POLITECNICO DI TORINO

Master's Degree in Communications and Computer Networks Engineering

Masters's Degree Thesis

Design and Verification of a CubeSat Ground Station

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Abstract

Small satellite platforms such as CubeSats are invaluable platforms for exploring space for research, military, and civilian purposes. Their small size, reduced cost, load, complexity, and flexibility allow various kinds of missions previously impossible. In support of its scientific missions, Politecnico di Torino's CubeSatTeam created the CubeSat Control Centre (C3) with extremely clear and well defined mission requirements: to build a ground station at the Politecnico di Torino under 30k€ capable of tracking and communicating with VHF/UHF/S/X-band low-Earth orbit CubeSats to be operated by students and non-professionals in pursuit of CubeSatTeam's missions with a certain level of autonomy.

This report details the design and verification of C3's CCSDS-compliant software-defined ground station. First, mission requirements and key performance indices are defined. Then, ground station requirements are derived. Next, its functional architecture is devised and followed by its trade-off analysis, leading to the ground station's physical architecture and a discussion about its design trade-offs. Following this discussion, analytical methods and numerical simulations are applied to estimate relevant performance metrics, such as mass, power, cost, and link budgets. Along the same line, the communication software is briefly discussed. Afterwards, the ground station's assembly, integration, and verification (AIV) procedures are developed and executed, culminating in the verification of components and units by testing, and of the ground-to-satellite communication link by simulation. To conclude, a preliminary data budget for future CubeSatTeam missions is suggested.

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Finally, I thank my friends and parents for supporting my endeavour in Italy, without whom I would never have become an engineer.

Se insisti e persisti, raggiungi e conquisti.
Trilussa

Table of Contents

List of Tables IX

List of Figures X

Acronyms XII

1 Introduction 1

2 Design of the CubeSat Control Centre's Ground Station 2

2.1 Introduction 2
2.2 Objective 2
2.3 Methodology 2
2.4 Functional Analysis 4
2.4.1 Requirements 4
2.4.2 Function and Product Trees 5
2.4.3 Connectivity Matrix 6
2.4.4 Risks 7
2.4.5 Functional Architecture 8
Introduction 8
Communication System's Functional Architecture 8
2.5 Physical Architecture 9
2.5.1 Introduction 9
2.5.2 Trade-off Analysis 10
2.5.3 Tracking Considerations 11
2.5.4 Architecture 14
Software Defined Radio 16
Design Considerations 18
Amplifier Design 18
Antenna and Feed Design 19
Polarization 20
Multiplexing 20

Cooling and Environmental Protection 21
Reliability 21
Connectors and Cabling 21
2.5.5 Footprint 22
2.5.6 Mass Budget 22
2.5.7 Power Budget 23
2.5.8 Cost Budget 23
2.5.9 Link Budget 26
Introduction 26
X-band 26
S-band 30
VHF/UHF 34
2.5.10 Model of UHF/VHF/S-band structure 41
2.6 Software Considerations 43
2.6.1 Introduction 43
2.6.2 Software Defined Radio Software 43
bladeRF-cli 43
Matlab/Simulink 44
GNU Radio 46
SDR-Console V3 47
2.6.3 Automation 48

3 Verification of the CubeSat Control Centre's Ground Station 49
3.1 Introduction 49
3.2 Assembly, Integration and Verification 49
3.2.1 Introduction 49
3.2.2 Verification Methods 51
3.2.3 Assembly, Integration and Verification Plan 52
Introduction 52
VHF/UHF Line Integration 53
S-Band Line Integration 54
CubeSat Control Centre System Integration 55
3.3 Verification 57
3.3.1 Simulation of a X-band satellite pass 57
Introduction 57
Simulation Parameters 57
Results 60
Data Budget 64
3.3.2 Tests 65
Introduction 65
Test Procedures 65

Test Results . . . 70
3.3.3 Assembly Procedures . . . 71

4 Epilogue 72
4.1 Conclusions . . . 72
4.2 Future Work . . . 73

Bibliography 74

A Risk Analysis 79

B Technical Requirements 81

C Function and Product Trees 97

D Function Product Matrix 101

E Noise Figure Analysis 108
E.1 Introduction . . . 108
E.2 Analysis . . . 108

F Simulation of Antenna Performance 111
F.1 Introduction . . . 111
F.2 Simulation of S-band Reflector with Helix Feed . . . 111
F.3 Simulation of X-band Reflector with Horn Feed . . . 112
F.4 Design and Simulation of a S-band Patch Antenna Array . . . 113

G Link Budget Calculations 116
G.1 Introduction . . . 116
G.2 X-band Link Budgets . . . 116
G.2.1 Uplink . . . 116
G.2.2 Downlink . . . 120
G.3 S-band Link Budget . . . 123
G.3.1 Uplink . . . 123
G.3.2 Downlink . . . 126
G.4 UHF Link Budget . . . 129
G.4.1 Uplink . . . 129
G.4.2 Downlink . . . 132
G.5 VHF Link Budget . . . 134
G.5.1 Uplink . . . 134
G.5.2 Downlink . . . 137

H S-band Line Integration Test Specification and Procedures 140

I Assembly Procedures 155

List of Tables

2.1 Mission Requirements 5
2.2 M&P HyperFlex 13 Cable [12] 21
2.3 Ground Station Mass Budget 22
2.4 Ground Station Power Budget 23
2.5 CubeSat Control Center Costs 25
2.6 X-band Link Budget 30
2.7 S-band Link Budget 34
2.8 UHF Link Budget 37
2.9 VHF Link Budget 39
2.10 E-ST@R-II Link Budget 41

3.1 X-Band Low-Earth Orbit Parameters 59
3.2 X-Band Simulated Link Budget 61
3.3 Simulation of X-band Data Budget 64
3.4 CUMULOS Sensor Specifications [46] 64
3.5 Receiver Test Results 71

E.1 Noise Figure Analysis Results 108

List of Figures

2.1 System Design Process [2] 3
2.2 Functional Analysis Trees 6
2.3 N2 Diagram - System-level Interfaces 6
2.4 Risk Matrix 7
2.5 High-level Functional Architecture of the Ground Station 8
2.6 High-level Architecture of the Communication System 9
2.7 Trade-off Analysis 11
2.8 Turin 30 year historic wind data, [3] 12
2.9 Antenna Azimuth-Elevation Model, [5] 13
2.10 Keyhole Problem [6] 13
2.11 Physical Architecture - Roof 14
2.12 Physical Architecture - Ground 15
2.13 AD9361 RF Agile Transceiver Functional Block [8] 17
2.14 Nuand bladeRF-2.0 micro Functional Diagram [9] 17
2.15 Compact Antenna Footprint 22
2.16 Cost Budgets of the CubeSat Control Centre 23
2.17 CCSDS AR4JA LDPC Code Performance [15]. Dashed lines refer to Frame Error Rate, solid lines to Bit Error Rate. Red curve corresponds to $R_c = 1/2$, LDPC(16384,8192). 26
2.18 Model of the UHF/VHF/S-band Antenna Structure [24] 42
2.19 bladeRF-cli 44
2.20 Simulink Communication Systems Model for bladeRf-2.0 micro . . . 45
2.21 GNU Radio Model of a QPSK Transmitter and Receiver using a USRP Sink and Source, $f_c = 2.45\ GHz$ 46
2.22 SDR-Console v3 Interface [34] 47

3.1 Verification Matrix 51
3.2 VHF Line Assembly, Integration and Verification Plan 53
3.3 UHF Line Assembly, Integration and Verification Plan 54
3.4 S-band Line Assembly, Integration and Verification Plan 55

3.5 CubeSat Control Centre System Assembly, Integration and Verification Plan . . . 56
3.6 X-band STK Scenario . . . 57
3.7 Simulated X-band Pass . . . 60
3.8 Simulated Environmental Effects . . . 63
3.9 S-band Test Configuration . . . 67
3.10 UHF Test Configuration . . . 68
3.11 VHF Test Configuration . . . 69
3.12 Received Test Signal Spectrum . . . 70

E.1 X-band Receivers . . . 109
E.2 S/UHF/VHF Ground Station Receivers . . . 110

F.1 Helix Feed on a 1.2m Reflector Matlab Simulation for S-band . . . 112
F.2 Horn Feed on a 1.2m Reflector Matlab Simulation for X-band . . . 113
F.3 Patch Array Design . . . 115

Acronyms

ADC Analog-to-digital Converter

ADCS Attitude Determination and Control System

AFSK Audio Frequency-Shift Keying

AGC Automatic Gain Control

AIV Assembly, Integration, and Verification

API Application Programmable Interface

ARM Advanced RISC Machine

BER Bit Error Rate

BPF Band-pass Filter

BPS Baseband Processing Server

BPSK Binary Phase-Shift Keying

BUC Block Upconverter

C3 CubeSat Control Centre

CCSDS Consultative Committee for Space Data Systems

CPU Central Processing Unit

CS Communication System

CUMULOS CubeSat Multispectral Observation System

CW Continuous Wave

DAC Digital-to-analog Converter

DSP Digital Signal Processing

DUT Device Under Test

ECSS European Cooperation for Space Standardization

EIRP Effective Isotropic Radiated Power

EO Earth Observation

FDIR Fault Detection, Isolation, and Recovery

FM Frequency Modulation

FPGA Field Programmable Gate Array

GPU Graphics Processing Unit

GS Ground Station

HEIF High Efficiency Image File

HPA High Power Amplifier

HPBW Half Power Beamwidth

I/Q In-Phase/Quadrature

IF Intermediate Frequency

IL Insertion Loss

ITU International Telecommunications Unit

JIT Just In Time

LDPC Low-density Parity Check

LEO Low-Earth Orbit

LHCP Left-hand Circular Polarization

LNA Low-Noise Amplifier

LNB Low-Noise Block Downconverter

LP Linear Polarization

MCS Mission Control System

MIMO Multiple Input/Multiple Output

NF Noise Figure

OMT Orthomode Transducer

PA Power Amplifier

PLL Phase-Locked Loop

QPSK Quadrature Phase-Shift Keying

RAAN Right Ascension of the Ascending Node

RF Radio-Frequency

RFFE Radio-Frequency Front-End

RHCP Right-hand Circular Polarization

RL Return Loss

RO Reference Oscillator

RX Receive

SDR Software-Defined Radio

SIC Self-interference Cancellation

SMD Surface Mount Device

SNR Signal-to-noise Ratio

SOC System-on-a-chip

SRRC Square-Root Raised-Cosine

SSB Single-sideband

SWaP Size, Weight and Power

T/R Transmit/Receive

TR Test Report

TS Tracking System

TSP Test Specification and Procedure

TX Transmit

VHDL VHSIC Hardware Description Language

VHSIC Very High Speed Integrated Circuits

VSWR Voltage Standing Wave Ratio

ZIF Zero IF

Chapter 1

Introduction

At the Politecnico di Torino, the CubeSatTeam[1] is a student association to design and develop small satellites such as low-Earth orbit (LEO) CubeSats and their payloads. It has launched two satellites (E-ST@R-I, in 2012, E-ST@R-II in 2016), the latter of which remains in orbit. In support of these missions, because it lacked a ground station, the CubeSatTeam relied on commercial and academic operators. However, determined to be independent, it decided to build the CubeSat Control Centre (C3), an innovative ground segment located within Politecnico di Torino, to communicate with and to control LEO CubeSats.

Within this context, the present report describes the research activities of the master thesis project "Design and Verification of a CubeSat Ground Station", aimed at designing and verifying C3's Ground Station (GS). This thesis is composed of two main sections. Chapter 2 details the design of the GS, starting with the definition of mission requirements. This is followed by an analysis of desired GS functionalities to derive the GS's requirements, its architecture, and key performance indices. Subsequently, its physical architecture is designed and followed by its detailed trade-off analysis. Then, the designed architecture is reviewed, examining design choices. Next, mass, cost, and link budgets are computed. Finally, its communication system's software is commented.

Chapter 3 is concerned with the verification of the GS designed in Chapter 2, and focuses on the GS's assembly, integration, and verification (AIV) procedures. First, an overview of verification methods and their objectives is presented. Then, a sequence of verification procedures, called the AIV plan, is defined. Afterwards, the AIV plan is executed to verify the GS, and its results are examined. In particular, Chapter 3 verifies components and units by testing, and the GS-CubeSat communication link by simulation, deriving the data budget to be used in future CubeSatTeam's missions. To conclude, Chapter 4 highlights key results, lists open points, and outlines a road map for future developments.

Chapter 2

Design of the CubeSat Control Centre's Ground Station

2.1 Introduction

In this chapter, we design the CubeSat Control Centre's Ground Station (GS) in detail. We start by defining the GS's objectives and requirements. Next, we design its functional architecture. Then, we define key performance indices and execute a trade-off analysis to identify the best GS physical architecture. Afterwards, we explain GS's design hypotheses and design choices, computing cost, mass and link budgets to estimate its performance. Finally, we briefly discuss the communication system's software.

2.2 Objective

For successful projects, clear stakeholder expectations are required. In the CubeSat Control Centre's Ground Station case, the objective is very precise: to build a ground station to communicate with VHF/UHF/S/X-band LEO CubeSats with the capabilities and autonomy of professional stations at reduced costs.

2.3 Methodology

To design the ground station, a Systems Engineering approach described in [2] and pictured in Figure 2.1 is required. The first step is to understand the mission requirements, from which everything derives.

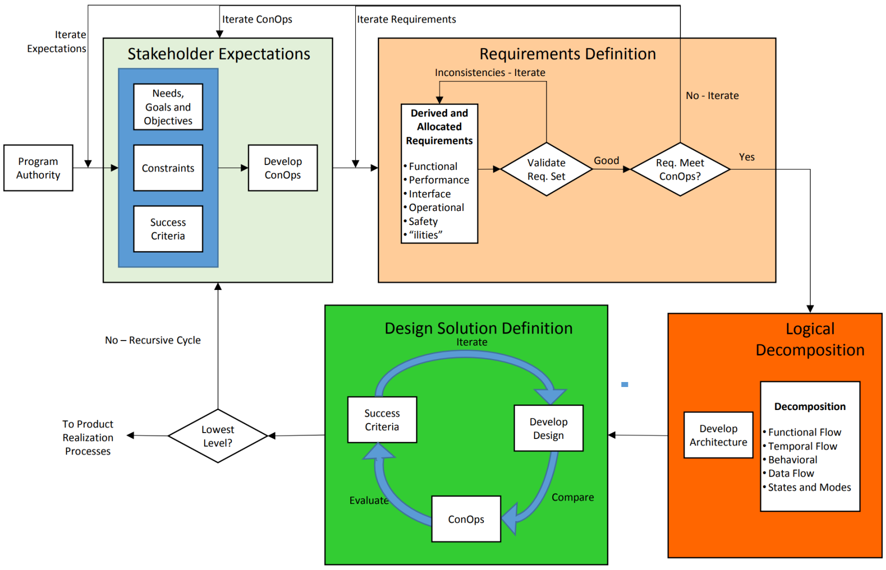


Figure 2.1: System Design Process [2]

From there, functional, interface, operational and safety requirements are established to determine how the mission can be fulfilled. Once validated, the logical decomposition process begins by answering the questions iteratively:

1. What are the functions needed to satisfy the requirements?

2. What are the products[1] that execute those functions?

3. What are the requirements imposed by the products?

From these answers, a hierarchical representation of the functions and products at four levels (System, Sub-system, Component and Unit) can be created and a functional architecture developed. Next, the design is assessed against all requirements. If they are validated, then the design proceeds to its physical architecture. Otherwise, a new iteration of the process begins.

As the ground station is a multidisciplinary project, containing a Tracking System (TS) in addition to the Communication System (CS), various iterations were necessary to arrive at a well defined functional architecture. At this point, the translation from high-level, abstract, products to real components began. Through research and communication with vendors, parts were identified and possible designs

[1]Products can be parts, components, sub-systems, or systems whose purpose is to execute a given function.

were modelled, simulated and evaluated against the requirements, resulting in a trade-off analysis that led to the final design.

2.4 Functional Analysis

2.4.1 Requirements

As discussed in Section 2.3, establishing and deriving requirements is the starting point of the design process. For this design, the requirements are classified into:

1. Mission: related to the needs of the mission.
2. Environmental: environmental conditions that must be satisfied. For example, regarding electromagnetic interference, temperature, wind, etc.
3. Operational: relative to the modes of operation of the station.
4. Interface: describe the requirements of the system's interfaces.
5. Physical: mechanical constraints. For instance, mass, weight, area, etc.
6. Configuration: how the different systems must be configured.
7. Design: what the system should do.
8. Verification: constraints on the verification procedure.

Before the end of the design, hundreds of requirements were identified (Appendix B). Table 2.1 contains the mission requirements, from which everything is derived.

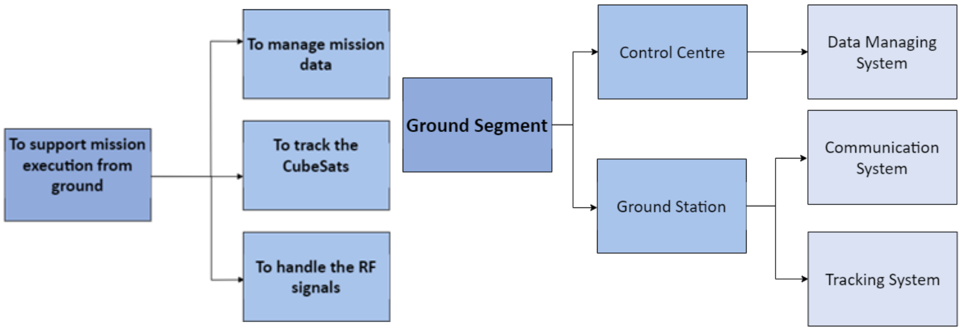
ID	Requirement
MIS-001	C3 shall support LEO Cubesat missions from the ground
MIS-002	C3 shall manage the operations of the PoliTO/Cubesat Team missions
MIS-003	C3 shall be located at Politecnico di Torino in TBD location
MIS-004	C3 shall manage mission data from the payloads of the CubeSats
MIS-005	C3 shall manage housekeeping data from the CubeSats
MIS-006	C3 shall manage the communication with CubeSats
MIS-007	C3 shall be operated by students and non-professional operators
MIS-008	C3 shall cost less than 30.000,00€
MIS-009	C3 shall implement at least E2 level of autonomy for the following C3 systems: -Tracking System (TS) - Communication System (RF)
MIS-010	C3 shall be designed manufactured, integrated and tested by the end of the first half of 2020
MIS-011	C3 shall be re-configurable with respect to the following communication parameters: - Communication Protocols - Frequency bands - Type of modulation
MIS-012	The C3 Communication System shall operate in the following bands: - VHF band - UHF band - S band - X band
MIS-013	C3 Mission Control System (MCS) shall be located at Politecnico di Torino in the CubeSat PoliTo Team StarLab
MIS-014	C3 shall be designed, manufactured, integrated and tested by students and non-professional operators.

Table 2.1: Mission Requirements

2.4.2 Function and Product Trees

Through their various iterations, the requirements of Section 2.4.1 produced the Function and Product Trees of the Ground Station, detailed in Appendix C. Here, their highest levels are represented in Figure 2.2. The essential function of the Ground Segment is to support mission execution from the ground. That means it must be capable of tracking CubeSats, handling (transmitting and receiving) radiofrequency signals, and managing mission data. The Ground Station is responsible for the first two functions while the Control Centre for the latter. From there, functions and subsystems are further decomposed.

Additionally, there is the Function to Product matrix, which associates functions to products. Ideally, there should be a one-to-one correspondence between them. If more than one function is associated to a product, there is no problem. However, if the same function is executed by two products then either those products are redundant or the function itself could have been further decomposed. All product to function matrices are contained in Appendix D.



(a) Function Tree **(b)** Product Tree

Figure 2.2: Functional Analysis Trees

2.4.3 Connectivity Matrix

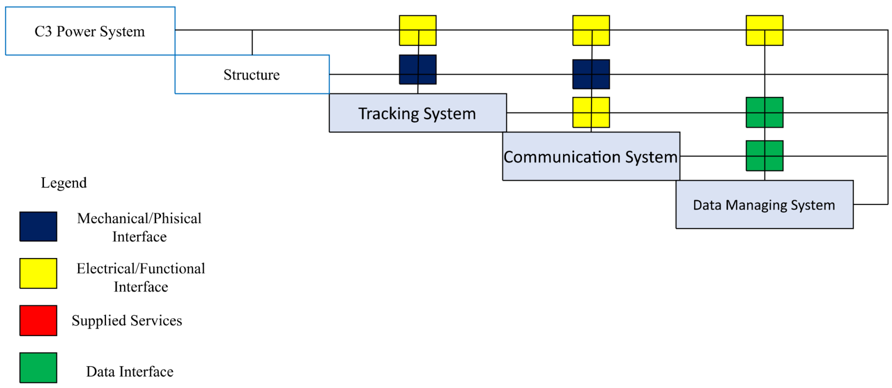


Figure 2.3: N2 Diagram - System-level Interfaces

After defining a product tree, one must comprehend how the products interact among themselves and the N2 diagram, shown in Figure 2.3, is a way to visualize their interfaces. As its complexity grows with the square of the number of products, for brevity, only the System-level interfaces are illustrated. They are classified into four types:

1. Mechanical / Physical: indicating mechanical connection between products.
2. Electrical / Functional: indicating electrical connection or functional dependence between products.
3. Data Interface: indicating sharing of data between products.
4. Supplied Services: indicating when and how one product provides services to another.

As expected, both TS and CS have mechanical interfaces to act upon: the structure of the antennas. They do not share data but directly communicate with the Control Centre's Data Management System. Finally, all components are connected to the power system because they require energy.

2.4.4 Risks

To ensure ground station support for critical missions with a bounded probability of failure, risk must be qualified and quantified. This means estimating system reliability by considering its possible failure modes with their allied severities and probabilities.

During the design iterations, risks were researched and represented by a triplet of likelihood, severity and total risk index from 1 to 5. Then, a choice had to be made: could the risk be mitigated at an acceptable cost or should it be accepted and monitored? High risks were unacceptable and had to be mitigated if present by iterating the design. Risks such as a failure of the Software-Defined Radio (SDR), while catastrophic, could be mitigated by having spare parts in cold or hot redundancy, while antenna damage by a lightning because it is of very low probability risk had to be accepted. A detailed list of risks are present in Appendix A, but they can be summarized by Figure 2.4. As the figure illustrates, no risk of classification greater than medium is present.

		SEVERITY					Legend
		Negligeble(1)	Significant (2)	Major (3)	Critical (4)	Catastrophic (5)	Very high
LIKEELIHOHOOD	E						high risk
	D			COM-03;			Medium risk
	C	COM-17; COM-18;	LT-01; SCH-06;COM-02;	LT-03; LT-06; SCH-03; SCH-08; COS-02; COM-05; COM-20;	COM-01; COM-06; COM-38; COM-39; COM-40; COM-41; COM-42;		low risk
	B	SCH-04	LT-02; LT-04; LT-10;	LT-07; SCH-02; SCH-05; COS-01; COM-23; COM-24; COM-25;	SCH-01; SCH-07; SCH-09; COS-03; COM-07	LT-09; COM-04; COM-08; COM-09; COM-19;	Very low risk
	A	COM-37	LT-05; COM-12; COM-11; COM-16; COM-34; COM-35;	LT-08; LT-11;LT-12	COM-13; COM-14; COM-43; COM-44; COM-45; COM-46;	COM-10; COM-15; COM-21; COM-22; COM-26; COM-27; COM-28; COM-29; COM-30; COM-31; COM-32; COM-33; COM-36;	

Figure 2.4: Risk Matrix

2.4.5 Functional Architecture

Introduction

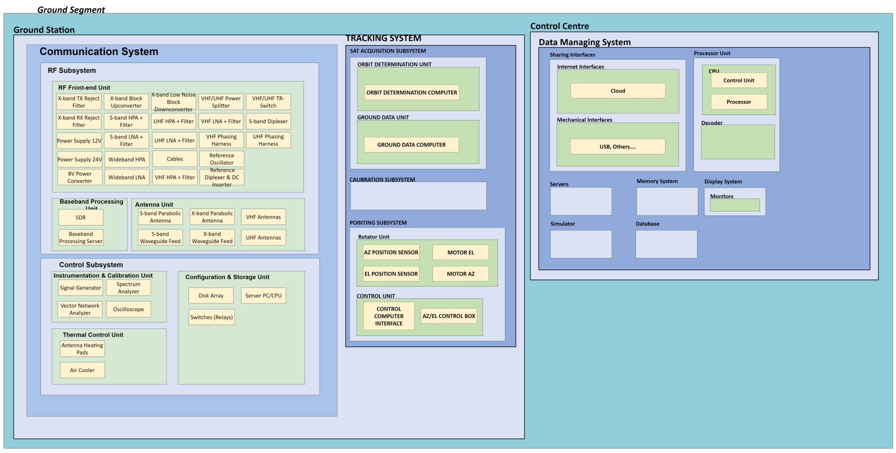


Figure 2.5: High-level Functional Architecture of the Ground Station

The Ground Segment's functional architecture, depicted in Figure 2.5, is divided into three systems: the Communication System (CS), the Tracking System (TS), and the Mission Control System (MCS). The CS transfers information between the ground station and the spacecraft by translating it from/to the digital to/from the analog domain through coding, modulation, signal processing, and by interfacing with the propagation medium through electromagnetic waves. The TS supports and points the antennas towards the target spacecraft, within the visibility cone of the ground station. Finally, the MCS is responsible for storing, classifying and processing that information.

Communication System's Functional Architecture

Figure 2.6 illustrates the high-level architecture of the CS, responsible for establishing and maintaining a communication link between the ground station and the spacecraft to enable the transmission of telecommands and the reception of telemetry and payload data in support of the mission. To do so, the CS must be capable of adapting to channel variations, interfacing with the propagation medium, processing the baseband signals and converting them to and from an intermediate frequency (IF), among other functions, all while respecting the applicable ITU, ECSS, and CCSDS standards regarding spurious emissions and interference. The CS is a digital system designed for transmission and reception of packet data and is composed of two subsystems: the Control Subsystem, responsible for the thermal management and configuration of the RF Subsystem, and the RF Subsystem responsible for the communication link itself, the foundation of which is the SDR.

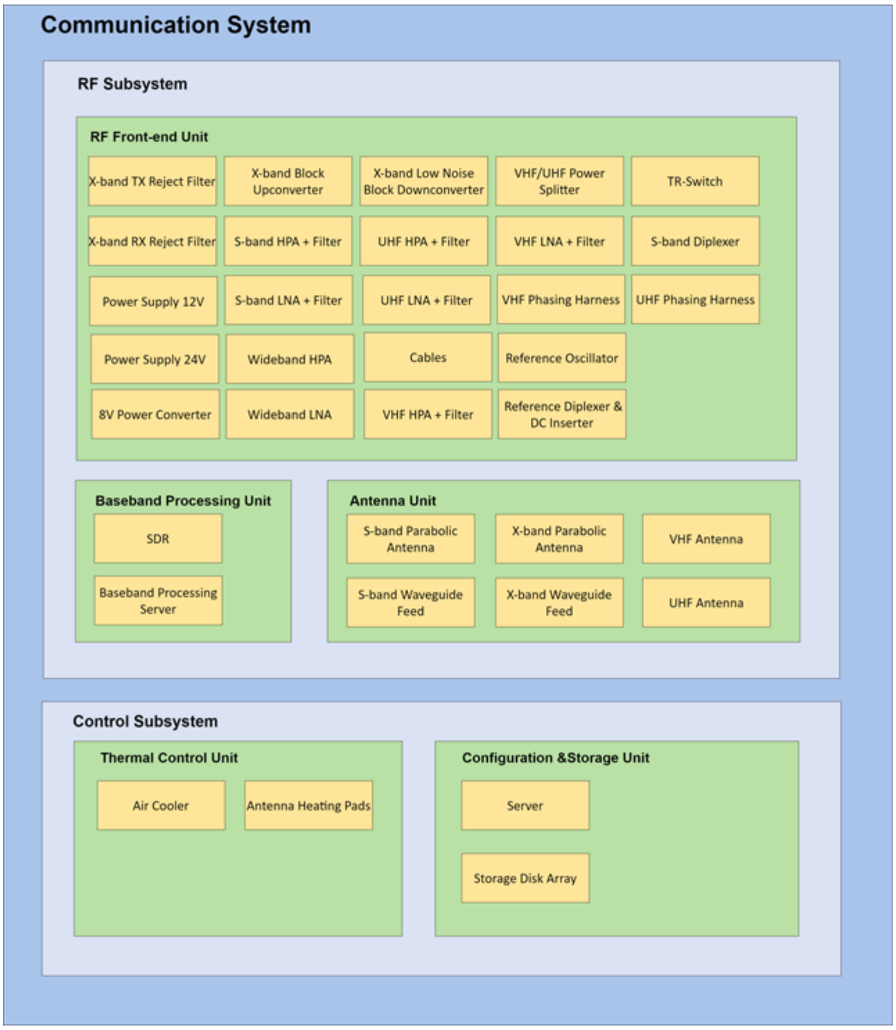


Figure 2.6: High-level Architecture of the Communication System

2.5 Physical Architecture

2.5.1 Introduction

Section 2.4.5 discusses the functional architecture of the ground station, its abstract components and how they interface. Now, this section defines the key performance indices and trade-offs involved in translating the functional architecture into the physical world. Then, design choices are described and its physical architecture is discussed.

2.5.2 Trade-off Analysis

Considering the requirements of Section 2.4.1 and the functional design of Section 2.4, proposals are evaluated with regards to:

1. Cost: Hard budget of 30k€.
   Common off-the-shelf components are prioritized to reduce the overhead of designing parts and costs. An increase in complexity is acceptable if it comes at a cost reduction. Spending is prioritized on frequency bands where reliability and component performance is critical, such as the X-band, while minimizing it where it is not.

2. CS Key Performance Indices:
   Bandwidth, efficiency, latency, power, noise figure, robustness to interference, error rate, among other radio frequency parameters.

3. Architectural Reliability:
   Failure probability, fault severity and recovery possibilities considered to improve system availability. Examples are the use of input protection, filtering and other protective measures of the radiofrequency front-end (RFFE), distribution of capabilities among the different communication lines, cold/hot redundancy and reduction of design complexity (fewer likely points of failure).

4. Footprint:
   Available roof space on Politecnico di Torino's building is very limited and must be used sparingly.

5. Mass:
   Maximum weight supported by the roof is low ($<$ 250 kg).

6. Flexibility:

   (a) Tracking: Fast, heavy-duty, high-resolution rotors are future-proof; moving to higher frequencies or medium orbit missions with larger antennas does not require their replacement.

   (b) RFFE: Wideband components that allow the GS to use different frequency bands without penalizing performance are favored.

   (c) How many satellites can be tracked and communicated with simultaneously.

7. Simplicity:
   Fewer interfaces and reduced complexity facilitates documentation, modelling, simulation, operation and management of the GS, leading to faster fault detection, isolation and recovery (FDIR).

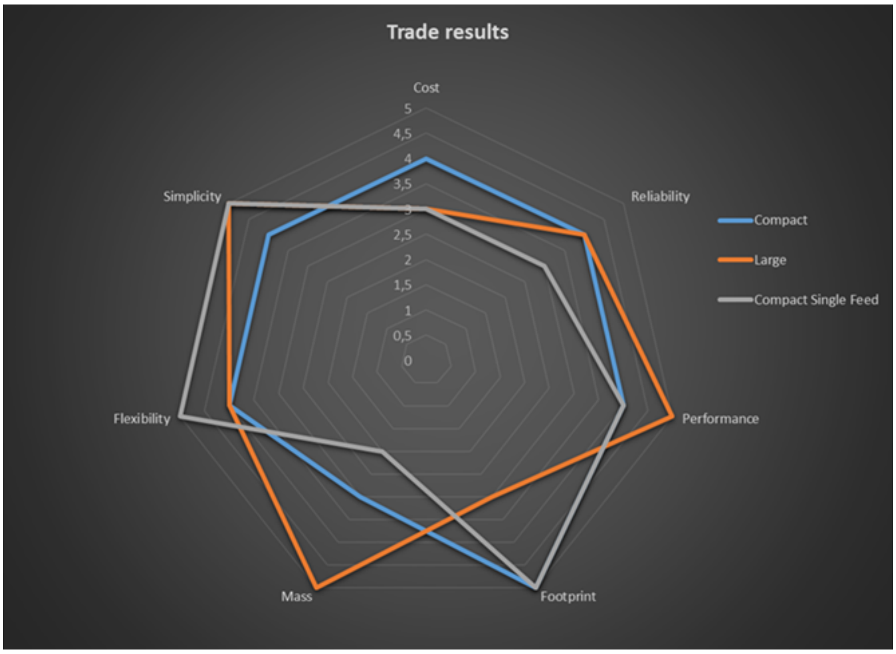


Figure 2.7: Trade-off Analysis

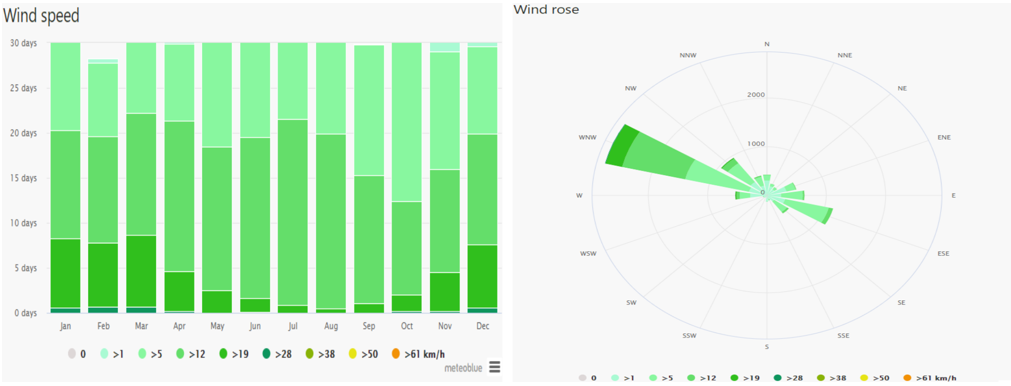
Three possibilities stood-out:

1. Compact Architecture: VHF/UHF/S-band share the same structure while X-band has its own structure.
2. Large Architecture: VHF/UHF, S-band, and X-band use independent structures.
3. Compact Single Feed Architecture: S/X-band share the the same parabola with a ultra-wideband wave-guide. VHF/UHF/S/X bands share the same structure.

Detailed trade-off analysis of the possible architectures, represented in Figure 2.7, led to the selection of the compact architecture because it was cheaper, simpler, lighter, and had the smallest footprint while offering excellent performance. Despite not being as flexible as the single-feed architecture, a TS failure does not compromise either X-band and S-band capabilities. Additionally, the compact architecture allows for independently tracking of at least two separate spacecrafts.

2.5.3 Tracking Considerations

While the Tracking System designed in [4] is not the focus of this work, tracking is a fundamental part of the ground station and its limitations and effects on



(a) Wind speed **(b)** Wind rose

Figure 2.8: Turin 30 year historic wind data, [3]

the design of the ground station's physical architecture must be discussed. LEO satellites move very quickly, several kilometers per second, and thus require tracking to maximize contact window duration. This can be performed mechanically by antenna rotors and mechanisms or electronically by beam-steering antennas. The latter was investigated, but deemed too expensive and complex for CubeSatTeam's purposes. Therefore, a mechanical solution was adopted.

High-gain antennas for X-band and S-band communication demand precise, high-resolution rotors with a pointing accuracy of 0.2°, but they also must support strong winds (Section 2.4.1). Turin's wind data [3], shown in Figure 2.8, suggests that wind very rarely ($< 0.1\%$ of the time) exceeds 40 kilometers per hour, corresponding to a strong breeze that is not hard to withstand. Yet, a meshed reflector was chosen for the S-band to reduce both wind load and cost. However, X-band communication demands a solid reflector of high surface quality. Considering performance, cost and wind-load constraints, we adopted a high-resolution heavy-duty Azimuth-Elevation tracking system with up to $6°/s$ angular speed, but whose maximum torque required light antennas, limiting their weight to 25 kg; corresponding to a 1.2m fiberglass reflector with its feed and structure.

Azimuth-Elevation systems as represented in Figure 2.9 also introduce a problem when elevations greater than 90 degrees are not supported. In this case, if a satellite is in a very high elevation pass, a change of azimuth by 180 degrees is required. However, such a change requires time, leading to a temporary loss of visibility. This is known as the keyhole or zenith-pass problem [6], illustrated in Figure 2.10. Likewise, losses of visibility happen when the tracking system's elevation rate is too low.

A solution to the keyhole problem is to add a lower gain antenna, which requires a lower pointing accuracy, to be used while the tracking system re-positions itself.

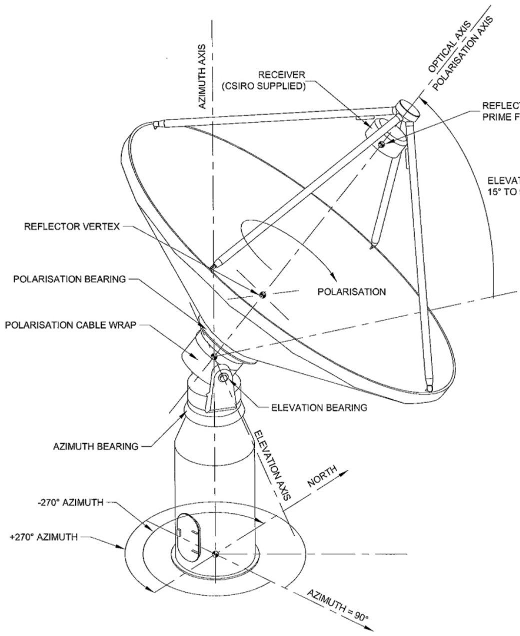


Figure 2.9: Antenna Azimuth-Elevation Model, [5]

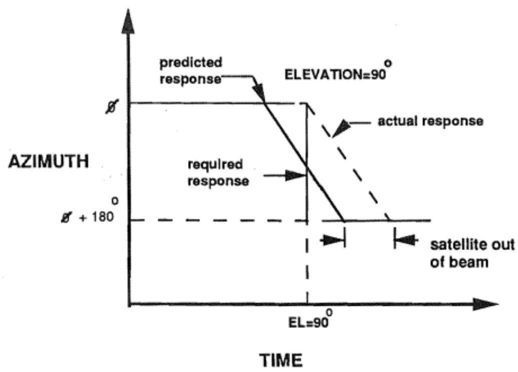


Figure 2.10: Keyhole Problem [6]

Moreover, because the propagation loss is at its minimum when the satellite is at the zenith, the lower gain antenna can sustain the communication link without performance loss.

However, the faster the tracking, the shorter the loss of visibility is. For satellites at a 400 km orbit and an elevation rate of $6°/s$, a loss of 30 seconds is expected [4]. Furthermore, high-elevation orbits are unlikely in current CubeSatTeam missions. Therefore, the visibility loss is accepted to avoid cost increase.

2.5.4 Architecture

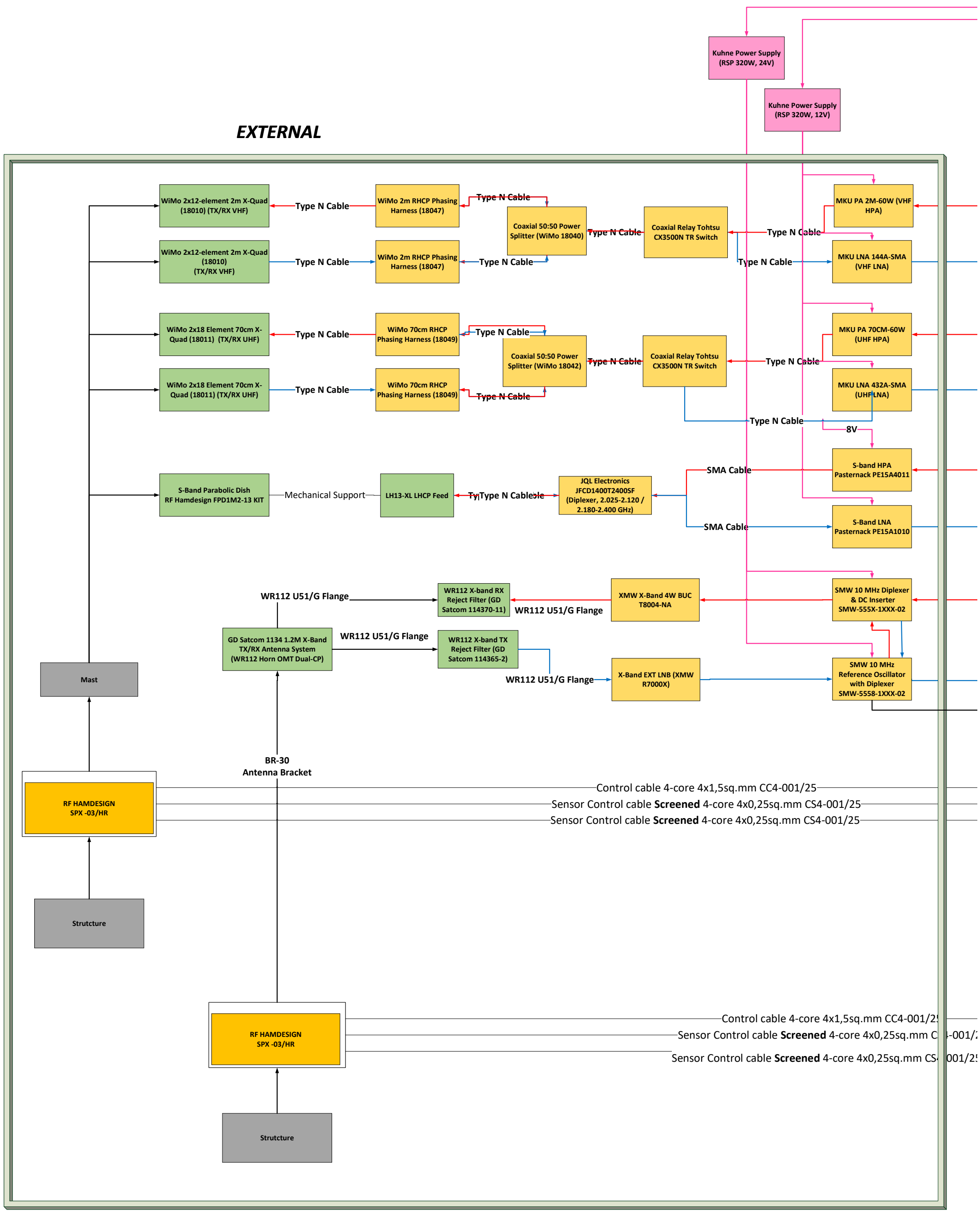


Figure 2.11: Physical Architecture - Roof

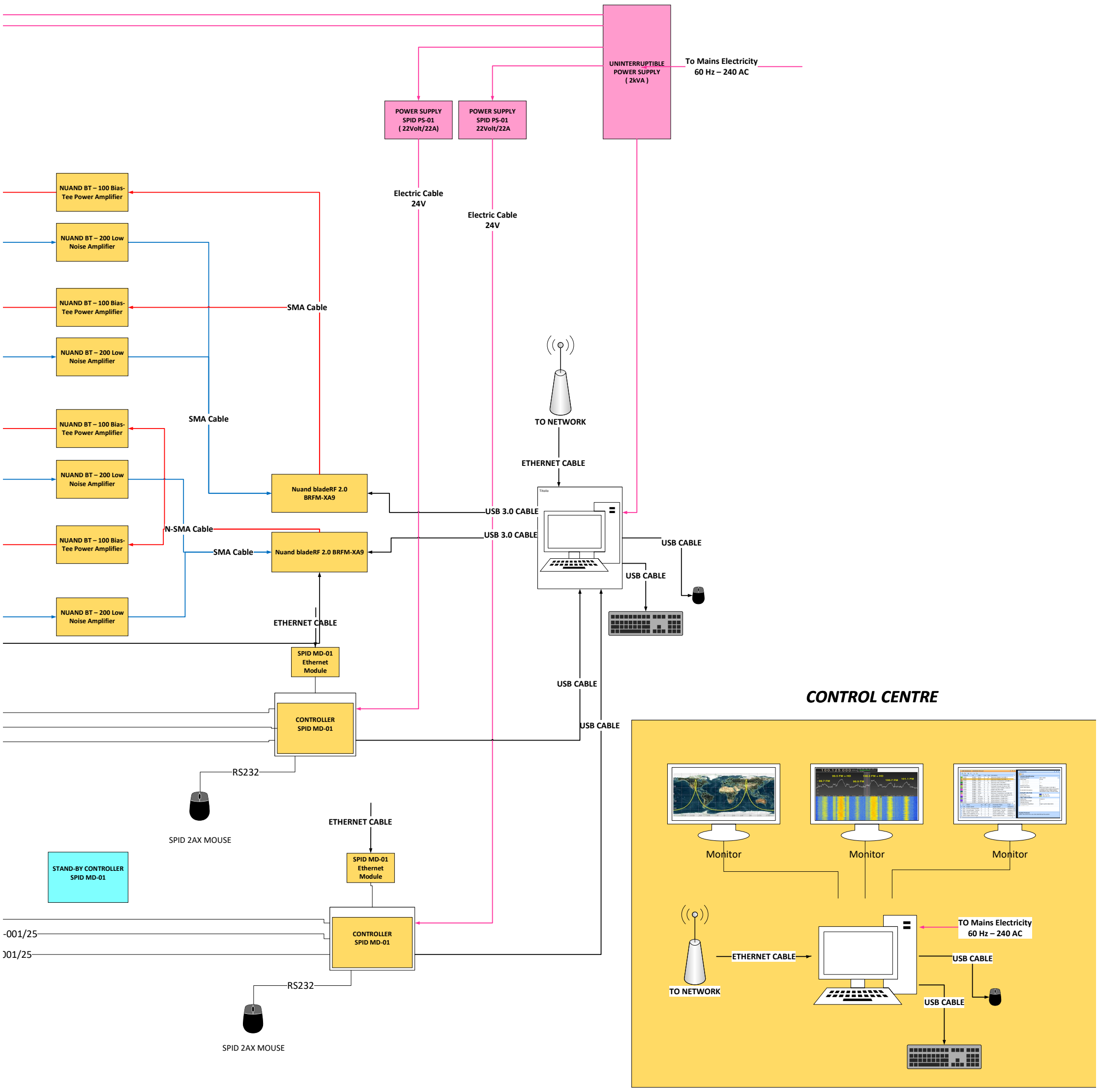


Figure 2.12: Physical Architecture - Ground

Figures 2.11 and 2.12 depict the entire architecture of the GS, split across various locations. The RF subsystem has its antennas and front-end components located on Politecnico di Torino's rooftop to ensure a clear line of sight between the antennas and the spacecraft. Moreover, the RF front-end is entirely contained within a weatherproof box, placed by the antennas and the spacecraft tracking system to minimize cable length. Consequently, the signal-to-noise ratio (SNR) is maximized and the costs are reduced. Instead, the back-end elements are located in the Control Room together with the MCS.

Finally, the TS is based on a dual-axis mechanism that allows independent movement of the elevation and azimuth axes (Section 2.5.3), divided into two parts: the actuators that rotate the antennas and their controller, composed of a computer and control boxes connected by coaxial cables.

This section is concerned with the RF subsystem, detailed below.

Software Defined Radio

Before delving into the details of the RF subsystem, one must comprehend what SDR is. Until the 2000s, the main solution to RF architectures were super heterodyne receivers based upon the cascade of specific single-purpose analog circuits optimized for a given configuration. This was especially true for microwave frequencies, where dedicated hardware was a must, and was usually built into a single System on a Chip (SoC). This allowed the designer to optimize each of the parameters of the communication system, such as bandwidth, gains at each stage, noise figure, among others. However, it had very high design and prototyping overheads as each component had to be custom-made.

Over the years, due to the development of very high speed, high resolution Analog-to-Digital (ADC) and Digital-to-Analog (DAC) converters, Field Programmable Gate Arrays (FPGA), and Central Processing Units (CPU), a new architectural paradigm based on digital signal processing (DSP) was born. Instead of using an external front-end with dedicated filters and mixers, a Zero-IF (ZIF) architecture uses a single complex mixer whose oscillator's frequency is set to the frequency of interest, allowing the receiver to directly sample the complex baseband signal. Therefore, complexity is enormously reduced [7].

Furthermore, modern ZIF architectures include electronically controlled amplifiers. Therefore, they can support different communication systems with unmatched flexibility, allowing parameters such as gain, bandwidth, carrier frequency, and filters to be quickly reconfigured. Figure 2.13 illustrates the ZIF architecture of the AD9361 RF Agile Transceiver. One can quickly notice its simplicity; each channel has a single mixer, band-pass filter, and power amplifier.

When modern ZIF transceivers are combined with FPGAs, a software-defined hardware architecture, the SDR is obtained. By design, SDRs have sensitive electronics and a very small footprint, thereby limiting their input and output powers. Consequently, input protection, and external high-power amplifiers (HPA) are required for satellite applications.

Considering the GS is required to support multiple missions, each with its own communication system, it is clear SDRs are the best cost-effective solution. Thus, the RF front-end is designed to use electronic and waveguide filters for input protection. And, to attain transmission powers and bandwidths required for satellite communication, the front-end contains wideband power amplifiers.

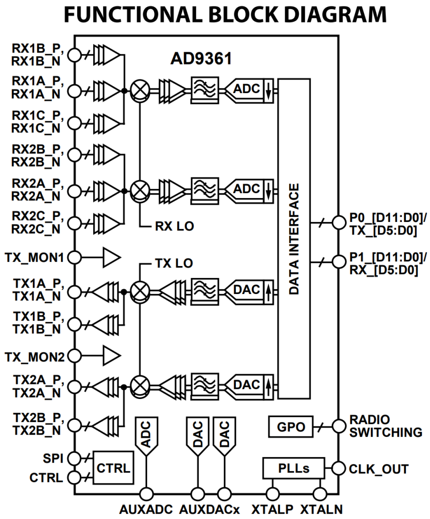


Figure 2.13: AD9361 RF Agile Transceiver Functional Block [8]

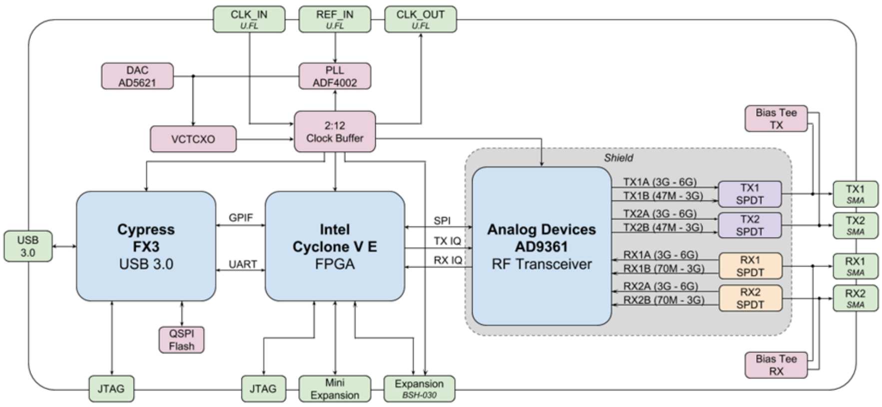


Figure 2.14: Nuand bladeRF-2.0 micro Functional Diagram [9]

The Communication System uses the Nuand bladeRF-2.0 micro SDR [9], represented in Figure 2.14. Its transceiver is the Analog Devices' AD9361 RF Agile Transceiver, which operates from 47 MHz to 6 GHz with a maximum In-phase/Quadrature (I/Q) sampling rate of 61.44 Msps, and a maximum analog filter bandwidth of 56 MHz - enough for most LEO applications. Two synchronous TX and two synchronous RX channels enable 2x2 Multiple-Input/Multiple-Output (MIMO) or multi-channel applications. Each TX and RX channel has a controllable attenuator and an internal low-noise amplifier (LNA) (NF $<$ 3 dB), respectively, to allow precise gain adjustments by the Automatic Gain Control (AGC). Moreover, the transceiver's Phase Locked Loops (PLL) can be locked to an external reference oscillator (RO) to synchronize the CS. Lastly, the AD9361 has a 12-bit ADC/DAC resolution and high linearity.

Focusing on the SDR, complex signal processing chains and applications are executed by a 301 kLE Intel Cyclone V FPGA, enabling high-performance energy-efficient communication. Moreover, the SDR can be programmed by combining DSP blocks in Mathworks' Matlab/Simulink or GNU Radio, thereby allowing rapid prototyping. This theme is examined in Section 2.6.

Design Considerations

The CS architecture of Figure 2.11 supports communication in VHF (144-146 MHz), UHF (430-440 MHz), S-band (2.025-2.120/2.200-2.400 GHz) and X-band (7.25-7.75 GHz/7.9-8.4 GHz), but can be reconfigured for other bands by replacing the minimum number of components, such as the input-protection filters.

Cost constraints precluded the purchase of a SDR capable of synthesizing X-band signals. Therefore, we use two frequency converters in the form of a Block Upconverter (BUC), which amplifies and upconverts signals from an Intermediate Frequency (IF) up to X-band, and a Low Noise Block Downconverter (LNB), which amplifies the X-band signal **before** downconversion to an IF.

Every line of Figure 2.11 has the same functional elements. The antenna receives/transmits the signal, which is filtered by the waveguide/electronic filters to reduce the amount of noise and interference entering/exiting the system. Low-noise Amplifiers (LNA) and High-Power Amplifiers (HPA) boost the signal for reception/transmission. Frequency converters, external (BUC/LNB) or internal to the SDR, translate the signal in frequency. Finally, to synchronize the system, the SDR, LNB, and BUC are connected to the same very low phase noise (< 155 dBc @ 1 kHz) 10 MHz reference oscillator. 12V and 24V power supplies power all components except the BUC, which uses a 10 MHz diplexer is together with a DC inserter.

Amplifier Design

An electronically controlled two-stage setup is employed to amplify the signal. Each stage can be independently powered or bypassed for coarse gain control, complementing the SDR's granular gain control. Moreover, to reduce spurious emissions and noise, the SDR's programmable digital filters are used.

For transmission, without compromising linearity, this approach reduces the cost of the power amplifiers. Instead of a large, costly, very high-gain HPA, a medium-gain PA drives a high-gain HPA. Consequently, the same output power is achieved at a fraction of the cost.

For reception, an ultra-low noise LNA defines the receiver's noise figure. Then, a second-stage medium-gain LNA boosts the signal above the receiver's sensitivity.

HPAs are operated at saturation for efficiency, because most LEO satellites use phase-only modulations, and thus HPA distortion can be neglected. The remaining amplifiers are operated at a back-off greater than 10 dB, meaning non-linear effects are not significant. Both the driving PA and the second-stage LNA are as wideband as the SDR for compatibility with any HPA and ultra-low noise LNA, respectively.

To conclude, the advantage of the BUC/LNB approach in the X-band must be highlighted. Filtering, amplification, and frequency conversion happen as close as possible to the antenna feed, reducing cost (Section 2.5.8), and insertion losses (IL). Hence, compared to traditional mixer architectures, less power is wasted in transmission and a better SNR is achieved during reception.

Antenna and Feed Design

As explained in Section 2.5.3, the rooftop where the antennas will be installed constrains their maximum weight and size, and therefore their gain. Instead, the CS demands large, highly directive, antennas. To balance these requirements, we explored two solutions: patch antennas and parabolic reflectors.

The former, a high-gain (> 36 dBi) patch antenna array with a beam-forming network capable of beam-steering, minimized weight (< 5 kg) and eliminated the need for mechanical tracking. However, its bandwidth limitations (< 100 MHz) and cost (> 10000 EUR) were unacceptable. Therefore, we use parabolic reflectors in centre-feed and offset-feed configurations, as they were more affordable than comparable Cassegrain and Gregorian antennas.

Considering the cost of S/X-band ultra-wideband waveguide feeds and that of the required filtering to separate these frequencies, we assign a reflector and feed to each frequency band.

X-band reflectors must have very low surface roughness to maximize their efficiency. Since lightweight aluminum reflectors were too expensive, we selected a heavier offset-feed fiberglass reflector illuminated by a horn feed. Instead, surface roughness is not as critical in the S-band. Consequently, we employ a steel mesh reflector with a central helix-feed to reduce the load on the tracking system without compromising performance. Both reflectors are 1.2m wide, which is the optimum trade-off between the tracking constraints, cost and gain. [2]

Lastly, in VHF and in UHF, we combine two compact high-gain X-quad antennas through a power splitter to improve directivity.

[2] High bitrate LEO applications require highly directive antennas, making the alignment of the transmit and receive antenna beams critical. Thus, fast high resolution tracking systems are required, increasing costs.

Polarization

All antennas use circular polarization because it nearly eliminates single reflections of a signal and reduces polarization mismatch losses from the misalignment of the transmitter's and receiver's antennas [3]. Furthermore, circular polarization is preferable when considering atmospheric effects and rainfall rates up to 12.5 mm/h [10], which is the case for Turin 99.9% of the time [11]. However, a 3 dB polarization mismatch loss is incurred when communicating with a linearly polarized spacecraft.

In VHF and UHF, a phasing harness generates right-hand circular polarization (RHCP). If left-hand circular polarization (LHCP) or linear polarizations (LP) are required, the phasing harness can be manually switched. In this way, we avoid a complex and costly polarization switching scheme without compromising performance. Instead, only RHCP is adopted in the S-band.

Finally, in the X-band, an Orthomode Transducer (OMT) separates LHCP from RHCP, allowing transmission in one polarization and reception in another. By adding a duplexer to the OMT's LHCP and RHCP ports, two channels per polarization are obtained.

Multiplexing

High-gain 1.2m parabolic reflector antennas and selective filters allow high bitrate ($\geq$ 1 $Mbps$) full-duplex communications in S/X band. Thus, telecommands, telemetry and payload data can be exchanged simultaneously between the ground station and spacecraft, reducing latency and increasing the throughput of the communication access.

Active self-interference cancellation (SIC) and dual-junction circulator approaches to full-duplex communications were researched, but rejected because they did not satisfy isolation and impedance matching requirements. Therefore, frequency-division duplexing is used instead.

In the S-band, a waveguide duplexer offers 50 dB of isolation between the TX and RX frequency bands. Likewise, in the X-band, the OMT is combined with TX and RX reject filters to achieve 90 dB of isolation between the TX and RX channels.

By contrast, in VHF and UHF, a Transmit/Receive (T/R) switch performs time-division duplexing. Thus, we avoid costly high-power cavity filters to isolate the RX channel from the from the high power TX channel.

[3] Many spacecrafts do not have a precise axis control and the polarization mismatch can be very high if it is 90° offset from what would be expected with linearly polarized antennas.

Cooling and Environmental Protection

All front-end components, except the BUC and LNB, are placed inside a weather-proof enclosure next to the antennas, reducing cable loss. Instead, the BUC and LNB attach directly to the X-band feed and have their own enclosures. Finally, heat is dissipated by conduction through aluminium heat-sinks that are cooled by forced-air.

Reliability

To maximize reliability,

1. Each frequency band has its own amplifiers, filters, and antennas. By using two SDRs, each band is operated independently. Hence, if one line fails, the others remain operational.
2. Redundancy is adopted whenever affordable. Every band uses identical SDRs and wideband amplifiers, allowing fault recovery of one line by cannibalizing components from other lines. Moreover, the UHF and VHF lines have cold-redundancy of all its amplifiers.
3. High-reliability components with input protection, built-in voltage regulation, and hermetically sealed enclosures are used for the S/X bands.
4. TX and RX filters protect the front-end electronics of all lines.

Connectors and Cabling

All lines use connectorized electronic components, connected by coaxial cables. A key design parameter is the total attenuation produced by these cables. In the design phase, we bounded the maximum cable loss to 3 dB and elected to use low loss cables in the GS. Table 2.2 illustrates their attenuation coefficients.

Frequency	Attenuation (dB/100 m) [4]
144 MHz	3.6
430 MHz	4.3
2400 MHz	16.6
8000 MHz	34.5

Table 2.2: M&P HyperFlex 13 Cable [12]

It is important to observe that if the LNB had not been used in the X-band, the signal would have been attenuated at a rate of 34.5 dB/100 m, degrading the quality of the communication link. Instead, in the IF (550 MHz), the signal is only attenuated at 4.3 dB/100m.

2.5.5 Footprint

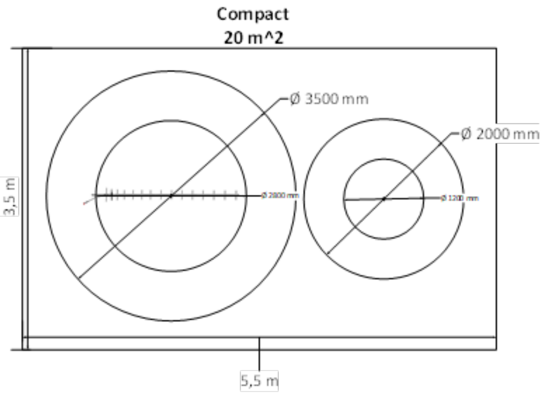


Figure 2.15: Compact Antenna Footprint

A preliminary footprint of the antenna structure is present in Figure 2.15, showing one possible antenna configuration. It is very compact, below 20 m^2. However, attention must be paid to prevent line-of-sight obstruction of one antenna by another. Moreover, the proximity between the antennas may affect their electromagnetic performance.

2.5.6 Mass Budget

Item	**Mass (kg)**
S-band + UHF/VHF Line	104
X-band Line	63
Antenna Structure	40
Total	**207**

Table 2.3: Ground Station Mass Budget

Table 2.3 lists the weight of each of the GS's lines, totalling 207 kg - within the 250 kg design requirement. The primary contributors to the weight are the rotors and the antenna's base and tower. Next, the X-band fiberglass parabolic reflector weigh in at 20 kg. Finally, the meshed S-band reflector and the UHF/VHF X-Quad antennas are the lightest components, at 5 kg each.

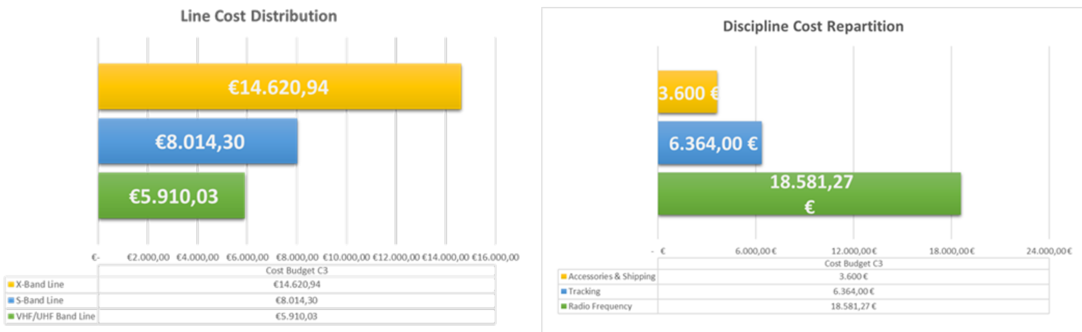
Component	Quantity	Maximum Power (W)
Kuhne Power Supply 12V	1	320
Kuhne Power Supply 24V	1	320
PS-02	2	485
Computer	1	400
	Total	**2010**

Table 2.4: Ground Station Power Budget

2.5.7 Power Budget

Table 2.4 classifies the power consumption of the GS. As one would expect, the power supplies that feed the power amplifiers are the main energy consumers, followed by the TS's rotors. Still, total power consumption is two kilowatts, meaning the GS can easily be powered, even by battery uninterruptible power supplies if necessary.

2.5.8 Cost Budget



(a) Cost Budget per Line

(b) Cost Budget per System

Figure 2.16: Cost Budgets of the CubeSat Control Centre

Figure 2.16 illustrates C3's cost by discipline and frequency band. As expected, the X-band is the most expensive line, followed by the S-band, and the VHF/UHF lines. From a system perspective, the CS is the costliest system (18k€). Then, the TS and its rotors (6k€). Lastly, the MCS and shipping expenses correspond to the remainder of the cost (3.6k€).

Table 2.5 lists part numbers and their prices[5]. Going into detail, the X-band

[5]Connectors are not included.

antenna system, its OMT, and TX/RX reject filters are the most expensive components (5k€ combined) because they are metal components machined at an extremely high precision. Next, the BUC and LNB (3k€ combined), the 10 MHz rubidium oscillator (1.8k€), and the SDRs (1.4k€). Finally, one can see that most of the VHF, UHF and S-band expenses are related to their amplifiers.

Item	**Quantity**	**Price (incl. VAT)**	**Total Price**
SPX-03/HR (R+C)	2	1.498,00 €	2.996,00 €
MD-02	1	430,00 €	430,00 €
PS-02	2	486,00 €	972,00 €
CC4-001/25 HR SPX CONTROL	2	66,00 €	132,00 €
CS4-001/25 HR SPX SENSOR	4	35,00 €	140,00 €
Ethernet Module MD-01	2	60,00 €	120,00 €
SPX-03 Heavy Duty Mast Pole Bracket	2	109,00 €	218,00 €
SPX-03 Counterweight	2	109,00 €	218,00 €
SPX Mast Pole Mount Base	2	69,00 €	138,00 €
Base	2	200,00 €	400,00 €
Tower	2	300,00 €	600,00 €
GD Satcom 1134 1.2M X-Band Tx/Rx Antenna System	1	2.227,27 €	2.227,27 €
WR112 Waveguide Terminator MAGNETIC AB H916	1	166,36 €	166,36
PB1597WD-UB-W X-Band Satcom Diplexer	1	3.200,00 €	3.200,00 €
XMW X-band 4W BUC T8004-NA	1	1.954,55 €	1.954,55 €
Nuand BT-200 LNA	1	27,27 €	27,27 €
Norsat X-1000HAN PLL LNB	1	977,27 €	977,27 €
SMW LREF-5558-1XXX-02	1	1.800,00 €	1.800,00 €
SMW-595X-1XXX-02	1	180,00 €	180,00 €
Nuand BT-100 Power Amp	1	27,27 €	27,27 €
Kuhne RSP320W24	1	79,00 €	79,00 €

Nuand bladeRF 2.0 BRFM-XA9	2	654,55 €	1.309,09 €
Nuand power supply 15W	2	18,18 €	36,36 €
bladeRF microcase	2	18,18 €	36,36 €
M&P HyperFlex 13 Cable (Type N)	1	600,00 €	600,00 €
WiMo 2x12-element 2m X-Quad (18010)	2	149,00 €	298,00 €
WiMo 2x18 Element 70cm X-Quad (18011)	2	149,00 €	298,00 €
WiMo 2m RHCP Phasing Harness (18047)	1	63,00 €	63,00 €
WiMo 70cm RHCP Phasing Harness (18049)	1	63,00 €	63,00 €
MKU PA 2M-60W	1	320,00 €	320,00 €
MKU PA 70CM-60W	1	320,00 €	320,00 €
MKU LNA 144A-SMA	1	189,00 €	189,00 €
MKU LNA 432A-SMA	1	189,00 €	189,00 €
Kuhne RSP320W12	1	79,00 €	79,00 €
Nuand BT-200 LNA	2	27,27 €	54,55 €
Nuand BT-100 PA	2	27,27 €	54,55 €
Pasternack PE15A1010	1	909,09 €	909,09 €
Pasternack PE15A4011	1	1.936,36 €	1.936,36 €
JQL Electronics JFCD1400T2400SF	1	746,36 €	746,36 €
Rfhamdesign FPD 1M2 Kit	1	265,00 €	265,00 €
LH13-XL LHCP Feed	1	121,00 €	121,00 €
UPS	1	1.000,00 €	1.000,00 €
PC	2	600,00 €	1.200,00 €
Shipping	1	1.400,00 €	1.400,00 €
		Total	**28.545,27 €**

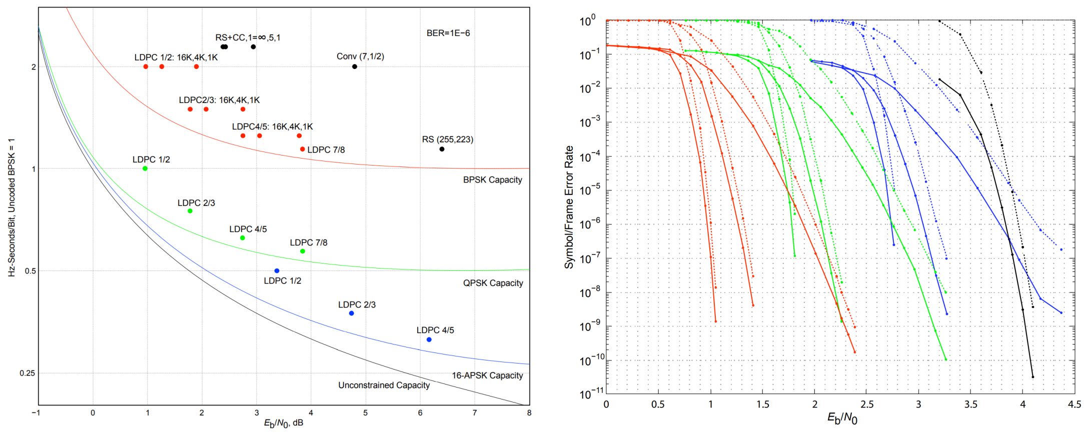
Table 2.5: CubeSat Control Center Costs

2.5.9 Link Budget

Introduction

This section reviews the link budget analyses [13][14] performed to estimate the Communication System's error performance. Further information can be found in Appendix E, which computes receiver noise figures, and Appendix G, which details the link budget calculations.

X-band



(a) Code Capacity **(b)** Error Performance

Figure 2.17: CCSDS AR4JA LDPC Code Performance [15]. Dashed lines refer to Frame Error Rate, solid lines to Bit Error Rate. Red curve corresponds to $R_c = 1/2$, LDPC(16384,8192).

The X-band (7.25-7.75 GHz Downlink / 7.9-8.4 GHz Uplink) links are statically designed for communication with LEO satellites at a 400 km altitude and 5° elevation angle. We assume the use of digital phase-only modulations such as QPSK and CCSDS-compliant LDPC coding [15] to support:

1. High data-rate downlinks ($R_b \geq 1\ Mbps$ @ $BER \leq 10^{-6}$)
2. Ultra-reliable, low-latency uplinks ($R_b \geq 64\ Kbps$ @ $BER \leq 10^{-12}$)

The error performance of such codes are represented in Figure 2.17. With a code-rate $R_c = 1/2$, the required E_b/N_0 for the downlink and uplink are:

$$E_b/N_0 = \begin{cases} 1\ dB & \text{, using LDPC(16384,8192)} \\ 5\ dB & \text{, using LDPC(128,64)} \end{cases} \tag{2.1}$$

. Furthermore, we assume:

1. All components are within specification.
2. Amplifiers operated at saturation.
3. Ground station located at the Politecnico di Torino, Turin - Piedmont (Italy) (45.079,17°N; 7.676,11°E).
4. Antenna height $h_A = 20\ m$.
5. Satellite's antennas are pointed at the ground station through the Attitude Determination and Control System (ADCS) or beam-steering.
6. Satellite uses 16 dBi X-band RHCP 4x4 Patch Array antennas and a SDR transceiver. These are state-of-the-art technologies for CubeSats [16] that are available on the market [17] [18] [19].
7. Antenna temperatures are:
   (a) 50 K for the clear sky conditions seen by the ground station at 5° elevation.
   (b) 290 K for the spacecraft that sees the Earth.
8. Environmental effects aiming at a 99.9% availability (0.1% outage probability):
   (a) Atmospheric attenuation of 1 dB is expected for frequencies below 10 GHz [20].
   (b) Rainfall rate of $R = 12\ mm/h$ [11] with a 4 km zero degree isotherm, producing:
      i. Antenna temperature increase to 181.82 K, 3.46 dB of attenuation in the downlink.
      ii. Antenna temperature increase to 290.00 K, 5.95 dB of attenuation in the uplink.
   (c) At Turin's latitude, strong ionospheric scintillations can be neglected because they are very rare [21].
   (d) Multi-path propagation effects are not significant because of circularly-polarized highly directive antennas.
9. SRRC filters with 20% roll-off are employed.
10. Implementation loss of 1 dB in uplink and downlink.
11. Link margin of 6 dB [22].

Studying the X-band link budget (Table 2.6), some conclusions can be drawn:

1. The link is closed with 14 dB margins at maximum slant range (1800 km) in uplink and downlink. Such high margins are expected because of the high gain antennas, high transmit power, efficient CCSDS encoding, and low noise receivers. Moreover, waveguide filters in the ground station and cavity filters in the spacecraft minimize the insertion and cable losses. Lastly, the controllable gains of the RX chain prevent saturation of the receiver in the downlink.

2. Tracking systems at the ground station, and at the spacecraft are responsible for the low pointing loss observed (0.1 dB).

3. The presence of rain more than tripled the antenna noise temperature in the downlink, reducing system margins.

4. Clearly, the choice of a high-gain patch antenna array is preferred. However, a single linearly-polarized patch antenna with 8 dB gain would still close the link. Alternatively, a 3 dB polarization mismatch loss can be accepted.

.

X-band Communication System	**Uplink**	**Downlink**
Parameters		
Frequency (GHz)	8.1	7.5
Modulation	QPSK	QPSK
Coding	LDPC(128,64)	LDPC(16384,8192)
Required Eb/N0 at Target BER	5 dB @ 1E-12 BER	1 dB @ 1E-6 BER
Symbol rate	64 ksps	1 Msps
Gross Bitrate	128 kbps	2 Mbps
Data Rate	64 kbps	1 Mbps
Bandwidth (20% SRRC roll-off)	76.8 kHz	1.2 MHz
Transmitter		
Transmitter Power (HPA)	4W / +36 dBm	2W / +33 dBm
Input Back off (dB)	0.00	0.00
RX Reject Filter Loss (dB)	-0.35	-1.00
Transmitter Cable Loss (dB) [6]	0.00	-0.20
Transmitter Waveguide Losses (dB)	-0.15 [7]	0.00

[6] After HPA.

[7] OMT + Feed Horn

Impedance Mismatch Losses (dB)	-0.04 [8]	-0.04
Connector Losses (dB)	0.00	-0.30
Transmitter Antenna Gain (dB)	36.90	16.00
Transmitter Antenna HPBW (*)	2.20	18.00
EIRP (dBm)	72.36	47.46
Propagation		
400 km orbit, 5° elevation		
Max Slant Range / Free Space Propagation Loss	1800 km / -175.70 dB	1800 km / -175.06 dB
Polarization Mismatch Loss (dB)	-0.25	-0.25
Atmospheric Absorption Loss (dB)	-1.00	-1.00
Rain Losses (dB)	-5.95	-3.46
Ionospheric Loss (dB)	0.00	0.00
Multipath Loss (dB)	0.00	0.00
Pointing Losses (dB) [9]	-0.10	-0.10
Total Propagation Loss (dB)	-183.03	-179.87
Receiver		
Received Isotropic Power (dBm)	-110.67	-132.41
Receiver Antenna Gain (dB)	16	37.50
TX Reject Filter Loss (dB)	-1.75	-0.25
Receiver Cable Loss (dB)	-0.20	0.00
Receiver Waveguide Losses (dB)	0.00	-0.15
Impedance Mismatch Losses (dB)	-1.20 [10]	-0.04
Received Signal Power (dBm)	-97.82	-95.35
Receiver Gain (dB)[11]	22.96	78.7
Receiver Noise Figure (dB) / Noise Temperature (K)	4.27 / 485.2	0.7 / 50.72
Equivalent Antenna Noise Temperature (K)	290	181.82

[8] VSWR < 1.2

[9] Accuracy: 0.2° ground, 5° ADCS.

[10] VSWR < 3

[11] AD9361 AGC off (0 dB RX Gain), 3 dB IL after LNA/LNB.

System Noise Figure (dB) / Temperature (K)	5.65 / 775.2	2.55 / 232.54
G/T (Figure of Merit) (dB)[12]	-12.89	13.83
Signal Power at SDR Input (dBm)	-74.86	-16.65
Received Noise Power (dBm)	-120.85	-114.14
SNR (dB) [13]	23.02	18.78
C/N0 (dBm/Hz) [14]	71.88	79.58
Eb/N0 (dB)	20.82	16.56
Implementation Loss (dB)	1.00	1.00
Required Eb/N0[15]	5.00	1.00
Required margin (dB)	6.00	6.00
Margin (dB)	**14.82**	**14.56**
	Link is closed	**Link is closed**

Table 2.6: X-band Link Budget

S-band

The S-band (2.025-2.120 GHz Downlink/2.200-2.400 GHz Uplink) links are statically designed for communication with LEO satellites at a 400 km altitude and 5° elevation angle. We assume the use of digital phase-only modulations such as QPSK and CCSDS-compliant LDPC coding [15] to support:

1. High data-rate downlinks ($R_b \geq 1\ Mbps$ @ $BER \leq 10^{-6}$)
2. Ultra-reliable, low-latency uplinks ($R_b \geq 64\ Kbps$ @ $BER \leq 10^{-12}$)

The error performance of such codes are represented in Figure 2.17 and the required E_b/N_0 for a code-rate $R_c = 1/2$ for the downlink and uplink are:

$$E_b/N_0 = \begin{cases} 1\ dB & \text{, using LDPC(16384,8192)} \\ 5\ dB & \text{, using LDPC(128,64)} \end{cases} \tag{2.2}$$

. Furthermore, we assume:

1. All components are within specification.

[12] Antenna gain to system noise temperature.

[13] At receiver input.

[14] At receiver input.

[15] Per information bit.

2. Amplifiers operated at saturation.

3. Ground station located at the Politecnico di Torino, Turin - Piedmont (Italy) (45.079,17°N; 7.676,11°E).

4. Antenna height $h_A = 20\ m$.

5. Satellite's antennas are pointed at the ground station through the Attitude Determination and Control System (ADCS) or beam-steering.

6. Antenna temperatures are:
   (a) 50 K for the clear sky conditions seen by the ground station at 5° elevation.
   (b) 290 K for the spacecraft that sees the Earth.

7. Environmental effects aiming at a 99.9% availability (0.1% outage probability):
   (a) Atmospheric attenuation of 1 dB is expected for frequencies below 10 GHz [20].
   (b) Rainfall rate of $R = 12\ mm/h$ [11] with a 4 km isotherm, producing:
      i. Antenna temperature increase to 53.00 K, 0.0547 dB of attenuation in the downlink.
      ii. Antenna temperature increase to 290.00 K, 0.0547 dB of attenuation in the uplink.
   (c) At Turin's latitude, strong ionospheric scintillations can be neglected because they are very rare [21].
   (d) Multi-path propagation effects are not significant because of circularly-polarized highly directive antennas.

8. SRRC filters with 20% roll-off are employed.

9. A 1 dB implementation loss is considered in uplink and downlink.

10. Satellite uses a S-band RHCP Patch Antenna Array (13 dBi gain), S-band Transmitter (2W/+33 dBm @ 2025-2110 MHz), and a low noise receiver (T = 485 K) [16]. To share the patch antenna between the transmitter and receiver, a 0.4 dB microstrip or ceramic (SMD) diplexer insertion loss was considered.

[16] These are reasonable values for SDR receivers with modern RFFEs. Moreover, by using a noise temperature equal to that of the X-band receiver, the S-band and X-band architectures can be compared cost-wise, given that they are subject to the same constraints. See Appendix F for a designed patch antenna capable of 13 dBi gain.

11. Spacecraft cable loss is considered very low (0.2 dB) due to the placement of the antenna close to the amplifiers.

12. Ground station has a 3 dB cable loss[17].

13. No external mixers are considered in uplink and downlink because the transmitters and receivers can directly synthesize the frequencies of interest.

14. Link margin of 6 dB in uplink and downlink.

The S-band link budget, shown in Table 2.7, demonstrates that the link has been closed in uplink and downlink, satisfying the design margins. In the downlink, without coding, it would not have been possible to reach the desired error performance at a bitrate of 1 Mbps. Moreover, it is crucial that the spacecraft uses the same polarization as the ground station.

S-band Communication System	**Uplink**	**Downlink**
Parameters		
Frequency (GHz)	2.205	2.105
Modulation	QPSK	QPSK
Coding	LDPC(128,64)	LDPC(16384,8192)
Required Eb/N0 at Target BER	5 dB @ 1E-12 BER	1 dB @ 1E-6 BER
Symbol rate	64 ksps	1 Msps
Gross Bitrate	128 kbps	2 Mbps
Data Rate	64 kbps	1 Mbps
Bandwidth (20% SRRC roll-off)	76.8 kHz	1.2 MHz
Transmitter		
Transmitter Power (HPA)	4W / +36 dBm	2W / +33 dBm
Input Back off (dB)	0.00	0.00
Diplexer (BPF) Loss (dB)	-0.40	-1.00
Transmitter Cable Loss (dB) [18]	-3.00	-0.20
Impedance Mismatch Losses (dB)	-0.04 [19]	-0.04
Connector Losses (dB)	-0.40	-0.40

[17] Unlike the X-band line, which amplified and frequency converted the signal near the antenna, the S-band line requires a considerable length of cabling to carry the signal from the antenna to the amplifier.

[18] After HPA.

[19] VSWR < 1.2

Transmitter Antenna Gain (dB)	25.50	13.00
Transmitter Antenna HPBW (*)	9.52	40.00
EIRP (dBm)	57.66	44.36
Propagation		
400 km orbit, 5° elevation		
Max Slant Range / Free Space Propagation Loss	1800 km / -164.43 dB	1800 km / -164.03 dB
Polarization Mismatch Loss (dB)	-0.25	-0.25
Atmospheric Absorption Loss (dB)	-1.00	-1.00
Rain Losses (dB)	-0.0547	-0.0547
Ionospheric Loss (dB)	-0.10	-0.10
Pointing Losses (dB) [20]	-0.10	-0.10
Total Attenuation (dB)	-165.93	-165.53
Receiver		
Received Isotropic Power (dBm)	-108.27	-121.17
Receiver Antenna Gain (dB)	13.00	25.10
Diplexer (BPF) Loss (dB)	-0.40	-0.40
Receiver Cable Loss (dB)	-0.20	-3.00
Impedance Mismatch Losses (dB)	-0.04	-0.04
Received Signal Power (dBm)	-95.91	-99.51
Receiver Gain (dB)[21]	55	58.3
Receiver Noise Figure (dB) / Noise Temperature (K)	4.27 / 485	4.3 / 490.5
Equivalent Antenna Noise Temperature (K)	290	53.00
System Noise Figure (dB) / Temperature (K)	5.56 / 775.00	4.838 / 543.50
G/T (Figure of Merit) (dB)[22]	-15.89	-2.25
Signal Power at SDR Input (dBm)	-40.91	-41.21
Received Noise Power (dBm)	-120.85	-110.45

[20] Accuracy: 0.2° ground, 5° ADCS.

[21] AD9361 AGC off (0 dB RX Gain), 3 dB IL after LNA.

[22] Antenna gain to system noise temperature.

SNR (dB) [23]	24.93	10.94
C/N0 (dBm/Hz) [24]	73.78	71.73
Eb/N0 (dB)	22.71	8.72
Implementation Loss (dB)	1.00	1.00
Required Eb/N0[25]	5.00	1.00
Required margin (dB)	6.00	6.00
Margin (dB)	**16.71**	**6.72**
	Link is closed	**Link is closed**

Table 2.7: S-band Link Budget

VHF/UHF

The VHF/UHF (144-146/430-440 MHz) links are designed for simplicity, targeting LEO satellites at a 400 km altitude and a 8° elevation angle. We assume the use of QPSK and dipole antennas by the spacecraft. Unlike the S/X band cases, tracking of the ground station by the satellite is not required. Design parameters are:

1. Medium data-rate downlinks ($R_b \geq 100\ kbps$ @ $BER \leq 10^{-6}$)
2. High-reliability, low-latency uplinks ($R_b \geq 64\ Kbps$ @ $BER \leq 10^{-8}$)

The required E_b/N_0 are:

$$E_b/N_0 = \begin{cases} 9.6\ dB & \text{, downlink} \\ 12\ dB & \text{, uplink} \end{cases} \tag{2.3}$$

. Furthermore, we assume:

1. All components are within specification.
2. Amplifiers operated at saturation.
3. Ground station located at the Politecnico di Torino, Turin - Piedmont (Italy).
4. Satellites use a RHCP crossed-dipole antenna (2.14 dBi gain) and have a noisy receiver (T = 485K).
5. Antenna temperature of 290 K for both the ground station and spacecraft.

[23] At receiver input.

[24] At receiver input.

[25] Per information bit.

6. Environmental effects aiming at a 99.9% availability (0.1% outage probability)
   (a) Atmospheric attenuation around 1 dB is expected for frequencies below 10 GHz [20].
   (b) Rainfall rate of $R = 12\ mm/h$ [11] does not produce significant attenuation or increase in noise temperature.
7. SRRC with 20% roll-off are employed.
8. Link margin of 3 dB in downlink and 6 dB in uplink [22].

Tables 2.8 and 2.9 show that all links are closed under the design constraints.
These link budget highlights the importance of VHF/UHF communication as backup communication links in modern missions. If the satellite is unable to track the ground station, because it is de-tumbling or has suffered an ADCS failure, high-reliability emergency communication with the ground station is still possible using a low-gain dipole antenna. However, one must observe that strong VHF or UHF interferers may prevent the link from working. Thus, it is important to measure man-made noise in the zone where the VHF/UHF antennas are installed to prevent the receiver from being jammed. [23].

UHF Communication System	**Uplink**	**Downlink**
Parameters		
Frequency (MHz)	435.00	435.00
Modulation	QPSK	QPSK
Coding	None	None
Required Eb/N0 at Target BER	12 dB @ 1E-8 BER	9.6 dB @ 1E-6 BER
Symbol rate	32 ksps	50 ksps
Gross Bitrate	64 kbps	100 kbps
Data Rate	64 kbps	100 kbps
Bandwidth (20% SRRC roll-off)	38.4 kHz	60 kHz
Transmitter		
Transmitter Power (HPA)	60W / +47 dBm	2W / +33 dBm
Input Back off (dB)	0.00	0.00
T/R Switch Loss (dB)	-0.10	-0.10
Transmitter Cable Loss (dB) [26]	-3.00	-1.00

[26] After HPA.

Impedance Mismatch Losses (dB)	-0.04 [27]	-0.04
Connector Losses (dB)	-0.40	-0.40
Transmitter Antenna Gain (dB)	15	2.14
Transmitter Antenna HPBW (*)	36	60
EIRP (dBm)	58.46	33.60
Propagation		
400 km orbit, 8* elevation		
Max Slant Range / Free Space Propagation Loss	1570 km / -149.13 dB	1570 km / -149.13 dB
Polarization Mismatch Loss (dB)	-0.25	-0.25
Atmospheric Absorption Loss (dB)	-1.00	-1.00
Rain Losses (dB)	0.00	0.00
Ionospheric Loss (dB)	-1.00	-1.00
Pointing Losses (dB)	-0.10	-0.10
Total Attenuation (dB)	-151.48	-151.48
Receiver		
Received Isotropic Power (dBm)	-93.02	-117.88
Receiver Antenna Gain (dB)	2.14	15.00
T/R Switch Loss (dB)	-0.1	-0.1
Receiver Cable Loss (dB)	-1.00	-3.00
Impedance Mismatch Losses (dB)	-0.04	-0.04
Received Signal Power (dBm)	-92.02	-106.02
Receiver Gain (dB)[28]	25.00	39.70
Receiver Noise Figure (dB) / Noise Temperature (K)	4.27 / 485	3.61 / 375.9
Antenna Noise Temperature (K)	290	290
System Noise Figure (dB) / Temperature (K)	5.56 / 775.00	5.18 / 665.9
G/T (Figure of Merit) (dB)[29]	-26.75	-13.23

[27] VSWR < 1.2

[28] AD9361 AGC off (0 dB RX Gain), 3 dB IL after LNA.

[29] Antenna gain to system noise temperature.

Signal Power at SDR Input (dBm)	-67.02	-66.32
Received Noise Power (dBm)	-123.86	-122.58
SNR (dB) [30]	31.84	16.55
C/N0 (dBm/Hz) [31]	77.68	64.34
Eb/N0 (dB)	29.61	14.34
Implementation Loss (dB)	1.00	1.00
Required Eb/N0[32]	12.00	9.60
Required margin (dB)	6.00	3.00
Margin (dB)	**16.61**	**3.74**
	Link is closed	**Link is closed**

Table 2.8: UHF Link Budget

VHF Communication System	**Uplink**	**Downlink**
Parameters		
Frequency (MHz)	145.00	145.00
Modulation	QPSK	QPSK
Coding	None	None
Required Eb/N0 at Target BER	12 dB @ 1E-8 BER	9.6 dB @ 1E-6 BER
Symbol rate	32 ksps	50 ksps
Gross Bitrate	64 kbps	100 kbps
Data Rate	64 kbps	100 kbps
Bandwidth (20% SRRC roll-off)	38.4 kHz	60 kHz
Transmitter		
Transmitter Power (HPA)	60W / +47 dBm	2W / +33 dBm
Input Back off (dB)	0.00	0.00
T/R Switch Loss (dB)	-0.10	-0.10
Transmitter Cable Loss (dB) [33]	-3.00	-1.00
Impedance Mismatch Losses (dB)	-0.04 [34]	-0.04
Connector Losses (dB)	-0.40	-0.40

[30] At receiver input.

[31] At receiver input.

[32] Per information bit.

[33] After HPA.

[34] VSWR < 1.2

Transmitter Antenna Gain (dB)	13	2.14
Transmitter Antenna HPBW (*)	47	60
EIRP (dBm)	56.46	33.60
Propagation		
400 km orbit, 8* elevation		
Max Slant Range / Free Space Propagation Loss	1570 km / - 139.60 dB	1570 km / - 139.60 dB
Polarization Mismatch Loss (dB)	-0.25	-0.25
Atmospheric Absorption Loss (dB)	-1.00	-1.00
Rain Losses (dB)	0.00	0.00
Ionospheric Loss (dB)	-1.00	-1.00
Pointing Losses (dB) [35]	-0.10	-0.10
Total Attenuation (dB)	-141.95	-141.95
Receiver		
Received Isotropic Power (dBm)	-85.49	-108.35
Receiver Antenna Gain (dB)	2.14	13.00
T/R Switch Loss (dB)	-0.1	-0.1
Receiver Cable Loss (dB)	-1.00	-3.00
Impedance Mismatch Losses (dB)	-0.04	-0.04
Received Signal Power (dBm)	-84.49	-98.49
Receiver Gain (dB)[36]	20.00	44.70
Receiver Noise Figure (dB) / Noise Temperature (K)	4.27 / 485	3.51 / 360.70
Antenna Noise Temperature (K)	290	290
System Noise Figure (dB) / Temperature (K)	5.56 / 775.00	5.11 / 650.7
G/T (Figure of Merit) (dB)[37]	-26.75	-15.13
Signal Power at SDR Input (dBm)	-64.49	-53.79
Received Noise Power (dBm)	-123.86	-122.68

[35] Accuracy: 0.2° ground, 5° ADCS.

[36] AD9361 AGC off (0 dB RX Gain), 3 dB IL after LNA.

[37] Antenna gain to system noise temperature.

SNR (dB) [38]	39.38	24.19
C/N0 (dBm/Hz) [39]	85.22	71.98
Eb/N0 (dB)	37.15	21.98
Implementation Loss (dB)	1.00	1.00
Required Eb/N0[40]	12.00	9.60
Required margin (dB)	6.00	3.00
Margin (dB)	**24.15**	**11.38**
	Link is closed	**Link is closed**

Table 2.9: VHF Link Budget

To conclude, a link budget for CubeSatTeam's E-ST@R-II CubeSat using 1200 bps uncoded AFSK is presented in Table 2.10. To satisfy the required margins, the link is designed considering an elevation of 39°, corresponding to a maximum slant range of 1000 km (675.9 km apogee), because E-ST@R-II's noisy receiver and low transmit power limit accesses to short range, high elevation passes.

E-ST@R-II Communication System	**Uplink**	**Downlink**
Parameters		
Frequency (MHz)	437.485	437.445
Modulation	AFSK	AFSK
Coding	None	None
Required Eb/N0 at Target BER	21 dB @ 1E-4	21 dB @ 1E-4
Symbol rate	1200 sps	1200 sps
Gross Bitrate	1200 bps	1200 bps
Data Rate	1200 bps	1200 bps
Bandwidth	2400 Hz	2400 Hz
Transmitter		
Transmitter Power (HPA)	60W / +47 dBm	0.5W / +27 dBm
Total Transmitter Loss (dB) [41]	-3.31	-3.00
Impedance Mismatch Losses (dB)	-0.04 [42]	-0.04
Transmitter Antenna Gain (dB)	15.00	2.14

[38] At receiver input.

[39] At receiver input.

[40] Per information bit.

[41] After HPA.

[42] VSWR < 1.2

Transmitter Antenna HPBW (*)	36	60
EIRP (dBm)	58.65	26.10
Propagation		
675.3 km orbit, 39* elevation		
Max Slant Range / Free Space Propagation Loss	1000 km / -145.25 dB	1000 km / -145.25 dB
Polarization Mismatch Loss (dB)	-3	-3
Atmospheric Absorption Loss (dB)	-1.00	-1.00
Rain Losses (dB)	0.00	0.00
Ionospheric Loss (dB)	-1.00	-1.00
Pointing Losses (dB)	-0.10	-0.10
Total Attenuation (dB)	-150.35	-150.35
Receiver		
Received Isotropic Power (dBm)	-91.70	-124.25
Receiver Antenna Gain (dB)	2.14	15.00
T/R Switch Loss (dB)	-0.1	-0.1
Receiver Cable Loss (dB)	-1.00	-3.00
Impedance Mismatch Losses (dB)	-0.04	-0.04
Received Signal Power (dBm)	-90.70	-112.39
Receiver Noise Figure (dB) / Noise Temperature (K)	4.27 / 485	3.61 / 375.9
Antenna Noise Temperature (K)	290	290
System Noise Figure (dB) / Temperature (K)	5.56 / 775.00	5.18 / 665.9
G/T (Figure of Merit) (dB)[43]	-26.75	-13.23
Received Noise Power (dBm)	-135.90	-136.56
SNR (dB) [44]	45.20	24.17
Eb/N0 (dB)	48.21	27.18
Required Eb/N0 (dB)	21.00	21.00
Required margin (dB)	6.00	3.00
Margin (dB)	**27.20**	**6.18**
	Link is closed	**Link is closed**

[43] Antenna gain to system noise temperature.

[44] At receiver input.

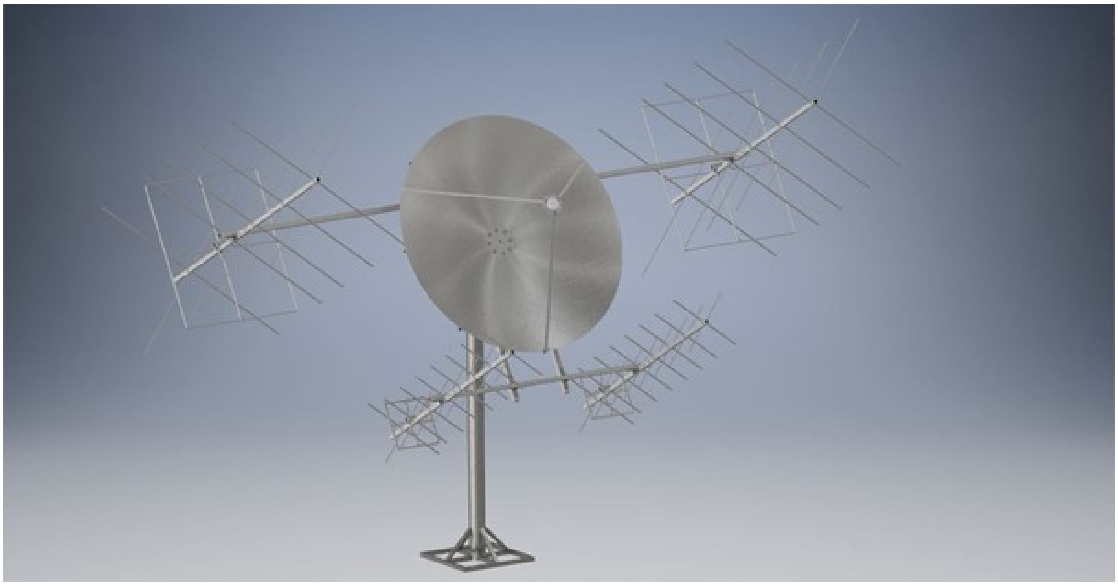
Table 2.10: E-ST@R-II Link Budget

2.5.10 Model of UHF/VHF/S-band structure

Figure 2.18 illustrates a preliminary model of the stainless steel structure that supports the four X-Quad antennas and the S-band parabolic antenna [24]. The X-Quad antennas are placed at a distance that maximizes their gain [45] and prevents line of sight obstruction of the parabola. Together with a counterweight for the parabola, they balance the structure.

Mechanical simulations suggest that the model's corrosion resistance and stiffness are satisfactory to support the expected wind-load of 60 N, corresponding to a 40 kph wind speed (Section 2.5.3 and the 6 mm mesh parabola [26]. However, since the dimensions are too preliminary, no electromagnetic simulation has been performed. Instead, the X-band antenna is sold with its own structure, and has not been modelled.

[45] 2.82m for 144 MHz, 1.1m for 432 MHz [25]



(a) Front-view

(b) Rear view

Figure 2.18: Model of the UHF/VHF/S-band Antenna Structure [24]

2.6 Software Considerations

2.6.1 Introduction

Software is essential to the Ground Station. Software controls the Communication System, manages and processes data, and implements the many digital signal processing (DSP) blocks, that, combined, are responsible for the transmission and reception of information. In particular, software defines the hardware architecture of the Software-Defined Radio (SDR) and controls its RF front-end, defining parameters such as carrier frequency, sample rate, filter bandwidth, TX and RX gains, among others. In this section, we are concerned with implementing a communication system on the bladeRF-2.0 mini SDR (Section 2.5.4).

To do so, there are two possibilities: to develop mission-specific applications and signal processing chains in VHDL, or to use the manufacturer's Application Programmable Interface (API) [27]. The former, a complex and time consuming process, is critical where extreme performance and energy efficiency are concerned. Instead, the latter simplifies programming the SDR and allows rapid prototyping of communication systems through development environments such as Mathworks' Matlab/Simulink [28] and GNU Radio [29] Therefore, to support multiple missions and to reduce mission turn-around time, the Communication System's software uses the second approach.

2.6.2 Software Defined Radio Software

bladeRF-cli

The bladeRF-2.0 mini SDR is provided [30] with the bladeRF-cli [31], an extremely simple and robust command-line interface, whose commands are listed in Figure 2.19. Using this utility, the SDR can transmit and receive signals - in particular, the test signals of Section 3.2. However, the interface's modest functionalities mean the DSP blocks of the communication system must be built from scratch. Thus, a better development environment was required.

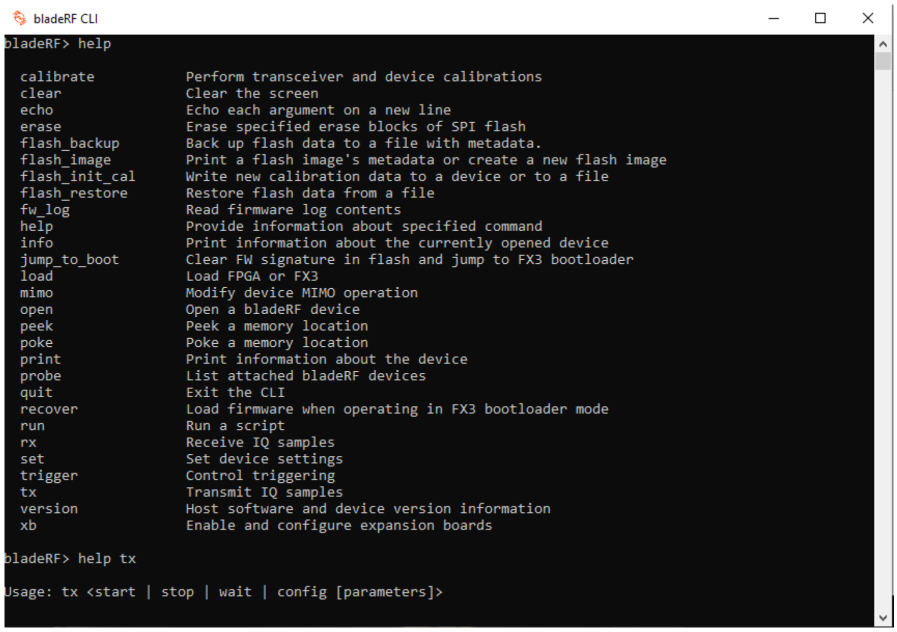


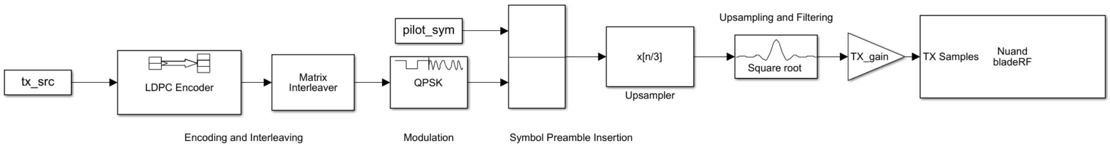
Figure 2.19: bladeRF-cli

Matlab/Simulink

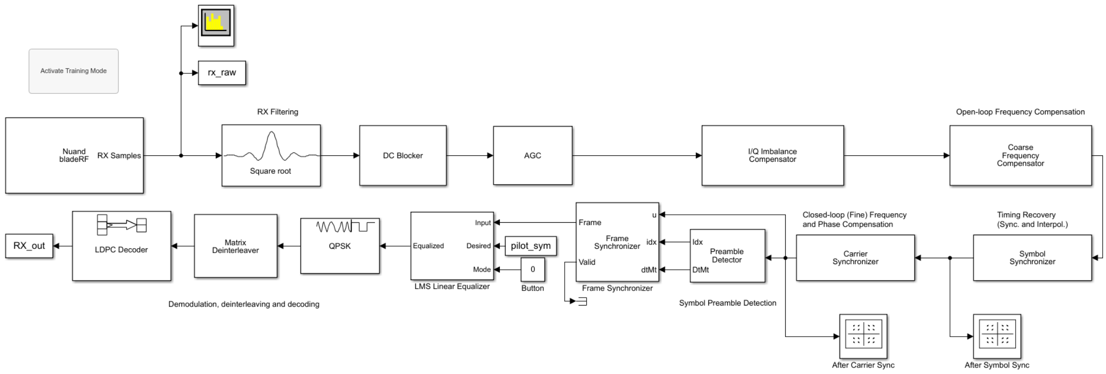
Mathworks' Matlab prototyping environment is perfect for designing, modelling, simulating, and operating communication systems due to its dynamic typing, interpreted language with just-in-time (JIT) compilation, availability of many algorithms, abstraction of memory management details and embedded compiler and debugger. Matlab's Communication Systems Toolbox includes not only hardware support for SDRs, but also a multitude of coding, modulation and other physical layer algorithms, making it quick and easy to develop, test and prototype algorithms. From these prototypes, further low-level implementations of these algorithms can be created through Matlab's automatic code generation toolboxes (HDL Coder [32] and Embedded Coder [33]) or manually.

Furthermore, Mathwork's Simulink can be used to complement Matlab and establish a common user-interface that ensures commonality between users, and faster portability between platforms. Initially, these were intended to be the development environments. However, in the end, GNU Radio was adopted because of its low cost (free).

Figure 2.20 shows a modelled communication system for transmission of telecommands and reception of telemetry. Parameters such as the sample rate, carrier frequency, transmitter and receiver gains and the analog band-pass filters of the bladeRF-2.0 SDR are not represented, but have been configured. In transmission,



(a) Telecommand Transmitter Model



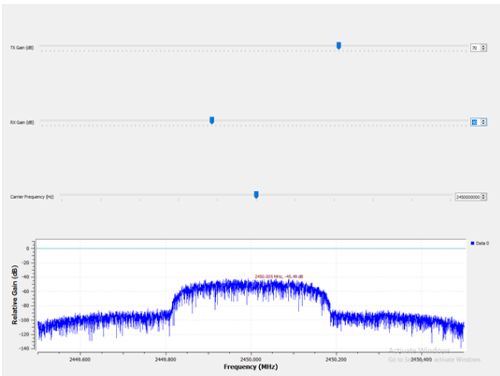
(b) Telemetry Receiver Model

Figure 2.20: Simulink Communication Systems Model for bladeRf-2.0 micro

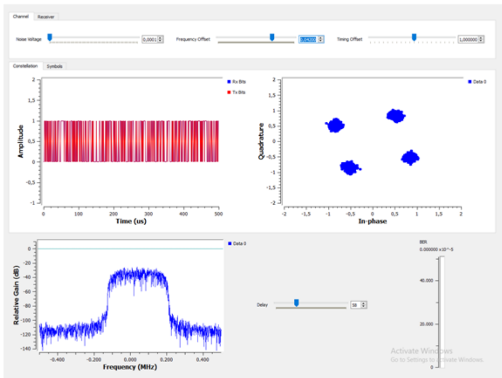
a very simple system composed of a LDPC encoder is followed by a matrix interleaver whose output is modulated using QPSK. The pilot symbol sequence is inserted before up-sampling the signal and applying pulse shaping using a SRRC filter with configurable roll-off. It is amplified and sent to the bladerf-2.0 sink for transmission. In reception, the signal incoming from the bladerf-2.0 source, already filtered by its analog band-pass filters, is filtered by another SRRC filter. Then, any remaining DC component is eliminated and AGC is applied to scale the incoming signal such that it maintains an average power, avoiding numerical issues and preventing saturation of the receiver (i.e. by trying to apply a large gain to a large signal input). At that point, I/Q imbalance compensation is done to minimize the effects of a non-ideal 90° phase offset between the components. Then, timing and frequency synchronization is applied to identify the optimum sampling time and compensate for frequency offsets between transmitter and receiver. Lastly, frame synchronization at the symbol level is performed to recover the start of the received sequence before demodulating, de-interleaving and decoding the data.

It is important to highlight that once the receiver is started, the training mode must be activated by pressing the corresponding button. After the initial training with pilot sequences, the equalizer will not reset until the button is pressed again. Finally, frequency compensation does not take into account any exogenous trajectory information about the satellite. Therefore, the most critical component of the frequency offset, the Doppler effect, is eliminated indirectly. If trajectory information were to be taken into account, the frequency offset correction would be improved.

GNU Radio



(a) Spectrum



(b) Constellation rotated due to frequency offset

Figure 2.21: GNU Radio Model of a QPSK Transmitter and Receiver using a USRP Sink and Source, $f_c = 2.45\ GHz$

GNU Radio is a free toolkit that contains numerous DSP blocks and supports various SDRs to facilitate the design, development, and operation of digital communication systems. Console and graphical programming interfaces are available to quickly build signal processing chains by connecting the available DSP blocks and SDRs. Being open source and easy to extend through the creation of Python and C++ DSP blocks, when necessary, GNU Radio was chosen as the software environment for the communication system.

Figure 2.21 shows the result of a simulation of channel impairments with two SDRs that exchange random data using dipole antennas and QPSK modulation. A centre frequency of 2.45 GHz and a SRRC filter with 50% roll-off were used. After verifying the two SDRs were communicating with an acceptable BER (1E-6), the frequency of the transmitter was slightly increased with regards to the receiver to determine the maximum acceptable frequency offset (4% of the bandwidth). Finally, due to the very high transmit and receive gains, the QPSK constellation can be clearly distinguished in 2.21.

SDR-Console V3

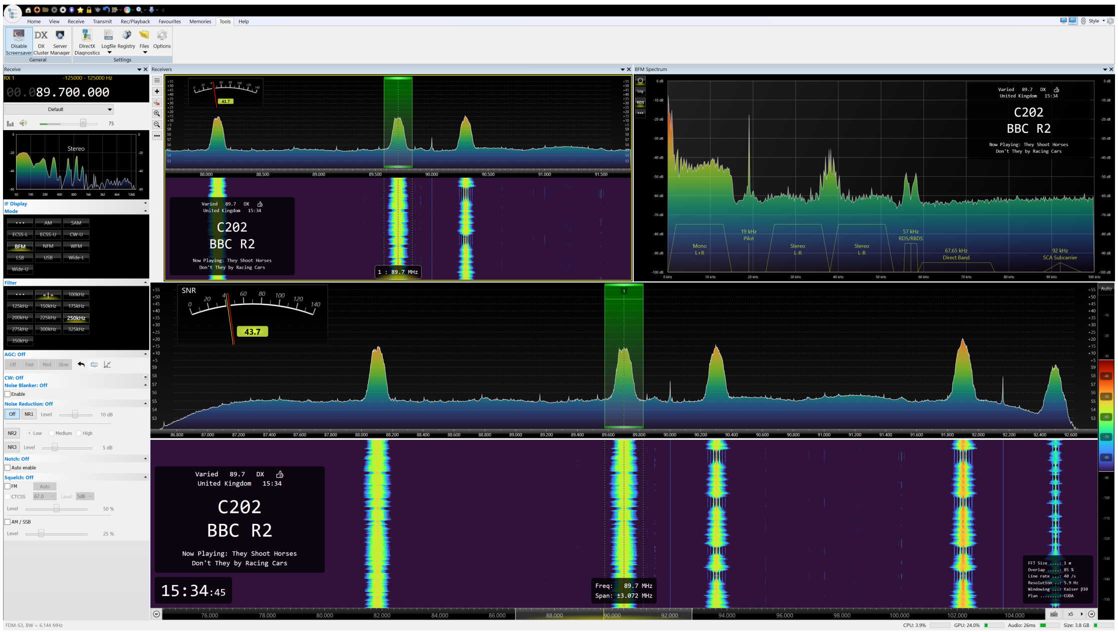


Figure 2.22: SDR-Console v3 Interface [34]

All software discussed so far was related to the operation of a communication system with minimal interaction from operators, and focusing on modern communication systems. However, the capability to use amateur radio protocols and to operate manually was of interest for compatibility and didactic reasons. Accordingly, SDR software to analyze, receiving, and transmit packets was procured.

SDR-Console v3 [35] was identified as the most appropriate solution due to its intuitive easy-to-use interface and included functionalities. It can display data from multiple SDRs at the same time, schedule the transmission and reception of packets, and apply DSP techniques. Moreover, SDR-Console supports satellite modulations more often used by amateurs, such as AFSK, CW, SSB, and FM.

Figure 2.22 illustrates the SDR-Console interface, where one can see a 6.144 MHz wide filter centered at 89.7 MHz being applied to receive a broadcast FM transmission with an estimated SNR of 43.7 dB.

2.6.3 Automation

To automate the Ground Station's operational workflow and Fault Detection, Isolation, and Recovery (FDIR) capabilities, two topics are being explored by the CubeSatTeam. First, an online interface between the Mission Control System (MCS) and Communication System (CS) is planned, allowing the MCS to poll the CS for telemetry and, likewise, allowing the CS to poll the MCS for telecommands. Second, electronically controlled switches and power splitters can be added to the architecture of the CS, enabling the SDR to sample signals at key points of the RF front-end (RFFE) to detect faults. Once a fault is identified, it may be bypassed by rerouting signals through the RFFE using the switches, thereby improving the reliability of the CS. Consequently, by defining appropriate detection and control algorithms, FDIR can be automated.

Chapter 3

Verification of the CubeSat Control Centre's Ground Station

3.1 Introduction

In this chapter, we develop the assembly, integration and verification (AIV) procedures to verify the correctness of the CubeSat Control Centre (C3)'s Ground Station (GS), designed in Chapter 2. Then, we define a sequence of AIV procedures, known as the AIV plan. Following this plan, we verify the ground station's design by simulating ground-to-satellite communication links, from which we derive a data budget for low-Earth orbit CubeSat Earth Observation (EO) missions. To conclude, we verify components and units by testing, discussing the results.

3.2 Assembly, Integration and Verification

3.2.1 Introduction

To verify the ground station, we follow European Cooperation for Space Standardization (ECSS) testing and verification standards [36] [37] [38] [39] [40]. Consequently, we:

1. Define and organize the verification procedures to ensure all requirements are covered.

2. Define the test facilities and ground support equipment.

While taking into account test constraints such as duration, cost, reproducibility, availability of ground support equipment, simplicity, requirement of qualified personnel, and risks of equipment damage.

To record the verification process, we define four documents:

1. Test Specification and Procedure (TSP): to specify the device under test (DUT), test requirements, test procedures, test schedules, ground support equipment, and pass/fail criteria.

2. Test Report (TR): to describe the executed test, including deviations from the TSP, and test results.

3. Verification Control Matrix: to assign a verification method to each requirement.

4. Verification Matrix: to verify that project requirements are covered by the tests; it is divided into disciplines, related to the system or subsystem under test. Each discipline is assigned a set of requirements, TSPs, and test status (open, scheduled, closed). To illustrate, an excerpt of the Verification Matrix is shown in Figure 3.1.

FUNCTIONAL REQUIREMENTS									
Discipline	#	ID	Requirement Text	Verification Methods				TSP Doc. Name	Status and Close out
				System	Subsystem	Unit	Component		
RF	001	FUN-001	The RF System shall establish the communication link when CubeSats are in visibility of the antennas		T				To be Scheduled
RF	002	FUN-002	The RF System shall receive signals with power above -120 dBW considering up to a 10 MHz bandwidth		T				To be Scheduled
RF	003	FUN-003	VHF line shall transmit signals with EIRP below 20-30 dBW			A			Scheduled
RF	004	FUN-004	UHF line shall transmit signals with EIRP below 20-30 dBW			A			Scheduled
RF	005	FUN-005	S line shall transmit signals with EIRP below 30-40 dBW			A			Scheduled
RF	006	FUN-006	The SDR shall generate and receive waveforms from 47 MHz to 6 GHz with a complex channel bandwidth of 56 MHz with a 12-bit ADC/DAC resolution				T	[TSP]C3-RF-008	Closed
RF	007	FUN-007	Power supply shall provide up to 320 W at 12 V				RoD		Scheduled
RF	008	FUN-008	Power converter shall convert 12 V into 8 V supporting up to 30 W				RoD		Scheduled
RF	009	FUN-009	The VHF band TX amplification line shall guarantee at least a 45 dB gain		T		T	[TSP]C3-RF-001	Scheduled
RF	010	FUN-010	The VHF band RX amplification line shall guarantee at least a 45 dB gain		T		T	[TSP]C3-RF-004	Closed
RF	011	FUN-011	The UHF band TX amplification line shall guarantee at least a 45 dB gain		T		T	[TSP]C3-RF-002 [TSP]C3-RF-014	Scheduled
RF	012	FUN-012	The UHF RX band amplification line shall guarantee at least a 42 dB gain		T		T	[TSP]C3-RF-005 [TSP]C3-RF-014	Closed
RF	013	FUN-013	The S band TX amplification line shall guarantee at least a 34 dB gain		T		T	[TSP]C3-RF-003	Scheduled
RF	014	FUN-014	The S band RX amplification line shall guarantee at least a 50 dB gain		T		T	[TSP]C3-RF-006	Closed
RF	015	FUN-015	The VHF TX amplification line shall have a Return Loss value lower than -10 dB		T		T	[TSP]C3-RF-001	Scheduled
RF	016	FUN-016	The VHF RX amplification line shall have a Return Loss value lower than -10 dB		T		T	[TSP]C3-RF-004	Closed
RF	017	FUN-017	The UHF TX amplification line shall have a Return Loss value lower than -10 dB		T		T	[TSP]C3-RF-002 [TSP]C3-RF-014	Scheduled
RF	018	FUN-018	The UHF RX amplification line shall have a Return Loss value lower than -10 dB		T		T	[TSP]C3-RF-005 [TSP]C3-RF-014	Closed
RF	019	FUN-019	The S-band TX amplification line shall have a Return Loss value lower than -10 dB		T		T	[TSP]C3-RF-003	Scheduled
RF	020	FUN-020	The S-band RX amplification line shall have a Return Loss value lower than -10 dB		T		T	[TSP]C3-RF-006	Closed
RF	021	FUN-021	The VHF TX amplification line shall operate in the Linearity Zone within 60 W		T		T	[TSP]C3-RF-001	Scheduled
RF	022	FUN-022	The UHF TX amplification line shall operate in the Linearity Zone within 60 W		T		T	[TSP]C3-RF-002	Scheduled
RF	023	FUN-023	The S-band TX amplification line shall operate in the Linearity Zone within 4 W		T		T	[TSP]C3-RF-003	Scheduled
RF	024	FUN-024	The VHF TX amplification line shall have a reflected power lower than 6 dBm within the Linearity Zone				T	[TSP]C3-RF-001	Scheduled
RF	025	FUN-025	The UHF TX amplification line shall have a reflected power lower than 6 dBm within the Linearity Zone		T		T	[TSP]C3-RF-002 [TSP]C3-RF-014	Scheduled
RF	026	FUN-026	The S-band TX amplification line shall have a reflected power lower than 6 dBm within the Linearity Zone				T	[TSP]C3-RF-003	Scheduled
RF	027	FUN-027	The VHF RX amplification line shall have a noise figure lower than 0.4 dB				T	[TSP]C3-RF-004	Closed
RF	028	FUN-028	The UHF RX amplification line shall have a noise figure lower than 0.56 dB		T		T	[TSP]C3-RF-005 [TSP]C3-RF-014	Closed
RF	029	FUN-029	The S-band RX amplification line shall have a noise figure lower than 1 dB				T	[TSP]C3-RF-006	Closed

Figure 3.1: Verification Matrix

3.2.2 Verification Methods

ECSS standards specify that verification is performed through at least one of four methods [36]:

1. Analysis [A]: An analysis estimates a device's performance by analytical or computational techniques; an analysis can be performed independently or to complement a test.

2. Inspection [I]: A visual inspection of the DUT, without any support equipment; it is frequently used to verify electrical and mechanical connections.

3. Test [T]: A test evaluates a device under operating, emergency, or destructive

conditions; it is the only acceptable method for safety critical requirements.

4. Review-of-design [RoD]: A review-of-design proves a device satisfies requirements by reviewing its documentation; it is frequently employed when devices are certified by their manufacturers.

3.2.3 Assembly, Integration and Verification Plan

Introduction

To formally prove the correctness of a project, one must specify **what** are the verification procedures, **where** they apply, and **when** they are executed; that is, one must construct the AIV plan: the definition and scheduling of AIV procedures.

Ideally, the verification methods of Section 3.2.2 should be applied at every level (system, subsystem, unit, and component) and phase (design and development, qualification and acceptance, and operation) of a project.

Usually, during the design and development phase, a review-of-design guides and assists the design procedure by studying component, unit, and subsystem data-sheets, technical notes, and test reports. Following this review, analyses and simulations estimate the design's performance. Then, in the qualification and acceptance phase, extensive tests validate the system. Finally, during operation, tests detect and identify faults.

There is a trade-off between the cost and thoroughness of the verification procedures: the more requirements have to be validated, the longer and more expensive becomes the test campaign. To illustrate this trade-off, consider two AIV strategies: bottom-up and top-down. The former starts from the lowest project level, verifying components and assembling them into an unit. Then, units are validated and integrated into subsystems. To conclude, subsystems are assembled into a system, which is then verified. Clearly, this is the most extensive, complex, and expensive technique; every level of the project is **proven** to be correct.

Instead, the latter starts from the highest project level, assembling and testing the system. If its high-level requirements are satisfied, then the system is **assumed** to be verified. Otherwise, its subsystems must be tested, and so on. Consequently, while minimizing the number of tests, the top-down approach can lead to false assumptions of correctness [1].

From a practical point of view, ground stations are mostly concerned with system-level performance and, as a result, use top-down approaches to reduce

[1]For instance, consider the gain of a two-stage power amplifier has been verified. In the top-down approach, one would assume each stage is within specification when, in reality, both can be out of specification; if the first-stage's gain is lower than specified, but the second-stage's gain is higher than specified, they can compensate each other and satisfy the total gain requirement.

their verification complexity. However, for correctness, C3's Ground Station uses a bottom-up strategy. Finally, considering the available test facilities, only its VHF/UHF/S-band lines are tested; its X-band line is verified exclusively by analysis and review-of-design because it is certified by its manufacturer. Consequently, it is not represented below.

VHF/UHF Line Integration

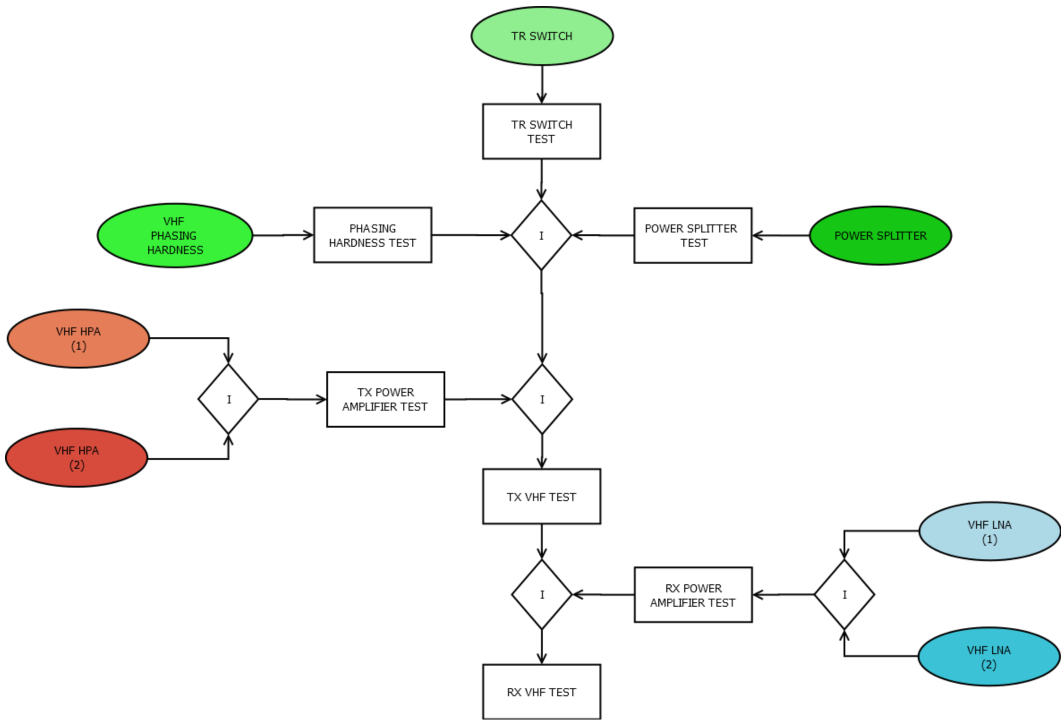


Figure 3.2: VHF Line Assembly, Integration and Verification Plan

Figures 3.2 and 3.3 illustrate the AIV plans of the VHF and UHF lines, respectively. They start by assembling, integrating, and testing the phasing harnesses, power splitters, and transmit/receive (T/R) switches. Then, these components are assembled into an unit while the high power amplifiers (HPA) are integrated and tested. Afterwards, the HPAs, phasing harnesses, power splitters, and T/R switches are connected, forming a TX unit. At this point, a transmission test is performed. Next, the low-noise amplifiers (LNAs) are assembled into a RX unit, which is then tested. Finally, the TX and RX units are integrated and a reception test is executed.

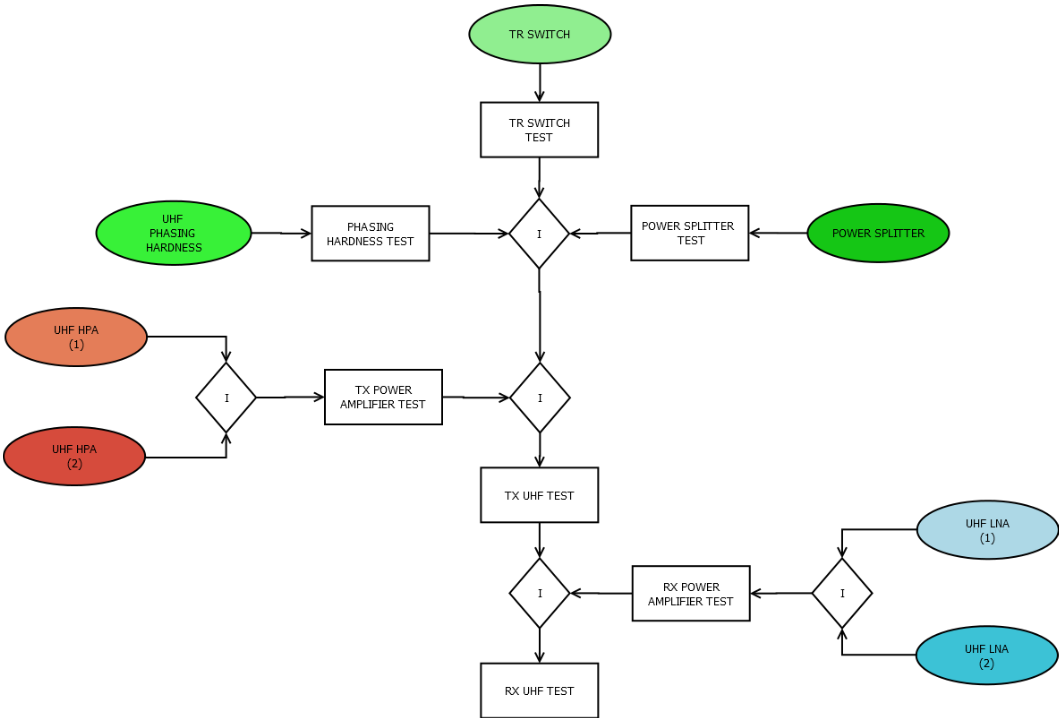


Figure 3.3: UHF Line Assembly, Integration and Verification Plan

S-Band Line Integration

The AIV plan of the S-band line starts by testing the diplexer. Then, the HPAs are assembled, tested, and integrated with the diplexer into a TX unit, to which a transmission test is applied. Next, the LNAs are assembled into a RX unit and tested. To conclude, the TX and RX units are integrated and a reception test is executed.

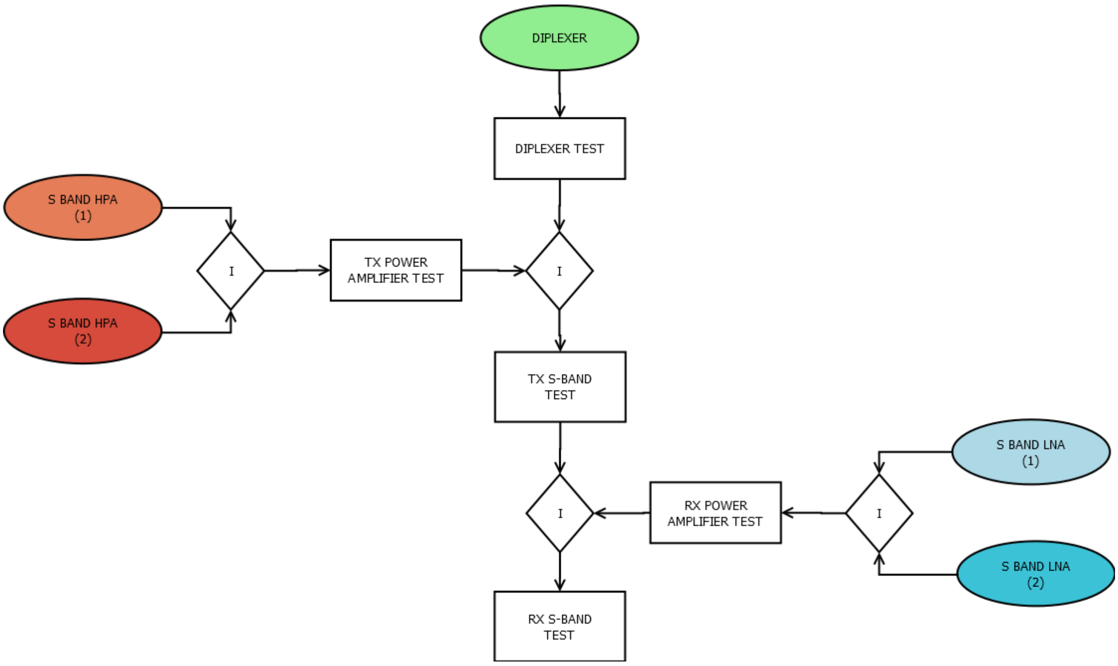


Figure 3.4: S-band Line Assembly, Integration and Verification Plan

CubeSat Control Centre System Integration

The last part of the AIV plan is to assemble and integrate the Tracking System (TS), the Communication System (CS), and the Mission Control System (MCS). First, the TS is connected to the antennas and tested. Then, the VHF line is connected to the SDR, the antennas, and the TS. At this point, a VHF communication test with a moving satellite is performed. Next, the remaining lines are integrated and tested, one by one. After connecting all the lines, a communication test in VHF, UHF, and S-band is executed to verify the ground station's functionalities. Finally, the MCS is integrated with the ground station, resulting in an operational acceptance test.

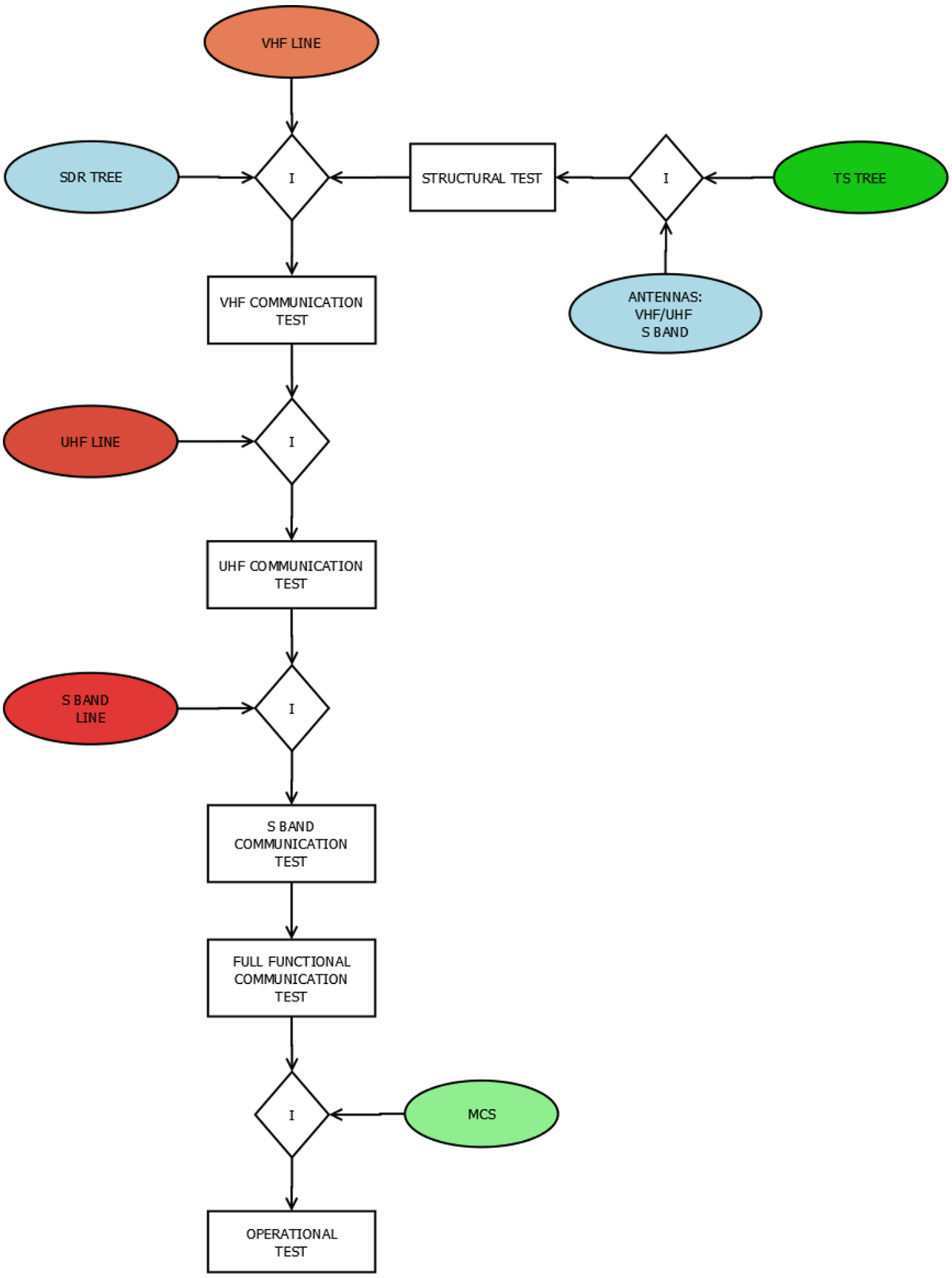


Figure 3.5: CubeSat Control Centre System Assembly, Integration and Verification Plan

3.3 Verification

3.3.1 Simulation of a X-band satellite pass

Introduction

Nowadays, modeling and simulation tools such as the Analytical Graphics Inc.' Systems Toolkit (STK) [41] are sufficiently powerful to allow modern, statistical, dynamic designs. Through these tools, we can simulate ground-to-satellite communication links over long periods of time, incorporating information about the position of celestial bodies, antenna alignment, weather conditions, line-of-sight obstructions by terrain, and many other factors. From these simulations, we can extract relevant performance metrics such as the duration and frequency of communication opportunities, environmental effects, link budgets, etc.

In this section, we use STK to model and simulate a realistic communication link between the ground station and a X-band CubeSat in LEO under worst-case conditions, leading to the verification of the designed X-band link; the hardest and costliest to design and verify.

Simulation Parameters

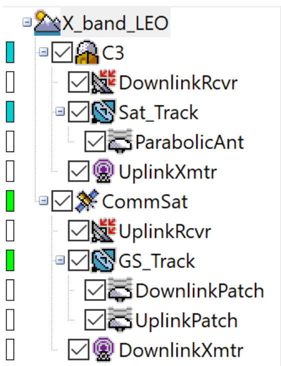


Figure 3.6: X-band STK Scenario

The scenario's models are represented in Figure 3.6. Table 3.1 describes the orbital parameters of the satellite. We apply the following constraints:

1. Ground Station located at the Politecnico di Torino, Turin - Piedmont (45°03'28.28" N, 7°39'23.91" E).

2. Antenna height of 20 meters.

3. Terrain line-of-sight obstructions.

4. Earth temperature of 290 K.
5. Celestial bodies and cosmic background noise increase antenna temperature.
6. Man-made noise (ITU-R P.372-14 [23]).
7. A minimum elevation of 5°.
8. Azimuth and elevation rates are limited to $6°/s$ by the tracking system.
9. Satellite targets the ground station with its antenna (0.2° angular accuracy [42]).
10. Environmental effects considering an outage probability of 0.1% (99.9% availability):
    (a) Ionospheric scintillation and fading (ITU-R P.531-13 [21]).
    (b) Atmospheric absorption (ITU-R P.676-10 [20]).
    (c) Rain (ITU-R P.618-12 [43]), using a surface temperature of 20°C.
    (d) Cloud and fog (ITU-R P.840-8 [44]), using a 0°C cloud temperature.
    (e) Atmospheric refraction.
11. Thermal radiation effects on a 6U (20x30x60 cm) CubeSat with [45]:
    (a) Emissivity = 0.90
    (b) Absorptivity = 0.248
    (c) Earth Albedo = 0.340
    (d) Heat-dissipation of 10 Watts
12. Maximum Doppler shift $|f_D| \leq 200\ kHz$ [2].
13. Uplink parameters:
    (a) LDPC(128,64) coding.
    (b) Target $BER = 10^{-12}$.
    (c) $\left.\frac{E_b}{N_0}\right|_{min} = 5\ dB$.
    (d) $R_s = 64\ ksps$.
    (e) $f_c = 8.1\ GHz$.

[2]Maximum frequency offset supported by the receiver's Coarse Frequency Compensator, discussed in Section 2.6.

(f) SRRC filter, roll-off $\rho = 0.2$.
(g) QPSK modulation.
(h) 1 dB of implementation loss.
(i) $\mu = 6\ dB$ link margin.

14. Downlink parameters:
    (a) LDPC(16384,8192) coding.
    (b) Target $BER = 10^{-6}$.
    (c) $\left.\frac{E_b}{N_0}\right|_{min} = 1\ dB$.
    (d) $R_s = 1\ Msps$.
    (e) $f_c = 7.5\ GHz$.
    (f) SRRC filter, roll-off $\rho = 0.2$.
    (g) QPSK modulation.
    (h) 1 dB of implementation loss.
    (i) $\mu = 6\ dB$ link margin.
15. Amplifiers operated at saturation [3].
16. Spacecraft uses a RHCP 4x4 Patch Array Complex Transmitter model (16 dB gain) in uplink and downlink.
17. Ground station uses a 1.2m parabolic antenna.
18. Link margin constraint applied to the minimum E_b/N_0.
19. Accesses that do not satisfy all constraints are discarded.

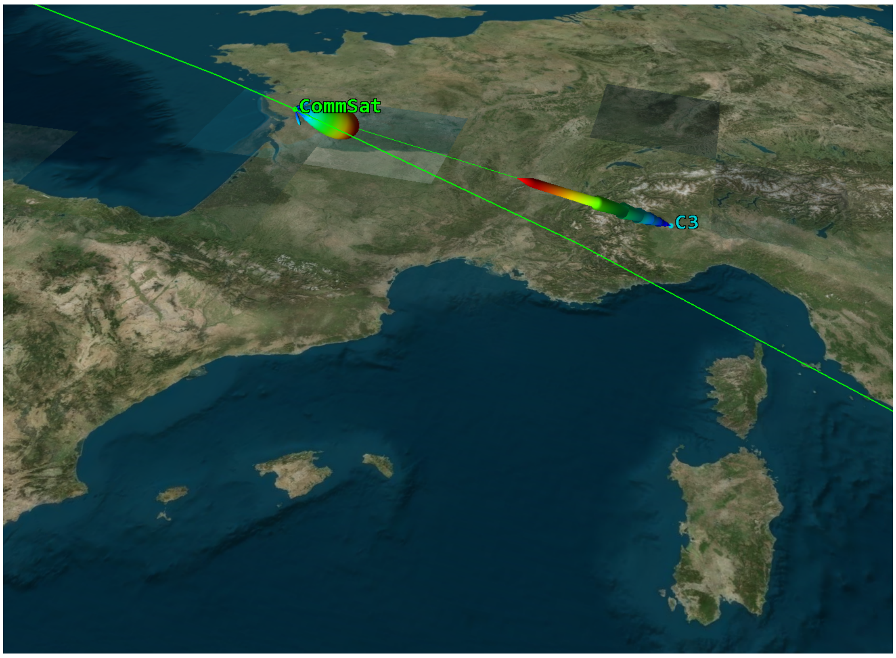
Eccentricity	0°
Inclination	45°
Orbit Altitude	400 km
RAAN	−180°

Table 3.1: X-Band Low-Earth Orbit Parameters

Among all possible low-Earth orbits, the circular orbit of Table 3.1 was chosen because it resembles CubeSatTeam missions under development. Moreover, a low 400 km altitude implies a high satellite speed, complicating tracking and increasing Doppler effects.

[3] Amplifier distortion is neglected because we use phase-only modulations.

Results



(a) 3D Model of the Access illustrating the antenna pass

(b) 2D Satellite Track

Figure 3.7: Simulated X-band Pass

Figure 3.7 illustrates a satellite access by the ground station and the satellite's ground track; it is possible to see the satellite pointing its antenna beam towards Turin (C3) while it is being illuminated by the ground station.

The worst-case link budget results, presented in Table 3.2, indicate design margins are satisfied in downlink and uplink, validating the design of Section 2.5.9.

Downlink		Uplink	
TX Power (dBm)	33	TX Power (dBm)	36
TX Gain (dB)	17.012	TX Gain (dB)	38.083
EIRP (dBm)	49.925	EIRP (dBm)	73.456
Free Space Loss (dB)	176.3178	Free Space Loss (dB)	177.022
Atm. Loss (dB)	0.7906	Atm. Loss (dB)	0.826
Rain Loss (dB)	4.2308	Rain Loss (dB)	5.427
Clouds Loss (dB)	1.3494	Clouds Loss (dB)	1.621
Scint. Loss (dB)	14.589	Scint. Loss (dB)	15.957
Ion. Loss (dB)	0.1244	Ion. Loss (dB)	0.1066
RX Frequency (MHz)	7499.828	RX Frequency (MHz)	8099.814
Doppler Shift (kHz)	-171.914	Doppler Shift (kHz)	-185.674
RX Power (dBm)	-106.026	RX Power (dBm)	-122.017
RX Gain (dB)	37.4152	RX Gain (dB)	17.012
Atm. Temp. (K)	19.327	Atm. Temp. (K)	40.265
Rain Temp. (K)	91.242	Rain Temp. (K)	209.140
Cloud Temp. (K)	36.476	Cloud Temp. (K)	82.100
Scint. Temp. (K)	131.828	Scint. Temp. (K)	266.221
Antenna Temp. (K)	311.026	Antenna Temp. (K)	943.667
Equiv. Temp. (K)	398.075	Equiv. Temp. (K)	2254.691
g/T (dB/K)	11.415	g/T (dB/K)	-16.518
C/No (dB*MHz)	7.013	C/No (dB*MHz)	60.063
Bandwidth (MHz)	1.2	Bandwidth (MHz)	76.800
Eb/No (dB)	7.013	Eb/No (dB)	12.001
Margin (dB)	6.013	Margin (dB)	6.001

Table 3.2: X-Band Simulated Link Budget

As expected, coarse frequency compensation is crucial for communication with fast LEO satellites. Table 3.2 shows that the narrowband telecommands are subject to Doppler shifts of 180 kHz, close to the 200 kHz limit of the digital receiver of Section 2.6.2.

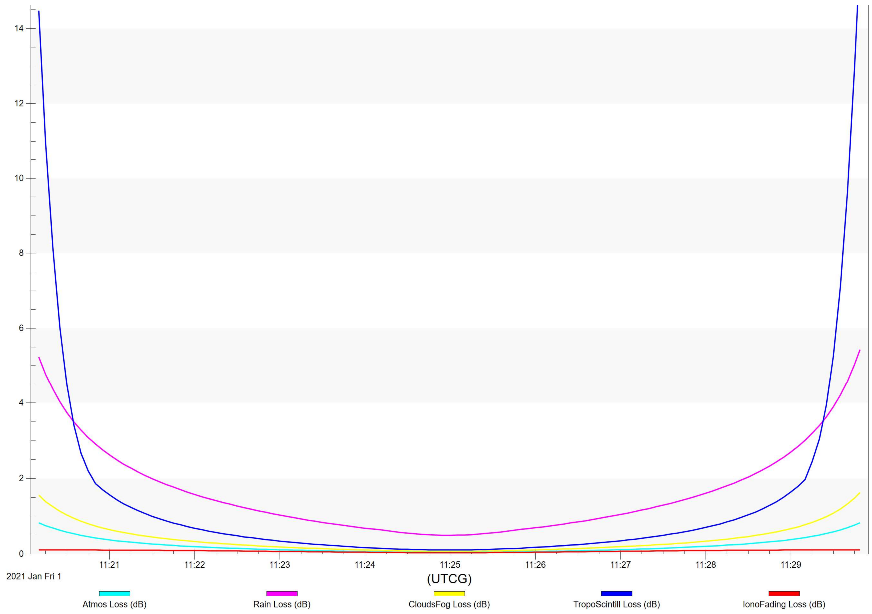
Comparing the designed link budget to the simulation's results, the most critical difference one can observe is the presence of tropospheric scintillations, of stochastic nature. Compounded with other environmental effects, pictured in Figure 3.8, they increase channel losses and antenna temperatures, degrading the link's quality. While their effects are known to be significant at low latitudes, low elevations, and high frequencies [43], an attenuation of 16 dB at a 5° elevation is surprising. Critically, this attenuation eliminates the extra margin of the static design. However, when the satellite is closer to the ground station, the paths of the electromagnetic waves through the atmosphere and ionosphere are shortened, and the link quality improves.

Additionally, the antenna temperature (943 K) is much higher than the design hypothesis (50 K); in the instant the link budget was calculated, the antenna was partially pointing at the Sun.

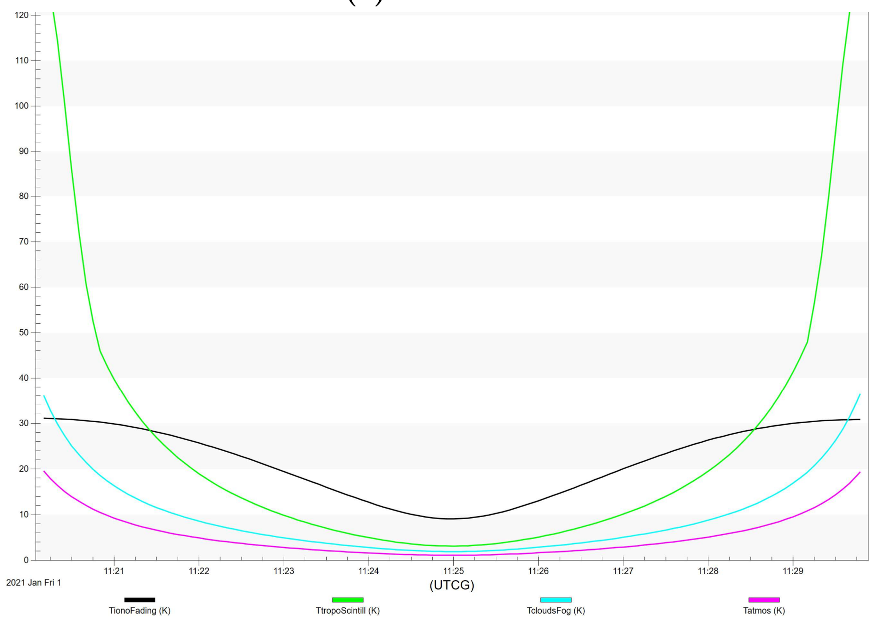
Attenuation by rain is 4.23 dB in the downlink and 5.42 dB in the uplink, respectively - compatible with the design hypothesis (3.46 dB and 5.95 dB).

Furthermore, for this orbit, line-of-sight obstructions by Piedmont's mountainous terrain are not as critical as believed; the Politecnico di Torino's main building, located in the centre of Turin, is sufficiently far from the mountains.

Finally, we observe that frequent satellite accesses are possible even in the worst-case scenario. There are four to six communication opportunities per day, with an expected duration of 10 minutes.



(a) Attenuation



(b) Noise Temperature

Figure 3.8: Simulated Environmental Effects

Data Budget

Average Access Duration	600s
Average Number of Passes	4
Total Access Duration	2400s
Net Uplink Bitrate	64 kbps
Net Uplink data	19.2 MB
Net Downlink Bitrate	1 Mbps
Net Downlink data	2.4 Gb (300 MB)

Table 3.3: Simulation of X-band Data Budget

Payload	Visual	Short-wavelength Infrared	Long-wavelength Infrared
Quantization bits	10	14	14
Array-size (pixels)	1280 x 1024	640 x 512	640 x 512
Image Size (MB)	4.915 [4]	0.573	0.573

Table 3.4: CUMULOS Sensor Specifications [46]

Given a minimum of four 10 minute satellite accesses per day by the simulation, we want to determine how much information can be sent daily. Using the designed bitrates, we obtained the results of Table 3.3, which indicate a capacity to send up to 19.2 MB in uplink and receive 300 MB in downlink. To put these numbers into perspective, a full firmware update for the Nuand bladerf-2.0 SDR is around 121 KB while its FPGA image is around 10 MB. Therefore, it is possible to update the software of the satellite's communication system with a 50% margin for more usual telecommands, such as those for satellite maneuvering.

In the downlink, optical and multi-spectral payloads in Earth-observation missions such as the CubeSat Multispectral Observation System (CUMULOS) can produce image triplets of 6 MB, as indicated in Table 3.4. Therefore, considering a 20% margin for satellite telemetry, 40 images can be transmitted daily. If state-of-the-art image compression standards such as High Efficiency Image File (HEIF) formats [47] were used, more images could be transmitted or the sensor resolution could be increased.

3.3.2 Tests

Introduction

Initially, we selected the Politecnico di Torino Department of Electronics and Telecommunications' facilities to execute the AIV plan because they contained the expensive ground support equipment required to collect data regarding the linearity (harmonic distortion and compression points), S-parameters (return and insertion loss), and noise figures of the devices-under-test [48][49][50].

However, for reasons beyond our control, the test facility was changed to the CubeSatTeam's STARLab, which did not contain them. Consequently, executing the full AIV plan was not feasible anymore; key low-level requirements could not be tested without specialized tools. As a result, we decided to skip to the final stages of the AIV plan, conducting high-level tests that required little to no ground support equipment. Moreover, since the antennas and their structure were not available, we deviated from the AIV plan of Section 3.2.3; instead of starting the verification with the power amplifiers, we started with the SDRs, and then proceeded to test the VHF/UHF/S-band amplification lines. These tests are described below.

Test Procedures

High-level tests are simple and self-contained; designed to verify the requirements of Section 2.4.1 using solely the ground station's own components - in particular, the SDRs. To do so, we assume they are within specification; it is a reasonable assumption since they are factory-calibrated and verified. Consequently, we can employ them as instrumentation devices for measurements; one SDR becomes a signal generator, and the other a signal analyzer.

The first step of the tests is to perform an initial health check of the SDRs to ensure they are operational. Next, we assemble the transmission and reception lines. To prevent high power signals from damaging the receiver SDR, each line is tested separately. Therefore, in the transmission test, the output of the second-stage HPA is connected to the input of the SDR. Instead, in the reception test, the output of the SDR is connected to the input of the first-stage LNA.

Then, using only the bladeRF-cli software (Section 2.6) provided by the manufacturer, we transmit test signals from one SDR to the other, simulating operating conditions. These signals are modulated (1 MHz pass-band bandwidth) around the desired carrier frequency (VHF/UHF/S-band) using BPSK and sampled at 4 Msps (4 samples per symbol). Then, we compute a link budget to estimate the expected signal-to-noise ratio (SNR) at the receiver SDR. Finally, we measure the SNR from the received samples; if it is within a 3 dB margin of its expected value, we deem the test successful.

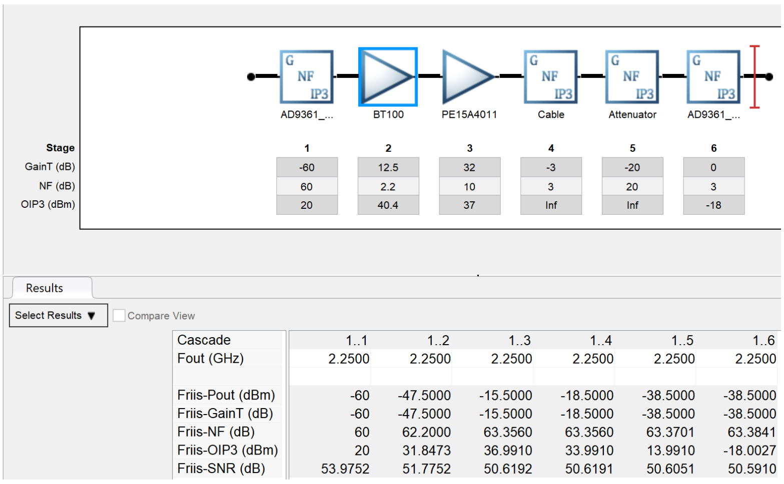
To prevent damage to the SDR from the high-gain, high power amplifiers, and low cable losses, we use an attenuator and set the SDR's transmit gain to 0 dB - reducing the transmit power to approximately -60 dBm [5] [6]. In this way, we verify high-level requirements at a reduced power level. However, the attenuation is too low to verify maximum power requirements without destroying the receiver.

Figures 3.9, 3.10, and 3.11 illustrate the S-band, UHF and VHF test configurations, and their link budgets. As one can observe, they are nearly identical; each band uses the same test signals, and amplifiers with similar gains and noise figures.

To discuss this further, consider the reception tests. The transmit SDR's internal attenuator and the 20 dB external attenuator determine the noise figure of the system. As a result, the small differences between the noise figures of each line's LNAs are negligible. Thus, we expect a 30 dB SNR for all lines when the attenuator is used, and 50 dB when it is not - if the SDR is not damaged. Instead, in the transmission tests, the signal is boosted by identical first-stage power amplifiers, which determine the noise figure of the system. Accordingly, the attenuator's effects on the SNR are negligible and we expect a 50 dB SNR for all lines. More details regarding these tests can be found in the step-by-step procedure of the S-band Line TSP, contained in Appendix H.

[5] A 60 dB transmit gain is defined as approximately 0 dBm output power [31].

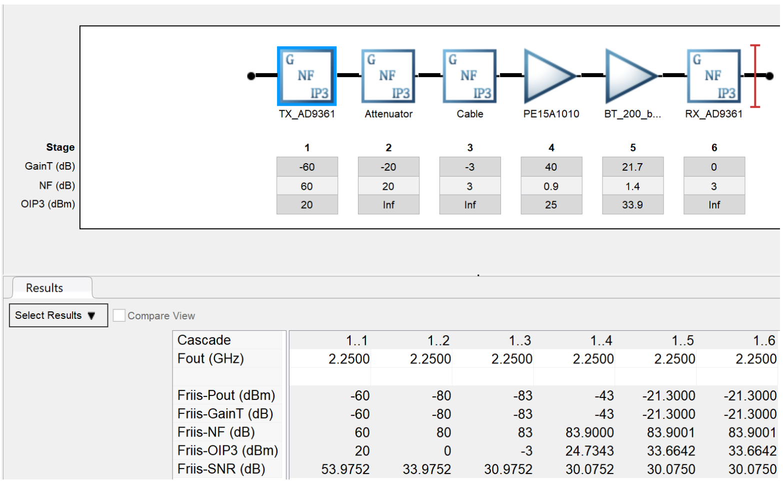
[6] At the hardware level, setting the transmit gain to 0 dB means the SDR sets its internal attenuator to 60 dB. This is important for the link budget analysis.



Stage	1	2	3	4	5	6
GainT (dB)	-60	12.5	32	-3	-20	0
NF (dB)	60	2.2	10	3	20	3
OIP3 (dBm)	20	40.4	37	Inf	Inf	-18

Cascade	1..1	1..2	1..3	1..4	1..5	1..6
Fout (GHz)	2.2500	2.2500	2.2500	2.2500	2.2500	2.2500
Friis-Pout (dBm)	-60	-47.5000	-15.5000	-18.5000	-38.5000	-38.5000
Friis-GainT (dB)	-60	-47.5000	-15.5000	-18.5000	-38.5000	-38.5000
Friis-NF (dB)	60	62.2000	63.3560	63.3560	63.3701	63.3841
Friis-OIP3 (dBm)	20	31.8473	36.9910	33.9910	13.9910	-18.0027
Friis-SNR (dB)	53.9752	51.7752	50.6192	50.6191	50.6051	50.5910

(a) Transmission

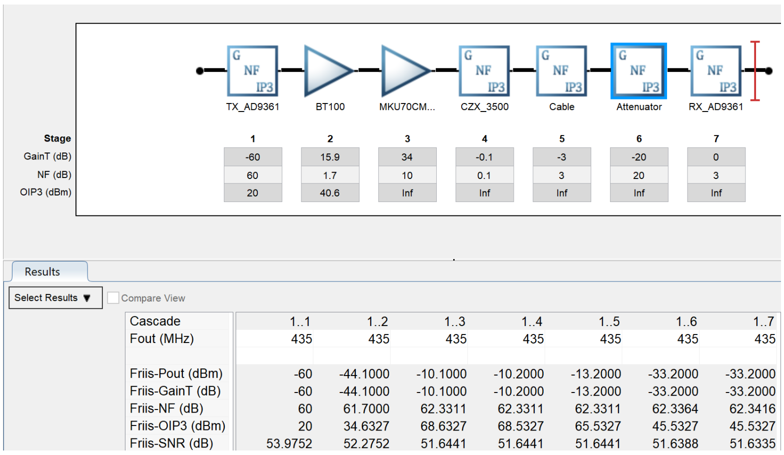


Stage	1	2	3	4	5	6
GainT (dB)	-60	-20	-3	40	21.7	0
NF (dB)	60	20	3	0.9	1.4	3
OIP3 (dBm)	20	Inf	Inf	25	33.9	Inf

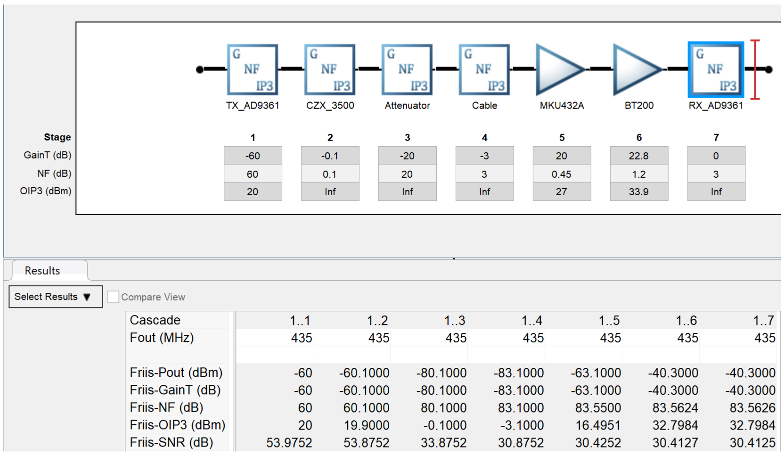
Cascade	1..1	1..2	1..3	1..4	1..5	1..6
Fout (GHz)	2.2500	2.2500	2.2500	2.2500	2.2500	2.2500
Friis-Pout (dBm)	-60	-80	-83	-43	-21.3000	-21.3000
Friis-GainT (dB)	-60	-80	-83	-43	-21.3000	-21.3000
Friis-NF (dB)	60	80	83	83.9000	83.9001	83.9001
Friis-OIP3 (dBm)	20	0	-3	24.7343	33.6642	33.6642
Friis-SNR (dB)	53.9752	33.9752	30.9752	30.0752	30.0750	30.0750

(b) Reception

Figure 3.9: S-band Test Configuration

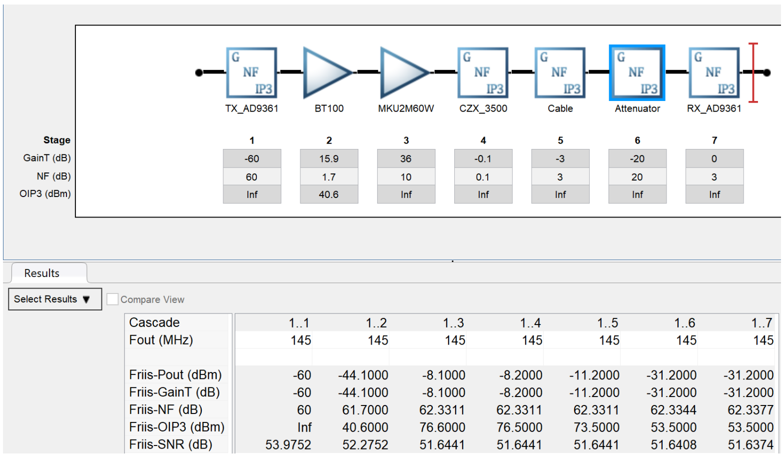


(a) Transmission



(b) Reception

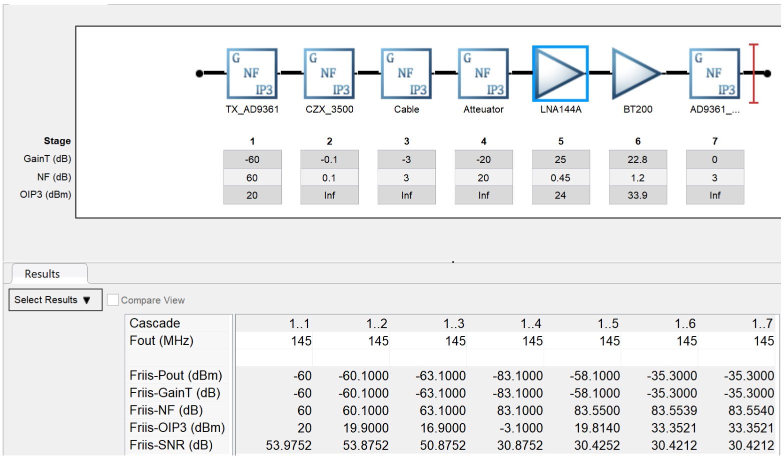
Figure 3.10: UHF Test Configuration



Stage	1	2	3	4	5	6	7
GainT (dB)	-60	15.9	36	-0.1	-3	-20	0
NF (dB)	60	1.7	10	0.1	3	20	3
OIP3 (dBm)	Inf	40.6	Inf	Inf	Inf	Inf	Inf

Cascade	1..1	1..2	1..3	1..4	1..5	1..6	1..7
Fout (MHz)	145	145	145	145	145	145	145
Friis-Pout (dBm)	-60	-44.1000	-8.1000	-8.2000	-11.2000	-31.2000	-31.2000
Friis-GainT (dB)	-60	-44.1000	-8.1000	-8.2000	-11.2000	-31.2000	-31.2000
Friis-NF (dB)	60	61.7000	62.3311	62.3311	62.3311	62.3344	62.3377
Friis-OIP3 (dBm)	Inf	40.6000	76.6000	76.5000	73.5000	53.5000	53.5000
Friis-SNR (dB)	53.9752	52.2752	51.6441	51.6441	51.6441	51.6408	51.6374

(a) Transmission



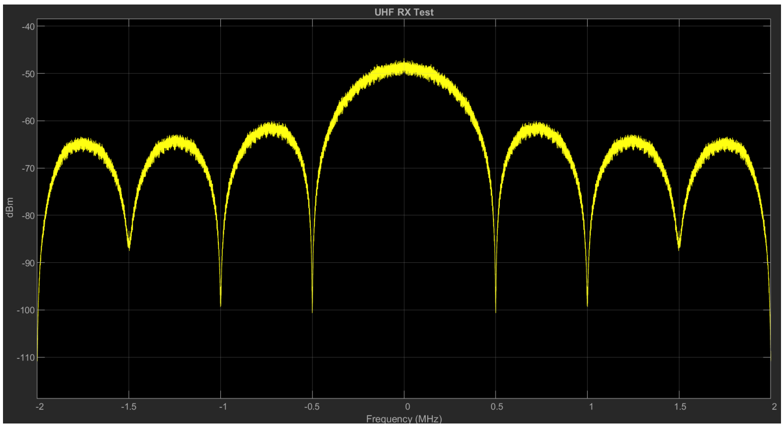
Stage	1	2	3	4	5	6	7
GainT (dB)	-60	-0.1	-3	-20	25	22.8	0
NF (dB)	60	0.1	3	20	0.45	1.2	3
OIP3 (dBm)	20	Inf	Inf	Inf	24	33.9	Inf

Cascade	1..1	1..2	1..3	1..4	1..5	1..6	1..7
Fout (MHz)	145	145	145	145	145	145	145
Friis-Pout (dBm)	-60	-60.1000	-63.1000	-83.1000	-58.1000	-35.3000	-35.3000
Friis-GainT (dB)	-60	-60.1000	-63.1000	-83.1000	-58.1000	-35.3000	-35.3000
Friis-NF (dB)	60	60.1000	63.1000	83.1000	83.5500	83.5539	83.5540
Friis-OIP3 (dBm)	20	19.9000	16.9000	-3.1000	19.8140	33.3521	33.3521
Friis-SNR (dB)	53.9752	53.8752	50.8752	30.8752	30.4252	30.4212	30.4212

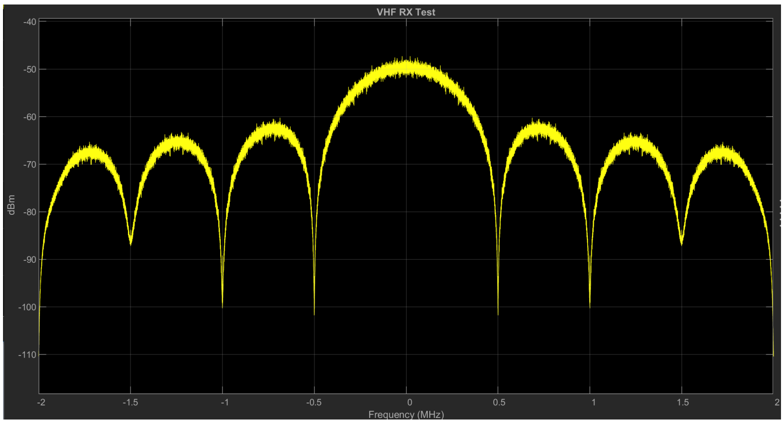
(b) Reception

Figure 3.11: VHF Test Configuration

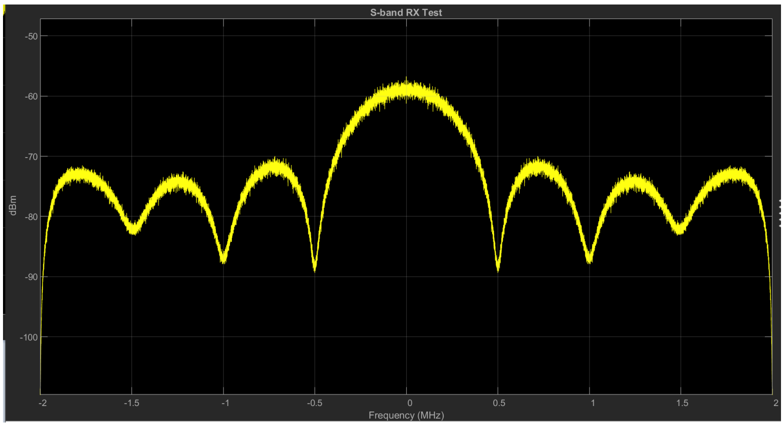
Test Results



(a) UHF



(b) VHF



(c) S-band

Figure 3.12: Received Test Signal Spectrum

Figure 3.12 illustrates the spectra of the received test signals, estimated from their samples by a Welch periodogram, using a Blackmann-Harris window with no overlap, 100 Hz resolution bandwidth, and a 50 Ohm reference load.

Looking at the VHF, UHF, and S-band signal spectra, one can clearly see the shape of a BPSK modulated signal, with its first null at $f = 0.5\ MHz$, corresponding to a baseband bandwidth of 0.5 MHz. Moreover, as expected from the test procedures, the VHF signal is nearly identical to the UHF signal.

Line	Signal Power (dBm)	Noise Power (dBm)	SNR (dB)
UHF	-12.20	-61.32	49.12
VHF	-13.04	-62.97	49.93
S-band	-22.38	-48.83	26.49

Table 3.5: Receiver Test Results

Table 3.5 reports the signal and noise power measurements obtained using the Spectrum Analyzer's channel measurements tools. Looking at the VHF and UHF results, we can see that they achieved almost 50 dB of SNR, suggesting that the test operator did not insert the attenuator during the test procedure. However, the received signal power is below the maximum SDR input power, and thus the SDR was not damaged. Consequently, we approved the VHF and UHF lines in reception.

Instead, studying the S-band results, we notice that the achieved SNR is 26.49 dB, below the pass-fail criteria ($30 \pm 3\ dB$). Therefore, the test failed. However, posterior analyses and discussions with the test operator indicated that extra connectors were used during the test, lowering the target SNR by more than 1 dB. In light of this information, we approved the S-band line in reception.

To conclude, the heat-sinks required by the high power amplifiers were unavailable during the test sessions. Hence, the verification of the VHF/UHF/S-band lines in transmission remains an open point.

3.3.3 Assembly Procedures

The radiofrequency front-end assembly procedures are described in Appendix I. Using these procedures, an end-to-end simulation of the communication system can be performed. This is very useful to test software in a hardware-in-the-loop configuration without ground support equipment or propagation of the signal through space. Instead, for operation, the SDR simulating the target satellite (SDR #1) is substituted by an antenna.

Chapter 4

Epilogue

4.1 Conclusions

After designing, modelling, simulating, and verifying the CubeSat Control Centre's Ground Station (GS), several conclusions can be drawn:

1. The GS is capable of tracking and communicating with VHF (144-146 MHz), UHF (430-440 MHz), S-band (2.025-2.120/2.200-2.400 GHz), and X-band (7.25-7.75 GHz/7.9-8.4 GHz) low-Earth orbit CubeSats, satisfying CCSDS standards and link margins for telemetry and telecommands.

2. High-bitrate ($R_b \geq 1\ Mbps$, $BER \leq 10^{-6}$), and ultra-high reliability ($R_b \geq 64\ kbps$, $BER \leq 10^{-12}$) full-duplex applications are supported in S/X bands. Instead, VHF/UHF bands support half-duplex medium bitrate, high reliability links ($R_b \geq 50\ kbps$, $BER \leq 10^{-6}$).

3. CCSDS coding, high-gain antennas, and tracking of the GS by the spacecraft are crucial to achieve the target error performances in S/X bands.

4. The GS can communicate with low-Earth orbit satellites at elevation angles of 5° in S/X band, and 8° in VHF/UHF.

5. The GS minimizes pointing losses by using a high-resolution (0.2°), high-speed ($6°/s$) mechanical tracking system.

6. The GS's state-of-the-art software-defined receivers minimize system noise temperatures, which range from 50 K in X-band to 490 K in S-band.

7. The GS satisfies the target 99.9% availability goal.

8. The GS's risk level supports critical missions.

9. The GS has a 20 m^2 footprint and weighs 207 kg, allowing it to be installed on Politecnico di Torino's rooftops.

10. The GS can be operated by students and non-professional operators.

11. The GS satisfies the tested requirements at the proposed cost and risk level.

12. Software-Defined Radios are fundamental to achieve key performance indexes, and to minimize turn-around time between missions.

13. Ionospheric scintillation effects can critically degrade the quality of the communication links at low elevation angles.

14. Well-designed high-level assembly, verification, and integration verification procedures considerably reduce the cost and duration of the GS's test campaign.

15. Advanced modelling and simulation techniques provided extremely accurate estimates of GS performance, validated in the test campaign.

16. In future CubeSatTeam missions, the GS can expect four to six 10 minute satellite accesses a day, allowing it to receive 40 images from state-of-the-art CubeSat Earth-Observation payloads per day.

4.2 Future Work

To conclude, C3 is an enormous multi-year project undertaken by the CubeSatTeam and many open points must be closed before it can become operational. Among them, we highlight:

1. Testing and verification must be completed; VHF, UHF, and S-band lines must be verified in transmission.

2. The precise position of the antennas on Politecnico di Torino's rooftop must be established, considering possible line-of-sight obstructions by buildings and objects.

3. Antenna structures must be finalized and verified.

4. Tracking, Mission Control, and Communication Systems have to be integrated for final acceptance tests.

Finally, two topics should be investigated in future developments: expansion of Fault Detection and Isolation capabilities to improve ground station reliability, and automation of the Communication System to reduce workloads and mission turn-around times.

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Appendix A

Risk Analysis

code	RISK	C3		
		Likelihood	Severity	Risk index
LT-01	Failure of the validation tests	2	3	6
LT-02	Failure of the power system	2	2	4
LT-03	Failure of the Ground Station's computer	2	3	6
LT-04	Structural failure of the antennas' support	2	2	4
LT-05	Failure to power the system	1	2	2
LT-06	Failure of integration tests	3	3	9
LT-07	Fully filled data storage	2	3	6
LT-08	Degradation of C3 units	1	3	3
LT-09	Operators errors	2	5	10
LT-10	Inability to have satellite in visibility	2	2	4
LT-11	Antennas installed in a poor spot	1	3	3
LT-12	Antenna struck by a lighting	1	3	3
SCH-01	Mission concept fails to satisfy the requirements	2	4	8
SCH-02	Delay due to inadequate documentation	2	3	6
SCH-03	Program exceeds schedule	3	3	9
SCH-04	Inability to find the desired components to realize the system	2	1	2
SCH-05	Mechanical design delay	2	3	6
SCH-06	Software design delays	3	2	6
SCH-07	Stakeholder's needs not fulfilled	2	4	8
SCH-08	Stakeholder's needs partially fulfilled	3	3	9
SCH-09	Delay in the delivery of purchased components	2	4	8
COS-01	Inability to predict the total cost of the project	2	3	6
COS-02	Price increase of COTS components	3	3	9
COS-03	Unexpected expense to replace a malfunctioning or out of spec system component	2	4	8
COM-01	Electrical interface issues between C3 power system and component	2	2	4
COM-02	Loss of acquired information	3	2	6
COM-03	Inability to acquire correct information to support the mission	4	3	12
COM-04	Inability to store acquired information	2	5	10
COM-05	Inability to elaborate collected data	3	3	9
COM-06	Degradation of communication between ground station and space segment	2	3	6
COM-07	Loss of communication among the satellites	2	5	10
COM-08	Failure of ground station's antennas	2	5	10
COM-09	Inability to rotate the ground station's antennas	2	5	10
COM-10	Inability to command the ground station's antennas	2	5	10
COM-11	Inability to send commands to the control box	1	5	5
COM-12	Tracking computer failure	1	2	2
COM-13	Inability to predict satellite passage	2	3	6
COM-14	Failure in analyzing data on the ground	1	4	4
COM-15	Wrong command sent	2	5	10
COM-16	Excessive delay between operator and satellite	1	5	5
COM-17	Failed simulation of commands	1	2	2
COM-18	Failure in accessing stored data	3	1	3
COM-19	Failure in receiving data	2	5	10
COM-20	Failure in transmitting data	3	3	9
COM-21	Failure of the SDR	3	3	9
COM-22	Failure of the VHF HPA	1	5	5
COM-23	Failure of the UHF HPA	2	3	6
COM-24	Failure of the S-band HPA	2	3	6
COM-25	Failure of the X-band HPA	2	3	6
COM-26	Failure of the VHF LNA	2	3	6
COM-27	Failure of the UHF LNA	1	5	5
COM-28	Failure of the S-band LNA	1	5	5
COM-29	Failure of the X-band LNA	1	5	5
COM-30	Failure of the X-band upconverter	1	5	5
COM-31	Failure of the X-band downconverter	1	5	5
COM-32	Failure of the X-band circulator	1	5	5
COM-33	Failure of the S-band circulator	1	5	5
COM-34	Failure of the switches	1	5	5
COM-35	Failure of the power supply	1	2	2
COM-36	Failure of the liquid cooler	1	5	5
COM-37	Failure of the antenna heating pads	1	5	5
COM-38	Failure of the S/X waveguide	1	1	1
COM-39	Failure of the UHF antenna	2	4	8
COM-40	Failure of the VHF antenna	3	3	9
COM-41	Failure of the S/X-band parabolic antenna	3	3	9
COM-42	Failure of the Instrumentation and Calibration Subsystem	3	3	9
COM-43	Failure of the Control Subsystem's Computer	3	3	9
COM-44	Failure of the CommSys to track the satellite	1	4	4
COM-45	Failure of the CommSys to adapt to channel variations	1	4	4
COM-46	Failure of the CommSys to satisfy emission regulations	1	4	4

Legend
Very high
high risk
Medium risk
low risk
Very low risk

Appendix B

Technical Requirements

10.1 Functional requirements

ID	Requirement Text
FUN-001	The RF System shall establish the communication link when CubeSats are in visibility of the antennas
FUN-002	The RF System shall receive signals with power above -120 dBW considering up to a 10 MHz bandwidth
FUN-003	VHF line shall transmit signals with EIRP below 20-30 dBW
FUN-004	UHF line shall transmit signals with EIRP below 20-30 dBW
FUN-005	S line shall transmit signals with EIRP below 30-40 dBW
FUN-006	The SDR shall generate and receive waveforms from 47 MHz to 6 GHz with a complex channel bandwidth of 56 MHz with a 12-bit ADC/DAC resolution
FUN-007	Power supply shall provide up to 320 W at 12 V
FUN-008	Power converter shall convert 12 V into 8 V supporting up to 20 W
FUN-009	The VHF band TX amplification line shall guarantee at least a 45 dB gain
FUN-010	The VHF band RX amplification line shall guarantee at least a 45 dB gain
FUN-011	The UHF band TX amplification line shall guarantee at least a 45 dB gain
FUN-012	The UHF RX band amplification line shall guarantee at least a 42 dB gain
FUN-013	The S band TX amplification line shall guarantee at least a 34 dB gain
FUN-014	The S band RX amplification line shall guarantee at least a 50 dB gain
FUN-015	The VHF TX amplification line shall have a Return Loss value lower than -10 dB
FUN-016	The VHF RX amplification line shall have a Return Loss value lower than -10 dB
FUN-017	The UHF TX amplification line shall have a Return Loss value lower than -10 dB
FUN-018	The UHF RX amplification line shall have a Return Loss value lower than -10 dB
FUN-019	The S-band TX amplification line shall have a Return Loss value lower than -10 dB
FUN-020	The S-band RX amplification line shall have a Return Loss value lower than -10 dB
FUN-021	The VHF TX amplification line shall operate in the Linearity Zone within 60 W
FUN-022	The UHF TX amplification line shall operate in the Linearity Zone within 60 W

FUN-023	The S-band TX amplification line shall operate in the Linearity Zone within 4 W
FUN-024	The VHF TX amplification line shall have a reflected power lower than 6 dBm within the Linearity Zone
FUN-025	The UHF TX amplification line shall have a reflected power lower than 6 dBm within the Linearity Zone
FUN-026	The S-band TX amplification line shall have a reflected power lower than 6 dBm within the Linearity Zone
FUN-027	The VHF RX amplification line shall have a noise figure lower than 0.4 dB
FUN-028	The UHF RX amplification line shall have a noise figure lower than 0.56 dB
FUN-029	The S-band RX amplification line shall have a noise figure lower than 1 dB
FUN-030	The VHF RX amplification line shall have a maximum output power lower than 0 dBm
FUN-031	The UHF RX amplification line shall have a maximum output power lower than 0 dBm
FUN-032	The S-band RX amplification line shall have a maximum output power lower than 0 dBm
FUN-033	The VHF Phasing Component shall provide two signals of equal power offset of 90 degrees to the antenna
FUN-034	The UHF Phasing Component shall provide two signals of equal power offset of 90 degrees to the antenna
FUN-035	HPA (1) first stage of VHF bands shall guarantee at least a gain of 10 dB
FUN-036	HPA (2) second stage of VHF band shall guarantee at least a gain of 34 dB
FUN-037	HPA (1) first stage of UHF band shall guarantee at least a gain of 10 dB
FUN-038	HPA (2) second stage of UHF band shall guarantee at least a gain of 34 dB
FUN-039	HPA (1) first stage of S band shall guarantee at least a gain of 10 dB
FUN-040	HPA (2) second stage of S band shall guarantee at least a gain of 32 dB
FUN-041	HPA (1) first stage of VHF band shall operate in the Linearity Zone within 20 dBm
FUN-042	HPA (2) second stage of VHF band shall operate in the Linearity Zone within 60W
FUN-043	HPA (1) first stage of UHF band shall operate in the Linearity Zone within 20 dBm
FUN-044	HPA (2) second stage of UHF band shall operate in the Linearity Zone within 60W
FUN-045	HPA (1) first stage of S band shall operate in the Linearity Zone within 20 dBm

FUN-046	HPA (2) second stage of S band shall operate in the Linearity Zone within 4W
FUN-047	HPA (1) first stage of VHF band shall operate with a Return Loss lower than -10dB
FUN-048	HPA (2) second stage of VHF band shall operate with a Return Loss lower than -10 dB
FUN-049	HPA (1) first stage of UHF band shall operate with a Return Loss lower than -10dB
FUN-050	HPA (2) second stage of UHF band shall operate with a Return Loss lower than -10 dB
FUN-051	HPA (1) first stage of S band shall operate with a Return Loss lower than -10dB
FUN-052	HPA (2) second stage of S band shall operate with a Return Loss lower than -10 dB
FUN-053	LNA (1) first stage of VHF band shall guarantee at least a gain of 25 dB
FUN-054	LNA (2) second stage of VHF band shall guarantee at least a gain of 16 dB
FUN-055	LNA (1) first stage of UHF band shall guarantee at least a gain of 20 dB
FUN-056	LNA (2) second stage of UHF band shall guarantee at least a gain of 16 dB
FUN-057	LNA (1) first stage of S band shall guarantee at least a gain of 40 dB
FUN-058	LNA (2) second stage of S band shall guarantee at least a gain of 16 dB
FUN-059	LNA (1) first stage of VHF band shall operate with a Return Loss lower than -10 dB
FUN-060	LNA (2) second stage of VHF band shall operate with a Return Loss lower than -10 dB
FUN-061	LNA (1) first stage of UHF band shall operate with a Return Loss lower than -10 dB
FUN-062	LNA (2) second stage of UHF band shall operate with a Return Loss lower than -10 dB
FUN-063	LNA (1) first stage of S band shall operate with a Return Loss lower than -10 dB
FUN-064	LNA (2) second stage of S band shall operate with a Return Loss lower than -10 dB
FUN-065	LNA (1) first stage of VHF band shall have a noise figure lower than 1 dB
FUN-066	LNA (2) second stage of VHF band shall have a noise figure lower than 2 dB
FUN-067	LNA (1) first stage of UHF band shall have a noise figure lower than 1 dB
FUN-068	LNA (2) second stage of UHF band shall have a noise figure lower than 2 dB

FUN-069	LNA (1) first stage of S band shall have a noise figure lower than 1 dB
FUN-070	LNA (2) second stage of S band shall have a noise figure lower than 2 dB
FUN-071	Cables shall have an insertion loss lower than 3 dB
FUN-072	S-band diplexer shall have an insertion loss smaller than 1 dB
FUN-073	S-band diplexer shall have a port to port isolation of at least 50 dB
FUN-074	S-band diplexer shall have a return loss lower than -10 dB
FUN-075	S-band diplexer shall separate frequencies in ranges of 2025-2120 MHz and 2200-2400 MHz
FUN-076	VHF Phasing Harness shall produce a 90 degrees phase shift between output signals
FUN-077	UHF Phasing Harness shall produce a 90 degrees phase shift between output signals
FUN-078	Power splitter shall equally divide power to its outputs
FUN-079	TR-Switch shall provide an isolation of at least 60 dB between input & output signal
FUN-080	TR-Switch shall switch between input & output signal according to PPT commands
FUN-081	UHF antenna shall have a gain of at least 12 dBI
FUN-082	VHF antenna shall have a gain of at least 10 dBI
FUN-083	S-band antenna shall have a gain above 22 dB
FUN-084	S-band antenna shall offer Right Hand Circular Polarization through a helix feed
FUN-085	X-band antenna shall have a gain above 36 dB
FUN-086	X-band antenna shall offer dual circular polarization through an Ortho-Mode Transducer
FUN-087	VHF antenna shall operate with a Return Loss lower than -10 dB
FUN-088	UHF antenna shall operate with a Return Loss lower than -10 dB
FUN-089	S band antenna shall operate with a Return Loss lower than -10 dB
FUN-090	X band antenna shall operate with a Return Loss lower than -10 dB
FUN-091	X-band TX reject filter shall have an insertion loss below 0.5 dB in the range of 7.25 - 7.75 GHz

FUN-092	X-band TX reject filter shall have a rejection above 90 dB outside the range of 7.25 - 7.75 GHz
FUN-093	X-band RX reject filter shall have an insertion loss below 0.5 dB in the range of 7.9 - 8.4 GHz
FUN-094	X-band RX reject filter shall have a rejection above 90 dB outside the range of 7.9 - 8.4 GHz
FUN-095	X-band BUC shall operate in the Linearity Zone within 4 W
FUN-096	The X-band BUC shall have a Return Loss lower than -10 dB
FUN-097	X-band BUC shall upconvert signals from the range of 950 - 1450 MHz to 7.9 - 8.4 GHz
FUN-098	X- band BUC shall guarantee at least a gain of 55 dB
FUN-099	X-band BUC shall lock to an external 10 MHz reference
FUN-100	X-band BUC shall have a phase noise below -75 dBc at 1 kHz
FUN-101	X-band LNB shall lock to an external 10 MHz reference
FUN-102	X-band LNB shall have a phase noise below -75 dBc at 1 kHz
FUN-103	X-band LNB shall support up to a -30 dBm input signal
FUN-104	X-band LNB shall down convert signals from the range from the range of 7.25 - 7.75 GHz to 950 - 1450 MHz
FUN-105	The X-band LNB shall have a noise figure lower than 0.9 dB
FUN-106	The reference oscillator shall have a maximum phase noise of -155 dBc at 1 kHz after warming up
FUN-107	The reference oscillator shall generate a 10 MHz reference signal
FUN-108	The X-band LNB shall have a Return Loss lower than -10 dB
FUN-109	X- band LNB shall guarantee at least a gain of 60 dB
FUN-110	C3 MCS shall identify the CubeSats incoming in the Ground Station visibility
FUN-111	C3 MCS shall give the following output for each type of input data: - correct output value - correct output type
FUN-112	C3 MCS shall share information with the mission stakeholders
FUN-113	C3 MCS shall share images with general public

FUN-114	C3 MCS shall recognize the following type of packets: - TM packets incoming from the CubeSats - IMAGE packets incoming from the CubeSats - RF data - TS data - Other type of packets according to the mission stakeholders requests
FUN-115	C3 MCS shall acquire the following type of packets: - TM packets incoming from the CubeSats - IMAGE packets incoming from the CubeSats - RF data - TS data - Other type of packets according to the mission stakeholders requests
FUN-116	C3 MCS shall save the following type of packets: - TM packets incoming from the CubeSats - IMAGE packets incoming from the CubeSats - RF data - TS data - Other type of packets according to the mission stakeholders requests
FUN-117	C3 MCS shall built the TC packets to send to the CubeSats
FUN-118	C3 MCS shall recognize the generated TC packets to send to the CubeSats
FUN-119	C3 MCS shall save the generated TC packets to send to the CubeSats
FUN-120	C3 MCS Scheduler shall recognize a specific structure for pre-set commands
FUN-121	C3 MCS Scheduler shall generate a unique ID for the pre-set commands each time a schedule is created
FUN-122	C3 MCS Scheduler shall provide an interface to display the commands generation
FUN-123	C3 MCS Scheduler shall generate a queue sort by the commands priority of execution
FUN-124	C3 MCS shall provide absence of bugs or infinite recursion and iteration condition when it runs
FUN-125	The C3 MCS calculator shall interpret all the programming languages used in the software
FUN-126	The C3 MCS calculator shall compile all the programming languages used in the software
FUN-127	The C3 MCS shall implement the same communication protocols of on-board CubeSats
FUN-128	The C3 MCS shall implement the following action to manage errors in transmission: - detect errors - isolate errors - resolve errors
FUN-129	The C3 shall keep track of all interactions of a user in a session
FUN-130	The Tracking Subsystem shall track the CubeSat
FUN-131	The Tracking Subsystem shall compute the desired antenna orientation

FUN-132	The Tracking Subsystem shall point the antennas toward the desired position with a manual input from control box
FUN-133	The SAT acquisition unit shall compute the following information with respect to the GS: - Position of the CubeSat - Velocity of the CubeSat
FUN-134	The SAT acquisition unit must be able to estimate the visibility period of the satellite
FUN-135	The pointing unit shall sustain the antennas
FUN-136	The pointing unit shall generate the position control signal
FUN-137	The Tracking Software shall acquire the TLE data from NORAD
FUN-138	The Tracking Software shall update the TLE at a given frequency (e.g. every week)
FUN-139	The Tracking Software shall propagate the orbit
FUN-140	The Tracking Software shall compute the CubeSat's altitude from the orbit propagation
FUN-141	The Tracking Software shall know the minimum antenna elevation angle
FUN-142	The rotators shall provide the following characteristics: - to rotate the motors at a speed of 6°/s - to measure of the rotator position (AZ/EL angles) with a accuracy of 0.1 deg - to move the rotator to a position (AZ/EL angles) with a precision of 0.2 deg - to provide a turning torque of TBD Nm
FUN-143	The structure shall support the following mechanical loads - TBD N of vertical load on the tower (approx 45/50 kg) - TBD Nm of torque on the tower - TBD N of vertical load on the rotator (approx 20/25kg) - TBD Nm of torque on the rotator (approx the same that is applied to the tower) - TBD N on the antenna frame
FUN-144	The power supply shall provide power to the control box
FUN-145	The control box shall determine the error between desired and measured antenna position
FUN-146	The control box shall apply the position control law
FUN-147	The SDR shall operate in near real time between processing and collecting data
FUN-148	The control box shall be able to exchange data with the tracking PC through one of the available interfaces
FUN-149	The power supply shall provide the following : • Maximum 15V between output 1 and ground • Maximum 24V between output 2 and ground
FUN-150	The Tracking Subsystem shall point the antennas toward the desired position with an input from the dedicated PC

10.2 Environmental requirements

ID	Requirement Text
ENV-001	The RF Subsystem shall satisfy ITU-R SM1541 standard regarding unwanted spurious emissions (EMI)
ENV-002	LNA (1) first stage of VHF band shall have a noise figure lower than 1 dB at 17°C
ENV-003	LNA (2) second stage of VHF band shall have a noise figure lower than 2 dB at 17°C
ENV-004	LNA (1) first stage of UHF band shall have a noise figure lower than 1 dB at 17°C
ENV-005	LNA (2) second stage of UHF band shall have a noise figure lower than 2 dB at 17°C
ENV-006	LNA (1) first stage of S band shall have a noise figure lower than 1 dB at 17°C
ENV-007	LNA (2) second stage of S band shall have a noise figure lower than 2 dB at 17°C
ENV-008	The control boxes shall be protected against temperatures which are outside their working range (-5 to +40°C)
ENV-009	The rotators shall be protected against temperatures which are outside their working range (-20 to +55°C)
ENV-010	The pointing subsystem shall be protected against lightning
ENV-011	The Tracking System shall withstand wind loads up to 40km/h
ENV-012	SDR Hardware shall be protected against EMI, and other environmental interferences

10.3 .Operational requirements

ID	Requirement Text
OPR-001	C3 shall implement a Visibility operative mode
OPR-002	C3 shall implement a Visibility Off operative mode
OPR-003	C3 shall implement a LEOP (Launch Early Orbit Phase) operative mode
OPR-004	C3 shall implement a Safe mode
OPR-005	C3 shall lead real time operation when CubeSats are in Visibility
OPR-006	C3 shall implement setting procedures to prepare CubeSats Visibility
OPR-007	C3 shall implement consistency check to monitor all its communication channels
OPR-008	C3 shall implement consistency check to monitor all its subsystems
OPR-009	C3 shall implement consistency check to detect failures
OPR-010	C3 shall establish a telemetry link with CubeSats when they are in visibility
OPR-011	C3 shall establish a command link with CubeSats when they are in visibility
OPR-012	C3 shall lead a post-processing activity after CubeSat visibility
OPR-013	Tracking Subsystem shall implement a safe mode in which the antenna is parked in a position in which the wind load is minimum
OPR-014	Tracking Subsystem shall implement a parking mode in which snow or rain have minimum impact on the mechanical loads
OPR-015	The SDR shall autonomously initiate the downlink to receive data from satellites based on Task Schedule

10.4 Interface requirements

ID	Requirement Text
INT-001	C3 shall interface with other stations/centres involved in a specific CubeSat Mission
INT-002	C3 MCS shall guarantee the existence of an interface between operators and PC
INT-003	C3 MCS shall provide a GUI to display the following data: - TM visualization - TC construction - MCS Scheduler
INT-004	C3 MCS GUI shall display requested information correctly
INT-005	C3 MCS shall use Electronic User Interfaces
INT-006	C3 MCS shall guarantee the existence of an interface between control centre and RF system
INT-007	C3 MCS shall guarantee the existence of an interface between control centre and Tracking system
INT-008	The Communication Subsystem shall exchange data with the MCS
INT-009	The Communication Subsystem shall receive configuration data from the User
INT-010	The Communication Subsystem shall use standard communication protocol in exchanging data
INT-011	The Communication Subsystem shall provide monitoring data to the User
INT-012	Internal Communication Subsystem interfaces shall make use of standard and documented computer interfaces
INT-013	The Baseband Processing Server of the Communication Subsystem shall provide a graphical user interface
INT-014	The Communication Subsystem shall store the monitoring data in a user-configurable location
INT-015	The Communication Subsystem shall provide access to the raw data coming from its Baseband Processing Unit for up to TBD hours
INT-016	The Communication Subsystem shall provide a programming environment with graphical capabilities
INT-017	The Communication System shall display: - the status of all monitored components in the receive chain - the status of all monitored components in the transmit chain

INT-018	The tracking computer shall communicate with the control boxes with at least one the following methods: - usb connection - ethernet connection
INT-019	The control computer shall exchange data with the control centre (e.g. to exchange data about the satellites to be tracked)
INT-020	The control box shall communicate with the rotator
INT-021	The power supply shall provide power to the control boxes
INT-022	The Tracking Subsystem shall store the monitoring data in a user-configurable location
INT-023	SDR shall have means to encode data in AFSK
INT-024	SDR shall have means to decode signals in AFSK
INT-025	SDR shall have means to encode data in QPSK
INT-026	SDR shall have means to decode signals in QPSK
INT-027	SDR shall forward data to RF front end
INT-028	SDR shall forward data to Mission Control Centre Computer
INT-029	The SDR shall have means to forward data from satellites to dedicated server
INT-030	The SDR shall have means to receive data to transmit to satellites from dedicated server
INT-031	The SDR shall have means to encode data in AX.25 packets
INT-032	The SDR shall have means to decode data in AX.25 packets

10.5 Physical requirements

ID	Requirement Text
PHY-001	C3 Ground Station shall consider the available physical space in the design phase
PHY-002	C3 structure shall physically support the antennas
PHY-003	The Antennas shall have a clearance of at least 3,5m x 5,5m
PHY-004	C3 shall have a total mass lower than 250 kg
PHY-005	The Tracking Subsystem shall not exceed the footprint decided during the design phase
PHY-006	The RF cables shall be long enough to allow to perform the Flip manoeuvre
PHY-007	The Tower shall allow to perform the flip manoeuvre also when the counterweights are installed on the rotators

10.6 Configuration requirements

ID	Requirement Text
CON-001	The Ground Segment C3 is composed by the following subsystems: - Radiofrequency Subsystem (RF) - Tracking Subsystems (TS) - Mission Control Centre Subsystem (MCS)
CON-002	The C3 shall have 4 computers for the following activities: - 3 for MCS - 1 for TS and RF
CON-003	RF Subsystem shall have at least two UHF-band antennas
CON-004	RF Subsystem shall have at least two VHF-band antennas
CON-005	RF Subsystem shall have one X-band parabolic antenna
CON-006	RF Subsystem shall have one S-band parabolic antenna
CON-007	RF Subsystem shall have the following two SDR: - 1 active SDR - 1 redundancy SDR
CON-008	The VHF line is composed by the following filter: - 1 HPA for transmission line - Up to 2 LNA for reception line

CON-009	The UHF line is composed by the following filter: - 1 HPA for transmission line - Up to 2 LNA for reception line
CON-010	The S-band line is composed by the following filter: - 1 HPA for transmission line - Up to 2 LNA for reception line
CON-011	The X-band line is composed by the following filter: - 1 HPA for transmission line - Up to 2 LNA for reception line
CON-012	RF Subsystem shall have 2 power supply to support RF front end
CON-013	RF Subsystem shall have a X-band Up/Down converter
CON-014	RF Subsystem shall have 1 computer to support its operations
CON-015	The RF Subsystem shall have a reference frequency with phase noise of TBD
CON-016	The RF Subsystem shall switch polarizations between LHCP and RHCP
CON-017	The HPA for each band is composed by the following stages: - HPA (1) first HPA stage - HPA (2) second HPA stage
CON-018	The LNA for each band is composed by the following stages: - LNA (1) first HPA stage - LNA (2) second HPA stage
CON-019	The C3 Structure is composed by the following parts: - the Tower (support element fixed to the ground) - the Rotator - the Antenna frame (elements fixed to the rotator that support the antennas)
CON-020	TS shall have at least 2 rotators to rotate the antennas
CON-021	TS shall have at least 3 control boxes to control the rotators include the redundancies
CON-022	TS shall have 2 power supply
CON-023	TS shall have 1 computer to support its operations
CON-024	Control centre shall have 3 computers to monitor: - RF operations - TS operations - CubeSats operations

10.7 Product Assurance requirements

ID	Requirement Text
PA-001	C3 shall reduce risks to operators
PA-002	C3 shall protect its subsystems
PA-003	C3 shall detect failures
PA-004	C3 shall implement redundancy
PA-005	C3 shall identify failures
PA-006	C3 shall recover from failures
PA-007	C3 shall manage at least two failure points protection to support the operation
PA-008	C3 shall manage at least two failure points protection to support the operators
PA-009	All the electronic components that are exposed to the weather / mounted on the antenna shall be encloses in weatherproof grounded, conductive and shielded box
PA-010	The tracking system shall implement the following redundancies in case of damage - control boxes - power supplies
PA-011	The Communication Subsystem shall implement a redundancy SDR in case of damage

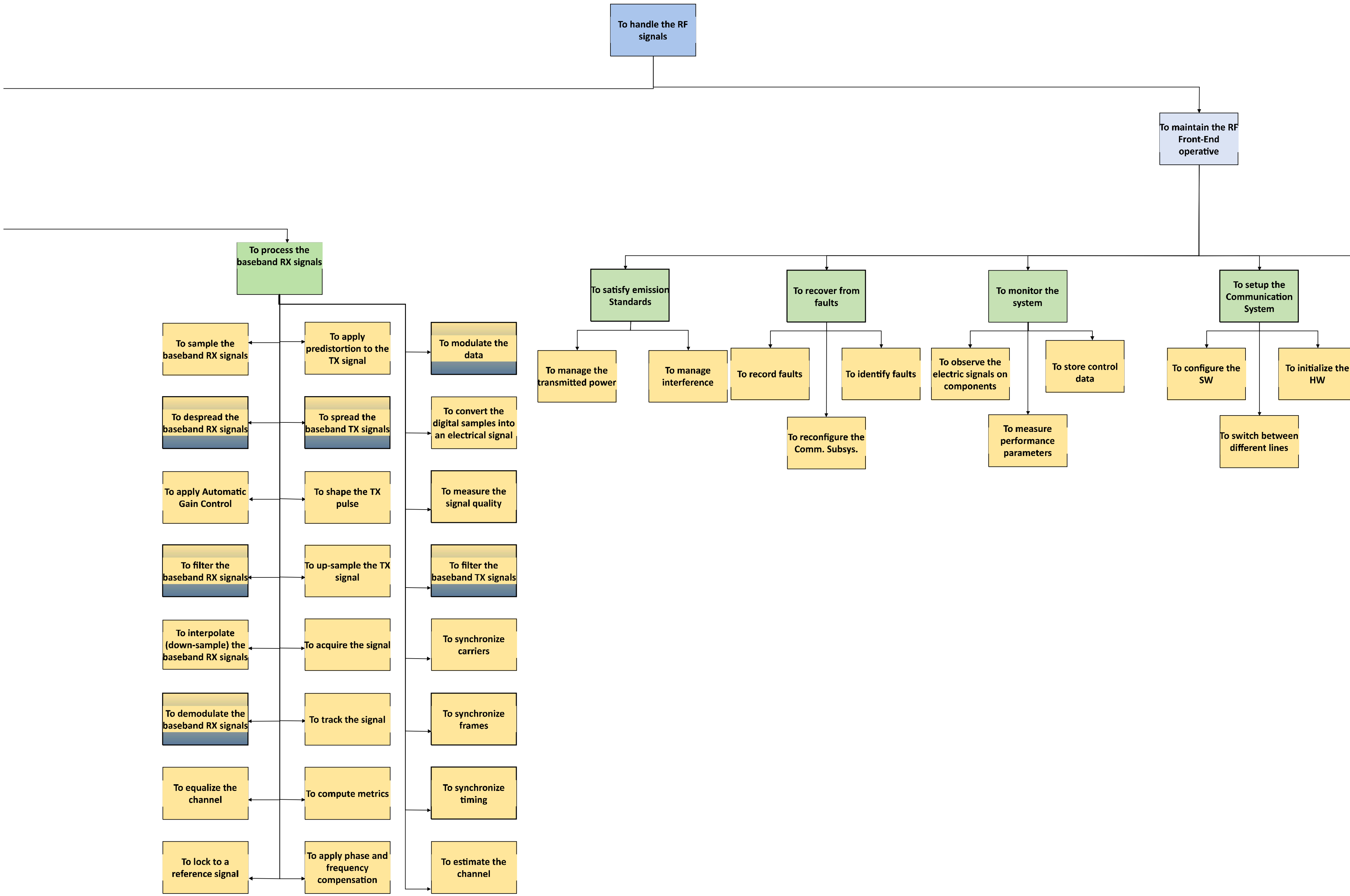
10.8 Design requirements

ID	Requirement Text
DES-001	C3 shall be developed according to ECSS standards
DES-002	C3 shall be compatible with most existing and planned CubeSat missions
DES-003	C3 shall be compliant to CCSDS standard
DES-004	C3 MCS software shall be implemented in Python
DES-005	C3 shall be flexible and reconfigurable for multiple missions
DES-006	C3 shall be reconfigurable with respect to the following communication parameters: - Communication Protocols - Frequency bands - Type of modulation

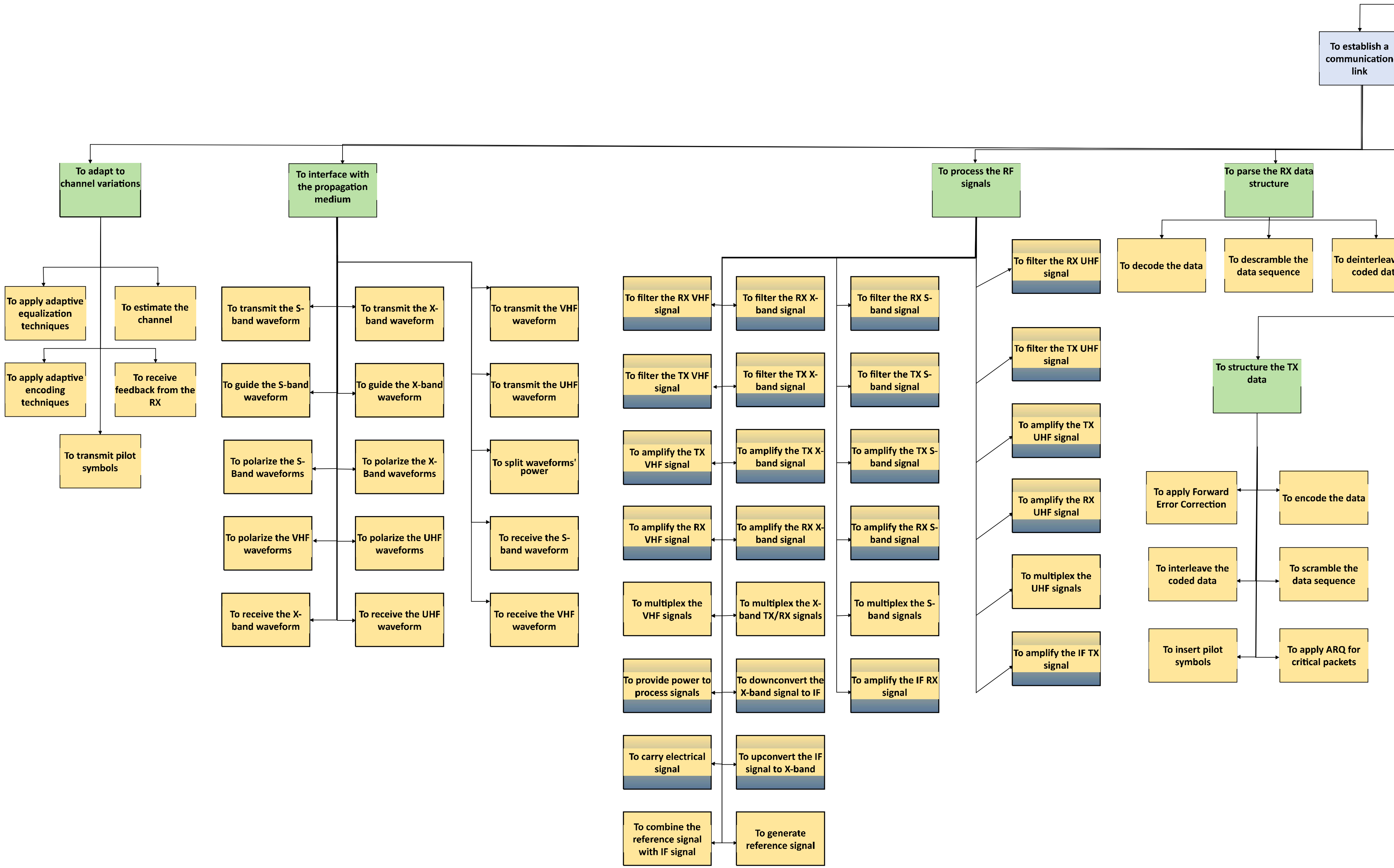
DES-007	The RF Subsystem shall support full-duplex operation for the following bands: - S-band (2025-2120/2200-2400 MHz) - X-band (7250-7750/7900-8400 MHz)
DES-008	The RF Subsystem shall be designed with fully independent VHF-UHF, S-band and X-band lines
DES-009	The RF Subsystem shall use standardized off-the-shelf components
DES-010	The RF Subsystem shall allow hardware upgrades during its lifetime
DES-011	The RF Subsystem shall allow software upgrades during its lifetime
DES-012	SDR software architecture shall be modular
DES-013	SDR software shall be flexible in respect to modification of existing modulation schemes
DES-014	SDR software shall support further additions of modulations to existing modulation schemes

Appendix C

Function and Product Trees



To handle the RF signals
To maintain the RF Front-End operative
To process the baseband RX signals
To satisfy emission Standards
To recover from faults
To monitor the system
To setup the Communication System
To manage the transmitted power
To manage interference
To record faults
To identify faults
To reconfigure the Comm. Subsys.
To observe the electric signals on components
To store control data
To measure performance parameters
To configure the SW
To initialize the HW
To switch between different lines
To sample the baseband RX signals
To apply predistortion to the TX signal
To modulate the data
To despread the baseband RX signals
To spread the baseband TX signals
To convert the digital samples into an electrical signal
To apply Automatic Gain Control
To shape the TX pulse
To measure the signal quality
To filter the baseband RX signals
To up-sample the TX signal
To filter the baseband TX signals
To interpolate (down-sample) the baseband RX signals
To acquire the signal
To synchronize carriers
To demodulate the baseband RX signals
To track the signal
To synchronize frames
To equalize the channel
To compute metrics
To synchronize timing
To lock to a reference signal
To apply phase and frequency compensation
To estimate the channel



To establish a communication link
To adapt to channel variations
To apply adaptive equalization techniques
To estimate the channel
To apply adaptive encoding techniques
To receive feedback from the RX
To transmit pilot symbols
To interface with the propagation medium
To transmit the S-band waveform
To transmit the X-band waveform
To transmit the VHF waveform
To guide the S-band waveform
To guide the X-band waveform
To transmit the UHF waveform
To polarize the S-Band waveforms
To polarize the X-Band waveforms
To split waveforms' power
To polarize the VHF waveforms
To polarize the UHF waveforms
To receive the S-band waveform
To receive the X-band waveform
To receive the UHF waveform
To receive the VHF waveform
To process the RF signals
To filter the RX VHF signal
To filter the RX X-band signal
To filter the RX S-band signal
To filter the TX VHF signal
To filter the TX X-band signal
To filter the TX S-band signal
To amplify the TX VHF signal
To amplify the TX X-band signal
To amplify the TX S-band signal
To amplify the RX VHF signal
To amplify the RX X-band signal
To amplify the RX S-band signal
To multiplex the VHF signals
To multiplex the X-band TX/RX signals
To multiplex the S-band signals
To provide power to process signals
To downconvert the X-band signal to IF
To amplify the IF RX signal
To carry electrical signal
To upconvert the IF signal to X-band
To combine the reference signal with IF signal
To generate reference signal
To filter the RX UHF signal
To filter the TX UHF signal
To amplify the TX UHF signal
To amplify the RX UHF signal
To multiplex the UHF signals
To amplify the IF TX signal
To parse the RX data structure
To decode the data
To descramble the data sequence
To deinterleav coded dat
To structure the TX data
To apply Forward Error Correction
To encode the data
To interleave the coded data
To scramble the data sequence
To insert pilot symbols
To apply ARQ for critical packets

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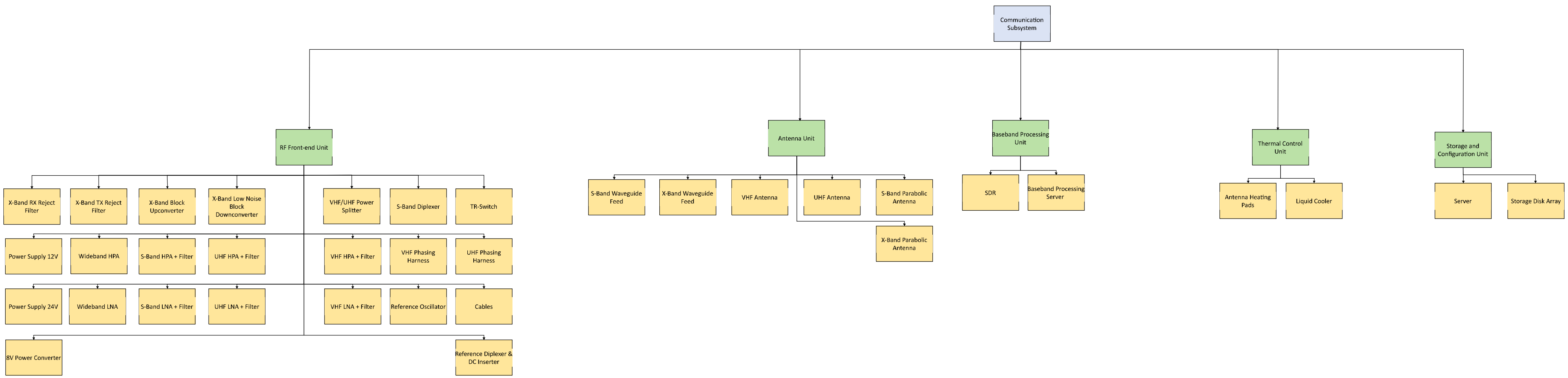


Communication Subsystem
RF Front-end Unit
X-Band RX Reject Filter
X-Band TX Reject Filter
X-Band Block Upconverter
X-Band Low Noise Block Downconverter
VHF/UHF Power Splitter
S-Band Diplexer
TR-Switch
Power Supply 12V
Wideband HPA
S-Band HPA + Filter
UHF HPA + Filter
VHF HPA + Filter
VHF Phasing Harness
UHF Phasing Harness
Power Supply 24V
Wideband LNA
S-Band LNA + Filter
UHF LNA + Filter
VHF LNA + Filter
Reference Oscillator
Cables
8V Power Converter
Reference Diplexer & DC Inserter
Antenna Unit
S-Band Waveguide Feed
X-Band Waveguide Feed
VHF Antenna
UHF Antenna
S-Band Parabolic Antenna
X-Band Parabolic Antenna
Baseband Processing Unit
SDR
Baseband Processing Server
Thermal Control Unit
Antenna Heating Pads
Liquid Cooler
Storage and Configuration Unit
Server
Storage Disk Array

Appendix D

Function Product Matrix

Functions\Systems	Ground Station
To handle the RF Signal	A

Functions\Subsystems	Communication Subsystem
To establish a communcation link	A
To maintain the RF Front-end operative	A

Functions\Units	RF Front-end	Baseband Processing	Antenna	Thermal Control	Configuration & Storage	
To process the RF signals	A					
To satisfy emission Standards	A					
To adapt to channel variations		A				
To parse the RX data structure		A				
To structure the TX data		A				
To process the baseband RX signals		A				
To monitor the system		A				
To interface with the propagation medium			A			
To control the temperature of the system				A		
To recover from faults					A	
To setup the Communication System					A	

Function	X-band TX Reject Filter	X-band Block Upconverter	X-band Low Noise Block Downconverter	VHAF/UHF Power Splitter	VHF/UHF TR-Switch	X-band RX Reject Filter	S-band HPA + Filter	UHF HPA + Filter	VHF LNA + Filter	S-band Diplexer	Power Supply 12V	S-band LNA + Filter	UHF LNA + Filter	VHF Phasing Harness	UHF Phasing Harness	Power Supply 24V	Wideband HPA	Cables	8V Power Converter	Wideband LNA	VHF HPA + Filter	Reference Diplexer & DC Inserter	Reference Oscillator	SDR	Baseband Processing Server	S-band Parabolic Antenna	X-band Parabolic Antenna	VHF Antenna	UHF Antenna	S-band Waveguide Feed	X-band Waveguide Feed	Antenna Heading Pads	Air Cooler	Server	Storage Disk Array
To filter the RX X-band signal	A (Redundancy)		A																																
To amplify the TX X-band signal		A																																	
To upconvert the IF signal to X band		A																																	
To filter the TX X-band signal		A (Redundancy)				A																													
To amplify the RX X-band signal			A																																
To downconvert the X-band signal to IF			A																																
To split waveforms' power				A																															
To multiplex the VHF signals					A																														
To multiplex the UHF signals					A																														
To filter the TX S-band signal							A																												
To amplify the TX S-band signal							A																												
To filter the TX UHF signal								A																											
To amplify the TX UHF signal								A																											
To filter the RX VHF signal									A																										
To amplify the RX VHF signal									A																										
To multiplex the S-band signals										A																									
To provide power to process signals											A					A (Redundancy)			A (Redundancy)																
To filter the RX S-band signal												A																							
To amplify the RX S-band signal												A																							
To filter the RX UHF signal													A																						
To amplify the RX UHF signal													A																						
To polarize the VHF waveforms														A																					
To polarize the UHF waveforms															A																				
To amplify the IF TX signal																	A																		
To carry electrical signal																		A																	
To amplify the IF RX signal																				A															
To filter the TX VHF signal																					A														
To amplify the TX VHF signal																					A														
To combine the reference signal with IF signal																						A													
To generate reference signal																							A												
To apply adaptive equalization techniques																								A	A (Redundancy)										
To estimate the channel																								A	A (Redundancy)										

To apply adaptive encoding techniques																								A	A (Redundancy)											
To receive feedback from the RX																								A	A (Redundancy)											
To transmit pilot symbols																								A	A (Redundancy)											
To decode the data																								A	A (Redundancy)											
To descramble the data sequence																								A	A (Redundancy)											
To deinterleave the coded data																								A	A (Redundancy)											
To apply Forward Error Correction																								A	A (Redundancy)											
To encode the data																								A	A (Redundancy)											
To interleave the coded data																								A	A (Redundancy)											
To scramble the data sequence																								A	A (Redundancy)											
To insert pilot symbols																								A	A (Redundancy)											
To apply ARQ for critical packets																								A	A (Redundancy)											
To apply predistortion to the TX signal																								A	A (Redundancy)											
To modulate the data																								A	A (Redundancy)											
To despread the baseband RX signals																								A	A (Redundancy)											
To spread the baseband TX signals																								A	A (Redundancy)											
To apply Automatic Gain Control																								A	A (Redundancy)											
To shape the TX pulse																								A	A (Redundancy)											
To measure the signal quality																								A	A (Redundancy)											
To filter the baseband RX signals																								A	A (Redundancy)											
To up-sample the TX signal																								A	A (Redundancy)											
To filter the baseband TX signals																								A	A (Redundancy)											
To interpolate (down-sample) the baseband RX signals																								A	A (Redundancy)											
To acquire the signal																								A	A (Redundancy)											
To synchronize carriers																								A	A (Redundancy)											
To demodulate the baseband RX signals																								A	A (Redundancy)											
To track the signal																								A	A (Redundancy)											
To synchronize frames																								A	A (Redundancy)											
To equalize the channel																								A	A (Redundancy)											
To compute metrics																								A	A (Redundancy)											
To synchronize timing																								A	A (Redundancy)											
To manage the transmitted power																								A	A (Redundancy)											
To manage interference																								A	A (Redundancy)											
To measure performance parameters																								A	A (Redundancy)											
To switch between different lines																								A	A (Redundancy)											
To sample the baseband RX signals																								A												

To convert the digital samples into an electrical signal																								A											
To observe the electric signals on components																								A											
To configure the SW																									A										
To store control data																																			A
To transmit the S-band waveform																										A									
To receive the S-band waveform																										A									
To transmit the X-band waveform																											A								
To receive the X-band waveform																											A								
To transmit the VHF waveform																												A							
To receive the VHF waveform																												A							
To transmit the UHF waveform																													A						
To receive the UHF waveform																													A						
To guide the S-band waveform																														A					
To polarize the S-Band waveforms																														A					
To guide the X-band waveform																															A				
To polarize the X-Band waveforms																															A				
To multiplex the X-band TX/RX signals																															A				
To heat the antenna																																A			
To cool power amplifiers																																	A		
To record faults																																		A	
To identify faults																																		A	
To reconfigure the Comm. Subsys.																																		A	
To initialize the HW																																		A	

Appendix E

Noise Figure Analysis

E.1 Introduction

To compute accurate link budgets (Appendix G), we must estimate a receiver's noise temperature [13][14]. Therefore, in this appendix, we use Mathwork's Matlab Noise Figure Analyzer to model the Ground Station's VHF, UHF, S-band and X-band receivers, and to design a state-of-the-art X-band CubeSat receiver. Then, we compute their noise figures and noise temperatures, with regard to a 290 K reference temperature.

E.2 Analysis

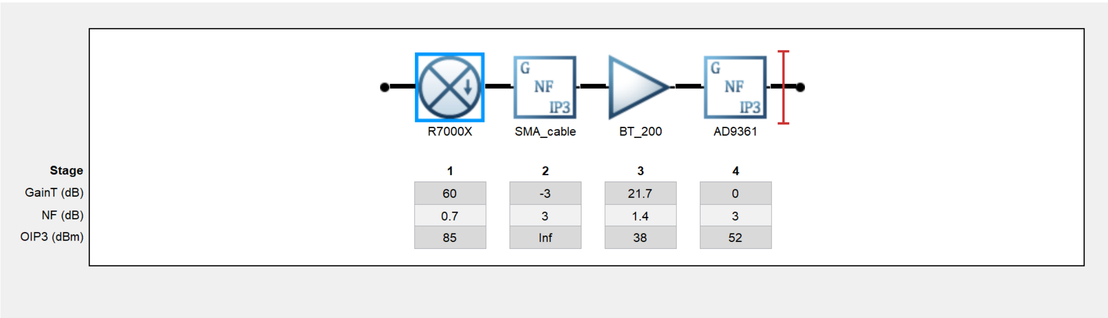
Receiver	Noise Figure (dB)	Noise Temperature (K)[1]
X-band CubeSat	4.27	485.2
X-band Ground Station	0.70	50.7
S-Band Ground Station	4.30	490.5
UHF Ground Station	3.61	375.9
VHF Ground Station	3.51	360.7

Table E.1: Noise Figure Analysis Results

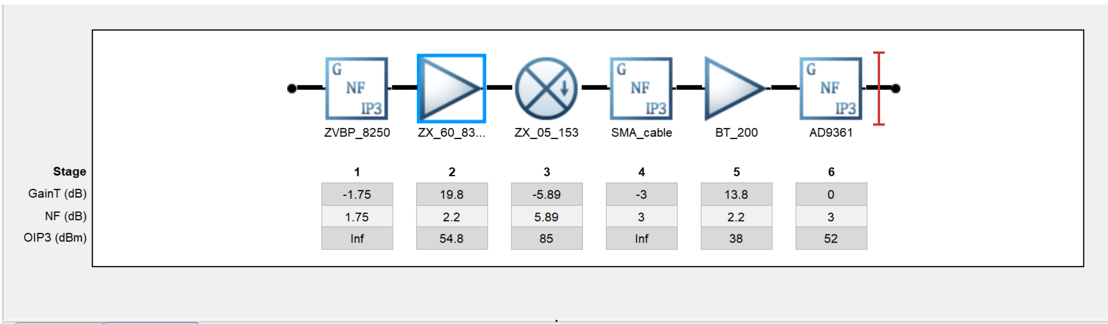
Table E.1 summarizes the noise figures and noise temperatures of each receiver architecture. From there, we can conclude that the X-Band Ground Station receiver (Figure E.1a) has the lowest noise temperature ($T_R = 50.7\ K$), at least seven times lower than the other receiver architectures. This is a result of its high-gain low-noise block downconverter (LNB), which amplifies the received X-band signal **before** downconverting it to an intermediate frequency. Therefore, minimal insertion losses are present and the LNB's mixer does not degrade the SNR considerably.

Instead, the VHF, UHF, and S-band architectures have significant insertion losses before the signal is amplified, and their first-stage amplifiers are noisier than the one used by the X-band Ground Station receiver. Consequently, their noise figures are higher. In particular, the S-band receiver (Figure E.2a) uses wideband amplifiers, and thus its total noise temperature ($T_R = 490.5\ K$) is approximately 120 K higher than those of the UHF and VHF receivers (Figures E.2b, E.2c), which use narrowband active filters.

Finally, the X-band CubeSat receiver (Figure E.1b) is composed of a small cavity filter, an extremely-wideband (0.5 to 8 GHz) power amplifier, and a high noise figure mixer. Hence, the receiver's noise temperature ($T_R = 485.2\ K$) is almost ten times higher than that of the X-band Ground Station receiver.

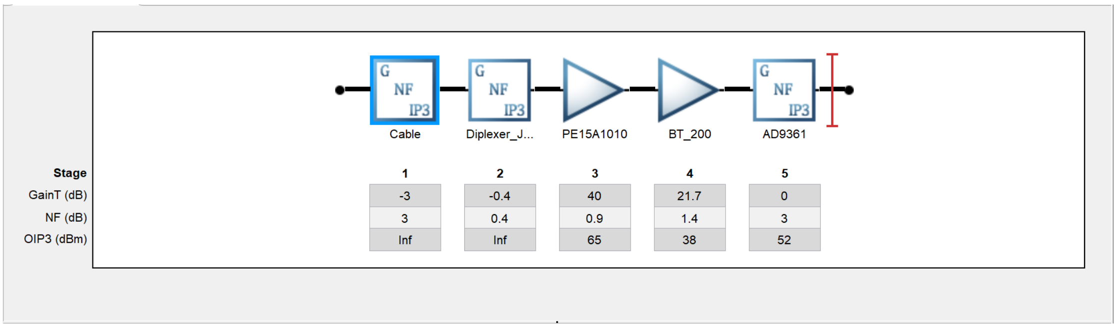


(a) Ground Station

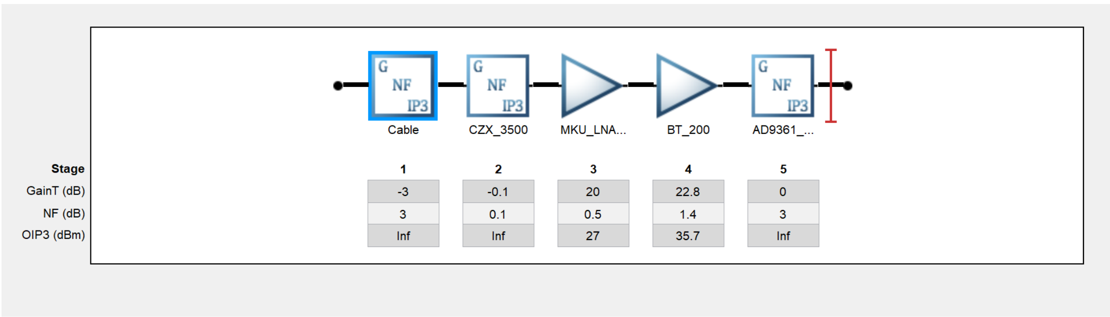


(b) CubeSat

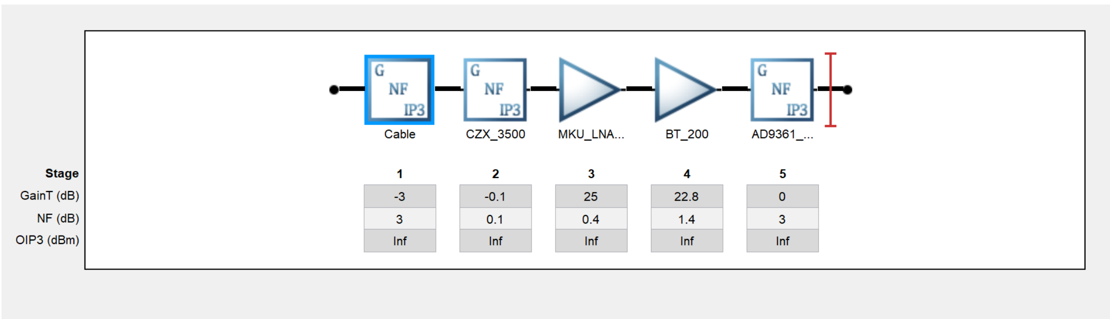
Figure E.1: X-band Receivers



(a) S-band



(b) UHF



(c) VHF

Figure E.2: S/UHF/VHF Ground Station Receivers

Appendix F

Simulation of Antenna Performance

F.1 Introduction

In this appendix, we simulate the ground station's parabolic antennas and a satellite patch antenna array to validate manufacturer specifications using Matlab's Antenna Toolbox [28][51] and Simulia's CST Microwave Studio [52].

F.2 Simulation of S-band Reflector with Helix Feed

Figure F.1 illustrates the radiation pattern of the modelled 1.2m parabolic antenna and helix feed, computed using the Method of Moments [53]. The obtained 22.2 dBi gain satisfies the requirements of Section 2.4.1, and corresponds to an antenna efficiency of 22.5%.

However, the manufacturer's specification indicates a gain of 25.5 dBi at 2.32 GHz, corresponding to an antenna efficiency of 40%. This increase in efficiency is likely due to differences in the positioning and construction of the real and the modelled helix feeds [54].

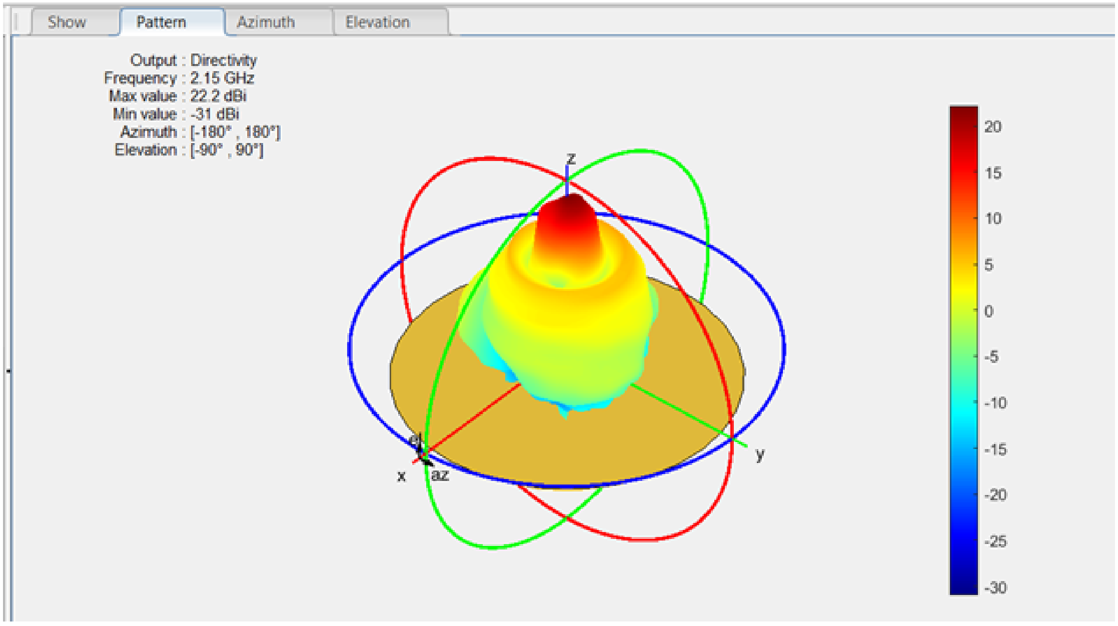


Figure F.1: Helix Feed on a 1.2m Reflector Matlab Simulation for S-band

F.3 Simulation of X-band Reflector with Horn Feed

Figure F.2 shows the radiation pattern of the offset-feed 1.2m X-band parabolic antenna and horn feed, modelled according to the manufacturer's specifications [55]. Feed positioning is accurate and we obtain a 35.4 dBi gain, matching the data-sheet [56] and satisfying the requirements of Section 2.4.1.

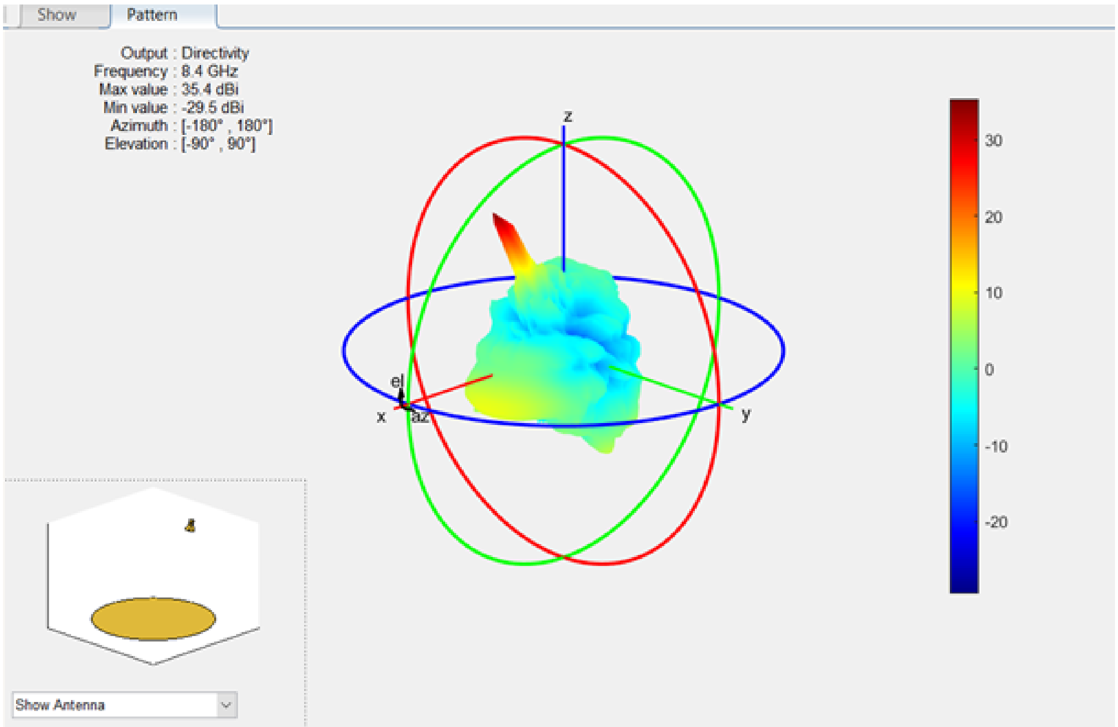


Figure F.2: Horn Feed on a 1.2m Reflector Matlab Simulation for X-band

F.4 Design and Simulation of a S-band Patch Antenna Array

To assist the design of the ground station and future CubeSatTeam missions, we designed and simulated a S-band patch antenna array with 4 elements in a broad-side configuration, fed by a corporate beam-forming network.

We started with the target objectives of:

1. Resonance frequency of $f_0 = 2.45\ GHz$
2. Input reflection parameter of $S_{ii} \leq -20\ dB$
3. Input impedance of $Z_{in} \approx 50\Omega$
4. FR-4 Substrate ($\epsilon_r = 4.3$)

Then, we designed a transmission-line fed patch antenna using the procedure described in [57]:

1. Defining the patch length L as $\frac{L}{\lambda} = 0.2$, where $\lambda = \frac{c}{f}$ is the design wavelength.

2. Using normalized patch impedance graphs and approximating the patch width $\frac{W}{\lambda} \approx 0.525$.

3. Applying a correction to patch length:

   (a) Computing the effective permissivity of the material $\epsilon_{r,eff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2} * (1 + 10 * \frac{h}{W})^{-2}$, where h is the substrate height.

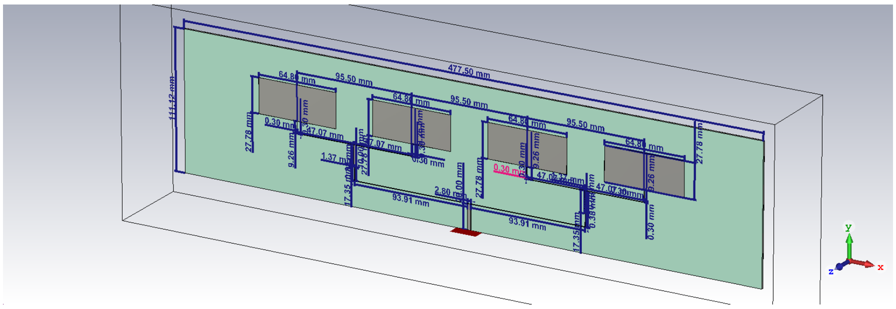
   (b) Computing the correction to the patch length $\Delta_L = h * 0.412 * \frac{\epsilon_r+0.3}{\epsilon_r-0.258} * \frac{\frac{W}{h}+0.264}{\frac{W}{h}+0.8}$.

   (c) Computing the final patch length $L = \frac{1}{2} * \frac{\lambda}{\sqrt{\epsilon_{r,eff}}} - 2 * \Delta_L$.

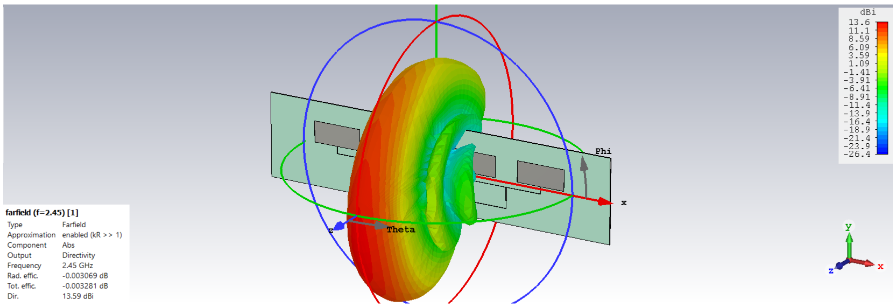
Then, the resulting patch was improved using CST Microwave Studio's Finite Difference Time Domain solver and its optimizer. Next, we combined the four patches into a uniformly spaced linear array designed to maximize the directivity of the antenna in the broadside direction ($\Theta = 90°$) [53], obtaining a 6 dB array gain.

At this point, all elements were connected by a corporate beam-forming network that feeds them with currents of equal magnitude and phase. Tapered junctions were used to minimize losses and the distance between array elements was slightly increased to reduce inter-element coupling. Finally, quarter-wave transformers were used to achieve the target 50 Ohm input impedance.

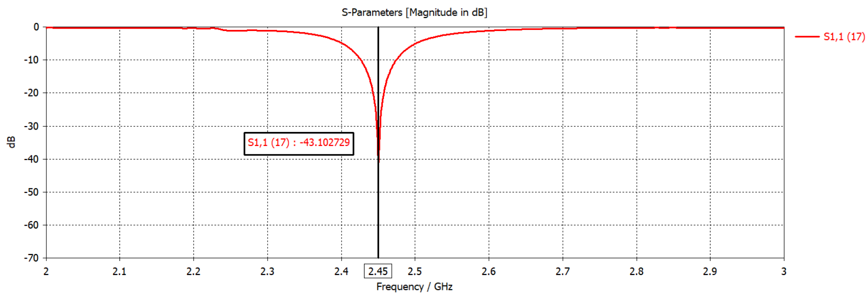
The results of this process are shown in Figure F.3, where all target goals have been achieved, obtaining a 13 dBi patch-array with very low reflection loss and 50 Ohm impedance over a bandwidth of approximately 15 MHz.



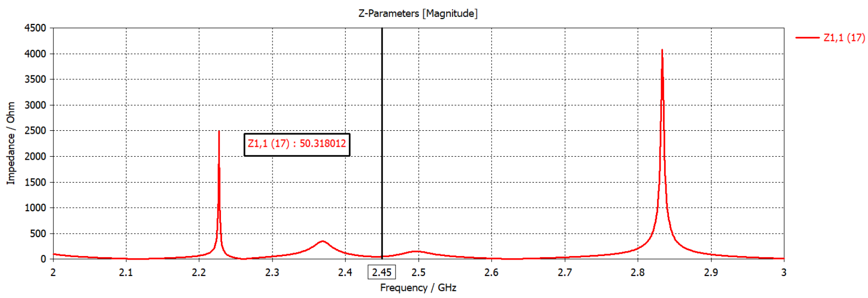
(a) Designed Patch Antenna



(b) Radiation Pattern of the Antenna



(c) Radiation Pattern of the Antenna



(d) Input Impedance of the Antenna

Figure F.3: Patch Array Design

Appendix G

Link Budget Calculations

G.1 Introduction

This appendix details the calculations performed in the link budget analyses [13][14] of Section 2.5.9. For more information regarding the receiver noise temperatures, Appendix E can be consulted.

G.2 X-band Link Budgets

G.2.1 Uplink

Starting from the system parameters:

$$\begin{cases} \text{LDPC(128,64) @ BER = 1E-12} & E_b/N_0\big|_{target} = 5\ dB \\ \text{LDPC(128,64) code-rate} & R_{code} = 1/2 \\ \text{Target bit-rate} & R_{b,net} = 64\ kbps \\ \text{QPSK Modulation} & m = 2 \text{ bits/symbol} \\ \text{Required margin} & \mu = 6\ dB \\ \text{Uplink Carrier Frequency} & f = 8.1\ GHz \\ \text{Antenna height} & h_A = 20\ m \\ \text{Satellite altitude} & h_{sat} = 400\ km \\ \text{Elevation angle} & \theta_{el} = 5° \\ \text{Rainfall rate} & R_{rain} = 12\ mm/h \\ \text{Receiver noise temperature} & T_{sys} = 485.2\ K \\ \text{Antenna temperature} & T_{ant} = 290\ K \end{cases}$$

We compute the gross bitrate:

$$R_{b,gross} = R_{b,net}/R_{code} = 128\ kbps \tag{G.1}$$

From it, we obtain the symbol-rate:

$$R_s = R_b/m = 64\ ksps \tag{G.2}$$

And the bandwidth occupied by the transmitted signal:

$$B = (1+\rho)R_s = 76.8\ kHz \tag{G.3}$$

In the transmitter, we have the following losses:

$$\begin{cases} L_{rx\ reject\ filter} = 0.35\ dB \\ L_{mismatch} = 0.04\ dB^1 \\ L_{waveguide} = 0.15\ dB \end{cases}$$

Considering the ground station's properties:

$$\begin{cases} P_{tx} = 36\ dBm \\ G_{tx} = 36.9\ dB \end{cases}$$

We compute the EIRP:

$$\begin{aligned} EIRP = P_{tx} + G_{tx} - L_{rx\ reject\ filter} - L_{mismatch} - L_{waveguide} = \\ = 36 + 36.9 - 0.35 - 0.04 - 0.15 = 72.36\ dBm \end{aligned} \tag{G.4}$$

Now, we account for the propagation of the signal through free-space. The user-to-satellite range is given by [58]:

$$r_{ue} = -R_e sin(\theta_{el}) + \sqrt{R_e^2(\sin^2\theta_{el} - 1) + r_{SV}^2} \approx 1800\ km \tag{G.5}$$

Where

$$\begin{cases} R_e = 6371\ km \text{ is the Earth's radius} \\ r_{SV} = R_e + h_{sat} = 6771\ km \text{ is the distance} \\ \text{from the satellite to the centre of the Earth} \\ \theta_{el} = 5° \text{ is the elevation angle} \end{cases}$$

Using the range, we calculate the free space path loss:

$$FSPL = 20\log_{10}(\frac{4\pi f r_{ue}}{c}) = 175.73\ dB \tag{G.6}$$

Where $c \approx 3 * 10^8\ m/s$ is the speed of light.
Rain attenuation is given by [59] [2]:

$$\gamma_R = kR_{rain}^{\alpha} = 0.004115 * 12^{1.3905} = 0.1303\ dB/km \tag{G.7}$$

The signal propagates through a layer of $h_R = 4\ km$ of rain[3] [13]. Considering the elevation angle, the effective distance is:

$$d_{eff} = \frac{h_R - h_A}{\sin\theta_{el}} = 45.65\ km \tag{G.8}$$

And the total rain attenuation:

$$L_{rain} = \gamma_R d_{eff} = 5.95\ dB \tag{G.9}$$

Accounting for atmospheric, polarization and pointing losses

$$\begin{cases} L_{atm} = 1\ dB \\ L_{pol} = 0.25\ dB \\ L_{point} = 0.1\ dB \end{cases}$$

The total propagation loss is

$$\begin{aligned} PL &= FSPL + L_{atm} + L_{pol} + L_{point} + L_{rain} = \\ &= 175.73 + 1 + 0.25 + 0.1 + 5.95 = 183.03\ dB \end{aligned} \tag{G.10}$$

Moreover, rain reduces the radiation modulation effects of the atmosphere [60], increasing the antenna temperature [14]:

$$T_{A,R} = \frac{T_{ant} + 290(L_{rain} - 1)}{L_{rain}} == \frac{290 + 290(3.936 - 1)}{3.936} = 290.00\ K \tag{G.11}$$

At this point, we compute the received isotropic power:

$$P_{rx,iso} = EIRP - PL = -110.67\ dBm \tag{G.12}$$

Considering the receiver's antenna gain and the receiver's losses

$$\begin{cases} G_{rx} = 16\ dB \\ L_{tx\ reject\ filter} = 1.75\ dB \\ L_{cable} = 0.2\ dB \\ L_{mismatch} = 1.2\ dB^{4} \end{cases}$$

[2]We consider the maximum attenuation between the horizontal and vertical polarization components.

[3]Zero degree isotherm.

we obtain the received signal power:

$$P_{rx,sig} = P_{rx,iso} + G_{rx} - L_{tx\ reject\ filter} - L_{waveguide} - L_{mismatch} = \\ = -110.67 + 16 - 1.75 - 0.2 - 1.2 = -97.82\ dBm \tag{G.13}$$

We determine the equivalent noise temperature of the system:

$$T_{sys} = T_{rec} + T_{A,R} = 485.2 + 290 = 775.2\ K \tag{G.14}$$

And the total noise power:

$$P_{noise} = 10\log_{10}(kBT_{sys}) = 10\log_{10}(1.38 * 10^{-23} * 76.8 * 10^{3} * 775.2) = \\ = -150.85\ dBW = -120.85\ dBm \tag{G.15}$$

Where $k = 1.38 * 10^{-23}\ JK^{-1}$ is the Boltzmann constant.

Next, we compute the performance metrics of the system:

$$\begin{cases} G/T = G_{rx} - 10\log_{10} T_{sys} = 16 - 28.89 = -12.89\ dBK^{-1} \\ SNR = P_{rx,sig} - P_{noise} = -97.82 + 120.85 = 23.03\ dB \\ C/N0 = SNR + 10\log_{10} B = 23.03 + 48.85 = 71.88\ dBm/Hz \\ E_b/N_0|_{info} = SNR - 10\log_{10}(R_{b,gross}/B) = 20.82\ dB \end{cases}$$

Finally, accounting for a 1 dB implementation loss, the system's margin is:

$$M = E_b/N_0|_{info} - E_b/N_0|_{min} - L_{impl} = 20.82 - 5 - 1 = 14.82\ dB > 6\ dB = \mu \tag{G.16}$$

And the link is closed.

G.2.2 Downlink

Starting from the system parameters:

$$\begin{cases} \text{LDPC(16384,8192) @ BER = 1E-6} & E_b/N_0\Big|_{target} = 1\ dB \\ \text{LDPC(16384,8192) code-rate} & R_{code} = 1/2 \\ \text{Target bit-rate} & R_{b,net} = 1\ Mbps \\ \text{QPSK Modulation} & m = 2 \text{ bits/symbol} \\ \text{Required margin} & \mu = 6\ dB \\ \text{Downlink Carrier Frequency} & f = 7.5\ GHz \\ \text{Antenna height} & h_A = 20\ m \\ \text{Satellite altitude} & h_{sat} = 400\ km \\ \text{Elevation angle} & \theta_{el} = 5° \\ \text{Rainfall rate} & R_{rain} = 12\ mm/h \\ \text{Receiver noise temperature} & T_{rec} = 50.72\ K \\ \text{Antenna temperature} & T_{ant} = 50\ K \end{cases}$$

We compute the gross bitrate:

$$R_{b,gross} = R_{b,net}/R_{code} = 2\ Mbps \tag{G.17}$$

From it, we obtain the symbol-rate:

$$R_s = R_b/m = 1\ Msps \tag{G.18}$$

And the bandwidth occupied by the transmitted signal:

$$B = (1+\rho)R_s = 1.2\ MHz \tag{G.19}$$

In the transmitter, we have the following losses:

$$\begin{cases} L_{rx\ reject\ filter} = 1\ dB \\ L_{cable} = 0.2\ dB \\ L_{mismatch} = 0.04\ dB^5 \\ L_{connector} = 0.3\ dB \end{cases}$$

Considering the satellite's properties:

$$\begin{cases} P_{tx} = 33\ dBm \\ G_{tx} = 16\ dB \end{cases}$$

We compute the EIRP:

$$EIRP = P_{tx} + G_{tx} - L_{rx\ reject\ filter} - L_{cable} - L_{mismatch} - L_{connector} = \\ = 33 + 16 - 1 - 0.2 - 0.04 - 0.3 = 47.46\ dBm \tag{G.20}$$

Now, we account for the propagation of the signal through free-space. The user-to-satellite range is given by [58]:

$$r_{ue} = -R_e sin(\theta_{el}) + \sqrt{R_e^2(\sin^2\theta_{el} - 1) + r_{SV}^2} \approx 1800\ km \tag{G.21}$$

Where

$$\begin{cases} R_e = 6371\ km \text{ is the Earth's radius} \\ r_{SV} = R_e + h_{sat} = 6771\ km \text{ is the distance} \\ \text{from the satellite to the centre of the Earth} \\ \theta_{el} = 5° \text{ is the elevation angle} \end{cases}$$

Using the range, we calculate the free space path loss:

$$FSPL = 20\log_{10}(\frac{4\pi f r_{ue}}{c}) = 175.06\ dB \tag{G.22}$$

Where $c \approx 3 * 10^8\ m/s$ is the speed of light.
Rain attenuation is given by [59] [6]:

$$\gamma_R = kR_{rain}^{\alpha} = 0.001915 * 12^{1.4802} = 0.0757\ dB/km \tag{G.23}$$

The signal propagates through a layer of $h_R = 4\ km$ of rain[7] [13]. Considering the elevation angle, the effective distance is:

$$d_{eff} = \frac{h_R - h_A}{\sin\theta_{el}} = 45.65\ km \tag{G.24}$$

And the total rain attenuation:

$$L_{rain} = \gamma_R d_{eff} = 3.46\ dB \tag{G.25}$$

Accounting for atmospheric, polarization and pointing losses

$$\begin{cases} L_{atm} = 1\ dB \\ L_{pol} = 0.25\ dB \\ L_{point} = 0.1\ dB \end{cases}$$

[6] We consider the maximum attenuation between the horizontal and vertical polarization components.

[7] Zero degree isotherm.

The total propagation loss is

$$\begin{aligned} PL &= FSPL + L_{atm} + L_{pol} + L_{point} + L_{rain} = \\ &= 175.06 + 1 + 0.25 + 0.1 + 3.46 = 179.87\ dB \end{aligned} \tag{G.26}$$

Moreover, rain reduces the radiation modulation effects of the atmosphere [60], increasing the antenna temperature [14]:

$$T_{A,R} = \frac{T_{ant} + 290(L_{rain} - 1)}{L_{rain}} == \frac{50 + 290(2.2185 - 1)}{2.2185} = 181.82\ K \tag{G.27}$$

At this point, we compute the received isotropic power:

$$P_{rx,iso} = EIRP - PL = -132.41\ dBm \tag{G.28}$$

Considering the receiver's antenna gain and losses

$$\begin{cases} G_{rx} = 37.5\ dB \\ L_{tx\ reject\ filter} = 0.25\ dB \\ L_{waveguide} = 0.15\ dB \\ L_{mismatch} = 0.04\ dB^{8} \end{cases}$$

we obtain the received signal power:

$$\begin{aligned} P_{rx,sig} &= P_{rx,iso} + G_{rx} - L_{tx\ reject\ filter} - L_{waveguide} - L_{mismatch} = \\ &= -132.41 + 37.5 - 0.25 - 0.15 - 0.04 = -95.35\ dBm \end{aligned} \tag{G.29}$$

We determine the equivalent noise temperature of the system:

$$T_{sys} = T_{rec} + T_{A,R} = 50.72 + 181.82 = 232.54\ K \tag{G.30}$$

And the total noise power:

$$\begin{aligned} P_{noise} &= 10\log_{10}(kBT_{sys}) = 10\log_{10}(1.38 * 10^{-23} * 1.2 * 10^{6} * 232.54) = \\ &= -144.14\ dBW = -114.14\ dBm \end{aligned} \tag{G.31}$$

Where $k = 1.38 * 10^{-23}\ JK^{-1}$ is the Boltzmann constant.

Next, we compute the performance metrics of the system:

$$\begin{cases} G/T = G_{rx} - 10\log_{10} T_{sys} = 13.83\ dBK^{-1} \\ SNR = P_{rx,sig} - P_{noise} = 18.78\ dB \\ C/N0 = SNR + 10\log_{10} B = 18.78 + 60.79 = 79.58\ dBm/Hz \\ E_b/N_0|_{info} = SNR - 10\log_{10}(R_{b,gross}/B) = 16.56\ dB \end{cases}$$

Finally, accounting for a 1 dB implementation loss, the system's margin is:

$$M = E_b/N_0|_{info} - E_b/N_0|_{min} - L_{impl} = 16.56 - 1 - 1 = 14.56\ dB > 6\ dB = \mu \tag{G.32}$$

And the link is closed.

G.3 S-band Link Budget

G.3.1 Uplink

Starting from the system parameters:

$$\begin{cases} \text{LDPC(128,64) @ BER = 1E-12} & E_b/N_0\Big|_{target} = 5\ dB \\ \text{LDPC(128,64) code-rate} & R_{code} = 1/2 \\ \text{Target bit-rate} & R_{b,net} = 64\ kbps \\ \text{QPSK Modulation} & m = 2 \text{ bits/symbol} \\ \text{Required margin} & \mu = 6\ dB \\ \text{Uplink Carrier Frequency} & f = 2.205\ GHz \\ \text{Antenna height} & h_A = 20\ m \\ \text{Satellite altitude} & h_{sat} = 400\ km \\ \text{Elevation angle} & \theta_{el} = 5° \\ \text{Rainfall rate} & R_{rain} = 12\ mm/h \\ \text{Receiver noise temperature} & T_{rec} = 490.5\ K \\ \text{Antenna temperature} & T_{ant} = 290\ K \end{cases}$$

We compute the gross bitrate required:

$$R_{b,gross} = R_{b,net}/R_{code} = 128\ kbps \tag{G.33}$$

And the symbol-rate:

$$R_s = R_b/m = 64\ ksps \tag{G.34}$$

And the bandwidth occupied by the transmitted signal:

$$B = (1 + \rho)R_s = 78.6\ kHz \tag{G.35}$$

In the transmitter, we have the following losses:

$$\begin{cases} L_{diplexer} = 0.4\ dB \\ L_{cable} = 3\ dB \\ L_{mismatch} = 0.04\ dB^{9} \\ L_{connector} = 0.4\ dB \end{cases}$$

Considering the ground station's properties:

$$\begin{cases} P_{tx} = 36\ dBm \\ G_{tx} = 25.5\ dB \end{cases}$$

We compute the EIRP:

$$\begin{aligned} EIRP = P_{tx} + G_{tx} - L_{rx\ reject\ filter} - L_{cable} - L_{mismatch} - L_{connector} = \\ = 36 + 25.5 - 0.4 - 3 - 0.04 - 0.4 = 57.66\ dBm \end{aligned} \tag{G.36}$$

Now, we must account for the signal propagation through free space. The user-to-satellite range is given by [58]:

$$r_{ue} = -R_e sin(\theta_{el}) + \sqrt{R_e^2(\sin^2\theta_{el} - 1) + r_{SV}^2} \approx 1800\ km \tag{G.37}$$

Where

$$\begin{cases} R_e = 6371\ km \text{ is the Earth's radius} \\ r_{SV} = R_e + h_{sat} = 6771\ km \text{ is the distance} \\ \text{from the satellite to the centre of the Earth} \\ \theta_{el} = 5° \text{ is the elevation angle} \end{cases}$$

Using the range, we calculate the free space path loss:

$$FSPL = 20\log_{10}(\frac{4\pi f r_{ue}}{c}) = 164.43\ dB \tag{G.38}$$

Where $c \approx 3 * 10^8\ m/s$ is the speed of light.
Rain attenuation is given by [59] [10]:

$$\gamma_R = kR_{rain}^{\alpha} = 0.0000847 * 12^{1.0664} = 0.0012\ dB/km \tag{G.39}$$

The signal propagates through a layer of $h_R = 4\ km$ of rain[11] [13]. Considering the elevation angle, the effective distance is:

$$d_{eff} = \frac{h_R - h_A}{\sin\theta_{el}} = 45.65\ km \tag{G.40}$$

And the total rain attenuation:

$$L_{rain} = \gamma_R d_{eff} = 0.0547\ dB \tag{G.41}$$

[10] We consider the maximum attenuation between the horizontal and vertical polarization components.

[11] Zero degree isotherm.

Accounting for atmospheric, ionospheric, polarization and pointing losses

$$\begin{cases} L_{atm} = 1\ dB \\ L_{pol} = 0.25\ dB \\ L_{point} = 0.1\ dB \\ L_{ion} = 0.1\ dB \end{cases}$$

The total propagation loss is

$$\begin{aligned} PL = FSPL + L_{atm} + L_{pol} + L_{point} + L_{ion} + L_{rain} = \\ = 164.43 + 1 + 0.25 + 0.1 + 0.1 + 0.0547 = 165.93\ dB \end{aligned} \tag{G.42}$$

Moreover, rain reduces the radiation modulation effects of the atmosphere [60], increasing the antenna temperature [14]:

$$T_{A,R} = \frac{T_{ant} + 290(L_{rain} - 1)}{L_{rain}} == \frac{290 + 290(1.0127 - 1)}{1.0127} = 290.00\ K \tag{G.43}$$

At this point, we compute the received isotropic power:

$$P_{rx,iso} = EIRP - PL = -108.27\ dBm \tag{G.44}$$

Considering the receiver's antenna gain and the receiver's losses

$$\begin{cases} G_{rx} = 13\ dB \\ L_{diplexer} = 0.4\ dB \\ L_{cable} = 0.2\ dB \\ L_{mismatch} = 0.04\ dB^{12} \end{cases}$$

we obtain the received signal power:

$$\begin{aligned} P_{rx,sig} = P_{rx,iso} + G_{rx} - L_{diplexer} - L_{cable} - L_{mismatch} = \\ = -108.27 + 13 - 0.4 - 0.2 - 0.04 = -95.91\ dBm \end{aligned} \tag{G.45}$$

We determine the equivalent noise temperature of the system:

$$T_{sys} = T_{rec} + T_{A,R} = 485 + 290 = 775.00\ K \tag{G.46}$$

And the total noise power:

$$\begin{aligned} P_{noise} = 10\log_{10}(kBT_{sys}) = 10\log_{10}(1.38 * 10^{-23} * 76.8 * 10^{3} * 775.00) = \\ = -150.85\ dBW = -120.85\ dBm \end{aligned} \tag{G.47}$$

Where $k = 1.38 * 10^{-23}\ JK^{-1}$ is the Boltzmann constant.

Next, we compute the performance metrics of the system:

$$\begin{cases} G/T = G_{rx} - 10\log_{10} T_{sys} = -15.89\ dBK^{-1} \\ SNR = P_{rx,sig} - P_{noise} = -95.91 + 120.85 = 24.93\ dB \\ C/N0 = SNR + 10\log_{10} B = 24.93 + 48.85 = 73.78\ dBm/Hz \\ E_b/N_0|_{info} = SNR - 10\log_{10}(R_{b,gross}/B) = 24.93 - 2.22 = 22.71\ dB \end{cases}$$

Finally, accounting for a 1 dB implementation loss, the system's margin is:

$$M = E_b/N_0|_{info} - E_b/N_0|_{min} - L_{impl} = 22.71 - 5 - 1 = 16.71\ dB > 6\ dB = \mu \tag{G.48}$$

And the link is closed.

G.3.2 Downlink

Starting from the system parameters:

$$\begin{cases} \text{LDPC(16384,8192) @ BER = 1E-6} & E_b/N_0\big|_{target} = 1\ dB \\ \text{LDPC(16384,8192) code-rate} & R_{code} = 1/2 \\ \text{Target bit-rate} & R_{b,net} = 1\ Mbps \\ \text{QPSK Modulation} & m = 2 \text{ bits/symbol} \\ \text{Required margin} & \mu = 6\ dB \\ \text{Downlink Carrier Frequency} & f = 2.105\ GHz \\ \text{Antenna height} & h_A = 20\ m \\ \text{Satellite altitude} & h_{sat} = 400\ km \\ \text{Elevation angle} & \theta_{el} = 5° \\ \text{Rainfall rate} & R_{rain} = 12\ mm/h \\ \text{Receiver noise temperature} & T_{rec} = 490.5\ K \\ \text{Antenna temperature} & T_{ant} = 50\ K \end{cases}$$

We compute the gross bitrate:

$$R_{b,gross} = R_{b,net}/R_{code} = 2\ Mbps \tag{G.49}$$

The symbol-rate:

$$R_s = R_b/m = 1\ Msps \tag{G.50}$$

And the bandwidth occupied by the transmitted signal:

$$B = (1+\rho)R_s = 1.2\ MHz \tag{G.51}$$

In the transmitter, we have the following losses:

$$\begin{cases} L_{rx\ reject\ filter} = 1\ dB \\ L_{cable} = 0.2\ dB \\ L_{mismatch} = 0.04\ dB^{13} \\ L_{connector} = 0.4\ dB \end{cases}$$

Considering the satellite's properties:

$$\begin{cases} P_{tx} = 33\ dBm \\ G_{tx} = 13\ dB \end{cases}$$

$$\begin{aligned} EIRP = P_{tx} + G_{tx} - L_{rx\ reject\ filter} - L_{cable} - L_{mismatch} - L_{connector} = \\ = 33 + 13 - 1 - 0.2 - 0.04 - 0.4 = 44.36\ dBm \end{aligned} \tag{G.52}$$

Now, we account for the propagation of the signal through free-space. The user-to-satellite range is given by [58]:

$$r_{ue} = -R_e sin(\theta_{el}) + \sqrt{R_e^2(\sin^2\theta_{el} - 1) + r_{SV}^2} \approx 1800\ km \tag{G.53}$$

Where

$$\begin{cases} R_e = 6371\ km \text{ is the Earth's radius} \\ r_{SV} = R_e + h_{sat} = 6771\ km \text{ is the distance} \\ \text{from the satellite to the centre of the Earth} \\ \theta_{el} = 5° \text{ is the elevation angle} \end{cases}$$

Using the range, we calculate the free space path loss:

$$FSPL = 20\log_{10}(\frac{4\pi f r_{ue}}{c}) = 164.03\ dB \tag{G.54}$$

Where $c \approx 3 * 10^8\ m/s$ is the speed of light.
Rain attenuation is given by [59] [14]:

$$\gamma_R = kR_{rain}^{\alpha} = 0.0000847 * 12^{1.0664} = 0.0012\ dB/km \tag{G.55}$$

The signal propagates through a layer of $h_R = 4\ km$ of rain[15] [13]. Considering the elevation angle, the effective distance is:

$$d_{eff} = \frac{h_R - h_A}{\sin\theta_{el}} = 45.65\ km \tag{G.56}$$

[14] We consider the maximum attenuation between the horizontal and vertical polarization components.

[15] Zero degree isotherm.

And the total rain attenuation:

$$L_{rain} = \gamma_R d_{eff} = 0.0547\ dB \tag{G.57}$$

Accounting for atmospheric, ionospheric, polarization, and pointing losses

$$\begin{cases} L_{atm} = 1\ dB \\ L_{pol} = 0.25\ dB \\ L_{point} = 0.1\ dB \\ L_{ion} = 0.1\ dB \end{cases}$$

The total propagation loss is

$$\begin{aligned} PL = FSPL + L_{atm} + L_{pol} + L_{point} + L_{ion} + L_{rain} = \\ = 164.03 + 1 + 0.25 + 0.1 + 0.1 + 0.0547 = 165.53\ dB \end{aligned} \tag{G.58}$$

Moreover, the presence of rain reduces the radiation modulation effects of the atmosphere [60], increasing the overall noise by T_{rain} [14]:

$$T_{A,R} = \frac{T_{ant} + 290(L_{rain} - 1)}{L_{rain}} == \frac{50 + 290(1.0127 - 1)}{1.0127} = 53.00\ K \tag{G.59}$$

At this point, we compute the received isotropic power:

$$P_{rx,iso} = EIRP - PL = 44.36 - 165.53 = -121.17\ dBm \tag{G.60}$$

Considering the receiver's antenna gain and the receiver's losses

$$\begin{cases} G_{rx} = 25.10\ dB \\ L_{diplexer} = 0.4\ dB \\ L_{cable} = 3\ dB \\ L_{mismatch} = 0.04\ dB^{16} \end{cases}$$

we obtain the received signal power:

$$\begin{aligned} P_{rx,sig} = P_{rx,iso} + G_{rx} - L_{diplexer} - L_{cable} - L_{mismatch} = \\ = -121.17 + 25.1 - 0.4 - 3 - 0.04 = -99.51\ dBm \end{aligned} \tag{G.61}$$

To estimate the noise power, we determine the equivalent noise temperature of the system:

$$T_{sys} = T_{rec} + T_{A,R} = 490.50 + 53.00 = 543.50\ K \tag{G.62}$$

And the total noise power:

$$P_{noise} = 10\log_{10}(kBT_{sys}) = 10\log_{10}(1.38 * 10^{-23} * 1.2 * 10^{6} * 543.50) = \\ = -140.45\ dBW = -110.45\ dBm \quad \text{(G.63)}$$

Where $k = 1.38 * 10^{-23}\ JK^{-1}$ is the Boltzmann constant.

Next, we compute the performance metrics of the system:

$$\begin{cases} G/T = G_{rx} - 10\log_{10} T_{sys} = -2.25\ dBK^{-1} \\ SNR = P_{rx,sig} - P_{noise} = -99.51 + 110.45 = 10.94\ dB \\ C/N0 = SNR + 10\log_{10} B = 10.94 + 60.79 = 71.73\ dBm/Hz \\ E_b/N_0|_{info} = SNR - 10\log_{10}(R_{b,gross}/B) = 10.94 - 2.22 = 8.72\ dB \end{cases}$$

Finally, accounting for a 1 dB implementation loss, the system's margin is:

$$M = E_b/N_0|_{info} - E_b/N_0|_{min} - L_{impl} = 8.72 - 1 - 1 = 6.72\ dB > 6\ dB = \mu \quad \text{(G.64)}$$

And the link is closed.

G.4 UHF Link Budget

G.4.1 Uplink

Starting from the system parameters:

$$\begin{cases} \text{Uncoded BPSK @ BER = 1E-8} & E_b/N_0\Big|_{target} = 12\ dB \\ \text{Target bit-rate} & R_b = 64\ kbps \\ \text{QPSK Modulation} & m = 2\ \text{bits/symbol} \\ \text{Required margin} & \mu = 6\ dB \\ \text{Uplink Carrier Frequency} & f = 435\ MHz \\ \text{Antenna height} & h_A = 20\ m \\ \text{Satellite altitude} & h_{sat} = 400\ km \\ \text{Elevation angle} & \theta_{el} = 8^\circ \\ \text{Receiver noise temperature} & T_{rec} = 485\ K \\ \text{Antenna temperature} & T_{ant} = 290\ K \end{cases}$$

We compute the symbol-rate:

$$R_s = R_b/m = 32\ ksps \quad \text{(G.65)}$$

And the bandwidth occupied by the transmitted signal:

$$B = (1+\rho)R_s = 38.4\ kHz \tag{G.66}$$

In the transmitter, we have the following losses:

$$\begin{cases} L_{TR\ switch} = 0.1\ dB \\ L_{cable} = 3\ dB \\ L_{mismatch} = 0.04\ dB^{17} \\ L_{connector} = 0.4\ dB \end{cases}$$

Considering the ground station's properties:

$$\begin{cases} P_{tx} = 47\ dBm \\ G_{tx} = 15\ dB \end{cases}$$

We compute the EIRP:

$$\begin{aligned} EIRP = P_{tx} + G_{tx} - L_{TR\ switch} - L_{cable} - L_{mismatch} - L_{connector} = \\ = 47 + 15 - 0.1 - 3 - 0.04 - 0.4 = 58.46\ dBm \end{aligned} \tag{G.67}$$

Now, we account for the signal propagation through free space. The user-to-satellite range is given by [58]:

$$r_{ue} = -R_e sin(\theta_{el}) + \sqrt{R_e^2(\sin^2\theta_{el} - 1) + r_{SV}^2} \approx 1570\ km \tag{G.68}$$

Where

$$\begin{cases} R_e = 6371\ km \text{ is the Earth's radius} \\ r_{SV} = R_e + h_{sat} = 6771\ km \text{ is the distance} \\ \text{from the satellite to the centre of the Earth} \\ \theta_{el} = 8^\circ \text{ is the elevation angle} \end{cases}$$

Using the range, we calculate the free space path loss:

$$FSPL = 20\log_{10}(\frac{4\pi f r_{ue}}{c}) = 149.13\ dB \tag{G.69}$$

Where $c \approx 3 * 10^8\ m/s$ is the speed of light.
Accounting for atmospheric, ionospheric, polarization and pointing losses

$$\begin{cases} L_{atm} = 1\ dB \\ L_{pol} = 0.25\ dB \\ L_{point} = 0.1\ dB \\ L_{ion} = 1\ dB \end{cases}$$

The total propagation loss is

$$\begin{aligned} PL = FSPL + L_{atm} + L_{pol} + L_{point} + L_{ion} = \\ = 149.13 + 1 + 0.25 + 0.1 + 1 = 151.48\ dB \end{aligned} \tag{G.70}$$

At this point, we compute the received isotropic power:

$$P_{rx,iso} = EIRP - PL = 58.46 - 151.48 = -93.02\ dBm \tag{G.71}$$

Considering the receiver's antenna gain and the receiver's losses

$$\begin{cases} G_{rx} = 2.14\ dB \\ L_{TR\ switch} = 0.1\ dB \\ L_{cable} = 1\ dB \\ L_{mismatch} = 0.04\ dB^{18} \end{cases}$$

we obtain the received signal power:

$$\begin{aligned} P_{rx,sig} = P_{rx,iso} + G_{rx} - L_{TR\ switch} - L_{cable} - L_{mismatch} = \\ = -93.02 + 2.14 - 0.1 - 1 - 0.04 = -92.02\ dBm \end{aligned} \tag{G.72}$$

We determine the equivalent noise temperature of the system:

$$T_{sys} = T_{rec} + T_{ant} = 485 + 290 = 775.00\ K \tag{G.73}$$

And the total noise power:

$$\begin{aligned} P_{noise} = 10\log_{10}(kBT_{sys}) = 10\log_{10}(1.38 * 10^{-23} * 38.4 * 10^{3} * 775.00) = \\ = -153.86\ dBW = -123.86\ dBm \end{aligned} \tag{G.74}$$

Where $k = 1.38 * 10^{-23}\ JK^{-1}$ is the Boltzmann constant.

Next, we compute the performance metrics of the system:

$$\begin{cases} G/T = G_{rx} - 10\log_{10} T_{sys} = -26.75\ dBK^{-1} \\ SNR = P_{rx,sig} - P_{noise} = -92.02 + 123.86 = 31.84\ dB \\ C/N0 = SNR + 10\log_{10} B = 31.84 + 45.84 = 77.68\ dBm/Hz \\ E_b/N_0|_{info} = SNR - 10\log_{10}(R_{b,gross}/B) = 29.61\ dB \end{cases}$$

Finally, accounting for a 1 dB implementation loss, the system's margin is:

$$M = E_b/N_0|_{info} - E_b/N_0|_{min} - L_{impl} = 29.61 - 12 - 1 = 16.61\ dB > 6\ dB = \mu \tag{G.75}$$

And the link is closed.

G.4.2 Downlink

Starting from the system parameters:

$$\begin{cases} \text{Uncoded BPSK @ BER = 1E-6} & E_b/N_0\big|_{target} = 9.6\ dB \\ \text{Target bit-rate} & R_b = 100\ kbps \\ \text{QPSK Modulation} & m = 2 \text{ bits/symbol} \\ \text{Required margin} & \mu = 3\ dB \\ \text{Downlink Carrier Frequency} & f = 435\ MHz \\ \text{Antenna height} & h_A = 20\ m \\ \text{Satellite altitude} & h_{sat} = 400\ km \\ \text{Elevation angle} & \theta_{el} = 8° \\ \text{Receiver noise temperature} & T_{rec} = 375.9\ K \\ \text{Antenna temperature} & T_{ant} = 290\ K \end{cases}$$

We compute the symbol-rate:

$$R_s = R_b/m = 50\ ksps \tag{G.76}$$

And the bandwidth occupied by the transmitted signal:

$$B = (1+\rho)R_s = 60\ kHz \tag{G.77}$$

In the transmitter, we have the following losses:

$$\begin{cases} L_{TR\ switch} = 0.1\ dB \\ L_{cable} = 1\ dB \\ L_{mismatch} = 0.04\ dB^{19} \\ L_{connector} = 0.4\ dB \end{cases}$$

Considering the satellite's properties:

$$\begin{cases} P_{tx} = 33\ dBm \\ G_{tx} = 2.14\ dB \end{cases}$$

We compute the EIRP:

$$\begin{aligned} EIRP = P_{tx} + G_{tx} - L_{TR\ switch} - L_{cable} - L_{mismatch} - L_{connector} = \\ = 33 + 2.14 - 0.1 - 1 - 0.04 - 0.4 = 33.60\ dBm \end{aligned} \tag{G.78}$$

Now, we account for the propagation of the signal through free-space. The user-to-satellite range is given by [58]:

$$r_{ue} = -R_e sin(\theta_{el}) + \sqrt{R_e^2(\sin^2\theta_{el} - 1) + r_{SV}^2} \approx 1570\ km \tag{G.79}$$

Where

$$\begin{cases} R_e = 6371\ km \text{ is the Earth's radius} \\ r_{SV} = R_e + h_{sat} = 6771\ km \text{ is the distance} \\ \text{from the satellite to the centre of the Earth} \\ \theta_{el} = 8° \text{ is the elevation angle} \end{cases}$$

Using the range, we calculate the free space path loss:

$$FSPL = 20\log_{10}(\frac{4\pi f r_{ue}}{c}) = 149.13\ dB \tag{G.80}$$

Where $c \approx 3 * 10^8\ m/s$ is the speed of light.
Accounting for atmospheric, ionospheric, polarization, and pointing losses

$$\begin{cases} L_{atm} = 1\ dB \\ L_{pol} = 0.25\ dB \\ L_{point} = 0.1\ dB \\ L_{ion} = 1\ dB \end{cases}$$

The total propagation loss is

$$\begin{aligned} PL &= FSPL + L_{atm} + L_{pol} + L_{point} + L_{ion} = \\ &= 149.13 + 1 + 0.25 + 0.1 + 1 = 151.48\ dB \end{aligned} \tag{G.81}$$

At this point, we compute the received isotropic power:

$$P_{rx,iso} = EIRP - PL = 33.60 - 151.48 = -117.88\ dBm \tag{G.82}$$

Considering the receiver's antenna gain and the receiver's losses

$$\begin{cases} G_{rx} = 15\ dB \\ L_{TR\ switch} = 0.1\ dB \\ L_{cable} = 3\ dB \\ L_{mismatch} = 0.04\ dB \end{cases}$$ [20]

we obtain the received signal power:

$$\begin{aligned} P_{rx,sig} &= P_{rx,iso} + G_{rx} - L_{TR\ switch} - L_{cable} - L_{mismatch} = \\ &= -117.88 + 15 - 0.1 - 3 - 0.04 = -106.02\ dBm \end{aligned} \tag{G.83}$$

We determine the equivalent noise temperature of the system:

$$T_{sys} = T_{rec} + T_{ant} = 375.9 + 290 = 665.90\ K \tag{G.84}$$

And the total noise power:

$$P_{noise} = 10\log_{10}(kBT_{sys}) = 10\log_{10}(1.38 * 10^{-23} * 60 * 10^{3} * 775.00) = \\ = -152.58\ dBW = -122.58\ dBm \tag{G.85}$$

Where $k = 1.38 * 10^{-23}\ JK^{-1}$ is the Boltzmann constant.

Next, we compute the performance metrics of the system:

$$\begin{cases} G/T = G_{rx} - 10\log_{10} T_{sys} = -13.23\ dBK^{-1} \\ SNR = P_{rx,sig} - P_{noise} = -106.02 + 122.58 = 16.56\ dB \\ C/N0 = SNR + 10\log_{10} B = 16.56 + 47.78 = 64.34\ dBm/Hz \\ E_b/N_0|_{info} = SNR - 10\log_{10}(R_{b,gross}/B) = 14.34\ dB \end{cases}$$

Finally, accounting for a 1 dB implementation loss, the system's margin is:

$$M = E_b/N_0|_{info} - E_b/N_0|_{min} - L_{impl} = 14.34 - 9.6 - 1 = 3.74\ dB > 3\ dB = \mu \tag{G.86}$$

And the link is closed.

G.5 VHF Link Budget

G.5.1 Uplink

Starting from the system parameters:

$$\begin{cases} \text{Uncoded BPSK @ BER = 1E-8} & E_b/N_0\Big|_{target} = 12\ dB \\ \text{Target bit-rate} & R_b = 64\ kbps \\ \text{QPSK Modulation} & m = 2 \text{ bits/symbol} \\ \text{Required margin} & \mu = 6\ dB \\ \text{Uplink Carrier Frequency} & f = 145\ MHz \\ \text{Antenna height} & h_A = 20\ m \\ \text{Satellite altitude} & h_{sat} = 400\ km \\ \text{Elevation angle} & \theta_{el} = 8° \\ \text{Receiver noise temperature} & T_{rec} = 485\ K \\ \text{Antenna temperature} & T_{ant} = 290\ K \end{cases}$$

We compute the symbol-rate:

$$R_s = R_b/m = 32\ ksps \tag{G.87}$$

And the bandwidth occupied by the transmitted signal:

$$B = (1+\rho)R_s = 38.4\ kHz \tag{G.88}$$

In the transmitter, we have the following losses:

$$\begin{cases} L_{TR\ switch} = 0.1\ dB \\ L_{cable} = 3\ dB \\ L_{mismatch} = 0.04\ dB^{21} \\ L_{connector} = 0.4\ dB \end{cases}$$

Considering the ground station's properties:

$$\begin{cases} P_{tx} = 47\ dBm \\ G_{tx} = 13\ dB \end{cases}$$

We compute the EIRP:

$$\begin{aligned} EIRP = P_{tx} + G_{tx} - L_{TR\ switch} - L_{cable} - L_{mismatch} - L_{connector} = \\ = 47 + 13 - 0.1 - 3 - 0.04 - 0.4 = 56.46\ dBm \end{aligned} \tag{G.89}$$

Now, we account for the signal propagation through free space. The user-to-satellite range is given by [58]:

$$r_{ue} = -R_e sin(\theta_{el}) + \sqrt{R_e^2(\sin^2\theta_{el} - 1) + r_{SV}^2} \approx 1570\ km \tag{G.90}$$

Where

$$\begin{cases} R_e = 6371\ km \text{ is the Earth's radius} \\ r_{SV} = R_e + h_{sat} = 6771\ km \text{ is the distance} \\ \text{from the satellite to the centre of the Earth} \\ \theta_{el} = 8^\circ \text{ is the elevation angle} \end{cases}$$

Using the range, we calculate the free space path loss:

$$FSPL = 20\log_{10}(\frac{4\pi f r_{ue}}{c}) = 139.60\ dB \tag{G.91}$$

Where $c \approx 3 * 10^8\ m/s$ is the speed of light.
Accounting for atmospheric, ionospheric, polarization and pointing losses

$$\begin{cases} L_{atm} = 1\ dB \\ L_{pol} = 0.25\ dB \\ L_{point} = 0.1\ dB \\ L_{ion} = 1\ dB \end{cases}$$

The total propagation loss is

$$PL = FSPL + L_{atm} + L_{pol} + L_{point} + L_{ion} = \\ = 139.60 + 1 + 0.25 + 0.1 + 1 = 141.95\ dB \tag{G.92}$$

At this point, we compute the received isotropic power:

$$P_{rx,iso} = EIRP - PL = 56.46 - 141.95 = -85.49\ dBm \tag{G.93}$$

Considering the receiver's antenna gain and the receiver's losses

$$\begin{cases} G_{rx} = 2.14\ dB L_{TR\ switch} = 0.1\ dB \\ L_{cable} = 3\ dB \\ L_{mismatch} = 0.04\ dB^{22} \end{cases}$$

we obtain the received signal power:

$$P_{rx,sig} = P_{rx,iso} + G_{rx} - L_{TR\ switch} - L_{cable} - L_{mismatch} = \\ = -85.48 + 2.14 - 0.1 - 1 - 0.04 = -84.48\ dBm \tag{G.94}$$

We determine the equivalent noise temperature of the system:

$$T_{sys} = T_{rec} + T_{ant} = 485 + 290 = 775.00\ K \tag{G.95}$$

And the total noise power:

$$P_{noise} = 10\log_{10}(kBT_{sys}) = 10\log_{10}(1.38 * 10^{-23} * 38.4 * 10^3 * 775.00) = \\ = -153.86\ dBW = -123.86\ dBm \tag{G.96}$$

Where $k = 1.38 * 10^{-23}\ JK^{-1}$ is the Boltzmann constant.

Next, we compute the performance metrics of the system:

$$\begin{cases} G/T = G_{rx} - 10\log_{10} T_{sys} = -26.75\ dBK^{-1} \\ SNR = P_{rx,sig} - P_{noise} = -84.48 + 123.86 = 39.38\ dB \\ C/N0 = SNR + 10\log_{10} B = 39.38 + 45.84 = 85.22\ dBm/Hz \\ E_b/N_0|_{info} = SNR - 10\log_{10}(R_{b,gross}/B) = 37.15\ dB \end{cases}$$

Finally, accounting for a 1 dB implementation loss, the system's margin is:

$$M = E_b/N_0|_{info} - E_b/N_0|_{min} - L_{impl} = 37.15 - 12 - 1 = 24.15\ dB > 6\ dB = \mu \tag{G.97}$$

And the link is closed.

G.5.2 Downlink

Starting from the system parameters:

$$\begin{cases} \text{Uncoded BPSK @ BER = 1E-6} & E_b/N_0\Big|_{target} = 9.6\ dB \\ \text{Target bit-rate} & R_b = 100\ kbps \\ \text{QPSK Modulation} & m = 2 \text{ bits/symbol} \\ \text{Required margin} & \mu = 3\ dB \\ \text{Downlink Carrier Frequency} & f = 435\ MHz \\ \text{Antenna height} & h_A = 20\ m \\ \text{Satellite altitude} & h_{sat} = 400\ km \\ \text{Elevation angle} & \theta_{el} = 8° \\ \text{Receiver noise temperature} & T_{rec} = 360.7\ K \\ \text{Antenna temperature} & T_{ant} = 290\ K \end{cases}$$

We compute the symbol-rate:

$$R_s = R_b/m = 50\ ksps \tag{G.98}$$

And the bandwidth occupied by the transmitted signal:

$$B = (1+\rho)R_s = 60\ kHz \tag{G.99}$$

In the transmitter, we have the following losses:

$$\begin{cases} L_{TR\ switch} = 0.1\ dB \\ L_{cable} = 1\ dB \\ L_{mismatch} = 0.04\ dB^{23} \\ L_{connector} = 0.4\ dB \end{cases}$$

Considering the satellite's properties:

$$\begin{cases} P_{tx} = 33\ dBm \\ G_{tx} = 2.14\ dB \end{cases}$$

We compute the EIRP

$$\begin{aligned} EIRP = P_{tx} + G_{tx} - L_{TR\ switch} - L_{cable} - L_{mismatch} - L_{connector} = \\ = 33 + 2.14 - 0.1 - 1 - 0.04 - 0.4 = 33.60\ dBm \end{aligned} \tag{G.100}$$

Now, we must account for the signal propagation through free space. The user-to-satellite range is given by [58]:

$$r_{ue} = -R_e sin(\theta_{el}) + \sqrt{R_e^2(\sin^2\theta_{el} - 1) + r_{SV}^2} \approx 1570\ km \tag{G.101}$$

Where

$$\begin{cases} R_e = 6371\ km \text{ is the Earth's radius} \\ r_{SV} = R_e + h_{sat} = 6771\ km \text{ is the distance} \\ \text{from the satellite to the centre of the Earth} \\ \theta_{el} = 8° \text{ is the elevation angle} \end{cases}$$

Using the range, we calculate the free space path loss:

$$FSPL = 20\log_{10}(\frac{4\pi f r_{ue}}{c}) = 139.60\ dB \quad \text{(G.102)}$$

Where $c \approx 3 * 10^8\ m/s$ is the speed of light.
Accounting for atmospheric, ionospheric, polarization and pointing losses

$$\begin{cases} L_{atm} = 1\ dB \\ L_{pol} = 0.25\ dB \\ L_{point} = 0.1\ dB \\ L_{ion} = 1\ dB \end{cases}$$

The total propagation loss is

$$\begin{aligned} PL &= FSPL + L_{atm} + L_{pol} + L_{point} + L_{ion} = \\ &= 139.60 + 1 + 0.25 + 0.1 + 1 = 141.95\ dB \end{aligned} \quad \text{(G.103)}$$

At this point, we compute the received isotropic power:

$$P_{rx,iso} = EIRP - PL = 33.60 - 141.95 = -108.35\ dBm \quad \text{(G.104)}$$

Considering the receiver's antenna gain and the receiver's losses

$$\begin{cases} G_{rx} = 13\ dB \\ L_{TR\ switch} = 0.1\ dB \\ L_{cable} = 3\ dB \\ L_{mismatch} = 0.04\ dB \end{cases}$$ [24]

we obtain the received signal power:

$$\begin{aligned} P_{rx,sig} &= P_{rx,iso} + G_{rx} - L_{TR\ switch} - L_{cable} - L_{mismatch} = \\ &= -108.35 + 13 - 0.1 - 3 - 0.04 = -98.49\ dBm \end{aligned} \quad \text{(G.105)}$$

To estimate the noise power, we determine the equivalent noise temperature of the system:

$$T_{sys} = T_{rec} + T_{ant} = 360.7 + 290 = 665.90\ K \quad \text{(G.106)}$$

And the total noise power:

$$P_{noise} = 10\log_{10}(kBT_{sys}) = 10\log_{10}(1.38 * 10^{-23} * 60 * 10^{3} * 665.90) = \\ = -152.68\ dBW = -122.68\ dBm \quad \text{(G.107)}$$

Where $k = 1.38 * 10^{-23}\ JK^{-1}$ is the Boltzmann constant.

Next, we compute the performance metrics of the system:

$$\begin{cases} G/T = G_{rx} - 10\log_{10} T_{sys} = -15.13\ dBK^{-1} \\ SNR = P_{rx,sig} - P_{noise} = -98.49 + 122.68 = 24.19\ dB \\ C/N0 = SNR + 10\log_{10} B = 24.19 + 47.48 = 71.97\ dBm/Hz \\ E_b/N_0|_{info} = SNR - 10\log_{10}(R_{b,gross}/B) = 21.98\ dB \end{cases}$$

Finally, accounting for a 1 dB implementation loss, the system's margin is:

$$M = E_b/N_0|_{info} - E_b/N_0|_{min} - L_{impl} = 23.98 - 9.6 - 1 = 11.38\ dB > 3\ dB = \mu \quad \text{(G.108)}$$

And the link is closed.

Appendix H

S-band Line Integration Test Specification and Procedures

CubeSat
polito team

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TEST SPECIFICATION AND PROCEDURE

S-band Line Integration Test

Project	CubeSat Control Centre (C3)
Doc. Ref.	[TSP]C3-RF-012
Doc. Type	Technical Note
Issue	1
Revision	0
Date of issue	02/07/2020
Prepared by	Gabriel Maiolini Capez; Lorenzo Maria Gagliardini
Signature	
Approved by	Lorenzo Maria Gagliardini
Signature	
Distribution	Internal Use

1 Document control data

1.1 Document change log and record

Change Log			
Reason for change	Issue	Revision	Date
Draft version 1	0	0	17.02.2020
Definitive	1	0	02.07.2020

Change records Issue 0 Revision 2		
Reason for change	Page(s)	Paragraph(s)
Completeness of document	All	

1.2 Applicable and reference documents

Applicable documents:	
Reference documents:	[1] Nuand bladeRF Install Guide
	[2] Nuand BladeRF - Verifying Basic Device Operation (Accessed 17/02/2020)
	[3] AD9361 RF Agile Transceiver Datasheet
	[4] Nuand BladeRF 2.0 micro xA9 Datasheet
	[5] Pasternack PE15A4011 Datasheet
	[6] Mini-Circuits PHA-1H+ Datasheet
	[7] Nuand BT-100 Datasheet
	[8] Nuand BT-200 Datasheet
	[9] Mini-Circuits TSS-53LNB+ Datasheet
	[10] Pasternack PE15A1010 Datasheet

2 Table of Contents

1 Document control data ... 2
1.1 Document change log and record ... 2
1.2 Applicable and reference documents ... 2
2 Table of Contents ... 3
3 Figures ... 3
4 Tables ... 3
5 Definitions and abbreviations ... 3
5.1 Definitions ... 3
5.2 Abbreviations ... 3
6 Introduction ... 4
7 Requirements to be verified ... 4
8 Test Approch and Test Requirements ... 4
8.1 Test Approch ... 5
8.2 Associated Requirements and Prerequisites to start tests ... 5
9 Test Facility ... 5
9.1 Description of Facility ... 5
9.2 Requirements on Facility ... 5
10 Test Description ... 6
10.1 Configuration of Item to be tested ... 6
10.2 Set-Up of Item and GSE before test ... 7
10.3 Ground Support Equipment and Tools required ... 7
10.4 Test Conditions ... 8
11 Documentation ... 8
12 Step-by-step procedure ... 9
13 Test organization ... 13

3 Figures

Figure 1: Testing Configuration #1 ... 6
Figure 2: Testing Configuration #2 ... 6
Figure 3: PE15A4011 Cables Configuration ... 7

4 Tables

Table 1: List of Requirements to be verified ... 4
Table 2: List of Test Requirements and Prerequisites ... 5
Table 3: List of Requirements for Facility Instrumentation ... 5
Table 4: Documentation ... 8
Table 5: Step-by-Step procedure ... 13
Table 6: List of roles needed for test execution ... 14
Table 7: Definition of Level of Experience ... 14

5 Definitions and abbreviations

5.1 Definitions

Ground Support Equipment: All items, tools and instrumentation needed to carry the tests out (both belong the facility and external items

5.2 Abbreviations

AIT	Assembly, Integration and Testing

AIT&V	Assembly, Integration, Testing and Verification
GSE	Ground Support Equipment
ID	Identification
RF	Frequency
TSPE	Test Specification and Procedures
SDR	Software Defined Radio

6 Introduction

In this procedure, the operation of the S-band line in transmission and reception at the bandwidth and frequencies of interest will be tested using two Software Defined Radios (SDR). To make the test as self-contained as possible, one SDR will be used as a transmitter of a BPSK signal with 1 MHz bandwidth centred at 2250 MHz and the other SDR as the receiver. It is important to observe that not all USB 3.0 controllers can operate the SDR at its maximum sample rate (61.44 MHz) or at rates that allow it to reach the full channel bandwidth (>= 2 MHz). Therefore, the choice of computer for the operation of the SDR is critical. Due to the maximum input power allowed by the SDR in reception (+0 dBm), this test must be performed with the use of a 20dB attenuator to prevent overamplifying the signal transmitted by transmit SDR, which is greater or equal to -60 dBm, a limitation of the SDR. Moreover, it is important to observe that the SDR receiver is capable of applying up to a 70 dB gain on the signal and to prevent damage, it should be set to 0 before reception.
If the SDR software based on GNU Radio or Matlab is ready by the time this test is executed, the SDR may be tested by using the software in test mode. The instructions contained in this test manually generate the signals and do not rely on any software other than the one provided by the manufacturer.

7 Requirements to be verified

The requirements texts and enumerations are consistent with the matrices *C3-Verification_I1R3* and *C3-Requirements_I1R3*.

Item to be tested	Requirements' ID	Requirement Description
S-band Line	FUN-013	The S-band TX amplification line shall guarantee at least a 34 dB gain
S-band Line	FUN-014	The S-band RX amplification line shall guarantee at least a 50 dB gain
S-band Line	FUN-019	The S-band TX amplification line shall have a Return Loss value lower than -10 dB
S-band Line	FUN-020	The S-band RX amplification line shall have a Return Loss value lower than -10 dB
S-band Line	FUN-026	The S-band TX amplification line shall have a reflected power lower than 6 dBm within the Linearity Zone
S-band Line	FUN-029	The S-band RX amplification line shall have a noise figure lower than 1 dB
SDR	FUN-147	The SDR shall operate in near real time between processing and collecting data

Table 1: List of Requirements to be verified

8 Test Approach and Test Requirements

8.1 Test Approach

Test shall be carried out according the AIT&V philosophy. Verification Philosophy requires that all tests are safe (without risk of damaging instrumentation and items) and simple

8.2 Associated Requirements and Prerequisites to start tests

ID of Test Requirements	Field of competence	Provenience of Requirements	Description of Requirements	Status of Requirements

Table 2: List of Test Requirements and Prerequisites

9 Test Facility

9.1 Description of Facility

The facility identified for performing the test is the CubeSatTeam's STARLab. For equipment, see Section 10.3.

9.2 Requirements on Facility

No requirements relative to the facility instrumentations were identified.

ID of Test Requirements	Field of competence	Provenience of Requirements	Description of Requirements	Status of Requirements

Table 3: List of Requirements for Facility Instrumentation

10 Test Description

10.1 Configuration of Item to be tested

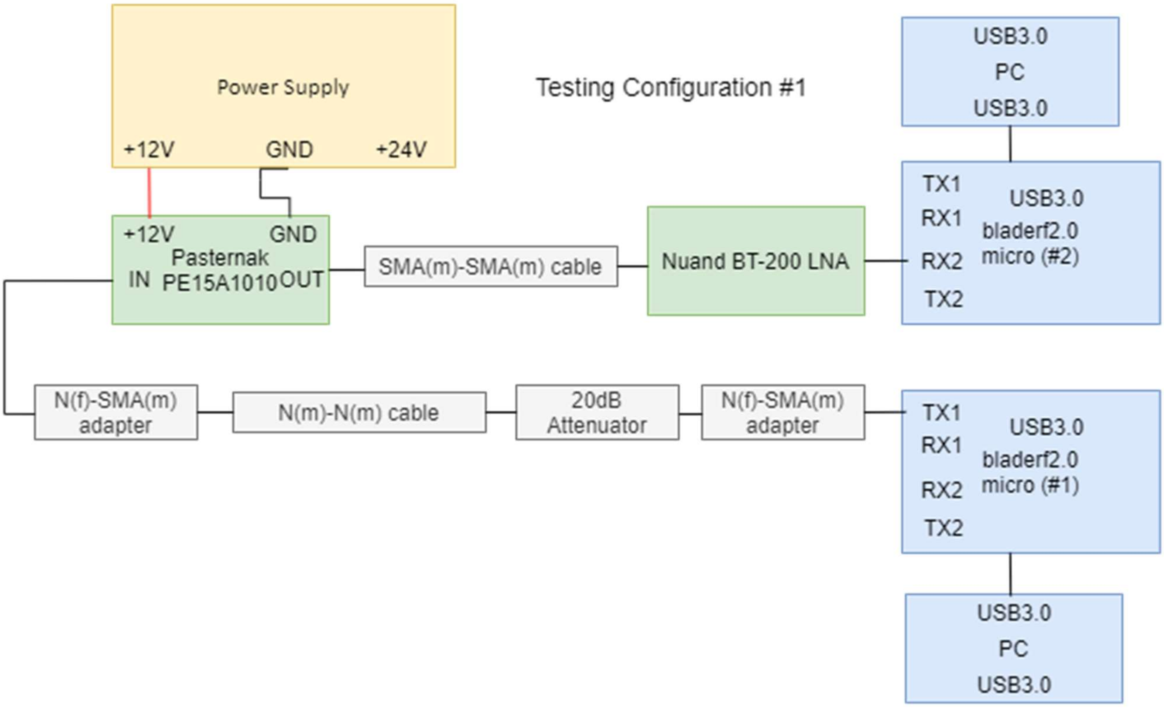

Figure 1: Testing Configuration #1

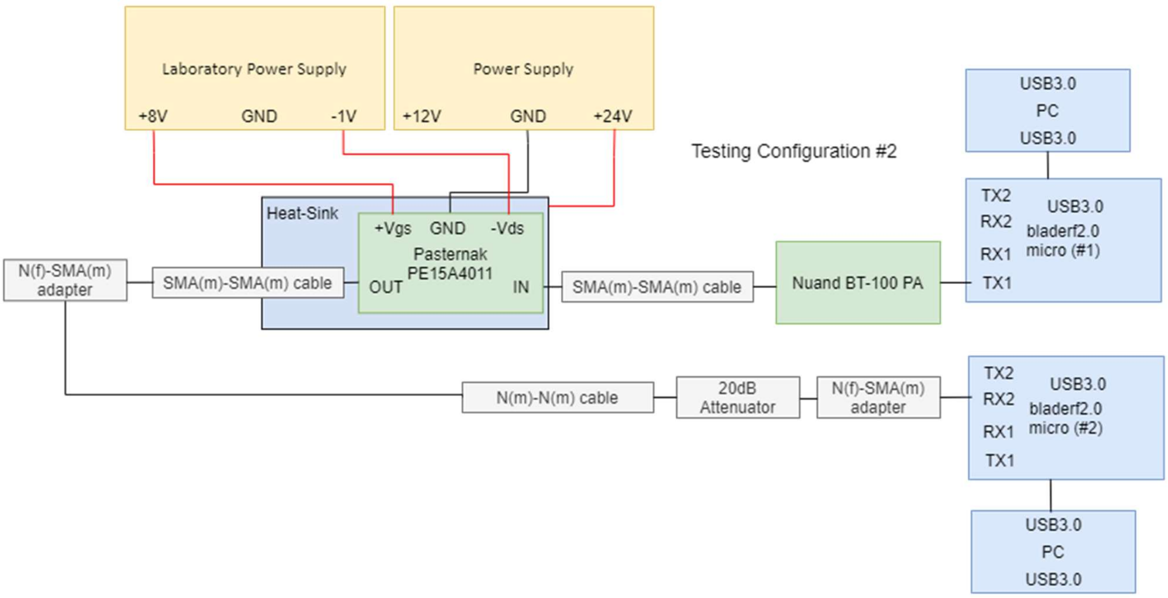

Figure 2: Testing Configuration #2

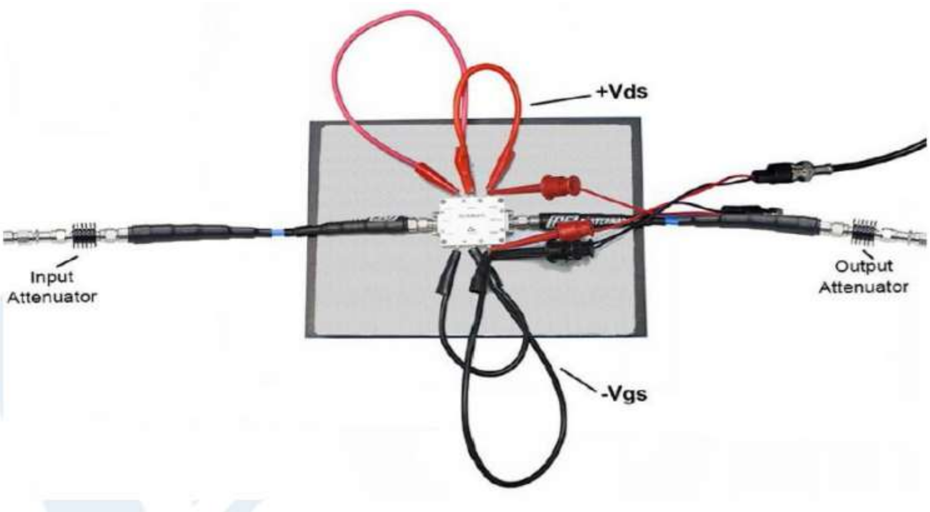

Figure 3: PE15A4011 Cables Configuration

1) Considering the TX noise floor of -154 dBm/Hz, that means that the noise power for a 1 MHz BW signal with a receiver noise figure of 3 dB at a reference temperature of 290 K the observed SNR shall be greater than 30 dB, for which the error rate for the BPSK modulation lower than 1E-6. With a 3 dB margin, this test can be accepted. Observe that since both SDRs are not synchronized to the same clock, there may be a frequency offset present in the signal which may worsen the receiver performance.
2) The test herein described is composed of two simmetrical configurations, the first designed to test the S-band LNA (Pasternack PE15A1010 + BT-200) line and the second designed to test the S-band HPA (BT-100 + Pasternack PE15A4011) line. To verify the proper functioning, as for the RX test, the SNR observed by the RX SDR shall be greater than 30 dB.
3) The test is designed to use a couple of identical bladeRF 2.0 micro xA9 Software Defined Radios (labelled SDR1 and SDR2) used respectively for transmission and reception of the signal in both the configurations.
4) In the transmission test (configuration #2), as reported in Table 5:
    a. SDR1 shall transmit a 2250 MHz test BPSK signal
    b. The signal is amplified by the HPA line
    c. The signal is then attenuated for safety reasons
    d. The signal is finally received by SDR2.
5) In the Reception test (configuration #1), as reported in Table 4:
    a. SDR1 shall transmit a 2250 MHz test BPSK signal
    b. The signal is attenuated for safety reasons
    c. The signal is then amplified by the LNA line
    d. The signal is finally received by SDR2.

    Observe that since both SDRs are not synchronized to the same clock, there may be a frequency offset present in the signal which may worsen the receiver performance.
6) The TX test is symmetrical to the RX test, with the only difference that the 20dB attenuator (representing the medium through which the signal is deprecated), in configuration 1, is loceted after the HPA line (just previous to the receiving SDR2) whereas, in configuration 2, it is located before the LNA line (right after the transmitting SDR1). The observed SNR shall be greater than 50 dB.
7) These two parts of the test (inclouding respectively configuration 1 and 2) are not conducted simultaneously.

10.2 Set-Up of Item and GSE before test

In order to perform this test, the Pasternak PE15A1010 shall be positioned on the heat-sink, capable of dissipating at least 30 W of heat power, using adequate items configuration to enhance heat dissipation (e.g. cooling vents, heat-transfer paste, etc..).

10.3 Ground Support Equipment and Tools required

- 2x USB 3.0 SuperSpeed Cable

- 2x bladeRF Software Defined Radio
- 2x USB 3.0 compatible computer
- 2x Power Supply with a +12V, +24V, +8V and -1V output ports
- 2x SMA(m)-SMA(m) cables
- 2x N(f)-SMA(m) adapters/ N(f)-SMA(m) cables
- 2x N(m)-N(m) cable
- 1x Heat-sink capable of dissipating at least 30 W
- 2x Banana-Banana cables
- 6x Banana-Alligator Cables
- 1x 20 dB attenuator (if available, for protection of the RX electronics) N(f)-N(m)

10.4 Test Conditions

There are no specific requirements for this test.

11 Documentation

The following Table gather all inputs needed to define this document (TSPE) and the origin of them (origin documents).

Document	Input given
AIV Plan	Verification Philosophy
Verification Matrix	Test schedule
	Verification ID
Requirements matrix	Requirement ID
Data Sheet	Interfaces

Table 4: Documentation

12 Step-by-step procedure

Step n°	Action	ID Requirement	Pass/Fail criteria	Expected results	Tolerance
1	Label the SDRs as SDR1 and SDR2				
2	Label the Laboratory power supply as PS1 and the second power supply as PS2.				
	Configuration #1				
3	Use the sdr_basic_waveform.m script to generate a 1 MHz BPSK signal.				
4	Connect the N(m)-N(m) cable to the TX1 port of SDR1 using N(f)-SMA(m) adapter.				
5	Connect the attenuator to the N(m)-N(m) cable				
6	Connect the attenuator to the input port of the PE15A1010 using N(f)-SMA(m) adapter.				
7	Connect the output of the PE15A1010 to the input of the BT-200 using an SMA(m)-SMA(m) cable.				
8	Connect the output of the BT-200 to the RX2 port of SDR2.				
9	Connect the GND port of PS2 to the GND pin of PE15A1010.				
10	Connect the +12V output port of PS2 to the +12V pin of the PE15A1010. Do not enable the output yet.				
11	The device has been assembled. Verify that all devices have been properly connected.			The assembly respects the configuration in Figure 1.	
12	Connect SDR1 and SDR2 USB ports to the host PC's device. Pay attention to use a USB3.0 controller capable of supporting the combined 4 MHz sample rate of the devices. Otherwise, use two PCs (suggested option). We are now ready to configure it.				
13	Install the bladeRF drivers and host libraries for the Operating System used by the computer following [RD-1].				
14	Invoke the terminal of the Operating System on both the PCs.				
15	Invoke the terminal of the Operating System.				
16	Run the bladeRF-cli utility in iterative mode twice, one for each SDR's serial number: "bladeRF-cli -I -d "*:serial=<serialnumber>"". Keep track of which serial number corresponds to SDR-1 and SDR-2.				
17	For each SDR, in the bladeRF-cli type: • "info" Take the serial number, access https://www.nuand.com/calibration/(Accesse				

	d on 17/02/2020) and retrieve the factory calibration value.				
18	Compare that VCTCXO calibration matches the factory value.			The values provided by the Nuand website match the output of the “info” command	
19	Run the Communication System software in test mode if it is available. Else, perform from Step20 to Step39.				
20	On both SDRs enter: • “print gain” to see the currently applied Overall gains to TX1, TX2, RX1 and RX2 ports. It comes from the Automatic Gain Control present in the AD9361 transceiver used and may be manually set by entering “set agc off” and then “set gain <port> <value>”, as from Step25.				
21	On both SDRs enter: • “set clock_ref enable”			Clock reference: REFIN to ADF4002 (unlocked!!)	
22	On both SDRs enter: • “set clock_ref disable”			Clock reference: none	
23	Set the sample rate of both SDRs to 4 Msps: • enter “set samplerate 4M” If during reception or transmission, LED1 (RX) or LED3 (TX) starts blinking or when verifying the received samples, there are missing samples, it may be due to the USB controller dropping samples. Reduce the sample rate until the problem ceases and register that value. It is the maximum sample rate that can be used with the computer chosen. It should be greater or equal to 4 Msps for the system to work. If the sample-rate is reduced, then sdr_tx_waveform should be regenerated considering the new sampling rate using the sdr_basic_waveform.m script.			(Blinking of LED2 is not a problem)	
24					
25	Before transmitting, set on both SDRs the TX gain to 0 dB and RX gain to 0 dB to avoid desensitizing the receiver: • Enter “set agc off” • Enter “set gain rx1 0” • Enter “set gain rx2 0” • Enter “set gain tx1 0” • Enter “set gain tx2 0”			**Expected results:** • RX1 AGC: Disabled RX2 AGC: Disabled • Setting TX1 overall gain to 0 dB Gain TX1 overall: 0 dB (Range: [-23.75, 66]) dsa: -90 dB (Range: [-89.75, 0]) • Setting TX2 overall gain to 0 dB Gain TX2 overall: 0 dB (Range: [-23.75, 66])	

				dsa: -90 dB (Range: [-89.75, 0]) • Note: This change will not be visible until the channel is enabled. Setting RX1 overall gain to 0 dB Gain RX1 overall: 60 dB (Range: [-15, 60]) full: 71 dB (Range: [-4, 71]) • Note: This change will not be visible until the channel is enabled. Setting RX2 overall gain to 0 dB Gain RX2 overall: 60 dB (Range: [-15, 60]) full: 71 dB (Range: [-4, 71])	
26	On SDR1, set the frequency of the transmitter: • Enter “set frequency tx1 <2250> M”				
27	On SDR2, set the frequency of the receiver: Enter “set frequency rx2 <2250> M”				
28	On SDR1, set the bandwidth of the transmitter to cut down the noise: • Enter “set bandwidth tx1 <bw> M” Where bw = 8 corresponds to the bandwidth to be used. This may be increased up to the maximum 56 MHz complex filter bandwidth.				
29	On SDR2, set the bandwidth of the receiver to cut down the noise: • Enter “set bandwidth rx2 <bw> M” Where bw = 8 corresponds to the bandwidth to be used. This may be increased up to the maximum 56 MHz complex filter bandwidth.				
30	On SDR2: • enter “set biastee rx on”.		Green LED on	The green LED turns on	
31	On bladeRF-cli of SDR1, enter: • “tx config channel = 1 file=sdr_tx_waveform format=bin”				
32	On bladeRF-cli of SDR2, enter: • “rx config channel=2 file=sband_rx_test<SDR2_iteration#> format=bin n=10M”. (the number # changes with the iterations). This operations states that the sink-file will gather 10M samples. Since the samplerate was set equal to 4Msps (Step21), the whole reception period will last for 2.5 second. If the reception does not work due to propagation delay, double n.				
33	On SDR2 enter:			**Expected results:**	

	• “print gain”			Gain RX1 overall: 0 dB (Range: [-15, 60]) full: 17 dB (Range: [-4, 71]) Gain RX2 overall: 0 dB (Range: [-15, 60]) full: 17 dB (Range: [-4, 71]) Gain TX1 overall: 0 dB (Range: [-23.75, 66]) dsa: -90 dB (Range: [-89.75, 0]) Gain TX2 overall: 0 dB (Range: [-23.75, 66]) dsa: -90 dB (Range: [-89.75, 0])	
34	Turn on the +12V output of PS1. (Both the outputs in case of Configuration #2).				
35	On SDR2 enter: • “rx start” to start the reception. Since from Step29 the reception period was set equal to 2.5s, Step31 (reception command) and Step32 (transmissions command) must be in fast consecution.				
36	On SDR1 enter: • “tx start” to start the transmission.				
37	Repeat Step32, Step35 and Step36 for a second iteration. Modify properly the destination filename in Step31.				
38	On SDR2, enter • “set biastee rx off”.		Green LED off	The green LED turns off	
39	Turn off the PS2 and disconnect the attached banana-alligator gables.				
40	Disconnect SDR1 from the adapter N(f)-SMA(m).				
41	Disconnect SDR2 from the BT-200.				
42	DO NOT disconnect the SDRs from the PCs. (Avoid this step in configuration #2).				
43	**Configuration #2**				
44	Attach the PE15A4011 to a heat-sink capable of dissipating at least 30W, as from Section 10.2. Do not proceed without it.				
45	Connect all common ports of the PE15A4011 using alligator cables; connect all +Vds ports together, connect all -Vgs ports together.				
46	Connect the input of the PE15A4011 to the output of the BT-100, using a SMA(m)-SMA(m) cable if needed due to the heat-sink.				
47	Connect the input of the BT-100 to SDR1 TX1 port.				
	For interface reasons, connect in series: 1) SMA(m)-SMA(m) cable 2) SMA(f)-N(f) adapter 3) N(m)-N(m) cable 4) The attenuator 5) N(f)-SMA(m) adapter				

	Connect the free end of the SMA(m)-SMA(m) cable to the output of the PE15A4011.				
	Connect the N(f)-SMA(m) adapter to SDR2 RX2 port.				
48	Connect all GND ports of PS1, PS2 and PE15A4011 together.				
49	Set the first output of PS1 to +1V.				
50	Connect the positive terminal of output 1 (+1V) to the PS1 GND port.				
51	Connect the negative terminal of output 1 (-1V, if the positive terminal is grounded) to the -Vgs port of the PE15A4011.				
52	Turn on the first output of PS1 (+1V).				
53	Set the second output of PS2 to +8V.				
54	Connect the negative terminal of output 2 to the PS1 GND port.				
55	Connect the positive terminal output (+8V) to the +Vds port of the PE15A4011.				
56	On SDR1, enter • "set biastee tx on"		Blue LED on	The blue LED turns on	
57	DO NOT PROCEDE WITH THIS STEP IF THE -1V TERMINAL IS NOT CONNECTED AND TURNED ON. (Step52). Turn on the second output of PS1 (+8V).				
58	Turn on the cooling vents.				
59	Repeat from Step32 to Step37				
60	On SDR1, enter • "set biastee tx off".		Blue LED off	The blue LED turns off	
61	Disconnect all the components, with particular care of having turned off the PS.				
	POST-PROCESSING				
62	Using any scripting language of choice, plot the transmitted and received samples and verify that the signals match, shifted of the initial delay for the transmission and that the SNR is as high as expected. Verify that the initial delay is smaller than 100 ms by computing D = sampling frequency * number of delayed samples.	FUN-147 FUN-013 FUN-014 FUN-019 FUN-020 FUN-026 FUN-029	SNR >= 30 dB for RX SNR >= 50 dB for TX		3 dB
63	Test has been finished, disassemble and power-off.				

Table 5: Step-by-Step procedure

13 Test organization

[Overall description of all test responsibilities and roles, number of operators and level of experience for roles. Description shall include also explanation for the major issues identified in this brief document]

Roles	Description of responsibilities	Level of experience required	Number of Operator required	Remarks
Tester	*Shall set-up, calibrate any required GSE and perform the testing procedure above*	*4*	*1*	
Verifier	*Shall assist the tester and verify compliance with the procedures described*	*3*	*1*	

Table 6: List of roles needed for test execution

Level of Experience	Description	Knowledge	Have experience?	Examples
1	No specific knowledge is required	None	NO	Everyone
2	Basic knowledge on test procedures and systems	Usage of standard laboratory instruments	NO	Basic Student
3	Knowledge on test procedures, system and specific field	Usage of standard laboratory instruments, RF testing peculiarities (reflection, termination problems)	LOW	Student
4	Knowledge about test procedures and system, previous testing experience	Usage of standard laboratory instruments at RF frequencies. Testing experience with RF and communication circuits.	YES	Trained student
5	In-depth knowledge about test procedures, systems and specific field	Mastery of laboratory instruments at RF frequencies and high amount of testing experience with RF and communication circuits.	YES	Highly trained student or professor

Table 7: Definition of Level of Experience

Appendix I

Assembly Procedures

11.4.1.2 VHF – band Line Assembly Sequence

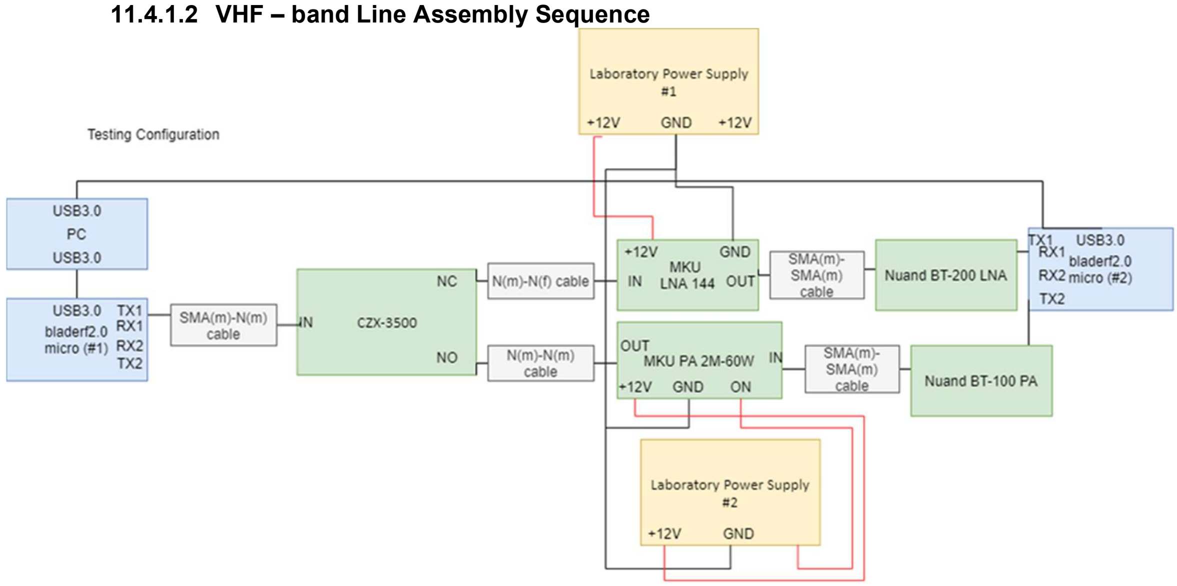

Figure 8: VHF - Band Line Configuration

1 Label the SDRs as SDR-1 and SDR-2 and the power supplies as PS1 and PS2.
2 Connect the SDR-1 TX1 port to the input of the coaxial relay using a SMA(m)-SMA(m) cable with a SMA(m)-N(m) adapter.
3 Connect the NC port of the coaxial relay to the input of the MKU LNA 144A-SMA using a N(m)-N(m) cable or SMA(m)-SMA(m) cable with a SMA(m)-N(m) adapter.
4 Connect the output of the MKU LNA144A-SMA to the input of the BT-200.
5 Connect the output of the BT-200 to the RX1 port of SDR-2.
6 Attach the MKU PA 2M-60W to a heat-sink capable of dissipating at least 144W. Do not proceed without it.
7 Connect the coaxial switch’s NO port to the output of the MKU PA 2M-60W.
8 Connect the input of the MKU PA 2M-60W to the output of the BT-100, using a SMA(m)-SMA(m) cable if needed due to the heat-sink.
9 Connect the input of the BT-100 to SDR-2 TX1 port.
10 Connect all GND ports of PS1, PS2, MKU LNA 144A-SMA, MKU PA 2M-60W and coaxial relay together using banana-alligator cables.
11 Set the first output of PS1 to +12V and connect it to the +12V of the MKU LNA144 A-SMA. Do not enable the output yet.
12 Set the second output of PS1 to +12V and connect it to the coaxial relay using banana alligator cables. Do not enable it yet.
13 Set the first output of PS2 to +12V and connect it to the MKU PA 2M-60W +12V and ON ports using banana alligator cables. Do not enable it yet.
14 Connect SDR-1 and SDR-2 USB ports to the host PC’s device. Pay attention to use a USB3.0 controller capable of supporting the combined 122.88 Msps sample rate of the devices. Otherwise, use two PCs. We are now ready to configure it.
15 The device has been assembled. Verify that all devices have been properly connected.

11.4.1.3 S – band Line Assembly Sequence

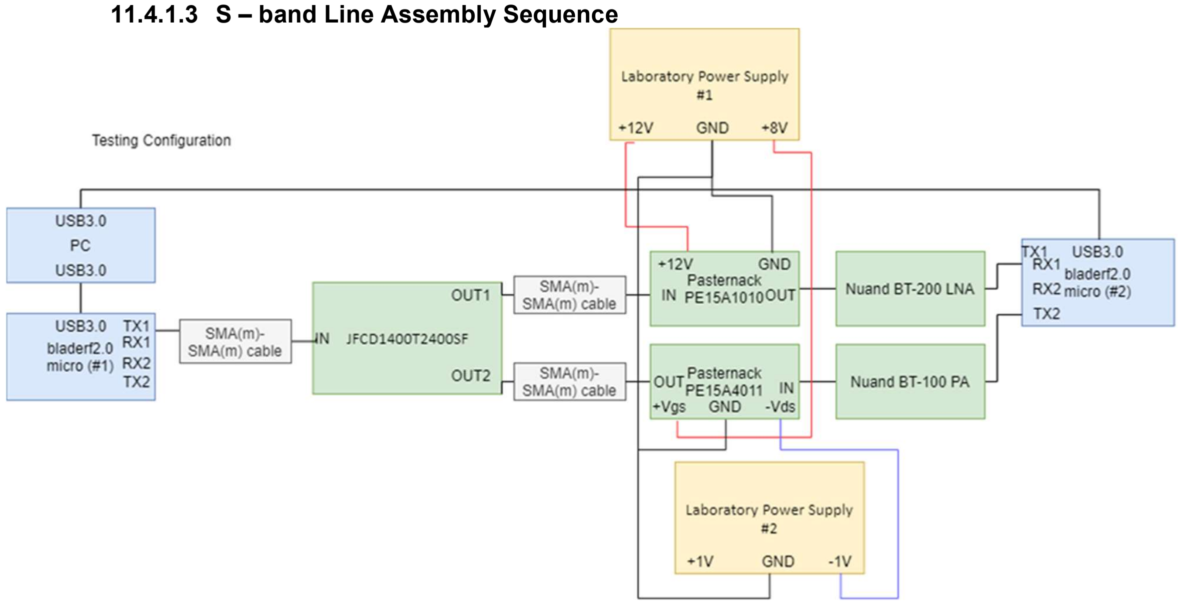

Figure 9: S - Band Line Configuration

1 Label the SDRs as SDR-1 and SDR-2 and the power supplies as PS1 and PS2.
2 Connect the SDR-1 TX1 port to the input of the diplexer using a SMA(m)-SMA(m) cable.
3 Connect the diplexer’s 2025-2120 (OUT1) port to the input of the PE15A1010 using a SMA(m)-SMA(m) cable.
4 Connect the output of the PE15A1010 to the input of the BT-200.

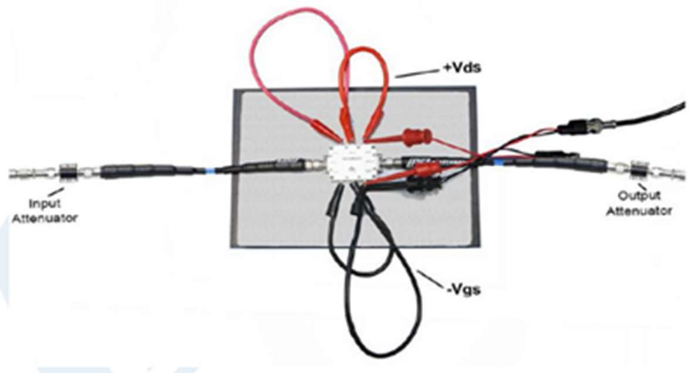

Figure 10: PE15A4011 Configuration. Neglect the Attenuators

5 Connect the output of the BT-200 to the RX1 port of SDR-2.
6 Attach the PE15A4011 to a heat-sink capable of dissipating at least 30W. Do not proceed without it.
7 Connect the diplexer’s 2200-2400 (OUT2) port to the output of the PE15A4011.
8 Connect all common ports of the PE15A4011 using alligator cables; connect all +Vds ports together, connect all -Vgs ports together.
9 Connect the input of the PE15A4011 to the output of the BT-100, using a SMA(m)-SMA(m) cable if needed due to the heat-sink.
10 Connect the input of the BT-100 to SDR-2 TX1 port.
11 Connect all GND ports of PS1, PS2 and PE15A4011 together.
12 Set the first output of PS1 to +12V and connect it to the +12V of the PE15A1010. Do not enable the output yet.
13 Set the first output of PS1 to +1V and connect the second output (-1V, symmetrical) to the -Vgs port of the PE15A4011. Do not enable the output yet.
14 Set the second output of PS2 to +8V and connect it to the +Vds port of the PE15A4011. DO NOT ENABLE THE OUTPUT YET, DOING SO WILL DESTROY THE DEVICE.

15 Connect SDR-1 and SDR-2 USB ports to the host PC's device. Pay attention to use a USB3.0 controller capable of supporting the combined 122.88 Msps sample rate of the devices. Otherwise, use two PCs. We are now ready to configure it.

16 The device has been assembled. Verify that all devices have been properly connected