Electronics and Computer Technology Department
EDA	Electronic Design Automation
EIRP	Equivalent Isotropically Radiated Power
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPS	Electrical Power System
EQM	Engineering Qualification Model
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESD	Electrostatic Discharge
FEC	Forward Error Correction
FFT	Fast Fourier Transformation
FM	Flight Model
FM	Frequency Modulation
FOM	Figure Of Merit
FPGA	Field-Programmable Gate Array
FSK	Frequency-Shift Keying
FSPL	Free Space Path Loss

FYS	Fly Your Satellite
GBL	Gerber Bottom Layer
GBO	Gerber Bottom Overlay
GBS	Gerber Bottom Solder
GCR	Galactic Cosmic Rays
GEO	Geosynchronous Earth Orbit
GKO	Gerber Keep Out
GMSK	Gaussian Minimum-Shift Keying
GNSS	Global Navigation Satellite System
GP1	Gerber inner Plane 1
GP2	Gerber inner Plane 2
GS	Ground Station
GTL	Gerber Top Layer
GTO	Gerber Top Overlay
GTS	Gerber Top Solder
HP	Horizontal Polarisation
HPA	High Power Amplifier
HPBW	High Power Beam Width
I2C	Inter-Integrated Circuit
IARU	International Amateur Radio Union
IC	Integrated Circuit
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronics Engineers
IL	Insertion Loss
INPE	Instituto Nacional de Pesquisas Espaciais
INTA	Instituto Nacional Técnica Aeroespacial
IPA	Isopropyl Alcohol
ISM	Industrial, Scientific, Medical
ISO	International Organization for Standardization
ISS	International Space Station
ITU	International Telecommunication Union

ITU-RR	ITU – Radio Regulations
J-SSOD	JEM Small Satellite Orbital Deployer
JAXA	Japan Aerospace Exploration Agency
KISS	Keep it Simple and Stupid
LEO	Low Earth Orbit
LHCP	Left-handed Circular Polarisation
LISA	Laser Interferometer Space Antenna
LNA	Low Noise Amplifier
LP	Linear Polarisation
LTCC	Low Temperature Co-fired Ceramics
MCU	Micro Controller Unit
MFSK	Multiple Frequency-Shift Keying
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MPSK	Multiple Phase-Shift Keying
NASA	National Aeronautics and Space Administration
NF	Noise Figure
NRCSD	NanoRacks CubeSat Deployer
NSC	Norwegian Space Centre
NSO	Netherlands Space Office
OBC	On-Board Computer
OOK	On-Off Keying
P-POD	Poly Picosatellite Orbital Deployer
PCB	Printed Circuit Board
pfd	power flux density
PSK	Phase-Shift Keying
QAM	Quadrature Amplitude Modulation

QPSK	Quadrature Phase-Shift Keying
REXUS	Rocket EXperiments for University Students
RF	Radio Frequency
RFSA	Russian Federal Space Agency
RHCP	Right-handed Circular Polarisation
RTOS	Real-Time Operative System
RX	Reception
SAW	Surface Acoustic Wave
SDR	Software Defined Radio
SEL	Single-event Latchup
SEU	Single-event Upset
SHF	Super High Frequency
SMD	Surface Mount Devices
SNSB	Swedish National Space Board
SoS	System of Systems
SPDT	Single Pole Double Throw
SPI	Serial Peripheral Interface
SSTV	Slow Scan Television
SW	Software
SWD	Serial Wire Debug
SWR	Stationary Wave Ratio
TCXO	Temperature Controlled XTAL Oscillator
TI	Texas Instruments
TID	Total Ionizing Dose
TLE	Two-Line Element set
TNC	Terminal Node Controller
TVAC	Thermal VACuum
TX	Transmission
UART	Universal Asynchronous Receiver Transmitter
UDP	User Datagram Protocol

UGR	University of Granada
UHF	Ultra High Frequency
UKSA	UK Space Agency
USB	Universal Serial Bus
VHF	Very High Frequency
VNA	Vector Network Analyser
VP	Vertical Polarisation
WBS	Work Breakdown Structure
WiMAX	Worldwide Interoperability for Microwave Access
WP	Work Package

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