Electrical Design of Radio Antenna for the TT&C Subsystem of the ORCASat Nanosatellite

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Dedicated to Graça and Luís.
Acknowledgments

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Resumo

Projeto elétrico da antena de rádio para o subsistema de telecomunicações do ORCASat, um CubeSat de 2 unidades. O principal objetivo é desenvolver o conceito da antena e respetivo circuito de adaptação de impedâncias, de modo a acomodar as limitações impostas pelo link budget. No desenvolvimento da antena o foco principal foi fazer com que esta tivesse frequência de ressonância nos 436.5MHz. Para este estudo é usado o solver High Frequency Structure Simulator (HFSS) do Analysis System (ANSYS). Quando à antena se junta o circuito de adaptação, o foco adicional é fazer com que a impedância de entrada da antena seja 50Ω nos 436.5MHz. Para o estudo do circuito de adaptação é usado o solver Advanced Design System (ADS). Os componentes são desenvolvidos em cinco iterações de simulações, até um projeto final ser obtido. Os resultados numéricos pretendem posteriormente ser comprovados com resultados obtidos em três testes experimentais – coeficiente de reflexão, padrão de radiação e ganho absoluto. É feito o projeto para uma Printed Circuit Board (PCB) onde o protótipo é montado e testado. Ao realizar o primeiro teste são encontradas incongruências com os resultados esperados das simulações. Procede-se à alteração do plano do primeiro teste de modo a tentar compreender, pelo menos, o comportamento da antena a nível de ressonância. Apesar de não ser o ideal, assemelha-se ao esperado, sendo por isso a antena validada, mas não o circuito de adaptação. Finalmente, são sugeridas medidas a tomar, de modo a terminar os testes e atingir a validação do sistema.

Palavras-chave: CubeSat; Antena; Circuito de Adaptação de Impedâncias; Frequência de Ressonância; Coeficiente de Reflexão; PCB.
Abstract

Electrical Design of a Radio Antenna for the Telemetry, Tracking and Command (TT&C) subsystem of the ORCASat 2U-CubeSat I proposed. The main goal is to develop the concept of the antenna and its impedance matching network, and to accommodate the limitations imposed by the link budget. In the development of the antenna, the focus was to make it have a resonance frequency of 436.5MHz. For this study, the solver High Frequency Structure Simulator (HFSS) from Analysis System (ANSYS) is used. When the matching network is added to the antenna, the additional focus is to make the input impedance of the antenna 50Ω at 436.5MHz. To study the matching network, the solver Advanced Design System (ADS) is used. The components are developed through five iterations of simulations, until a final design is obtained. The numerical results are later intended to be confirmed by results obtained in three experimental tests – return loss, radiation pattern and absolute gain. The design of a Printed Circuit Board (PCB) has been proposed, and the prototype has been assembled and tested. When performing the first test, inconsistencies with the expected results of the simulations were observed. The first test plan has been modified to try to understand at least the behavior of the antenna at the resonance level. Although it was not ideal, it was able to reproduce the computational predictions thus validating the antenna, however the matching network was not achieved. Finally, procedures are suggested to be taken to end the tests and achieve system validation.

Keywords: CubeSat; Antenna; Matching Network; Resonance Frequency; Return Loss; PCB.
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Nomenclature

Greek symbols

$\Delta \theta_{-3dB}$ Angle of the Half Power Beamwidth

$\eta$ Efficiency

$\Gamma$ Reflection factor

$\lambda$ Wavelength

$\omega$ Angular frequency

$\pi$ Pi (3.14159...)

$\theta, \varphi$ Spherical coordinates (angles)

$\varepsilon_r$ Relative permittivity

Roman symbols

$V$ Voltage

$AR$ Axial ratio

$C$ Capacitor value

$c$ Speed of light in vacuum ($3 \times 10^8$ m/s)

$D$ Directivity

$d$ Distance from the observation point to the antenna

$E$ Electric field

$e$ Euler's number (2.71828...)

$f$ Frequency

$G$ Gain

$H$ Magnetic field

$I$ Current
\( j \) Imaginary unit
\( k \) Wave number
\( L \) Inductor value
\( N \) Turns ratio
\( P \) Power
\( Q \) Ratio of the series reactance to the series resistance
\( R \) Resistive part of impedance (real)
\( r \) Resistive part of normalized impedance (real)
\( r \) Spherical coordinate (distance from point to origin)
\( S \) Scattering Parameters
\( S_{11} \) Input reflection coefficient
\( t \) Time
\( U \) Radiated power per unit of solid angle
\( v \) Version
\( X \) Reactive part of impedance (imaginary)
\( x \) Reactive part of normalized impedance (imaginary)
\( Z \) Impedance
\( z \) Normalized impedance
\( Z_{11} \) Input impedance
\( g \) Gap
\( L \) Length
\( T \) Thickness
\( W \) Width

**Subscripts**

\( 0 \) Reference
\( 1, 2 \) Iteration number
\( A \) Iteration reference
\( c \) Cutoff
i  Imaginary (reflection coefficient)

i  Input (Power)

in  Input

L  Load

r  Radiated (Power)

r  Real (reflection coefficient)

x, y, z  Cartesian components

Superscripts

+  Incident

–  Output (reflected)
Abbreviations

2D Two Dimensional
2U Two-unit
3D Three Dimensional
AC Alternating Current
ADCS Attitude Determination and Control System
ADS Advanced Design System
ANSYS Analysis System
BNC Bayonet Nut Coupling
CAD Computer Aided Design
CAGR Compound Annual Growth Rate
CFaR Centre for Aerospace Research
COTS Commercial Off-The-Shelf
CSA Canadian Space Agency
CST Computer Simulation Technology
DC Direct Current
DUT Device Under Testing
E&M Electric and Magnetic
EM Electromagnetic
EPS Electrical Power System
FEA Finite Element Analysis
FR4  Flame Retardant-4 (glass-reinforced epoxy laminate material)
GND  Ground
HFSS  High Frequency Structure Simulator
HPBW  Half Power Beamwidth
HQP  Highly Qualified Personnel
LEO  Low Earth Orbit
OBC  On-Board Computer
ORCASat  Optical and Reference Calibration Satellite
PC  Personal Computer
PCB  Printed Circuit Board
PCDM  Power Conditioning Distribution Module
PEC  Perfect Electric Conductor
PLA  Polylactic Acid (a plastic)
PVC  Polyvinyl Chloride
RF  Radio Frequency
RX  Receive
SMA  SubMiniature version A (coaxial connector)
SWR  Standing Wave Ratio
TBD  To Be Defined
TT&C  Telemetry, Tracking and Command
TX  Transmit
UBC  University of British Columbia
UHD  USRP Hardware Driver
UHF  Ultra-High Frequency
USB  Universal Serial Bus
USD  United States Dollar
**USR** Universal Software Radio Peripheral

**UVic** University of Victoria

**VHF** Very-High Frequency

**VNA** Vector Network Analyzer

**VS** Versus
Chapter 1

Introduction

1.1 Motivation

During my master's degree, I had the opportunity of doing Erasmus at Universität Stuttgart and improving my knowledge on satellites, more specifically on satellite communications. Later that summer I performed a summer internship where I was working with CubeSat. For all these reasons, I wanted to work on the ORCASat project for my master thesis to develop the communications subsystem.

ORCASat stands for Optical and Reference CAlibration Satellite. This project is an initiative by the Canadian Space Agency (CSA) to develop Highly Qualified Personnel (HQP) in Canada, strengthening the future of the Canadian space industry. This project is led by the University of Victoria (UVic) Centre for Aerospace Research (CFaR) and the undergraduate club UVic Satellite Design, with academic collaborators from the University of British Columbia (UBC). Together, they are developing a Two-unit (2U) CubeSat that will be launched into a Low Earth Orbit (LEO) in 2021.

The CSA is the customer of the ORCASat mission. Unlike most space missions, which are built around providing a service to a customer who has outlined functional and operational requirements for that service, ORCASat has no operational requirements. The goal of the mission is to provide opportunities for all students interested in developing hands-on experience through involvement in a real life mission.

However, to provide an experience beyond just building a satellite, it was self-defined by the ORCASat project team that ORCASat would demonstrate a new methodology of calibrating ground based optical telescopes by providing an in-situ-calibrated light source in LEO.

1.2 Topic Overview

CubeSats belong to the class of nanosatellites (1-10kg) [1]. They are built in standardized units, U's, where each unit is a 10x10x10 cm cube with maximum weight of 1.33kg. By assembling multiple units, as shown on Figure 1.1, it is possible to have CubeSats in 1U, 1.5U, 2U, 3U, 6U and 12U sizes.

CubeSats appear to be a very interesting way to reach space for many research teams as well
as private and governmental entities since they are small and relatively cheap to build [2]. They use equipment, such as structure and electronic, that are, in many cases, Commercial Off-The-Shelf (COTS) components which are cheap and available.

Since their first launch in 2003, the number of launched CubeSats have been increasing exponentially and it is planned to keep increasing this way, as we can state on Figure 1.2. According to [3], by April 19th of 2020, 1210 CubeSats have been launched.

The growth of the CubeSat business can also be measured and perceived by its market value. According to [5], in 2018 the Cubesat market was valued at 152 million United States Dollars (USDs) and it is expected to grow to 375 million USDs, more than double, by 2023, at a Compound Annual Growth Rate (CAGR) of 19.87%, as observed on Figure 1.3.

This continuous growth on the CubeSat's market can be justified by many factors, such as: [5]

- Focus on mission costs reduction
- Increased search of CubeSats for applications as Earth observation, communication, science, and technology
- Use of CubeSats for government and military purposes
1.3 Objectives

The success of the ORCASat nanosatellite mission relies on the team's ability to get information to and from the satellite. To this end, there is a need for a robust communication system which allows two-directional information transfer between the spacecraft and mission operations. The robustness of the communication system is quantified by the link margin, which determines how much unused power is available to overcome the communication obstacles between space and ground. This link margin, among other factors, is impacted by the relative orientation of the spacecraft and ground segment antennas with respect to each other.

The ground segment antenna is a circularly polarized Yagi located at the UVic campus. The space segment antenna is a half wavelength dipole, deployed from the port-starboard faces of the satellite that enable the radio transceiver to communicate with the ground station, while operating in the 435-438 MHz amateur satellite service allocated band.

The goal of this thesis is to conceptualize an antenna design for ORCASat, and evaluate the performance of this antenna design through simulation and laboratory testing on a prototype. From these simulations it will be determined how this radiation pattern compares to that of the ideal dipole and how this affects the link margin.

The satellite's radio antenna also needs to be impedance matched to the 50Ω radio transceiver, so a study on this matter will also be performed and a final proposal will be presented.

1.4 Thesis Outline

This thesis is organized as follows:

- **Chapter 2:** Presents the theoretical background on all of the antenna parameters used to support the analysis done through this thesis.

- **Chapter 3:** Provides an overview of the most common types of antennas used in past CubeSat missions and some possible ways to perform the matching network.
- **Chapter 4:** Explains the process of antenna design, through five simulation iterations until a final design is reached. The feeding structure and matching network are also studied in order to achieve the best possible performance for the antenna.

- **Chapter 5:** Explains the testing protocol for the three performed tests. Presents the PCB design with matching network and feed structures to mount the antenna prototype. The experimental results are presented and compared to the simulated ones and the conclusions presented.

- **Chapter 6:** Brief conclusions and achievements of this investigation and some recommendations for future work.

Figure 1.4 represents how the work in this thesis flowed. First, different types of antennas and matching networks that could fit in our mission, were studied. Then the simulation process started, where a system was simulated, improved and tuned and simulated again, until a final design was found. After this process, a real life prototype was manufactured, tested and the real and simulated results were compared. This was again an iterative process since it is normal for the results to show some differences. The prototype was refined and again tested and compared the results, until they converged and the project was finished.

![Figure 1.4: Thesis flowchart.](image)
Chapter 2

Antenna Theory Introduction

To work with antennas and make critical analysis of the simulation’s results, it is necessary to introduce the fundamental parameters and performance indicators that allow to characterize the functioning and performance of antennas in general.

2.1 Introduction

An antenna is a structure that promotes the transmission of a guided wave to a wave that propagates in free space, as it is possible to observe in Figure 2.1 [6].

Looking from the other way, the antenna captures some of the energy from the free space wave that hits the antenna and delivers that energy to the transmission line that connects it to the receiver. In the first case it is said that the antenna works in transmission, and in the second case in reception. (In general, it is intended that when coupling or capturing energy to the free space wave, the antenna does so privileging certain angular regions of the space.) [6]
2.2 Scattering Parameters

The way radio frequency energy flows in a multi-port system can be characterized by the scattering parameters. They give us a measure of how much of the energy flowed through the port and how much came back reflected and do this for all the ports. So as we can imagine, a generic network with \( X \) ports will have \( X^2 \) scattering parameters [8].

The incident signal can register a change both in amplitude and phase, so the scattering parameters are complex numbers.

On Figure 2.2 is represented a two-port system and the respective scattering matrix.

![Two-port system and respective scattering matrix.](image)

On the matrix, the first number on the index of \( S \) represents the output port we are referring to and the second one the input port the signal came from. So with this in mind, the 4 scattering parameters, for a two-port network, are defined as in equations (2.1).

\[
\begin{align*}
S_{11} &= \frac{b_1}{a_1}, \\
S_{12} &= \frac{b_1}{a_2}, \\
S_{21} &= \frac{b_2}{a_1}, \\
S_{22} &= \frac{b_2}{a_2}.
\end{align*}
\]

(2.1a, 2.1b, 2.1c, 2.1d)

For us, the most relevant one is \( S_{11} \), known as the input reflection coefficient and also defined as a voltage ratio as in equation (2.2),

\[
S_{11} = \Gamma_L = \frac{V^-}{V^+}
\]

(2.2)

where \( V^+ \) is the incident voltage and \( V^- \) the output (reflected) voltage.

2.3 Standing Wave Ratio/Return Loss

Impedance mismatches, between the load and the line characteristic impedance, result in standing waves along the transmission line.

Standing Wave Ratio (SWR) is defined in equation (2.3). It is the ratio between the maximum and
minimum values of $V(z)$, that occur, respectively, when $V^+$ and $V^-$ are added in phase or phase opposition. These maximums and minimums occur lagged by $\lambda/4$ from one another [6].

$$SWR = \frac{V_{\text{max}}}{V_{\text{min}}} = \frac{|V^+| + |V^-|}{|V^+| - |V^-|} = 1 + |\Gamma_L| \frac{1}{1 - |\Gamma_L|}$$

(2.3)

Just as $\Gamma_L$, SWR also provides a measure of the load reflection.

2.4 Radiation Patterns

Radiation pattern is the far field Three Dimensional (3D) graphical representation of the spatial distribution of the power density radiated by an antenna, as a function of direction ($\theta$, $\phi$), for a constant value of $r$ [6], where $\theta$, $\phi$ and $r$ are spherical coordinates, defined as in Figure 2.3. The antenna is placed in the origin of the axis.

![Figure 2.3: Spherical coordinates [9].](image)

However, although it is very useful to have a general and spatial idea of the radiation pattern, the 3D representation does not favor a quantitative assessment of the field values. For that purpose, it is common to have the radiation pattern presented in cuts that result from the intersection of the 3D figure with planes with constant $\theta$ or constant $\phi$ [6].

This logic for emission is equally valid for reception, since an antenna receives best from the directions in which it radiates best [10]. The reciprocity theorem states that both radiation patterns (emission and reception) are the same.

2.4.1 Examples

Represented on Figure 2.4 are the three major types of radiation patterns:

- **Isotropic** - provides equal radiation in all directions, but this is only a theoretical model, it doesn’t exist in reality.
• **Omnidirectional** - radiates equally in one specific plane.

• **Directional** - radiates majorly in one specific direction, inside a narrower beam.

![Images of radiation patterns](image)

Figure 2.4: Major types of radiation patterns [6].

### 2.4.2 Beamwidth

In practice, the radiation diagrams are presented as a set of lobes, from which stands out a principal that contains the maximum direction of radiation. All the other secondary lobes are unwanted and should be minimized.

An important parameter is the Half Power Beamwidth (HPBW), that is defined as the angle between the directions where the radiated power is reduced to half of the value registered in the maximum direction. In dB, a reduction by half means a loss of 3dB, so the HPBW is also represented as $\Delta \theta - 3\text{dB}$.

### 2.5 Directivity and Gain

**Directivity**

Directivity (D) is the quantification of the extent to which an antenna concentrates energy in a region of space, privileging a direction in relation to the others, when compared to an isotropic antenna [6].

It can also be defined as the quotient between the radiation intensity per unit of solid angle and the average value of radiation intensity per unit of solid angle, as stated on equation (2.4),

$$D(\theta, \varphi) = \frac{U(\theta, \varphi)}{<U(\theta, \varphi)>} = \frac{U(\theta, \varphi)}{P_r/4\pi}$$  \hspace{1cm} (2.4)

where $U(\theta, \varphi)$ is the radiation intensity per unit of solid angle and $<U(\theta, \varphi)>$ is the radiation intensity per unit of solid angle of an isotropic antenna [6].
**Gain**

Gain (G) can be defined in a similar way to directivity, but now the reference is the power that the antenna receives from the emitter, instead of the radiated power by the antenna [6].

It is the relation between the antenna’s radiated field and the field generated if the input power of the antenna was radiated isotropically, as seen on equation (2.5),

$$G(\theta, \phi) = \frac{U(\theta, \phi)}{P_i/4\pi}$$

(2.5)

where $U(\theta, \phi)$ is the radiated power per unit of solid angle and $P_i$ is the input power [6].

### 2.6 Antenna Efficiency

Efficiency ($\eta$) is the capacity to convert electrical energy into radio frequency waves [10].

Mathematically, the quotient between gain and directivity gives a measure of efficiency on how the antenna radiates the power it accepts from the associated emitter [6].

$$\eta = \frac{G}{D} = \frac{P_r}{P_i}$$

(2.6)

Equation (2.6) can assume values between $0 \leq \eta \leq 1$. The better the antenna, the higher the efficiency value and the lower the losses due to heat.

### 2.7 Impedance

The impedance is the relation between the voltage and the current. Normally it is a complex quantity, defined as in equation (2.7),

$$Z_A = R_A + jX_A$$

(2.7)

where the real part (resistive), $R_A$, is related to the dissipation and the complex part (reactive), $X_A$, is related to the accumulated energy near the antenna [6].

The impedance depends, among others, on the geometry of the antenna, feeding method and material. It may be influenced by the presence of objects in the antenna’s neighborhood [6].

### 2.8 Polarization

Polarization indicates the orientation of the Electric Field (E) with respect to the horizon. It can either be classified as linear (vertical or horizontal) or elliptical depending on the geometric figure described over time by a transversal vector in relation to the propagation direction [6, 10].

Linear polarization is obtained when we have one wave and elliptical polarization when there is two waves out of phase or with different magnitudes. Circular polarization can be right or left-handed, and it
is a specific case of elliptical polarization that happens when the two waves are exactly 90° out of phase from each other and have the same magnitude [11].

In order to maximize the amount of transferred energy, transmitter and receiver's polarization must be the same [10].

### 2.8.1 Axial Ratio

Axial ratio (AR) is defined as the quotient between the major axis and the minor axis of the polarization ellipse [6].

It is used to quantify how close the polarization is to the circular case. A perfect circular polarization will have $AR = 1$, linear polarization $AR = \infty$ [6] and elliptical polarization some value in between.

### 2.9 Bandwidth

Each characteristic of an antenna (side lobes level, gain, efficiency, impedance...) depends on the frequency in different ways. In general, antennas are sized in a way to present a frequency range where the performance of the antenna satisfies some specifications, when we consider all of those characteristics. We call this frequency range the bandwidth [6].
Chapter 3

Previous Missions

3.1 Most Common Cubesat Antenna Types

In the past, there were some missions that had problems when communicating back to Earth. This happened because the antenna orientation on the satellite body might not have been the correct one to guarantee sufficient gain in the direction of the Earth [12]. When choosing a satellite’s antenna, these are parameters (apart from size, weight, complexity and others) that we need to take into consideration when finding an equilibrium, taking into account all of the mission requirements and objectives. With a low-gain omnidirectional antenna there is no need for a perfect attitude control system (reducing the accuracy needed and the cost), but if we have heavy payload data that needs high-speed downlink, there is the need for a high gain antenna, thus implying a good attitude control system [13].

In order to make a wise choice on what type of antenna to use on ORCASat’s TT&C system, a literature review on some papers about other previous missions and studies was made.

Table 3.1 synthesizes the four most common CubeSat antenna types, which are going to be taken into consideration for the ORCASat mission.

The International Telecommunication Union has allocated the 435-438MHz, in the UHF band, for

<table>
<thead>
<tr>
<th>Type</th>
<th>Center Frequency</th>
<th>Deployable</th>
<th>Gain [dBi]</th>
<th>Radiation Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>VHF 250MHz [14, 15]</td>
<td>Yes</td>
<td>2-3</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td></td>
<td>UHF 437MHz [16]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monopole</td>
<td>VHF 145MHz [16]</td>
<td>Yes</td>
<td>2-3</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td></td>
<td>UHF 435-438MHz [12]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patch</td>
<td>UHF 420-452MHz [2]</td>
<td>No</td>
<td>&gt;5</td>
<td>Hemispherical</td>
</tr>
<tr>
<td>Turnstile</td>
<td>VHF, UHF 100MHZ [17]</td>
<td>Yes</td>
<td>0</td>
<td>Bidirectional</td>
</tr>
</tbody>
</table>
international amateur satellites. Besides this one, there are a large range of frequencies possible to use for amateur satellites. So for this, because the cheap COTS are built in a certain way and because it is easy to obtain a license, most of the nanosatellites built for research are working on the frequency range of 420-450MHz [2].

Dipole and monopole antennas are simple and cheap, which makes them easy to fabricate. It is also favorable that they provide a wide radiation-pattern coverage [13]. In order to take advantage of the radiation pattern, these kinds of antennas should be placed parallel to the Earth’s surface so the null at the center of the radiation pattern is avoided [16]. A limitation of these antennas is the fact that they don’t naturally produce circular polarization, unless they are crossed together with phase shifting [14].

The release mechanism of an antenna can prove to be a big risk for the mission in case of failure. Patch antennas are a good option to prevent risk, since they are like a sticker that needs no release. But patch antennas are not omnidirectional, so this advantage that they provide can be eliminated by the disadvantage of being pointed away from the ground station, thereby not providing the necessary coverage [18]. These antennas can be hard to manufacture for some frequencies, but they can produce circular polarization and adequate bandwidth [14].

When omnidirectional radiation pattern and linear polarization are required, turnstile antennas are normally used. The omnidirectional radiation pattern is achieved when the dipoles are fed in phase quadrature [17].

Some other antennas that were not considered for the mission but have interesting features that make them worth mentioning are helix antennas and log-periodic crossed-dipole array.

The helix antenna was not considered for our mission since it is too complex and provides a directional radiation pattern and an antenna with wider coverage was a requirement. The helix antenna also needed a release mechanism, although it was one of the simplest ones and when the antenna was folded during launch it was flattened on itself, which allowed for minimum space occupation. This is a very important thing to take into account when projecting a CubeSat, since space is limited [12]. These antennas are a good choice when a wide bandwidth of operation and natural circular polarization is required [14].

The log-periodic crossed-dipole array would add a huge amount of complexity on the release mechanism and would take much more space inside the CubeSat when it was folded. Even though its radiation pattern is not as directional as the one of a helical antenna, it still had a restrict coverage, mainly in one hemispherical plain [19]. This is also a high gain antenna with a wide bandwidth [15].

3.1.1 Dipole

Theory

The majority of the dipoles are the $\lambda/2$ [20] dipole and, as the name implies, they have the length of half the wavelength of the working frequency. It is composed of two arms, each one with length $\lambda/4$. Always keep in mind that the wavelength measure is the one of the wave travelling in the antenna conductors, which is a little bit shorter than the wave travelling in free space.
The impedance at feed point of a $\lambda/2$ dipole in free space is $73\Omega$. However, when in contact with other objects (for example, the satellite body) it can present an imaginary part [21].

The electric and magnetic field on a dipole antenna are given by equations (3.1) [21],

\[
E_\theta = \frac{j\eta I_0 e^{-jkr \cos(\frac{\pi \cos \theta}{2})}}{2\pi r \sin \theta}, \quad (3.1a)
\]

\[
H_\phi = \frac{E_\theta}{\eta}, \quad (3.1b)
\]

where $k = \frac{\omega}{c} = \frac{2\pi}{\lambda}$ is the free-space wave number and all variables are defined as in Figure 3.1.

Figure 3.1: Dipole antenna [20].

Figure 3.2: Radiation pattern of a dipole antenna.

**Radiation Pattern**

Using ANSYS HFSS a generic dipole antenna was simulated in order to obtain its radiation pattern. The result can be seen on Figure 3.2. The dipole was fed by a port placed in the middle of the two arms.

From figure 2.4 it is clear the the radiation pattern of the dipole is the omnidirectional type. It has the nulls aligned with the dipole arms and a toroidal/doughnut shape.

### 3.1.2 Monopole

**Theory**

The monopole is in every way similar to the dipole but half of its length. So instead of having two arms, the monopole has only one arm with length $\lambda/4$ of the working frequency.

A monopole mounted on a ground plane, as represented on Figure 3.3, is equivalent to a dipole, as told by the image theory. This implies that $Z_{\text{monopole}} = \frac{1}{2} Z_{\text{dipole}} = 36.5\Omega$, since it needs only half of the voltage for the same current [22].
Radiation Pattern

Using ANSYS HFSS a generic monopole antenna was simulated in order to obtain its radiation pattern. The result can be seen on Figure 3.4. The green circle simulated the Perfect Electric Conductor (PEC) and there is a port feeding the monopole between the PEC and the monopole arm.

From figure 2.4 it is clear the the radiation pattern of the dipole is the omnidirectional type, cut in half, with only one of the hemispheres. As the dipole, it has the null aligned with the arm and a toroidal/doughnut shape.

3.1.3 Patch

Theory

Patch antennas are also known by the name microstrip antennas.

Patch antennas can be directly printed on a circuit board or not, as the one on Figure 3.5, and fed by a microstrip transmission line. As we can see on Figure 3.5, patch antennas are made of four major parts; the microstrip antenna itself, the microstrip transmission line, the substrate and the ground plane. The ones in grey (microstrip antenna, microstrip transmission line, and ground plane) are made of a high conductivity metal that is normally copper. The substrate is a dielectric circuit board that stands in between the ground plane and the antenna. The substrate has its own permittivity $\varepsilon_r$ and thickness $h$, that is small when considering the wavelength it is working in, but should not be smaller than $\lambda/40$, otherwise the antenna efficiency will be decreased [23].

The two tuning parameters of these antennas are their length $L$ and width $W$.

$L$ determines the center of the working frequency that, for an antenna as the one on Figure 3.5, is approximately defined as in equation (3.2). By looking at this equation, it is possible to note that $L$ should be approximately $\lambda/2$ of the wave traveling in the substrate [23].
$f_c \approx \frac{c}{2L\sqrt{\varepsilon_r}}$ \hspace{1cm} (3.2)

$W$ determines the input impedance. For an antenna as the one on Figure 3.5 the impedance will be around 300\,\Omega. An increase in width would reduce the impedance, but achieving a 50\,\Omega would take a large antenna. $W$ also controls the electric field that generates the radiation pattern. The normalized radiation pattern is approximately given by equations (3.3) [23].

$$E_\theta = \frac{\sin(kW \sin \theta \sin \varphi)}{kW \sin \theta \sin \varphi} \cos \left(\frac{kL}{2} \sin \theta \cos \varphi\right) \cos \varphi,$$

(3.3a)

$$E_\varphi = -\frac{\sin(kW \sin \theta \sin \varphi)}{kW \sin \theta \sin \varphi} \cos \left(\frac{kL}{2} \sin \theta \cos \varphi\right) \cos \theta \sin \varphi = -E_\theta \sin \varphi.$$  

(3.3b)

But apart from the example shown on Figure 3.5, patch antennas can have other shapes of patches and different ways to be fed as shown on Figure 3.6.
Radiation Pattern

Using ANSYS HFSS a generic patch antenna was simulated in order to obtain its radiation pattern. The result can be seen on Figure 3.7. The green square simulates the substrate made of Flame Retardant-4 (glass-reinforced epoxy laminate material) (FR4), there is the yellow metal sheet on top of the substrate that is the actual antenna and there is another one with the size of the substrate under it, that is the ground. Both yellow sheets are PECs and there is a port feeding the patch between the two PECs.

From Figure 2.4, the radiation pattern of the patch is almost the isotropic one but only in one hemisphere, so its type is the hemispherical one. This antenna radiates only to the front of the patch, slightly less to the sides and nothing to the back.

3.1.4 Turnstile

Theory

Turnstile antennas are not an elementary unit. They are a form of array made by two dipoles crossed at 90°, as seen on Figure 3.8.

Turnstile antennas produce either linear or circular polarization, depending on whether they are fed in phase or out of phase.

For a generic turnstile antenna, in which the dipoles are fed with a phase difference of $\delta$, we have the electromagnetic fields in the far zone as defined in equation (3.4),

\[
\mathbf{B} = k^2 \frac{e^{j(kr-\omega t)}}{r} \hat{r} \times (p_1 + e^{-jkd} p_2) = p_0 k^2 \frac{e^{j(kr-\omega t)}}{r} \hat{r} \times (\hat{x} + e^{j(\delta - kd)} \hat{y}), \quad \mathbf{E} = \mathbf{B} \times \hat{r} \quad (3.4)
\]
that we can separate in the three spherical coordinates components as in equations (3.5),

\[ E_r = B_r = \hat{r} \cdot B = 0, \quad (3.5a) \]
\[ E_\theta = B_\phi = p_0 k^2 e^{j(kr - \omega t)} \cos \theta (\cos \varphi + e^{j(\delta - kd)} \sin \varphi), \quad (3.5b) \]
\[ E_\phi = -B_\theta = -p_0 k^2 e^{j(kr - \omega t)} (\sin \varphi - e^{j(\delta - kd)} \cos \varphi), \quad (3.5c) \]

where \( d \) is the distance from the observation point to the antenna, given by equation (3.6), considering that the antenna is in the origin and the observer in point \((x_2, y_2, z_2)\). The polarization produced in this case is circular in the vertical direction (\( \theta = 0 \)) [25].

\[ d = x_2 \sin \theta \cos \varphi + y_2 \sin \theta \sin \varphi + z_2 \cos \theta \quad (3.6) \]

Radiation Pattern

Using ANSYS HFSS a generic turnstile antenna was simulated in order to obtain its radiation pattern. The result can be seen on Figure 3.2. The turnstile was fed by two ports placed in the middle of each pair of arms (one pair with 90° phase shift in relation to the other one).

This is not any of the conventional types of radiation patterns from Figure 2.4 since it is the combination of two dipole antennas orthogonal to each other. It has the nulls aligned with the dipole arms and kind of a directional pattern in two ways.

3.2 Most Common Ways to Impedance Match for Dipole Antennas

When planning a communications system for a satellite, after choosing the antenna to be used, the choice of the matching network for the antenna is also important [26]. Since power is a very important, hard and expensive thing to achieve in space communications, it is of great importance to be able to transmit to the antenna as much power as possible without reflections back to the source which are caused by some impedance mismatch [26]. A downside of this reflected wave is that it can damage or overheat the system and also generate a standing wave [26].

Some advantages of proper termination and matching are listed below: [26]

- Amplitude reduction
- Phase error reduction
- Power loss reduction
- Signal to noise ratio improvement
- Optimal parameters such as return loss, efficiency and gain, that result in advantages, for example maximum power transfer
- Easier and faster antenna frequency tuning (rather than modifying the antenna geometry), more relevant for antenna tuners
- Improved bandwidth (due to added resonances)
- Allowance of last minute design changes (independent choice of values for discrete elements)

So, the goal when performing impedance matching is to make sure that the characteristic impedance of the line is equal to the impedance of the load (antenna's feed) \[27\] in order to obtain a reflection coefficient of 0, meaning that there is no waste of power. Normally, antennas are matched at 50\(\Omega\) because almost all of the sources and lines are built to work at this characteristic impedance \[26\].

As we can now see, impedance matching is a very important thing to take into account when designing an antenna and for this very reason, there is a wide amount of literature on this topic and many different ways to perform impedance matching, even more specifically for each different type of antenna \[26\]. Since dipole antennas are one of the main kinds used in space applications and the most likely to be used for this mission, this review will focus on impedance matching for this type.

Impedance is a ratio between voltage and current. In a \(\lambda/2\) dipole that is fed in the center, the impedance is 73\(\Omega\), in free space \[27\]. Even though it is not a perfect match, this 23\(\Omega\) difference is considered to be minimal, generating a SWR of 1.5:1 which translates to 5% of power being wasted \[28\].

### 3.2.1 Transformer

As the name implies, transformers perform transformations \[29\]. They convert values of voltage, current and impedance \[29\].

There are many types of transformers, but for this thesis, the ones that are used for Radio Frequency (RF) and microwave signal applications are the ones that matter \[29\]. RF transformers are, basically, at least 2 coils connected by a common magnetic field that are wound around or inside a magnetic or non-magnetic core \[29\]. They are commonly used in electric circuits with low power \[30\].

The principle of work of transformers depends on the number of turns each coil has. On the primary one, an Alternating Current (AC) voltage is applied, generating a varying flux. The flux's amplitude will depend on the applied voltage and number of turns on the primary coil. Since the coils are connected by the same magnetic field, the varying flux on the primary coil will induce a voltage, which once again will have a certain amplitude depending on the number of turns of the secondary coil. Choosing the right amount of turns on the primary and secondary coils, it is possible to perform a wanted step-up or step-down \[29\].
Transformers are ruled by the set of equations (3.7),

\[
\begin{align*}
N &= N_2/N_1 \\
V_2 &= NV_1 \\
I_2 &= I_1/N \\
Z_2 &= N^2Z_1
\end{align*}
\]  

(3.7)

where \( N \) is the turns ratio, \( N_1, V_1 \) and \( I_1 \) are, respectively, the number of turns, voltage and current of the primary coil, as defined on Figure 3.10 and \( N_2, V_2 \) and \( I_2 \) are the same for the secondary coil.

Figure 3.10: Schematic of a transformer [29].

### 3.2.2 Balun

Balun is the mix of the words balanced and unbalanced. They are devices that transform and link balanced impedances (no terminal connected to ground) to unbalanced impedances (one terminal connected to ground), as we can see on Figure 3.11 [29].

Figure 3.11: Schematic of a balun [29].

They can match the feed impedance of the antenna to the 50Ω impedance of the coaxial cable [31]. However, the main goal of baluns is not to perform impedance match. In the transition between balanced and unbalanced, their main goal is to isolate current paths and differences in voltages between the two mediums [32].

### 3.2.3 L-network

The L-network are normally used to match circuits for unbalanced loads with one frequency band of operation [33].
As we can see on Figure 3.12, it is made of 2 adjustable capacitors/inductors, placed in an L shape. One of them is in parallel with the load’s complex impedance, canceling its inductive reactance (tuning). The other is in series and steps down the impedance in order to match the impedance of the line (matching) [34].

![Figure 3.12: Schematic of an L-network [33].](image)

It is possible to have, instead, two capacitors, two inductors or one of each in inverse order. The option shown on Figure 3.12 is the most common on amateur uses since it has a low-pass that reduces harmonics [33].

Lossless L-networks are ruled by the set of equations (3.8),

\[
\begin{align*}
Q &= \sqrt{\frac{R_P}{R_S}} - 1 = \frac{X_s}{R_S} = \frac{R_P}{X_P} \\
X_s &= QR_S = \frac{QR_P}{1+Q^2} \\
X_P &= \frac{R_P}{Q^2} = \frac{R_S R_P}{X_P} = \frac{R_P^2 + X_P^2}{X_P} \\
R_S &= \frac{R_P}{Q^2+1} = \frac{X_S X_P}{R_P} \\
R_P &= R_S (1 + Q^2) = Q X_P = \frac{R_P^2 + X_P^2}{R_S}
\end{align*}
\]

where \( Q \) is the ratio of the series reactance to the series resistance and a parameter of the network and \( X_S, X_P, R_S \) and \( R_P \) are the values of the elements as defined on Figure 3.12. Knowing any two parameters, makes it possible to calculate the other two.

However it is not possible to match all impedances to 50 \( \Omega \) with L-networks. For this to happen, load and source impedances must have a specific relation [33].

### 3.2.4 Pi-network

The Pi-network offers more flexibility than the L-network since it presents an extra parameter, as we can see on Figure 3.13 [33]. It can be used to match low impedances to high ones, for example matching 50\( \Omega \) to thousands of \( \Omega \) or, on the other way, 1\( \Omega \) to 50\( \Omega \).

![Figure 3.13: Schematic of a Pi-network [33].](image)
Lossless Pi-networks are ruled by the set of equations (3.9), for $R_1 > R_2$,

\[
\begin{aligned}
X_{C1} &= \frac{R_1}{Q} \\
X_{C2} &= R_2 \sqrt{\frac{R_1/R_2}{Q^2 + 1 - R_1/R_2}} \\
X_L &= \frac{(Q \times R_1) + \frac{R_1 \times R_2}{N^2}}{Q^2 + 1} \\
X_L &\leq \sqrt{R_1 \times R_2}
\end{aligned}
\]  

where $Q$ is the ratio of the series reactance to the series resistance and is a parameter of the network and $X_{C1}, X_{C2}, X_L, R_1$ and $R_2$ are the values of the elements as defined on Figure 3.13. Knowing any two parameters makes it possible to calculate the other three.

### 3.2.5 T-network

The T-network can show itself to be very flexible when matching a wide range of loads, as the high-pass one shown on Figure 3.14, but can also waste power that we need and want for the antenna, since it is more lossy than the others. This has an even bigger impact at lower frequencies, when the load resistance is low [33].

![Figure 3.14: Schematic of a T-network [33]](image-url)
Chapter 4

ORCASat’s TT&C Antenna and Matching Network Design

In this section, the results of the simulations of the antenna’s radiation will be presented. These simulations were made over 5 iterations, where from one to another, a level of complexity was added, starting with the most basic design and ending with the complex full representation of the satellite.

Simulations where performed using ANSYS Electronics Desktop 2020 R1 and where also validated with Computer Simulation Technology (CST) Microwave Studio Academic Edition 2019.

4.1 Antenna Choice

After all the literature review stated on section 3.1 and the specific theory on each type of antenna on subsections 3.1.1 to 3.1.4, it is now time to make a decision on which antenna to use on ORCASat.

The final choice must take in consideration not only the electrical performance, but also the mechanical and structural point of view [14], so let’s recap the major factors to make the decision.

The dipole antenna has a simple design and it is cheap to manufacture (can even be done with measuring tape), but needs a release mechanism.

The patch antenna has the great advantage of not needing any deployment system. A downside is that it is very hard to manufacture for the frequency we are working in, since it would need dielectric loading to allow miniaturization, otherwise it would be too big (in the order of the wavelength size) and take up a whole side of the satellite.

Finally, there is the turnstile antenna, but it is a hard design and would take up too much space that we don’t have.

So, for all these reasons stated, the dipole was the chosen antenna for ORCASat TT&C subsystem.
4.2 Matching Network Choice

The same that was done for the choice of the antenna has to be done to choose the matching network used. This will take into consideration the literature review stated in section 3.2 and the specific theory on each kind of network in subsections 3.2.1 to 3.2.5, so let's recap the major factors to make the decision.

The impedance matching network has to exist for two major reasons:

- The antenna is a balanced impedance and the feed line is unbalanced, so it is necessary to have something in between to make the link,
- The line and the feed of the antenna have different impedance values.

Transformers transform currents, voltages and impedances. Their work depends on the number of turns each coil has in relation to the one another.

The balun is a device to transform and link balanced to unbalanced impedances. Although it can match the feed impedance of the antenna to the $50\,\Omega$ impedance of the coaxial cable, this is not its main goal.

Finally there are the L, Pi and T networks, but they don't allow all kinds of matching with $50\,\Omega$. They are harder to understand and manipulate and don't allow the connection between balanced and unbalanced impedances.

So, for the reasons listed above, what we need for the impedance matching network is not one of these systems, but a transformer and a balun combined. A balun can be a transformer (having a transformer inside the block diagram on Figure 3.11), but the impedance transformation can only be done on real values of impedance. As a result of this, it is necessary to perform simulations of the antenna mounted on the satellites body, because the body interference will most certainly generate an imaginary component of the antenna impedance. With the simulations it is possible to know precisely this imaginary value and with a smith chart see if it is necessary a capacitor or an inductor in order to cancel the imaginary part. Then, having to deal only with real parts, it is only necessary to calculate the ratio between the number of coils for the transformer.

4.3 Computational E&M Simulations

First it is important to focus only on the antenna radiation to learn the influence that the diverse design parameters will have in the end results.

4.3.1 Iteration 1: Antenna Only

The simplest simulation we can run is the antenna on its own. Some setup configurations that were defined and taken in consideration for this design are listed below.

- $\lambda/2$ copper tape dipole in free space at working frequency (fc) of 435MHz (as seen on Figure 4.1) with PML as the open region boundary.
• Parametric drawing allowing sweeps.

• Center feed with 50Ω lumped port.

• Maximum number of passes was 99 and maximum delta S 0.001.

• Lambda refinement as default 0.3333, 30% of maximum refinement per pass.

![Figure 4.1: Dipole in free space.](image)

The main goals established for this first iteration were:

• Simulation of the effect of length, width, thickness and feed gap variations on |S11| at fc=435MHz,

• Coming up with rough parameters that allow minimal |S11| and at least a 3MHz 3dB bandwidth,

• Producing Electric (E) and Magnetic (H) fields of radiation pattern cuts and 3D view of the full pattern.

**Results**

As mentioned before, the antenna was designed not in a fixed way, it was drawn with parameters, that would allow easy sweeps to test the impact of their change on the antenna radiation characteristics. The created parameters were length, width, thickness and feeding gap length between the two dipole arms.

The parametric sweep was performed in one parameter at a time, leaving the others constant. The general results are listed below.

• Increase length - fc goes down, return loss doesn’t change much.

• Increase gap - fc goes down, return loss gets better.

• Variation in thickness has minimal effect when kept less than 1mm. If increased for 5mm the fc goes down, return loss gets better.
- Increase width - $fc$ goes down, return loss doesn’t change much.

The results of the parametric sweeps, for the four design variables are presented on Figure 4.2.

Figure 4.2: Results of the parametric sweeps, for the four design variables.
After the sweep, and with an increased knowledge on the impact that each parameter variation will imply on the final design, it was estimated that optimal dipole dimensions and respective electrical result, should be the ones presented below:

- Length: 145mm (per dipole arm),
- Gap: 14mm,
- Thickness: 0.15mm,
- Width: 12.5mm,
- fc: 450.5MHz,
- $|S11|$: -15.3dB,
- -3dB bandwidth in $|S11|$: 30.57MHz.

The $|S11|$ results are shown in Figure 4.3.

The far field E ($\theta=90^\circ$, x/y plane) and H field ($\phi=90^\circ$, y/z plane) radiation pattern cuts are shown in Figure 4.4, at working frequency of 435MHz.

The 3D far field pattern of the antenna is shown in Figure 4.5. The far field simulation gives a directivity of 2.1dBi.

### 4.3.2 Iteration 2: Antenna and Satellite Body

For the second iteration a new degree of complexity will be added. It made sense that would be the satellite body only. It is important to make it as similar as possible to how the antenna is mounted on the satellite body. The view of ORCASat in its on orbit configuration is shown in Figure 4.6.

Some setup configurations that were defined and taken in consideration for this design are listed below.

- Annealed copper tape dipole with dimensions from Dipole V1.
  - Length: 145mm (per dipole arm)
• Gap: 14mm
• Thickness: 0.15mm
• Width: 12.5mm

- Mounted near wake face of 2U CubeSat body (as seen on Figure 4.7).
  - Distance from dipole center to wake face: 25mm
- CubeSat body modelled as hollow aluminum box.
Figure 4.6: ORCASat on orbit configuration.

- 200x100x100mm box with 10mm wall thickness

- 15x5mm cut-out for dipole.

- Center feed with 50Ω lumped port.

- Maximum number of passes was 99 and maximum delta S 0.001.

- Lambda refinement 0.17, 30% of maximum refinement per pass.

Figure 4.7: CubeSat body model integrated with dipole.

The main goals established for this second iteration were:

- Simulation of the effects of CubeSat body on radiation pattern, |S11| and comparison to dipole v1,
• Simulation of the new structure without change in mechanical antenna parameters and observation of the effects.

Results

Previously we had the antenna alone resonating in the free space. Now, with the satellite body, the radiation pattern and other characteristics of the antenna suffered slight changes. Below are listed some general results observed, when compared to the dipole with the same dimensions from Iteration 1.

• Large upward frequency shift in fc.

• Worse return loss.

• Widened 3dB bandwidth.

To be more specific, the new results obtained are listed below. As shown, the return loss worsened by 3.49dB, the 3dB bandwidth in return loss has increased by 52.99MHz and the operating frequency increased as well, by 58.5MHz:

• fc: 509.0MHz,

• |S11|: -11.81dB,

• 3dB bandwidth in |S11|: 83.56MHz.

The new |S11| results are shown in Figure 4.8.

![Figure 4.8: |S11| results for the model including the satellite body.](image)

The far field E (θ=90°, x/y plane) and H field (φ=90°, y/z plane) radiation pattern cuts are shown in Figure 4.9, at working frequency of 435MHz. As shown, the presence of the satellite body modified the E and H field patterns.

The 3D far field pattern of the antenna is shown in Figure 4.10. The far field simulation gives a directivity of 2.8dBi.
4.3.3 Comparative Table

The side by side comparison of the simulation results is shown in Table 4.1. As indicated, the effect of the body is a much wider bandwidth, less efficient antenna with significantly worse return loss characteristics.
Table 4.1: Iterations 1 and 2 side by side comparison.

<table>
<thead>
<tr>
<th></th>
<th>Dipole v1</th>
<th>Dipole v2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_c ) [MHz]</td>
<td>450.5</td>
<td>509.0</td>
</tr>
<tr>
<td>(</td>
<td>S11</td>
<td>) [dB]</td>
</tr>
<tr>
<td>(-3\text{dB} ) bandwidth [MHz]</td>
<td>30.5</td>
<td>83.56</td>
</tr>
<tr>
<td>Directivity [dBi]</td>
<td>2.1</td>
<td>2.8</td>
</tr>
</tbody>
</table>

| 4.4 Circuit Simulations for Matching Network |

Now that the Electric and Magnetic (E&M) behavior of the antenna is known, it is easier to join the matching network design and know if a change of a specific parameter will influence the end result.

4.4.1 Iteration 3: Antenna and Satellite Body (simplified design)

For the third iteration the new degree of complexity added was the matching network.

Some setup configurations that were defined and taken in consideration for this design are listed below.

- Stainless steel tape dipole in floating aluminum box.

- Starting dimensions from dipole v2.
  - Length: 145mm (per dipole arm)
  - Gap: 14mm
  - Thickness: 0.15mm
  - Width: 12.5mm

- Mounted near wake face of 2U CubeSat body (as seen on Figure 4.11).
  - Distance from dipole center to wake face: 25mm

- CubeSat body modelled as hollow aluminum box.
– 200x100x100mm box with 10mm wall thickness

• 15x5mm cut-out for dipole.

• Center feed with 50Ω lumped port.

• Maximum number of passes was 99 and maximum delta S 0.001.

• Lambda refinement 0.17, 30% of maximum refinement per pass.

![Figure 4.11: Setup of dipole v3.](image)

The main goals established for this third iteration were:

• Determine dipole input impedance when mounted in metal box,

• Conceptualize and simulate impedance matching network.

Results

When a dipole is in free space, its impedance is well documented. In the satellite, that changes as a result of nearby objects. To determine the extent of this change, the complex S11 can be determined from a simulation, and from it, the actual input impedance of the dipole can be determined according to the following equations,

\[
 r_L = \frac{1 - \Gamma_r^2 - \Gamma_i^2}{(1-\Gamma_r)^2 + \Gamma_i^2},
\]

\[
 x_L = \frac{2\Gamma_i}{(1-\Gamma_r)^2 + \Gamma_i^2},
\]

where \( z_L = r_L + jx_L = Z_L/Z_0 \) [35]. This is demonstrated using the following example. (Dimensions like Dipole v2 iteration except feed gap, g=2mm). The magnitude plot of S11 is shown in Figure 4.12 and the complex Im/Re plot of S11 is shown in Figure 4.13 below.
From this, the input impedance is calculated as follows. Figure 4.13 marks:

\[
\begin{align*}
\text{Re}\{S_{11}\} & = \Gamma_r = -0.25, \\
\text{Im}\{S_{11}\} & = \Gamma_i = 0.17.
\end{align*}
\] (4.3)

Using equations (4.1) and (4.2), the values obtained are,

\[
\begin{align*}
r_L &= 0.5709, \\
x_L &= 0.2136,
\end{align*}
\] (4.4)

that correspond to the \( z_L \), that is the normalized value of \( Z_L \). To get the desired value it is necessary to multiply the previous components by \( Z_0 = 50\Omega \). From this the final impedance value is obtained, as stated in (4.5).

\[
\begin{align*}
R_L &= 28.5472\Omega, \\
x_L &= 10.6824\Omega.
\end{align*}
\] (4.5)

ANSYS also calculates this as the Z11 impedance parameter. The Z11 values in Figure 4.14 match those calculated above, indicating that this method of determining the \( Z_{in} \) of the dipole is valid.
Ideally, by changing the feed gap and the length of the antenna, a combination of physical parameters could be obtained which would make the antenna impedance to be near 50Ω in the real part, with an imaginary part which could be cancelled with a series capacitor or inductor (while making the antenna resonant on or near 435MHz with decent bandwidth).

Capacitors have negative impedance and inductors have positive impedance, both being purely imaginary values. This means that with the correct value, a capacitor can cancel a positive imaginary value and an inductor a negative one. The equations to calculate the impedance of capacitors and inductors are stated bellow.

\[ X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C} \quad (4.6) \]

\[ X_L = \omega L = 2\pi f L \quad (4.7) \]

In equation (4.6) the negative sign for the impedance is not stated by convention, \( X_C \) is the impedance of the capacitor (value we want to cancel), \( C \) is the capacitance/value of the capacitor. In equation (4.7) \( X_L \) is the impedance of the inductor (value we want to cancel), \( L \) is the inductance/value of the inductor.

By trial and error, it was found that an arm length of 175mm and a feed gap of 12mm yields such a combination at 435MHz. In Figure 4.15 below \( Z_{in} = 50.01 + j6.94\Omega \) for these dimensions. This is extremely desirable, because it means that a series capacitor of value \( C = 1/(2\pi \times 435 \times 10^6 \times 6.94) = 52.7195pF \), according to equation (4.6), will cancel this, leaving a purely real dipole input impedance which is the same as the impedance of the feeding microstrip line (allowing the use of a 1 to 1 balun).
Since the balun is used first, the capacitor value needs to be converted into use in a balanced system, meaning that each dipole arm should be fed via a capacitor value of $2C = 105.4390\text{pF}$ (equivalent of having two capacitors in series). To test this arrangement, an Electromagnetic (EM)/circuit co-simulation was set up in ANSYS Electronics Desktop, as shown in Figure 4.16 below. In this simulation, the transformer is 1:1 and it is ideal.

The simulation results ($Z_{11}$) for this setup, shown in Figure 4.17 indicates that the imaginary part of the dipole impedance has been eliminated, and an impedance match has been achieved in a configuration which also transforms the unbalanced microstrip feed into a balanced input for the dipole.
This is further supported by the return loss plot, which indicates resonance around 435MHz, with a 3dB bandwidth of 3.27MHz, as shown in Figure 4.18. The return loss is better than -30dB, so this narrow bandwidth is not an issue.

![Return loss plot](image1.png)

**Figure 4.18: Return loss.**

The far field E ($\theta=90^\circ$, x/y plane) and H field ($\varphi=90^\circ$, y/z plane) radiation pattern cuts are shown in Figure 4.19, at working frequency of 435MHz.

![Far field E and H patterns](image2.png)

**Figure 4.19: Far field subplots for dipole on satellite body.**

The 3D far field pattern of the antenna is shown in Figure 4.20. The far field simulation gives a directivity of 2.9dBi.

![3D far field pattern](image3.png)

**Figure 4.20: 3D far field pattern.**

Based on what has been shown in this document, it seems to be feasible to use the transformer/capacitor.
(or transformer/inductor) setup described above to feed the antenna of ORCASat. Now, a more accurate satellite structure needs to be simulated with refined details. This will help conceptualize the physical layout of the feed concept and allow the construction of a real life test artifact which will then be suitable to validate this simulation.

4.4.2 Iteration 4: Antenna and Satellite Body (complete CAD)

The best way to understand the real effects of the surrounding satellite is to simulate the antenna inside the real satellite. This can be done by importing to ANSYS a Computer Aided Design (CAD) model of the satellite (must be in *.sat or *.step format, being the *.step better). The design is represented on Figure 4.21 and the constituent material of each component is:

- PCBs and antenna clamp are FR4, epoxy in the middle with copper on the top and bottom,
- Antenna is made of steel, stainless,
- Rail panel, side panel and module bracket are in aluminum,
- Box and door are plastic (Delrin 150).
Some setup configurations that were defined and taken in consideration for this design are listed below.

- Starting dimensions from CAD design.
  - Length: 175mm (per dipole arm)
  - Gap: 11.9mm
  - Thickness: 0.15mm
  - Width: 12.5mm
- Center feed with 50Ω lumped port.
- Maximum number of passes was 20 and maximum delta S 0.001.
- Lambda refinement with default value of 0.3333, 30% of maximum refinement per pass.

The main goals established for this fourth iteration were:

- Determine dipole input impedance when mounted in the simplified satellite with the most relevant parts,
- Simulate impedance matching network.

**Results**

With new components added, S11 will have a new variation, when compared to previous simulations. To determine the extent of this change, the complex S11 and $Z_{in}$ can be determined from a simulation. The plot of $|S11|$ is shown in Figure 4.22 and the Z11 is shown in Figure 4.23 below.

![Figure 4.22: Dipole $|S11|$](image-url)
By trial and error, it was found that an arm length of 184mm and a feed gap of 11.9mm yields such a combination at 435MHz. In Figure 4.24 below Z11 is shown as $Z_{in} = 7.53 - j16.94\,\Omega$ for these dimensions. This is extremely desirable, because it means that a series inductor of value $L = 16.94/(2\pi \times 435 \times 10^6) = 6.1979\,nH$, according to equation (4.7), will cancel this, leaving a purely real dipole input impedance that can be matched to the impedance of the feeding microstrip line with the use of a 5 to 2 transformer to make the balanced/unbalanced connection.

Since the balun is used first, the inductor value needs to be converted into use in a balanced system, meaning that each dipole arm should be fed via an inductor value of $L/2 = 3.0989\,nH$ (equivalent of having two inductors in series). To test this arrangement, an EM/circuit co-simulation was set up in ANSYS Electronics Desktop, as shown in Figure 4.25 below. In this simulation, the transformer is 5:2 and it is ideal.
The simulation results (Z11) for this setup, shown in Figure 4.26 indicates that the imaginary part of the dipole impedance has been eliminated, and an impedance match has been achieved in a configuration which also transforms the unbalanced microstrip feed into a balanced input for the dipole.

This is further supported by the return loss plot, which indicates resonance around 435MHz, with a
3dB bandwidth of 11.80MHz. This is shown in Figure 4.27. The return loss is better than -30dB, so this narrow bandwidth is not an issue.

![Figure 4.27: Return loss.](image)

The far field E ($\theta=90^\circ$, x/y plane) and H field ($\varphi=0^\circ$, x/z plane) radiation pattern cuts are shown in Figure 4.28, at working frequency of 435MHz.

![Figure 4.28: Far field subplots for dipole on satellite body.](image)

The 3D far field pattern of the antenna is shown in Figure 4.29. The far field simulation gives a directivity of 3.2dBi.
4.4.3 Feed Details

The way to feed the antenna is an important detail that needs to be defined by both the TT&C team and the Mechanical team. The solution found must work from an E&M point of view but also, the structural part and physical space occupied by the feed must be approved by the Mech team. It also needs to get along with other already existing components, like the release mechanism and circuit.

Some solutions that were studied are represented on Figure 4.30.

The details of each solutions and reasons for rejection are listed below:

a. Small PCB in contact to each dipole arm inside the box, with copper on the touching side, connected by two screws. 2x2 pins (sensor connectors) to physically attach the antenna to the board. The pins on the board side are standing on a copper square printed on the PCB. This option was not considered since it was showing poor E&M performance.

b. Copper L bracket in contact to each dipole arm inside the box and passing under the arm to the outside, 0.15mm thickness (same as the dipole), connected by screws to the antenna and to the PCB. The bracket is standing on a copper square printed on the PCB. This option was refused by the Mech team since it was not solid enough from the structural point of view.

c. Copper L bracket in contact to each dipole arm inside the box and passing under the arm to the outside, 1mm thickness, connected by screws to the antenna and to the PCB. The bracket is standing on a copper square printed on the PCB. This option was refused by the Mech team since it was passing under the dipole arm, what was causing it to be slightly raised and there was not enough space for that. The structural performance was also a concern.

d. Copper L bracket in contact to each dipole arm inside the box turned to the inside too, 1mm thickness, connected by screws to the antenna and to the PCB. The bracket is standing on a copper square printed on the PCB. This option was refused by the Mech team since it was standing in the space for the release mechanism.

e. Aluminum block in contact to each dipole arm outside of the box (the box had to suffer a cut to allow this), 5x16mm footprint, connected by screws to the antenna. The block is standing on a copper square printed on the PCB. This option was not considered since it was showing poor E&M performance.
f. Aluminum (better structural performance) L bracket in contact to each dipole arm outside the box (the box had to suffer a cut to allow this) turned to the outside too, 1mm thickness with added walls with 2mm to increase the structural stability, connected by screws to the antenna and to the PCB. The bracket is standing on a copper square printed on the PCB. This option was good but the bracket had a higher unnecessary complexity. Since a better solution was found this one was not considered.

After this intensive study, the final design is the one presented on Figure 4.31. It consists of an aluminum L bracket in contact with each dipole arm placed between the box and the arm and turned to the outside, with a 1.6mm thickness that guarantees the structural stability without the need of the walls (and facilitates the manufacture process of the bracket), connected by screws to the antenna and to the
PCB. The bracket is standing on a copper patch printed on the PCB. This is a very simple solution that satisfies all the requirements and limitations.

![Figure 4.31: Final feed design.](image)

### 4.4.4 Iteration 5: Final Design

This final simulation was performed to evaluate the performance of the feeding solutions presented on Figures 4.30 and 4.31.

Some setup configurations that were defined and taken in consideration for this design are listed below.

- Tuned dimensions of the antenna.
  - Length: 192mm (per dipole arm)
  - Gap: 11.9mm
  - Thickness: 0.15mm
  - Width: 12.5mm

- Design setup as the one on Figure 4.32.

- Center feed with 50Ω lumped port.

- Maximum number of passes was 6 and maximum delta S 0.02 (default values).

- Lambda refinement with default value of 0.3333, 30% of maximum refinement per pass.
The details of the feeding port can be seen on Figure 4.33. The port is connected to the pads under the L brackets.

Results

The plot of $|S_{11}|$ is shown in Figure 4.34 and the $Z_{11}$ is shown in Figure 4.35 below, for the tuned dipole.

Unlike the previous iterations, the Matching Network on this one was not simulated using ANSYS EM/circuit co-simulation. Instead, the S11 matrix of values was exported from ANSYS on a *.S1P file and imported to another program, with better accuracy in circuit design, ADS. Since the real part of the input impedance was already very close to 50Ω, a decision was made to use a 1:1 transformer. In order to correctly simulate the transformer and know the impact this component would have on the input impedance, the S-parameter of the chosen component was imported to the circuit too. This way, using
the smith chart, like on Figure 4.36, it was possible to calculate the values for the necessary components to add to the circuit (represented on Figure 4.37) that would result in a perfect match.
According to Figure 4.36, the normalized impedance value is $z_L = 0.976 - j0.119$ that corresponds to an input impedance of value $Z_L = 48.75 - j5.95\Omega$, what represents an almost perfect match. For this last version, a decision was made to place the matching network on the unbalanced side so there is no need to have two components feeding each arm of the dipole. This represents a reduction by half in capacitors/inductors.

The far field $E$ ($\theta=90^\circ$, x/y plane) and $H$ field ($\phi=0^\circ$, x/z plane) radiation pattern cuts are shown in Figure 4.38, at working frequency of 435MHz.

The 3D far field pattern of the antenna is shown in Figure 4.39. The far field simulation gives a directivity of 3.2dBi.
Figure 4.38: Far field subplots for dipole on satellite body.

Figure 4.39: Far field 3D directivity pattern for dipole on satellite body.
4.5 Evaluation of the Design From the Simulation Results

In theory, the length of the dipole should be half of the frequency wavelength. If that was the case, the dipole length was expected to be:

$$\lambda = \frac{c}{f} \Rightarrow \lambda = \frac{3 \times 10^8}{435 \times 10^6} = 0,689655m,$$

$$\frac{\lambda}{2} = 0,3448275m$$  \hspace{1cm} (4.8)

where \(c\) is the velocity of light in vacuum and \(f\) the working frequency. The length \(\lambda/2\) should be the total of the two arms combined. So each arm should measure around 170mm.

Even-though the antenna is an electrical half wavelength, as stated on subsection 4.4.4, the actual arm size is bigger than the expected calculated above for a signal travelling in free space. This is explained due to the surrounding elements to the antenna.

However, if the antenna was simulated by itself, it was expected for it to be slightly shorter than the calculated wavelength \([14]\), as it is actually present on subsection 4.3.1.

To better analyse the obtained results, on Figures 4.40 and 4.41 it is possible to see the far field plots projected on the simulated body.

![Figure 4.40: Far field subplots projected on the simulated body.](image)

From the analyze of the above images it is possible to have a better understanding of the actual effect of the surrounding elements to the dipole, on its performance. The doughnut pattern that was expected to be observed exists, however, the fact that the null is centered on the structure and not along the line of the dipole, gives the impression that the dipole is formed more by the structure than by the antenna wire itself.

Another thing possible to observe in all of the images is the fact that the omnidirectional part of the doughnut is not perfect. Since the dipole is placed next to the bottom side of the satellite body, that direction is the one with less power. The place with more power will then be the top side of the body.

In the future, the matching network may suffer some small changes. It will go through a final simulation an ADS were the PCB layers will be imported to simulate it with the exact copper layers in the
surrounding of the antenna. That change might reflect only in the position of the capacitor (series Versus (VS) parallel) or in its value.
Chapter 5

Prototyping and Testing

This is the last chapter with work developed for this thesis. It has the development and testing of the prototype designed to verify the performance of the antenna that was simulated on the previous chapter.

5.1 Board Layout and Assemble on PC104 Card

5.1.1 Board Layout

On the satellite, the whole TT&C subsystem needs to be on the same PCB. This means that not only the antenna and matching network will be there, but also the deploy circuit for the antenna and the transceiver. However, for this thesis, only the antenna and matching network are interesting and were designed, the other components were responsibility of other team members. In the end, the three PCBs designs were assembled together on the same board.

The antenna and matching network are placed on the bottom side of the board along with the release mechanism and the transceiver is located on the top layer of the board. The signal comes from the top side to the bottom one through SubMiniature version A (coaxial connector) (SMA) connectors. The board was designed using Altium and it is made of four layers, where the top and bottom ones are the ones described above and the middle ones are set as Ground (GND).

On Figure 5.1 it is possible to see the 3D render of the TT&C board form Altium and on Figure 5.2 the top an bottom layers layout.

On Figure 5.1 (b) it is possible to notice two SMA connectors. The board is made like this for testing purposes, this way it is possible to test the transceiver without the antenna and vice versa. For a functioning board (where the transceiver signal passed for the antenna) a coax cable should be attached to both SMA connectors.

On Figure 5.2 (b), the highlighted area inside the red square is the one that will be studied for the purpose of this thesis and comprises the feeding pads and the matching network, ending on one of the SMA connectors.

As it is possible to notice, some small changes were made after the simulations. The patches were rounded to reduce the radiation irradiated through the corners. Originally, on the simulations the patches
were represented with sharp corners but just to be sure, a new simulation was made on ANSYS with the round corners and the results were almost the same as before, so there was no problem on having patches with round corners. All of the tracks that carry RF signals were also made out of continuous curve lines, instead of lines that bend in $45^\circ$, once again to avoid radiation irradiated through the corners.

All of the tracks and patches that belong to the antenna and matching network are surrounded by GND vias to isolate the path and prevent the signal to escape and spread to others parts of the board or even to avoid getting signal that escaped from other tracks.
The Stackup of the four layers was the one specified by the manufacturer. The project leaders made the decision to use the “4 Layer Prototype Service” from OSHPARK, since their default substrate material is FR4. The Stackup characteristics are the ones defined in [36].

5.1.2 Final Simulations

Now that the PCB is fully designed, a final simulation was performed on ADS. The goal was to check the full influence that all of the four copper layers and respective track lines might have on the antenna and to confirm if the previous matching network will still be suitable or if it needs to be tuned.

On Figure 5.3 it is possible to see the cutout made on Altium, from the antenna layer, that was imported to ADS to perform the final simulation.

![Figure 5.3: Cutout of the PCB layer from Altium.](image)

The cutout from Figure 5.3 was then imported to ADS and connected to the other components (antenna, transformer and capacitor). The simulation was run and a small tuning had to be performed. The capacitor changed in value only and kept the same position. On Figure 5.4 it is possible to see the setup circuit and on Figure 5.5 there is the Smith chart used to perform the matching network tuning and the final S11 parameter of the antenna.

It is not explicit on Figure 5.4, but the other three layers were also added to the simulation, placed at the right distance from each other (as stated on the respective Stackup [36]) and the right connections between each other were made and grounded. This means that in this co-simulation the PCB was EM full wave simulated and circuit components are added to achieve the final design.

The final matching network is composed by the following elements:

- 1x series capacitor of value 15pF (the one presented in [37])
- 1x 1:1 balun (presented in [38])
5.1.3 PCB Assemble

In this subsection the manufacturing process of the prototype to perform the antenna tests will be described and documented with some photographs.

Figure 5.6 shows the top and bottom view of the main board of the TT&C subsystem and also both views of a smaller PCB card that contains the Transmit (TX) watchdog and will be attached to the top side of the main board.
Figure 5.6: Space segment real life PCBs.

Figure 5.7 is a microscope view of the feed pads and matching network, after soldering the components. The antenna arms are not soldered so they will later be screwed onto the board.

Figure 5.7: Feed and matching network detail of assembled PCB, viewed under the microscope.

On Figure 5.8, it is possible to see a dipole arm made out of measuring tape. On picture (a) it shows that a part of the paint was removed, on the beginning of the arm. It was made in order to provide a direct contact from the bracket to the metallic arm, allowing the RF signal to pass with less issues. On picture (b) the arm is already screwed to the bracket that later will be mounted on the PCB. On both images it is possible to see that some marks were made with permanent black marker. These were made to facilitate the tuning process, while testing, since the measuring tape is in inches and the simulations were made in millimeters. This way it is possible to know the exact size of each arm and tune them by
cutting a certain known amount of its length.

(a) Arm made out of measuring tape.

(b) Arm with bracket to mount on the PCB.

Figure 5.8: Dipole antenna arm.

Finally, Figure 5.9 presents the fully assembled TT&C board, with all the components necessary to perform antenna tests. This means that all of the bottom side of the PCB was assembled except the components for the release circuit. Nothing was soldered on the top side of the PCB (transceiver side). Therefore, the board had the antenna, antenna box, matching network (transformer and capacitor), two SMA connectors and the pin header (to mount onto the board on top of this one in the PCB stack of the satellite).

(a) Top view.

(b) Perspective view.

Figure 5.9: Assembled PCB with antenna and matching network.

However, to perform antenna tests, it will be also necessary one Electrical Power System (EPS) board, responsible for making the GND connection of the satellite structure.

For this reason, a reduced PCB stack was mounted only for antenna testing and it can be seen on Figure 5.10. On the final, ready to fly version of the satellite, this stack is bigger and it includes other satellite subsystems, such as, Attitude Determination and Control System (ADCS), Payload, On-Board Computer (OBC) and the remaining boards of the EPS.
The last step to have a fully assembled prototype to perform antenna tests is to insert the PCB stack inside the metallic structure of the satellite (Figure 5.11) and then to cover it with the solar panel PCBs (Figure 5.12).

Figure 5.12 presents the final prototype that will be used during antenna tests. The coaxial cable coming out of the satellite is connected, at one end, to the SMA connector right after the matching network and, during tests, the other end will be connected to the respective devices to get the desired results.
5.2 Test Plan

This subsection pretends to describe, with high detail, the three tests that are planned to be performed on the prototype.

5.2.1 Return Loss Test

The objective of this test is to characterize the return loss of the ORCASat antenna as a function of frequency over the 435.0-438.0MHz amateur satellite allocation.

Test Setup

1. Mate the TT&C motherboard with the EPS PCDM board via their backplane connector. Make sure that the components responsible for making the chassis ground connection have been installed besides the plated trough mounting hole next to the backplane connector, and the antenna is in its deployed configuration.

2. Install the mated boards inside of the satellite structure.

3. Use the 12” SMA male to SMA male test lead to tap into the antenna connection at the antenna side loopback connector on the TT&C motherboard.
4. Take the nadir solar panel and drill a hole which will allow the SMA test lead to pass into the fiberglass pipe.

5. Install the solar panel mockups and make sure to route out the SMA test lead through the pipe flange.

6. Pass the long Bayonet Nut Coupling (BNC) terminated coax through the fiberglass pipe and use the SMA female to BNC female adapter to connect it to the SMA test lead.

7. Mount the DUT to the end of the Polyvinyl Chloride (PVC) pipe using the test lead.

8. Set up the tripod in the middle of the UVic Quad (as represented on Figure 5.15). Use the hose clamps to attach the PVC pipe to the tripod.

9. Fully extend the tripod. At this point, the end of the BNC test cable should be available at the base of the tripod.

10. Use the BNC female to N male adapter to attach the BNC test cable to the AA-1000.

11. At this point you are ready to begin the test. The test setup should look like as illustrated in Figure 5.16.

Figure 5.15: Proposed location of the return loss test in the UVic Quad.
Test Procedure

1. Configure the DUT for the test as outlined in the previous section.

2. Measure and record raw return loss data over the entire frequency range of the analyzer.

3. Measure and record raw return loss data over 430-440MHz.

4. Download the data from the analyzer to the Personal Computer (PC). For this, use the Antscope software provided by the manufacturer [39] and the Universal Serial Bus (USB) cable.

5. Take the test setup apart.

6. Consult [40] and use the spectrum analyzer to determine the insertion loss of the cables and connectors between the loopback connector and the antenna analyzer.

   (a) For this, the SMA test lead needs to be connected to the BNC terminated test cable using the SMA female to BNC female adapter, and the insertion loss of the total assembly must be determined.

7. Convert the SWR measured at the end of the cable to SWR at the antenna port using the reference table in [41] and the insertion loss determined in the last step.
Table 5.1: Comparison of test sites for the gain pattern test.

<table>
<thead>
<tr>
<th>Site ID</th>
<th>AC Power</th>
<th>Fall Arrest</th>
<th>Access</th>
<th>Line of Sight To</th>
<th>Metal on Parapet?</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Easy</td>
<td>Not Required</td>
<td>Elevator, but blocked by cell phone site cable tray</td>
<td>B</td>
<td>No</td>
</tr>
<tr>
<td>B</td>
<td>Easy</td>
<td>Not Required</td>
<td>Elevator</td>
<td>A</td>
<td>Yes</td>
</tr>
<tr>
<td>C</td>
<td>Very difficult</td>
<td>Required</td>
<td>Many flights of stairs</td>
<td>None, tree blocking</td>
<td>No parapet</td>
</tr>
<tr>
<td>D</td>
<td>Difficult</td>
<td>Not Required</td>
<td>Many flights of stairs, ladder</td>
<td>None, tree blocking</td>
<td>Yes</td>
</tr>
<tr>
<td>E</td>
<td>Easy</td>
<td>Not Required</td>
<td>Elevator</td>
<td>None, tree blocking</td>
<td>Yes</td>
</tr>
<tr>
<td>F</td>
<td>Moderate</td>
<td>Not Required</td>
<td>Elevator</td>
<td>None, building blocking</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Expected Outcomes

- Resonance around 436.5MHz
- SWR of 1.5 or less over 435-438MHz

Limitations and Assumptions

This test is limited by the presence of objects around the DUT which will not be present during nominal operation in orbit. This has the ability to affect the measurement results. This is mitigated by using a fiberglass/Polylactic Acid (a plastic) (PLA) support combined with the tripod to remove most conductive objects from the near field of the antenna. The calculation of distance to far field is presented in Appendix A, subsection A.1.2.

5.2.2 Gain Pattern Test

The objective of this test is to attempt to characterize the gain pattern of the ORCASat antenna at 436.5MHz, in the plane of the antenna nulls.

Test Setup

This test is to be conducted outdoors, at the location illustrated in Figure 5.17. As shown, it consists of two sub-sites, Site A on the rooftop of the Elliot Building and Site B on the rooftop of the Bob Wright Center (both located at UVic). The reason why rooftops are used is to minimize ground reflections by transmitting and receiving from the edge of the roof. For the same reason, this test is to take place on a dry day when the ground isn’t wet to minimize its RF reflectivity. The particular locations on the two rooftops have been selected from a number of alternatives (Sites C, D, E and F on Figure 5.17) after a site visit, and they are a compromise between ease of access, access to AC power, fall arrest requirements, and unobstructed line of sight between the two buildings. These are summarized in Table 5.1.
The test itself consists of four distinct configurations. Two of these consist of calibrating the test setup by using a simple UHF sleeve dipole in place of the DUT. Once the procedure and its limitations are well understood using this simple configuration, the sleeve dipole will be swapped out to the spacecraft, and the test will be repeated, thus making up the third and fourth configuration. The gain patterns will be evaluated for both transmit and receive, allowing the comparison of these as an extra layer of verification. The summary of the configurations are listed below.

- **Configuration 1**: Transmit with stationary standard gain antenna and receive with sleeve dipole.
- **Configuration 2**: Transmit with sleeve dipole and receive with stationary standard gain antenna.
- **Configuration 3**: Transmit with stationary standard gain antenna and receive with DUT.
- **Configuration 4**: Transmit with DUT and receive with stationary standard gain antenna.

The mechanical configuration of the **standard gain antenna** does not change during the tests. It is to be mounted as illustrated in Figure 5.18, following the procedure presented below.

1. Mount standard gain antenna to tripod.
2. Attach a coaxial test lead to the standard gain antenna.
3. Point standard gain antenna to other test site. Situate the setup as close to the roof edge as feasible, while observing any and all regulations regarding work at height.

The mechanical configuration of the **sleeve dipole antenna** is illustrated in Figure 5.19. To set this up, the following procedure must be observed.

1. Mount sleeve dipole antenna to tripod.
2. Attach coaxial test lead to sleeve dipole antenna.
3. Situate sleeve dipole antenna with dipole arms parallel to roof edge, as close to it as feasible while observing any and all regulations regarding work at height.

4. Cut out a 10" circle from the cardboard. At the center of this circle, cut a circular hole with 2" diameter.

5. Use the protractor and the permanent marker to mark spokes on this doughnut shaped piece of cardboard, in 30° increments, over the entire circle.

6. Use the hot glue gun to attach the marked cardboard to the fiberglass mast holding the DUT, just above where it is attached to the tripod.

7. Use the permanent marker to create a reference on the tripod, and make sure that the 0° mark on the cardboard aligns with this.
The mechanical configuration of the **DUT** is illustrated in Figure 5.14. To set this up, the following procedure must be observed. At the end, the setup should look like as shown in Figure 5.20.

![DUT configured for gain pattern test. Start position shown.](image)

1. Mate the TT&C motherboard with the EPS powerboard. Make sure that the antenna is in its deployed configuration.

2. Install the mated boards inside of the satellite structure.

3. Use the 12” SMA male to SMA male test lead to tap into the antenna connection at the antenna side loopback connector.

4. Take the nadir solar panel and drill it out to be able to mount the pipe flange. Make sure to drill a hole which will allow the SMA test lead to pass into the fiberglass pipe.

5. Install the solar panel mockups and make sure to route out the SMA test lead through the pipe flange.

6. Pass the long BNC terminated coax through the fiberglass pipe and use the SMA female to BNC female adapter to connect it to the SMA test lead.

7. Mount the DUT to the end of the PVC pipe using the test lead.

8. Set up the tripod, fully extended as close to the edge of the roof as possible, while observing any and all regulations regarding work at height. Make sure that the dipole arms are extended, and the ram face of the DUT points at the other test site.

9. Cut out a 10” circle from the cardboard. At the center of this circle, cut a circular hole with 2” diameter.

10. Use the protractor and the permanent marker to mark spokes on this doughnut shaped piece of cardboard, in 30° increments, over the entire circle.
11. Use the hot glue gun to attach the marked cardboard to the fiberglass mast holding the DUT, just above where it is attached to the tripod.

12. Use the permanent marker to create a reference on the tripod, and make sure that the 0° mark on the cardboard aligns with this.

Test Procedure

Equipment Calibration

The Universal Software Radio Peripherals (USRPs) are capable of transmitting and receiving RF signals but they are not as accurate as a spectrum analyzer or a signal generator in doing so. Therefore, they need to be calibrated. Each USRP needs to be fed a known signal from a signal generator and the offset between the signal power displayed in GNU Radio and the injected signal power needs to be determined. The same thing is true for transmissions. The signal transmitted by the USRPs needs to be measured to determine the offset between what is configured in GNU Radio and what is measured by the spectrum analyzer. The following points must be also considered:

- Effect of cables between USRP and test equipment used for calibration
- Choice of front end A or B - it must be decided which front end is to be used for what
  - Use TX/Receive (RX) port to minimize reconfigurations
- RF front end settings - gain, etc.

Configuration 1

In this configuration, the standard gain antenna is used for transmissions and the sleeve dipole is used for receptions. The standard gain antenna is stationary, and it is fed by an USRP, and the sleeve dipole rotates in a plane defined by its dipole arms, configured to be parallel to the roof. The sleeve dipole feeds another USRP, thus enabling power measurements.

- Test site with standard gain antenna
  1. Set up the mechanical configuration prescribed for the standard gain antenna.
  2. With the USRP turned off, attach its RX A TX/RX port to the standard gain antenna using the BNC test cable, and the BNC female to N male and SMA male to BNC female adapters.
  3. Use the USB A to B cable to attach the USRP to the PC.
  4. Spin up GNU Radio and configure it according to Appendix A, subsection A.2.4. Do not enable the RF output yet.
  5. Set the power to 0dBm in GNU Radio, and ensure that the antenna is pointed at the other test site. Configure the frequency of operation for 436.5 MHz. Make sure that an unmodulated carrier will be transmitted.
  6. Call the person manning the other site on their cell phone. Use headphones so your hand remains free.
7. Once the call is established, enable the USRP RF output and let the person manning the other test site via the phone that you did so.

8. Once the person manning the other test site tells you so, disable the USRP RF output.

- Test site with sleeve dipole antenna

1. Set up the mechanical configuration prescribed for the sleeve dipole antenna.

2. With the USRP turned off, attach its RX A TX/RX port to the sleeve dipole antenna via the 0dBm pin diode limiter.

3. Use the USB A to B cable to attach the USRP to the PC.

4. Spin up GNU Radio and configure it according to Appendix A, subsection A.2.5.

5. Stand by for the call from the person manning the other test site. Use headphones so your hands remain free.

6. Once the call arrives, and it is confirmed that the transmission from the other site started, record the power measured by GNU Radio.

7. Rotate the assembly clockwise so the cardboard ring indicates a shift of 30°.

8. Measure and record the power observed in GNU Radio.

9. Repeat from Step 6 until the entire circle has been traversed on 30° increments.

10. Let the person manning the other test site know that the transmission can be terminated.

- Configuration 2
  
The procedure is the same as for Configuration 1, except now the sleeve dipole is fed by one USRP, and the standard gain antenna feeds the other USRP.

- Configuration 3
  
The procedure is the same as for Configuration 1, except now the sleeve dipole is replaced by the DUT.

- Configuration 4
  
The procedure is the same as for Configuration 1, except now the sleeve dipole is replaced by the DUT, which is fed by one USRP, and the standard gain antenna feeds the other USRP.

After all the test data has been obtained plot the results on a polar graph. Normalize the readings to the maximum received power value observed in each test. Make sure to account for the equipment calibration conducted at the beginning of this test.

**Expected Outcomes**

It is expected that the transmit and receive pattern of the same antenna (sleeve dipole and DUT) will closely match one another. The gain pattern of both of these antennas is also expected to take a form similar to what is shown in Figure 4.40 (a), with the nulls being located alongside the dipole arms, and the direction of maximum radiation right angle to it.
Limitations and Assumptions

This test would ideally be conducted in a suitable anechoic chamber, thus it has a number of limitations. Efforts have been made to do this test in such a chamber, but this turned out to be infeasible due to logistical and financial reasons. Some limitations are listed below.

- The gain measurements are relative values.
- While efforts have been made to mitigate them (rooftop site, directional standard gain antenna), the effect of ground reflections and multipath propagation are unknown.
- Since ANSYS simulations shown that the gain pattern of the dipole is relatively constant in the xz plane (see Figure 4.41), this has not been tested, as it affords significant reduction is the mechanical complexity of the tests as the DUT does not need to have two degrees of freedom for rotation.
- The angular resolution of the test (30°) is low.
- USRPs are not great at measuring power

5.2.3 Absolute Gain Test

The objective is to attempt to estimate the absolute gain of the ORCASat antenna.

Test Setup

Same as for Configuration 3 and Configuration 4 of the gain pattern test. This test must be completed after the gain pattern test has been conducted so that the direction of maximum radiation and nulls is known.

Test Procedure

For this test, the following must be characterized ahead of time

- Insertion loss between the USRP output and the transmit antenna
  - See [40]
- Insertion loss between the USRP input and the receive antenna
  - See [40]
- Correction factor between GNU Radio power readings and actual readings for TX and RX on spectrum analyzer and signal generator
  - See Calibration section in gain pattern test
- Return loss of DUT in situ
- Measure using portable antenna analyzer

- Return loss of standard gain antenna in situ
  - Measure using portable antenna analyzer

TX Stationary Standard Gain Antenna & RX DUT

Test site with standard gain antenna:
1. Set up the mechanical configuration prescribed for the standard gain antenna.
2. Measure and record the return loss of the standard gain antenna.
3. With the USRP turned off, attach its RX A TX/RX port to the standard gain antenna using the BNC test cable, and the BNC female to N male and SMA male to BNC female adapters.
4. Use the USB A to B cable to attach the USRP to the PC.
5. Spin up GNU Radio and configure it according to Appendix A, subsection A.2.4. Do not enable the RF output yet.
6. Set the power to 0dBm in GNU Radio, and ensure that the antenna is pointed at the other test site. Configure the frequency of operation for 436.5MHz. Make sure that an unmodulated carrier will be transmitted.
7. Call the person manning the other site on their cell phone. Use headphones so your hand remains free.
8. Once the call is established, enable the USRP RF output and let the person manning the other test site via the phone that you did so.
9. Once the person manning the other test site tells you so, disable the USRP RF output.

Test site with DUT:
1. Set up the mechanical configuration prescribed for the DUT.
2. Make sure that the direction of maximum radiation, determined in the gain pattern test, is pointed right at the other test site.
3. Measure and record the return loss of the DUT.
4. With the USRP turned off, attach its RX A TX/RX port to the DUT antenna side loopback connector via the 0dBm pin diode limiter.
5. Use the USB A to B cable to attach the USRP to the PC.
6. Spin up GNU Radio and configure it according to Appendix A, subsection A.2.5.
7. Stand by for the call from the person manning the other test site. Use headphones so your hands remain free.
8. Once the call arrives, and it is confirmed that the transmission from the other site started, record the power measured by GNU Radio.
9. Rotate the assembly so that the null direction determined in the gain pattern test points at the other test.

10. Measure and record the power observed in GNU Radio.

11. Let the person manning the other test site know that the transmission can be terminated.

RX Stationary Standard Gain Antenna & TX DUT
Same as for the previous section, except now standard gain antenna is used for RX, and DUT for TX.

Expected Outcomes

It is expected that since the transmit power, the receive power, the transmit and receive return loss, the insertion loss of the test cables and connectors, and the free space path loss is known between the sites, the DUT antenna gain for TX and RX along the direction of maximum and minimum radiation degree of accuracy can be estimated according to [42]. The gain along the same direction for TX and RX is expected to be the same.

Limitations and Assumptions

Same as for the gain pattern test for the site. Also, the antenna is not a real standard gain antenna, and the power measurement abilities of an USRP are less accurate than lab test equipment, even when calibrated. The effect of polarization is also not considered.

5.3 Final Evaluation of the Prototype

In this section, an analyze of the prototype will be done using the respective test plan from section 5.2.

5.3.1 Return Loss Test Results

For this test, the results that need to be collected are the following ones:

- Return loss capture Direct Current (DC)-1GHz, and saved raw data
- Return loss capture 430-440MHz, and saved raw data
- Cable assembly insertion loss
- SWR converted to antenna port at 435, 436.5 and 438MHz

The fist step to start the return loss test was to measure the insertion loss of the cables that were going to be used to connect the prototype to the antenna analyzer. By looking at Figure 5.21, it is possible to see that the insertion loss of the cables is $-10dB$ at the working frequency of the antenna, $436.5MHz$. 
After performing the test, the results obtained with the antenna analyzer are the ones presented on Figure 5.22. In order to fully understand the behaviour of the antenna depending on its length, the test was done multiple times with different arm length values. With the simulations we had an idea that it would resonate at 436.5 MHz with the length of 192 mm (each arm), therefore the initial arm length was made larger, allowing a complete study of the antenna behaviour at each length, which will result in a good antenna tuning. From each iteration to the next one, 10 mm of each arm were cut. Eleven iterations were performed in total, starting at 250 mm and finishing at 150 mm. The results of all of the iterations were very similar to each other and that's why on Figure 5.22 only five of the iterations are shown, the initial size, last, ideal and two more in between.

Figure 5.21: Setup used to determine the insertion loss of the cables (line attenuation) used during the return loss test.

Figure 5.22: Results of the return loss test obtained with the antenna analyzer.
Overall, a length of $10\,\text{cm}$ was cut off the antenna, which is quite a large amount. While performing simulations, a small change of 1 or $2\,\text{mm}$ on the arms length would generate a much larger change in the resonant frequency and corresponding impedance than the ones observed in this test. The test was even run with one person covering the antenna arms inside its hands and once again, the result was pretty much the same as all of the others.

This led us to question the method and the device used in the test. Since there was a Vector Network Analyzer (VNA) in another lab of UVic we asked to use it to analyze the board.

As a first attempt, a decision was made to test the antenna on the PCB only, without the rest of the satellite body. This can be seen on Figure 5.23, where the antenna board is connected to the VNA that was located inside an anechoic chamber.

![Figure 5.23: Antenna inside the anechoic chamber, connected to the VNA.](image)

Two sizes of antenna arms were used during this test with the VNA, the remaining ones from the previous test that had $150\,\text{mm}$ and some new ones with $190\,\text{mm}$.

The results obtained are summed up on Table 5.2. It is also possible to see the results for $190\,\text{mm}$ length on Figure 5.24.

<table>
<thead>
<tr>
<th>Arm length</th>
<th>$S_{11}$</th>
<th>$Z_{in}$</th>
<th>$f_c$</th>
<th>Expected $f_c$</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>150mm</td>
<td>-3.474dB</td>
<td>19.748+j60.125Ω</td>
<td>458.3MHz</td>
<td>499.65MHz</td>
<td>-8.28%</td>
</tr>
<tr>
<td>190mm</td>
<td>-16.587dB</td>
<td>71.403+j0.699Ω</td>
<td>447.0MHz</td>
<td>394.46MHz</td>
<td>13.32%</td>
</tr>
</tbody>
</table>

Overall, the results obtained showed that the dipole works and resonates around the expected frequency. The expected $f_c$ values are calculated considering the antenna in free space. This has no consideration for the surrounding elements, such as the PCB board, metallic brackets, measuring devices and the ground pour on the different layers of the PCB, which also affects the antenna impedance.
which could not be fully taken into account while simulating the antenna since the PCB design was not finalized then and changed as the project moved forward. These are some of the common differences between real and simulated environments and can explain part of the error. Looking at the error values, they are within acceptable ranges (less than 15%).

The S11 values were higher than expected. This can indicate an impedance mismatch, which can be caused by a faulty or poorly designed matching network. The imaginary part of the impedance can be easily tuned by changing the capacitor value if that turns out to be the problem on a final simulation with the satellite body. The behaviour of the transformer was simulated for the frequency of 436 MHz which is lower than the $f_c$ of the antennas tested. The way that the transformer acts on the antenna at higher frequencies isn’t known so this can be an explanation for the real part mismatch. The mounting mechanism can also affect the antenna performance. The discontinuity at the points where the antenna arms are bolted to the brackets, or brackets to the PCB, highly affects the results. The simulation assumes the connections are ideal. With this test setup, no further conclusion can be taken about how the matching network would behave on a test with the satellite body and no comparisons can be made with the simulated results.

However, it is necessary to take into account that this test was only performed with the antenna board and not with it inside the satellite body. So that influence was not tested neither taken in consideration. This being said, this test is not considered to be finished and some more detailed analyses should be done. This extra work that needs to be performed will be furthermore explained and suggested in chapter 6.
5.3.2 Gain Pattern Test Results

Unfortunately, since the return loss test was not fully finished and a tuned antenna was not obtained, it wasn’t possible to perform this test.

However, the results that were going to be collected in this test were the following:

- Normalized TX gain plot and raw data for sleeve dipole
- Normalized RX gain plot and raw data for sleeve dipole
- Normalized TX gain plot and raw data for DUT
- Normalized RX gain plot and raw data for DUT
- Port specific calibration data for both USRPs
- Direction of minimum and maximum gain in xy plane

5.3.3 Absolute Gain Test Results

Just like the gain pattern test, this one couldn’t be performed either.

However, the results that were going to be collected in this test were the following:

- Port specific calibration data for both USRPs
- Insertion losses of TX and RX cable/connector assemblies
- Distance between test sites on from Google Earth
- Return loss of the standard gain antenna and the DUT in situ
- Transmit and receive power data along the direction of minimum and maximum radiation. This is collected for both antennas, for TX and RX

Results calculated:

- Free space path loss
- RX and TX gain of the DUT
Chapter 6

Conclusions and Future Work

This thesis is defined by two main goals. The first one is to design a dipole antenna that satisfies all of the requirements from the TT&C subsystem. The second one is to come up with a matching network that matches the antenna to the 50Ω impedance of the line.

The designs of the antenna and matching network where made in parallel. It was made this way since it’s easier to tune them at the same time and immediately observe the influence that a certain change will produce on the whole system. The process of developing this thesis has two parts. First some simulations where performed to develop the model and secondly, tests where realised to confirm and validate the design obtained.

The simulations where divided in five iterations (two initial ones only with the antenna and the last three that already included the study of the matching network) each more complex than the previous one. The study was performed by using the program ANSYS with the solver HFSS for the antenna part and ADS for the more detailed studies of the matching network. From the simulations results, the antenna and matching network system would meet the requirements for the ORCASat TT&C system. The return loss was -22.499dB at the working frequency of 436MHz and the match was almost perfect with value 55.3-j5.9. The absolute gain was 3.2dBi, which is also in agreement with the requirements.

However, these simulations results won’t necessarily be the same when a prototype is built. The antenna and matching network had to be tuned in order to obtain the expected results and validate the prototype to meet the requirements.

This thesis was intended to be supported by three sets of tests to be performed at UVic, each with a different goal. The fist one was the return loss test, where the antenna was going to be tuned in order to resonate at the intended working frequency. The return loss value at that frequency was the goal of this test and for validation this value would have to be lower than -12dB. The second test was intended to check if the radiation pattern had the expected behaviour and shape on the nulls plan. The third and last test was supposed to obtain the value of the antenna gain. For validation of this test, the gain had to be higher than 0dB, in order to close the link.
6.1 Future Work

As stated on chapter 5 only one of the tests was performed and not even with a successful ending. This being said, the antenna and matching network are not yet completely designed. More work has to be done and some changes in the process have to be taken.

For future work, the first recommendation is that sample boards should be manufactured. This way it would be possible to test each component on its own (antenna, transformer, capacitor, SMA connector). This might be the way to debug the circuit and check if any and which part of the circuit is faulty and not working as expected. After having these boards, the respective component would have to be soldered to the board and the return loss test on the VNA would have to be repeated for each sample board. Taking in consideration the unusual and so different results that were obtained while testing the complete circuit, it is highly probable that at least one of the components is not working as expected. The antenna seems to be working as expected, since it is resonating around the expected value, so the problem should exist inside the matching network components. After finding out which one is faulty and having its accurate S11 behaviour, a new simulation should be performed and a new matching network designed and tuned for the found needs. After this being done, a tuned antenna is obtained and the second and third tests should be performed. Without further knowledge it is not certain, but they should run smoothly with no problems, since their goals are just to check some relative behaviours of the antenna.

After doing all of these recommendations on how to proceed with the work, the antenna and matching network should be ready and well designed. However, a new rerun of the three tests, with the fully assembled TT&C board (antenna, matching network, release mechanism and transceiver) inside the satellite body, should be done.

To conclude, besides these recommendations, the team is advised to read this thesis carefully and use it as a guide for future antenna and matching network design.
Bibliography


Appendix A

Test Plan

A.1 Return Loss

A.1.1 Equipment Used

- 1x DUT, consisting of
  - 1x Aluminum satellite structure
  - 1x Mock up solar panel set
  - 1x Assembled TT&C motherboard
  - 1x EPS PCDM board with at least backplane connector and chassis ground components populated
- 1x RigExpert AA-1000 portable antenna analyzer
- 1x Heavy duty tripod, consisting of
  - 6x Aluminum tripod members
  - 1x Aluminum four way junction
  - 1x Plastic tripod stabilizer
- 1x 12” SMA male to SMA male test lead
- 1x SMA female to BNC female adapter
- 2x BNC female t to N male adapter
- 1x Flexible BNC terminated coax test lead, > 30’ length
- 1x DUT mounting hardware, consisting of
  - 1x Fiberglass pipe, > 3’ length
  - 1x PLA pipe flange with mounting screws, designed for fiberglass pipe
• 1x Personal computer
• 1x USB A to B cable
• 2x Hose clamps
• 1x Flat head screwdriver
• 1x Spectrum analyzer with tracking generator

A.1.2 Far Field Calculation

The distance $r$ to far field for an antenna is determined by,

$$ r \geq \frac{2D^2}{\lambda} \quad (A.1) $$

where,

• $r$ is the distance to far field, in meters,
• $D$ is the maximum physical dimension of the antenna, in meters,
• $\lambda$ is the wavelength of operation, in meters.

For a half wavelength dipole antenna operating at 436.5MHz, these corresponding operating wavelength is,

$$ \lambda = \frac{c}{f} = \frac{3 \times 10^8}{436.5 \times 10^6} = 0.69 \text{m}. \quad (A.2) $$

Since the dipole has the size of half wavelength, this means that,

$$ D = \frac{0.69}{2} = 0.34 \text{m}. \quad (A.3) $$

So, according to equation (A.1),

$$ r \geq \frac{2 \times 0.34^2}{0.69} = 0.34 \text{m}. \quad (A.4) $$

So the region beyond 0.34 m distance from the antenna in any direction belongs to the far-field.

A.2 Gain Pattern

A.2.1 Equipment Used

• 1x DUT, consisting of
  – 1x Aluminum satellite structure
  – 1x Mock up solar panel set
- 1x Assembled TT&C motherboard
- 1x EPS PCDM board with at least backplane connector and chassis ground components populated

- 1x DUT test cables and adapters
  - 1x 12” SMA male to SMA male test lead
  - 1x SMA female to BNC female adapter
  - 1x BNC female to SMA female adapter
  - 1x Flexible BNC terminated coax, > 30’ length

- 1x DUT mechanical support system
  - 1x Fiberglass pipe, > 3’ length
  - 1x PLA pipe flange with mounting screws, designed for fiberglass pipe
  - 2x Hose clamps
  - 1x Flat head screwdriver
  - 1x Heavy duty tripod, consisting of
    * 6x Aluminum tripod members
    * 1x Aluminum four way junction
    * 1x Plastic tripod stabilizer

- 1x Standard gain antenna mechanical support system
  - 1x Heavy duty tripod, consisting of
    * 6x Aluminum tripod members
    * 1x Aluminum four way junction
    * 1x Plastic tripod stabilizer
  - To Be Defined (TBD)

- 1x Sleeve dipole mechanical support system
  - TBD

- 1x RF test equipment
  - 1x SMA male to BNC female adapter
  - 1x BNC female to N male adapter
  - 2x USRP B210
  - 1x RF signal generator
  - 1x Spectrum analyzer
- 21x Laptop computers with
  * GNU Radio 3.8 or greater
  * USRP Hardware Driver (UHD) drivers for USRP
- 1x Directional standard gain antenna (see subsection A.2.2 for details)
- TBDx Coaxial test leads and adapters for directional standard gain antenna
- TBDx Coaxial test leads and adapters for sleeve dipole antenna for UHF
- 1x Sleeve dipole antenna for UHF (see subsection A.2.3 for details)
- 2x PIN diode 0dBm power limiter

- Other supplies
  - 2x Cell phones with headset
  - 1x Protractor
  - 1x Elliot building lower roof key from Prof. Albert
  - 1x Bob Wright building roof key from Prof. Albert
  - Cardboard
  - Scissors
  - Permanent marker
  - Hot glue gun
  - 2x plastic table or lab cart for test equipment
  - 2x 30m grounded extension cord

A.2.2 Standard Gain Antenna Characteristics

Not yet defined.

A.2.3 Sleeve Dipole Characteristics

Not yet defined.

A.2.4 GNU Radio USRP TX Configuration

Not yet defined.

A.2.5 GNU Radio USRP RX Configuration

Not yet defined.
A.3 Absolute Gain

A.3.1 Equipment Used

- As for the gain pattern test
- Portable antenna analyzer
Appendix B

ANSYS Guide step by step

This Appendix serves the purpose of documenting all the process of making a simulation on ANSYS, to help the team with future work when using this software, since I was the first person.

B.1 Design an object and set a simulation

To set a simulation on ANSYS, the steps to follow are listed bellow:

1. Design the antenna using parameters (when defining the origin and dimensions of the object use letter and attribute them a value, this way it will be easier to later make changes on the design);

2. When designing a dipole, design a solid for the gap between the two arms (the material of this solid should be vacuum so it won’t interfere with the antenna);

3. Setting a variable medium section to place the port on [Modeler>Surface>Section...>Choose plane>OK]. If the section where the port is going to be placed is not on one of the three planes, the best way to have a medium section is to create the solid with one of the faces containing the wanted plane and then perform the following action [right click>Selection Mode>Faces>select the desired face>Modeler>Surface>Create Object From Face];

4. Define the port [right click on the section>Assign Excitation>Lumped Port...>50Ω>NEXT>Integration Line>New Line...>define>NEXT>FINISH];

5. Define the open region [right click>Create Open Region...>435MHz>PML>OK];

6. Set simulation (1) [right click on Analysis>Add Solution Setup>Advanced>435MHz>refine mesh>OK];

7. Set simulation (2) [right click on solution setup>Add Frequency Sweep>name it>start frequency>end frequency>OK];

8. Validation check (it won’t validate the 3D part if there is any part overlapping another, a subtraction action might have to be used);

9. Analyze all;
10. Generate results [right click on Results->Create Modal Solution Data Report->Rectangular Plot] for $S_{11}$, $Z_{in}$ plots, [right click on Results->Create Far Field Report->3D Polar Plot] for 3D radiation pattern and [right click on Results->Create Far Field Report->Radiation Pattern] for E and H fields radiation pattern.

## B.2 Mesh refinement

Meshes are used to divide a CAD model into smaller elements. During simulation, a Finite Element Analysis (FEA) is applied to these elements. The accuracy of the results is higher when the elements are smaller. This process is called mesh refinement.

In order to perform mesh refinement on ANSYS, some parameters to change are the following:

- **Right click on the fist setup in Analysis->General tab->Maximum Delta S**: a good refinement will be achieved with a value in the order of $10^{-3}$;

- **Right click on the fist setup in Analysis->General tab->Maximum Number of Passes**: when the mesh is too refined it might be better to decrease this value to reduce the time of simulation since it will be harder for the model to converge so it is pointless for it to be running for 50 passes or more, for example;

- **Right click on the fist setup in Analysis->Options tab->Lambda Target**: Can be as default or decreased to $0.1 - 0.2$;

- **Right click on the fist setup in Analysis->Options tab->Maximum Refinement Per Pass**: should be between 25% and 35%.

## B.3 Parametric sweep

To perform the parametric sweep registered on Figure 4.2, a new setup must be performed. This is how it is done:

1. **Click on section "Simulation"->Optimetrics->Parametric**;

2. **Add->choose the variable to perform the sweep->start size->stop size->define step (Linear Step mode)->Add->OK**;

3. **Click on "Options" tab->check the "Save Fields And Mesh" box->OK**;

4. On the project tree, on the left side, under "Analysis" there is a section called "Optimetrics" where a "ParametricSetup" was created inside;

5. **Right click on the setup->Analyze**;

6. Generate result as on a normal solution.

It is necessary to generate a new setup for each different variable that is going to be swepted.
B.4 Circuit design

Finally, here are the instructions to set a circuit simulation of a matching network:

1. Place all the components, port, ground, transformer (search under "show all" in symbols) and capacitor/inductor;

2. Bring antenna model to the circuit (right click on HFSS project on the tree and drag until the middle of the circuit board);

3. Notice how the antenna appears only with one port, since the signal is a differential one, the right way to do it is to connect the positive to one terminal of the antenna and the negative signal to the ground of the antenna. In order to correctly make the connection it is necessary to pull a pin for the ground [right click on the antenna model> Edit Symbol> Pin Locations...> Reference: Show common reference port> OK];

4. Connect every component (all the "ports" on the top side of the transformer and all the ground/reference on the bottom side of the transformer);

5. Setup analysis [right click on Analysis> Add Nexxim Solution Setup...> Linear Network Analysis> Add...> Linear Step> Start/Stop/Step=10MHz> Add> OK> OK];

6. Run [right click on Analysis> Analyze (F10)];

7. Generate results [click on section "Results"> Standard Report> Two Dimensional (2D)] for $S_{11}$, $Z_{in}$ plots.

Always keep in mind that circuit to run, it has to have information from the antenna, so it is always necessary to run first the HFSS project before the circuit one.