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Innovation and Creativity

Design of ground station antenna for a double CubeSat student project

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Problem Description

Give an introduction to the proposed double CubeSat system and an overview of communication requirements and the propagation characteristics that influence the link budget. Based on the above findings, derive requirements for the ground station antenna. Emphasize simplicity and easy construction and propose an antenna system that may meet the requirements. Investigate it theoretically with available software to optimize its dimensions. A scale model of the antenna should finally be built and its main properties measured in an anechoic chamber.

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Abstract

This Master Thesis describes a possible design of the ground station antenna system for a small student satellite. This is a part of a bigger project where other students and teachers from NTNU are involved. An introduction to the proposed double CubeSat system can be found in the first two chapters. In the second chapter an overview of communication requirements and the propagation characteristics that influence the link budget are given.

The rest of the chapters are focused on the ground station antenna design. The requirements for the ground station antenna are derived from the above findings, emphasizing simplicity and easy construction. An antenna system that may meet the requirements is proposed. The system has been investigate theoretically with available software to optimize its dimensions. And finally, a scale model of the antenna has been built and its main properties measured in an anechoic chamber.

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List of Abbreviations

ADCS Attitude Determination and Control System

ASK Amplitude Shift Keying

BER Bit Error Rate

EIRP Equivalent Isotropically Radiated Power

FSK Frequency Shift Keying

GMSK Gaussian minimum Shift Keying

LEO Low Earth Orbit

NAROM Norwegian Centre for Space-related Education

NTNU Norwegian University of Science and Technology

OBDH On-Board Data Handling

P_POD Poly Pico-satellite Orbital Deployer

PSK Phase Shift Keying

TT&C Telemetry, Tracking and Control

VSWR Voltage Stationary Wave Ratio

Chapter 1

Introduction

This thesis is a part of the Student Satellite program at NTNU. Previously some other students worked on the satellite design, and this thesis is going to begin the ground station description. In particular it will describe the antenna system located on the ground station.

The satellite is a double CubeSat. CubeSat is a program founded by Stanford University that provide the opportunity to students to work in the construction of small satellites, or CubeSat. A CubeSat is a small satellite with dimensions 10x10x10 cm, weighing no more than one kilogram. This program is building a double satellite then with dimensions 10x10x20 cm.

The project pretends to have one or more satellites launched in the period 2008-2011.

In this chapter a description of the CubSat concept, the NAROM program and the starting point of the present thesis will be given. In chapter 2 the radio link between the satellite and the ground station is described. Chapter 3 includes the theoretical antenna design and the antenna theory which has been taken into consideration during this designing work. Chapter 4 and 5 talk about the final design. In chapter 4 computer simulations of the antenna model are done, and in chapter 5 the measurements of a scaled model are carried out. Finally, in chapter 6 the conclusions will be found.

1.1 The CubeSat Project

The CubeSat project was developed by the California Polytechnic State University, San Luis Obispo and Standford university's Space System Development Lab. The CubeSat program offers launch opportunities to universities that, otherwise, would be unable to have access to space.

There are around 60 universities and institutions taking part in the program. Students will develop their aptitudes and experience in the aerospace engineering.

The CubeSat program strives to provide launch opportunities to small satellites and their loads. They provide a standard physical layout and design guidelines, that has to be followed. A CubeSat is a cube with side equal to 10 cm and a mass of up to 1 kg, so they can fit into the P-POD.

The Poly Picosatellite Orbital Deployer, or P-POD, is a tubular mechanism that takes up very little space. The CubeSat will be introduced inside this mechanism and it can be integrate in any launch vehicle. Inside each P-POD they can be included three CubeSat, as seen in figure 1.1.

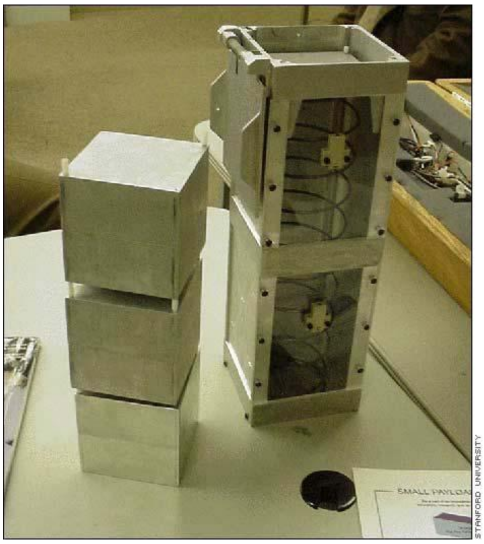


Figure 1.1: The P-POD and three CubeSats

The project is in charge to coordinate the launch so developers can focus on the design and develop and not on obtain the launch licences. The CubeSat standard [3] describes the dimensions, the recommended material, the principal restrictions and scheduled that refer to integration and launch.

1.2 The NAROM Project

The new satellite project at NTNU aspire to launch one or more satellites before 2011. The first launch is planed to be launch in early 2009. The project would like to have its own ground station at NTNU, and the present thesis is going to start this work.

The launch will be carried out by NAROM (Norwegian Centre for Space-related Education) [10].

NAROM has a Student Satellite Program. The aim of the project is to organise space education and to stimulate the interest for science in general. They encourage students and universities to build a small satellite. The students must write a proposal and, by the end of 2011, four of them will be built and launched.

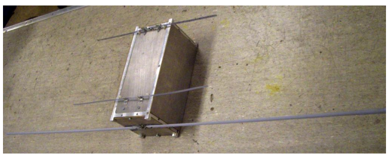
The main goals are to ensure recruitment to the Norwegian space activities and to be an important link between the Norwegian space industry and the educational system.

In 2001 Andøya Rocket Range and the Norwegian Space Centre (NSC), started this project. Two satellites were built, NCUBE-1 and NCUBE-2. Their lunch were unsuccessful, but NAROM decided to start a new student satellite program involving universities and educational institutions in Norway.

1.3 Starting Point and Aims of the Project

This small student satellite project involves both students and employees from various departments in NTNU.

In previous reports, [2], the satellite design has been started. In that previous report a proposal to NAROM can be found. It includes, beside this proposal to NAROM, an specification about the radio system parameters, and the antenna system, on-board the satellite. A satellite design has been done as well. The project consists to build a satellite platform based



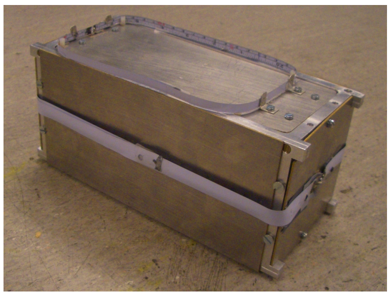


Figure 1.2: The satellite model with antennas extended (left) and stowed (right)
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on the CubeSat standard, in a double configuration. It includes two radio transceivers at 145 MHz and 437 MHz bands, an On Board Data Handling-system (OBDH), and Attitude Determination and Control System (ADCS), a Power Supply and Management System (PSMS), and a colour camera for earth imaging as initial payloads. The mission goals will include deliver a satellite, contact establishment, attitude control, capture an image, transmit the image to the ground, establish two-way communication, take a picture of Earth and transmit the picture to the ground.

The 145 MHz transceiver was designed as a TT&C-radio. The 437 MHz transceiver was designed, primarily intended as a payload downlink. It is implemented with a directivity antenna, that consist in a dipole with a reflector. The 145 MHz antenna is near omnidirectional, and it is a dipole. The two dipoles and the reflector are made with measuring tape, so they can be folded around the satellite so it can fit inside the P-POD, and then extended when the satellite is in orbit. A satellite prototype was implemented and it can be seen in figure 1.2. In chapter 2 there will be more specifications of this satellite that has been done previously.

This present report intend to continue the work that other students have already begun. Since the satellite design was being done by other students, it has been decided to work in different tasks. Here you will find a first work with the ground station. This study has to be with the antenna that will be situated on the ground that will communicate with the satellite antenna. So the present design will take into account, as seen in next chapter, what has been designed before.

Chapter 2

Link Analysis

An essential part of the planning of a satellite system is the link-budget calculation. This chapter will talk about these calculations that are essential to guarantee reliable communication between the satellite and the ground station. This analysis will give the necessary considerations that will be taken into account on the next chapter where the antenna system is designed.

For a complete communication system design, it is necessary to know all losses and gains occurred in it. A link budget specifies all losses and gains that take place from the transmitter antenna since the receiver.

In this link analysis all the parameters that have been set previously in [2] have to be taken into account. For this paper, some of the most relevant parameters are the transmitted power by the transmitter, the gain at the receiver antenna, the losses in the transmitter and receiver, the height and shape of the satellite orbit. Those are aspects related with the design of the satellite that has been made previously in the mentioned project [2], at NTNU.

As it is expounded later in this chapter, the most relevant effects are the ones produced by the ionosphere. Them will be determinant for the ground station antenna design.

2.1 Path losses and atmospheric effects

On the satellite link some losses due to different factors will occur, for instance attenuation due to propagation in free space and additional losses that also have to be considered due to the atmospheric effects or the electrical connection between the antenna and the other devices. In this section only the propagation effects are described.

2.1.1 Wave Propagation in Free Space

Free space path loss (L_p) is the loss in signal that would result if no other obstacles nearby were present. It does not include any gain nor any loss related to the atmosphere or any other cause. The free space loss is

$$L_p = \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2.1}$$

As seen in equation 2.1 the the free space path loss depends on the signal frequency and on the distance between the satellite and the ground station (d).

The satellite will transmit and receive signal at two different frequencies, 437.305 MHz for high speed data link, and 145.98 MHz, for uplink and downlink TT&C.

The satellite orbit is LEO (Low Earth Orbit) circular and sun-synchronous with 98 degrees of inclination. Thus the orbit height will be lower than 1500 km. In particular, the orbit height in this case will be between 400 km and 800 km. Since the orbit is LEO, the wave propagation is influenced by the low atmospheric layers, the troposphere and the ionosphere.

Although a perfect circular orbit is assumed the distance between the satellite is not constant (as figure 2.1 shows). With very low elevation angles (El), the signal would be very influenced by the interference effects produced by the ground surface. Therefore a minimum elevation angle must be determined. In this case the minimum elevation angle for an active link is 20 degrees.

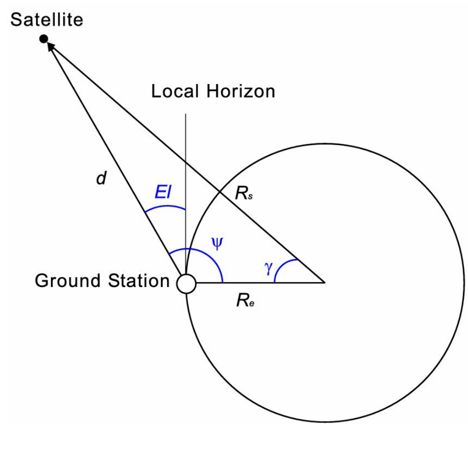


Figure 2.1: Geometry of elevation angle and distance calculation.

With the law of cosines, the maximum distance between the satellite and the ground station can be found ([13]). The equation is

$$R_s^2 = d^2 + R_e^2 - 2R_e d\cos(90 + El) \tag{2.2}$$

where R_e[1] is the Earth radius and R_s the orbit radius. With the equation 2.2 the maximum distances d for a height equal to 400 km and 800 km are respectively 984 km and 1768 km.

In table 2.1 the propagation losses are summarized. It can be found, for both frequencies, losses at 400 km and 800 km with 90 and 20 degrees of elevation angle.

Frequency(MHz)	height (km)	El (degrees)	distance (km)	loss (dB)
437	400	90	400	137.29
437	800	90	800	143.31
437	800	20	1768	150.20
145	400	90	400	127.71
145	800	90	800	133.73
145	800	20	1768	140.62

Table 2.1: Free-space propagation losses.

2.1.2 Tropospheric and Gases Effects

The troposphere is an atmospheric layer situated at 12 km above the ground. It is divided in different layers. That fact produces variation in the refraction index and produces scintillations in the received power.

This is disadvantageous in elevation angles below 5 °, then, as the minimum elevation angle has been set at 20 °, that is not a big problem.

Losses due to atmospheric gases are nearly independent of atmospheric temperature, mean density and relative humidity at frequencies below 2 GHz. It depends on the path between the spacecraft and the ground station and it means that the losses from or to the satellite are elevation angle dependent. When the elevation angle is 20 °, the minimum elevation angle, the losses are below 1 dB (**??**).

The rain and absorbing effects in this layer are, in general, important above about 3 GHz, and can be considered equal to 0 dB.

2.1.3 Ionospheric Effects

This is the atmospheric layer that extends since 100 km to 400 km above the earth surface.

This layer has a large amount of electrons and ions. One of its most important effects is the Faraday rotation. Waves that travel through the ionosphere can be decomposed into two characteristics waves, that travel with constant velocity. But the velocity is different in each wave, so when the wave have passed through the ionosphere the two characteristics waves

[1] $R_e = 6378km$

	Average	Peak Seasonal	Solar Flare
11 GHz	0.3^o	1^o	1.6^o
437 MHz	190^o	632^o	1012^o
145 MHz	1703^o	5680^o	9000^o

Table 2.2: Typical values for satellite paths in Northern Europe.

have different phases. Therefore, the incident wave have changed the phase. This effects is called Faraday rotation, and it is precisely a rotation ϕ of the electronic field vector. The rotation angle ϕ is proportional to $1/f^2$. With some data found for instance in [13], the Faraday rotation in the satellite frequencies can be found as expressed in table 2.2

In higher frequencies the polarization rotation is no so significant and it is possible to rectify this shift polarization with compensation adjustments. But in VHF and UHF frequencies the rotations are considerable.

It is necessary to solve this problem in a more efficiently and easy way. The best thing to do is to use in the receiver circular polarization. This would produce a fixed loss of 3 dB but will ensure the signal reception despite the remarkable depolarization.

2.2 Satellite System Overview

This section is an overview of the principal parameters that have to be taken into account in the link budget calculations.

An isotropic radio transmitter radiates its power P_t equally in all directions. The flux density S in this case can be calculated using the following formula:

$$S = \frac{P_t}{4\pi d^2} \tag{2.3}$$

In practice, the emitted power will be concentrated into a certain direction, depending on the antenna directivity. Directivity is the ratio between the full $4 \times \pi$ steradians spherical coverage and the actually illuminated solid angle ω. Power is evenly distributed over ω and zero outside this area. $AntennaGain(G)$ is the ratio of the flux density in a specific direction at a distance d and the flux density from the same transmitter using a hypothetical isotropic antenna.

At the receiving antenna, an "effective area" is assumed, in order to calculate the amount of electromagnetic energy received. The effective area is related with the antenna gain:

$$A_r = \frac{\lambda^2}{4\pi} G_r \tag{2.4}$$

Then, the total collected power is $P_r = S \times A_r$

The antenna gain depends on the antenna design. The antenna system on-board the Satellite consists of a 145 MHz dipole, and a 437 MHz dipole with a reflector. The 145 MHz antenna has 2 dB gain, and the second one, 437 MHz antenna has a theoretical gain of 6 dB, checked in the simulations. This antenna has an increased gain thanks to the reflector, that also makes the antenna more directive instead of the almost omnidirectional behaviour of the VHF antenna.

The antennas do not have a complete adaptation, so some power can be loss at the antenna connection. The solution could be to include an integrated balun, because of the reduced dimensions it is not possible to use a conventional balun. Another possibility is to use a pair of cables instead to a coaxial cable between the antenna and the transceiver. This could be done because the distance is very reduced. In the future it has to be studied if these considerations are useful or if the adaptation is good enough without as it is now.

An antenna in reception receives both signal and noise. The noise power in the antenna terminals has an associated antenna noise temperature, T_a,

$$P_N = kT_aB \tag{2.5}$$

where P_N is the available noise power, W is the bandwidth, and $k = 1,38 \times 10^{-23} J/K$ is the Boltzmann's constant.

The noise figure is related to a reference noise temperature $T_0 = 290K$. The corresponding noise temperature is calculated by considering all the noise as coming from a resistor at temperature T_e at the input of the device and the device as being noiseless. Then, it can be said that

$$T_e = T_0(F-1) \tag{2.6}$$

$$F = 1 + \frac{T_e}{T_0} \tag{2.7}$$

$$\tag{2.8}$$

In satellite communication systems the reduction of noise is all important owing to the low signal levels, hence the bandwidth is usually reduced to contain the signal and immediate sidebands.

The noise seen by the satellite is dominated by the earth noise of 290 K.

EIRP is the power required by the transmitter output stage if the antenna radiated equally in all directions. The Equivalent Isotropically Radiated Power (EIRP) is the quantity $P_t + G_t$ (in dBW).

The CubeSat will be equipped with a 1 W transmitter feeding. Then the EIRP is equal to 2 dBW, for the dipole antenna and 6 dBW for the dipole antenna with its reflector.

This EIRP will be a little lower because of the antennas efficiency and the attenuation on the transmission lines and connectors.

In a low-earth orbiting satellite, the path loss is not such a problem, but Doppler shift and multipath problems become severe. When the satellite has a relative velocity of vm/s along the line of sight, then the received signal has a frequency shift on it given by v/λ where λ is the wavelength of the carrier signal. The frequency shift is positive as the satellite comes towards the receiver and negative as it goes away. This Doppler shift can, according to the orbit and the carrier frequencies used, be nay times the bandwidth of the receiver, for example for Leo satellites 50 kHz, and hence requires the use of frequency tracking n the receiver.

A more major problem is that the direct line of sight from the satellite is obscured or shadowed, so that the signal reaching the receiver, particularly at low satellite elevation angles, is made up of a number of signals reflected form buildings as well as a possible direct signal. At high elevation angles, the main problems is shadowing due to buildings and trees, but at low elevation angles the problem is a mixture of multipath and shadowing. In practice, the satellite or the receiver is moving, so that the path difference, and hence signal strength is constantly changing giving fading. Since the phase of the resultant is also varying quickly, this does cause major problems for the demodulator, particularly where the information is being carried as phase modulation.

Because of these problems it is important to use an appropriate modulation. A number of different technologies to modulate a digital signal onto an analog carrier exists, like $Amplitude - ShiftKeying(ASK)$, $Phase - ShiftKeying(PSK)$ or $Frequency - ShiftKeying(FSK)$. ASK is more susceptible to errors than the other mentioned techniques, therefore it is not useful in space-applications.

GMSK and $\pi/4$-DQPSK are examples of differential schemes. Differential modulation schemes use previous bits to determine the encoding of the next bit. An error in the demodulation of one symbol will propagate to the next symbol, so these modulations seem not to be appropriate. FSK has worse bit error rate performance than the other mentioned modulations, but it is a nonlinear modulation scheme with constant envelope. In order to have a BER (Bit error rate) equal to 10^{-5} it is necessary to receive a minimum Eb/N_0 equal to 10.3 dB, obtained from MATLAB as seen in figure 2.2.

2.3 Ground System Overview

The ground station antenna system will consist of two antenna. One of these antennas will transmit and receive at the frequency of 145.98 MHz and the other one at 437.305 MHz.

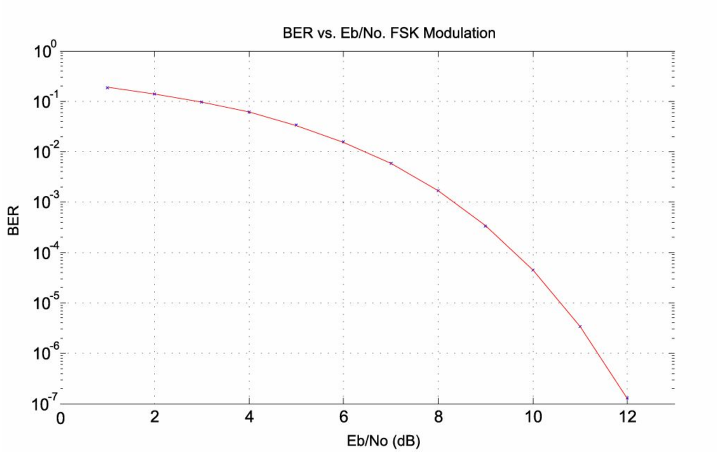


Figure 2.2: Performance of FSK modulation

While working at the ground station it is possible to have a more powerful amplifier, then the transmitter power can be greater than on-board the satellite. The antenna gain can be greater as well, then the EIRP from the ground station will have a higher value than on the satellite case.

The ground antenna has different noise sources. One of them is the free space temperature, that is estimated as 3 °, the temperature from the stars, the atmosphere or the ground noise. Then, the antenna noise temperature varies, mainly by the atmosphere temperature. The temperature can vary from 500 K to 1000 K more or less. The antenna temperature will have to be checked, but an approximate value is T=600 K.

2.4 Link Calculations

The link budget is the basis for designing a radio link. It is possible to express the relationship between the transmitting power and the power at the output terminal of the receiving antenna by:

$$
\begin{aligned}
P_r &= \frac{P_t G_t}{4\pi d^2} A_r && (2.9)\\
&= \frac{P_t G_t}{4\pi d^2} \frac{\lambda^2}{r\pi} G_r && (2.10)\\
&= (\frac{\lambda}{4\pi d^2})^2 P_t G_t G_r && (2.11)\\
&= (\frac{c}{4\pi d f})^2 P_t G_t G_r && (2.12)\\
& && (2.13)
\end{aligned}
$$

Where $(\frac{c}{4\pi df})^2$ can be denoted as L_p^{-1} and called the $PathLoss$. The relationship between the received and transmitted power can be expressed with:

$$\frac{P_r}{P_t} = \frac{G_t G_r}{L_p} \tag{2.14}$$

The signal to noise ratio (SNR) is the relation between the received signal and noise power, and in the dB-domain it can be expressed by:

$$SNR = P_s|dBW - P_n|dBW \tag{2.15}$$

where P_s is the signal power, P_n is the noise power, and using the link budget equation in dB:

$$P_r = P_t + G_t + G_r - L_p \tag{2.16}$$

it is obtained

$$SNR = P_t + G_t + G_r - L_p - P_n \tag{2.17}$$

The energy per information bit divided by the noise spectral density, $\frac{E_b}{N_0}$ is

$$\frac{E_b}{N_0} = \frac{P_r \tau_s}{KN_0} = \frac{P_r \tau_b}{N_0} = \frac{P_r}{BN_0} = \frac{P_r}{BkT} \tag{2.18}$$

where τ_s is the symbol period, τ_b the bit period and B the bit rate of the digital data.

Then, with the precedent formula and with the link budget equation, from [12] the $\frac{E_b}{N_0}$ can be expressed as:

$$\frac{E_b}{N_0} = EIRP + 10log\frac{G_r}{T} - L_p - 10log\frac{B}{1Hz} - 10log\frac{k}{1J/K}[dB] \tag{2.19}$$

$\frac{G}{T} = G_r - 10log\frac{T}{1K}[dB/K]$ if the $figureofmerit$, a measure of the quality factor or performance of the receiver and important characteristic for both the satellite and the ground station receiver.

The formulas are ideal, but in reality losses have to be considered as well.

As seen before, rain and gases attenuation at that frequencies are not very important. The problem is that they can very greatly. As seen before, the ground station is going to have an antenna with circular polarization. This will prevent the Faraday rotation effects but it will introduce 3 dB loss. Finally, an important effect in the low atmospheric layers are scintillation, that can introduce some losses as well. Also, the ground station and satellite devices will introduce some extra attenuation.

These considerations are used to make the link budget calculations. The link budget for the uplink and the downlink at both frequencies can be found in the appendix.

The link budgets state that a gain equal to 20 dB is required for the ground station antenna. This gain will guarantee the minimum level at reception and will provide an extra margin, the fading margin, in case the attenuation will be greater than the considered here due to atmospheric effects or to interferences, besides the ground station losses that will have to be calculated when the whole system is described.

Chapter 3

Antenna Design

In this current chapter the design of the antenna system in the ground station is going to be started. Here only a theoretical description will be found and it can be modified afterwards to improve the design.

The antenna system has to achieve the conditions that have been set in the previous chapter. So certain aspects of the antenna are conditioned for this parameters, like the main frequency, polarization and gain.

The characteristics that are more important in the antenna system design are the required frequencies, fixed in previous studies [2], the minimum gain required, condition found out in the link budget study, and the antenna polarization, imposed due to the ionospheric effects as seen in the previous chapter.

The designed satellite works at two different frequencies in both ways, transmission and reception. Therefore, the ground station has to be able to transmit and receive as well at the same frequencies, 145.98 MHz and 437.305 MHz.

As it is usual in satellite communication, the signal will arrive to the ground station with a big attenuation due that the satellite can not transmit at a great power, and the large distance makes the signal to suffer big losses along the link. In the up-link there is the same problem, the satellite has not a big powerful amplifier that allows very weak signal to be received properly. Hence, it is important that the ground station antenna, where in general

It has been seen that one of the most significant effects is the Faraday rotation, produced by the ionosphere. Due to this effect, the signal will suffer an important depolarization while passing through the ionosphere. This depolarization is quite a lot outstanding. It is not suitable to use a linear polarized antenna as a receptor because it would be not guarantee that any signal is received.

In order to receive the signal, the easiest way is to use a circular polarization in reception. A circular polarized antenna that is receiving a linear polarized signal would have a 3 dB power loss. But this is not a very decisive loss, bearing in mind that with this solution we ensure to receive always some signal.

To get this circular polarization, it has been decided to use helix antennas as receiver ones. A helix antenna basically consists of a wire spirally shaped, with a proper ground plane. The antenna will radiate in the helix axis direction. The helix turns diameter and the space between turns must be specified so to achieve that the antenna radiates in a desired frequency.

3.1 Theoretical Background

In this section is exposed the theory about helix antennas that has been needed in order to design the antenna.

A helical antenna is an antenna consisting of a conducting wire wound in the form of a helix. The geometrical parameter that describe a helix are shown below, on figure 3.1. The turn length can be related with the diameter and the spacing between turns as illustrated in the triangle in the same figure. These parameters and their symbols are listed below

D = diameter of helix

C = circumference of helix = πD

S = spacing between turns

α = pitch angle = $arctan(\frac{S}{\pi D})$

L = length of 1 turn

n = number of turns

A = axial length = nS

d = diameter of helix conductor

Depending on the helix dimensions there are two principal operation modes: normal (broadside) mode or axial (endfire) mode. In the normal mode, the direction of the main lobe is normal to the helix axis. In the axial mode, the direction of the maximum is aligned with the helix axis direction.

A helix is operating in the normal mode, when the wire length is enough smaller than the wavelet λ. The wire length used in one turn is

$$L = \sqrt{S^2 + (\pi D)^2} \tag{3.1}$$

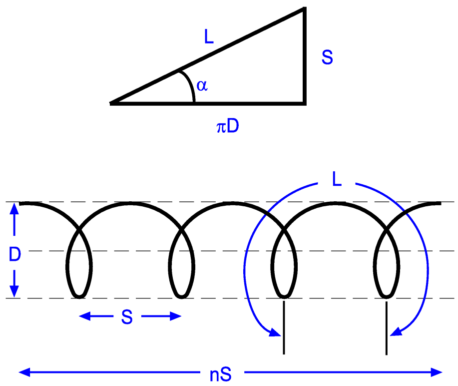


Figure 3.1: Helix and associated dimensions and their relation.

Hence, if the helix has N turns, the helix will be working in normal mode when $NL << \lambda$.

This radiation mode presents a very low radiation resistance and a very narrow bandwidth. Both could be increased by increasing the size of the helix, but in order to maintain the normal mode some phase shifter should be placed at intervals along the helix. The radiation efficiency is in general Small, due to the losses in the wire that can be alike the radiation resistance. Hence, the normal mode of radiation from a helix has practical difficulties.

These inconveniences are not present when the helix is working in the axial mode. In this mode, the helix dimensions are at or above the wavelength of operation λ. The geometrical conditions that allow to obtain an optimum behaviour are

$$\begin{aligned} \frac{3}{4} &< \frac{C}{\lambda} < \frac{4}{3} \\ S &\approx \lambda/4 \end{aligned} \tag{3.2}$$

In the axial mode, the antenna is located under the class of waveguide antennas. In practice it has been verified that a helix satisfying the conditions 3.2, is an structure capable to support a progressive wave. Its phase velocity depends on the helix geometry, being lower than the propagation velocity in the vacuum. In a helix with optimum dimensions, the phase velocity is approximately 0.8 times the propagation velocity in the vacuum. The helix can be seen as an array, in which the elements are at a distance equal to S and there is also a progressive phase given by $\alpha = -K_pL$, where k_p is the phase constant on the progressive wave in the helix and L is the wire length in a helix turn; hence, if the conditions above are accomplished it is given the next phase progressive between the different turns

$$\alpha = -k_p L \approx -\frac{k}{0.8}\sqrt{C^2 + S^2} \approx -kS - \delta \tag{3.3}$$

then, it has a phase $-kS$ that corresponds to the axial radiation condition and another phase that corresponds to the helix geometry and to the phase velocity of the progressive wave. This second phase is $-\delta$, and, surprisingly, when the antenna has the required conditions, is approximately $-\pi/N$, what indicates that it can be interpreted as a super directive array with the *Hansen-Woodyard* condition. The helix antenna in axial mode, can be seen as a Hansen-Woodyard array, where the radiating elements are the helix turns. Since this is an array with big dimensions (the turn length is about λ) the radiation pattern is very dependent on the number of elements in the array.

The radiation pattern of a helix turn can be obtained as the flat loop pattern, with circumference equal to the perimeter in the helix , hence it will be similar to λ. Due to the fact that the radiation pattern for an array is more narrowed and directive than the element pattern, it will be only necessary to obtain which is the pattern near the maximum of radiation.

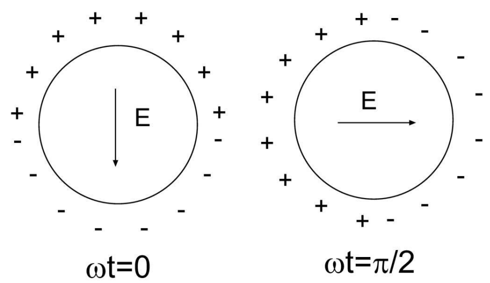


Figure 3.2: Charge distribution and electric field in a helix turn working the axial mode

In the figure 3.2 it can be seen that in a definite instant, it can be found a current distribution with a phase shift equal to 360 ° along a whole turn. Then, it exists a positive charge distribution in half the turn and a negative one in the other half. Due to these charge distributions there is an electric field that is orthogonal to the axis direction. Due to the temporal variation of the currents the field is turning creating a circular polarization. When the helix is oriented in the z axis, the normalized radiated field can be written as

$$|E_N(\theta)| = \left|\sin\left(\frac{\pi}{2N}\right)\cos\theta\frac{\sin(N\Psi/2)}{\sin(\Psi/2)}\right| \tag{3.4}$$

$$\Psi = kS(\cos\theta - 1) - \frac{\pi}{N}$$

In practice, the axial relation depends on the number of turns and can be written approximately

$$RA = \frac{2N+1}{2N} \tag{3.5}$$

A helix working in axial mode has a radiation resistance R_r that is approximately

$$R_r \approx 140\frac{C}{\lambda} \tag{3.6}$$

The helix antennas have a ground plane that can be either squared or circular shaped, with dimension rounding 1 or 2 λ. The antenna can be easily fed with a coaxial cable, connecting the inner conductor to the antenna and the outer conductor to the ground plane. Then, it is necessary to match the antenna to the coaxial cable.

The bandwidth is about

$$\Delta\theta_{-3dB} = \frac{52}{(C/\lambda)\sqrt{NS/\lambda}}(\,^\circ) \tag{3.7}$$

and the directivity

$$D = \frac{15NC^2S}{\lambda^3} \tag{3.8}$$

3.2 Required Parameters

This kind of antenna are made with a spiral shaped wire. There are several types of helix that can be done, and depending on the helix shape it is possible to change the band with, the central frequency, the input impedance and the antenna gain. In the previous chapter those parameters have been specified and will established the antenna design parameters.

In this case the most important parameters are the polarization, that has to be circular, the antenna gain, that it is supposed to be at least 20 dB, and the main frequencies, the antenna has to be able to work at two frequencies 145,98 MHz and 437,305 MHz.

3.2.1 Polarization

Radio waves passing through the Earth's ionosphere are subject to Faraday rotation. The effect is proportional to the square of the wavelength. At 437 MHz, one should expect in the order of 1.5 complete rotations of the wavefront as it transits the ionosphere, this value is even worse in the 145 MHz, where the depolarization can be about 10 complete rotations.

That is the main reason to use a helix antenna in the ground station, to avoid the coupling loss due to the Faraday rotation. These kind of antenna are often used in space communications at VHF and UHF frequencies, as in this case.

The antenna can have either a clockwise (right-handed) or counter-clockwise (left-handed) polarization. It depends on which sense the wire is wounded. In both cases it will be able to receive the signal with the same condition.

3.2.2 Gain

One of the design goals is to obtain a gain about to 20 dB so the link has a good behaviour.

The helix antenna can be seen as an array. The radiating elements are turns with dimensions around λ, so the whole helix is an array with big dimensions and therefore the radiation pattern will mainly depend on the number of turns.

According to experimental expressions that can be found for instance in [1] or in [8] there is a maximum gain that the antenna can achieve with a certain number of turns. The theoretical directivity D that could be achieved by an antenna is found with the expression

$$D = 15C_\lambda^2 n S_\lambda{}^1 \tag{3.9}$$

where C_λ is the circumference length of the theoretical cylinder where the helix is turned, in terms of the wavelength. S_λ is the spacing between turns also in terms of the wavelength. It is an experimental formula and is only useful for certain values of C and S. These values are $0.8 < C_\lambda < 1.2$ and $S_\lambda = \frac{1}{4}$. The values will be approximated and will have to be proved and measured afterwards in practice.

As an initial point we get as the circumference length $C_\lambda = 1$, and spacing between turns $S_\lambda = 0.25$. With these values it will be estimated the number of turns necessary to achieve the derided directivity.

With these chosen reference values, the number of turns necessary would be at least 26. For the biggest antenna, the one at 145.98 MHz, the space between turns would be $S = 0.5138m$, then the antenna would have a total length about 15 m. As can be seen that is not a practical solution. The ground station has to be as practical as possible, then it will be necessary to found another solution more available, so the antenna is more easy to use.

In order to achieve this gain a first solution could be to use a parabolic receptor with a helix antenna as a feeder. But there would be the same problem, because the dimensions that it would need.

[1]In some other literature the given expression is $D = 12C_\lambda^2 n S_\lambda$

A general expression for parabolic antennas directivity is

$$D = \frac{4\pi}{\lambda^2} A_{ef} \quad \text{with} \quad A_{ef} = A_{geom} \times \eta_t \tag{3.10}$$

where A_{ef} is the reflector effective area, then and A_{geom} the geometric area and η_t the total antenna efficiency.

If the η_t is 0.7 (normal values), and a directivity equal to 20 dB is wanted, with the equation 3.10 the antenna area will be obtained. In table 3.1 it can be found the necessary area for both frequencies.

frequency MHz	**Area** m^2	**Diameter** m
145.98	48	7.8
437.305	5.3	2.6

Table 3.1: Necessary diameter and area to have 20 dB in both frequencies with parabolic reflector.

As shown in the table, in order to have 20 dB it would be necessary a parabolic reflector with a 7.8 m diameter. The same problem as before is present, and even worse because the parabolic reflector with these dimensions would be very expensive.

Another possible way to have this gain is with an array. This array will have as radiant element a helix antenna. In particular, the array will be a 2 dimension array with 2×2 elements.

The total gain will be at least 20 dB. The array is lineal and the distance between elements will be equal to λ. The total directivity can be assumed as 4 times the directivity of each element. Then each antenna will have a directivity of $20dB - 6dB = 14dB$. Using the same expression as before 3.8 it is found the the number of turns needed in each antenna is 9 turns.

Helical antennas are mounted over a ground plane. This plane usually is circular or squared with dimensions between 1 or 2 λ. The array will be mounted in the same ground plane. It will be a square that the side length is two wavelengths. That is equivalent to have four antennas that have a square with a 1-wavelength side as a ground plane.

3.2.3 Working with two frequencies

The satellite works at two different frequencies, one in the VHF band, 145.98 MHz, and the other in the UHF band, 437.305 MHz. So the ground antenna has to be able to work at these two frequencies as well. Since the frequencies are in the VHF and UHF bands, antenna dimensions can have a length of some meters, and they may be rather big. It is preferable that the antenna does not occupy too much space.

To have two antennas working at different frequencies will take up a lot of space. So the goal is to work with an only antenna capable to work at both frequencies at the same time.

A first solution could be to work with a only antenna that works at the two frequencies. There exist several types of antennas that can do that. One possible solution is to include the UHF-antenna inside the VHF-antenna, as shown in figure 3.3 and suggested in [5]. And other possibility is to use a only helix but with variable dimensions, the first turns would have a big size and a big space between them and the last ones will be smaller and closer. An example of this second method can be found at [4].

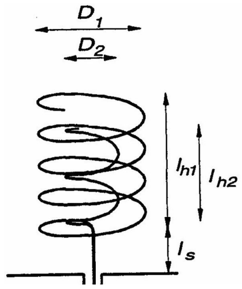


Figure 3.3: Two helical antennas one within the other

In the first case the solution would be to design one antenna for each frequency separately and then situate the small antenna inside the big one. But in this case, the big antenna is influencing a lot the small one.

The second solution is a unique helix but with a variable dimension. But the problem is that the two antenna have a very different frequency. That means that the beam-width has to increase a lot, and then both signals would be rather influenced by the other.

It does not seem very easy to produce a same helix antenna for both frequencies. So finally, two different antenna will be designed. In particular there will be two array, each with 4 helix. The fact that the size is different for each array will allow to sit one array inside the other, so the final design will be similar to have only one antenna.

3.3 Antenna design

First an individual design of each antenna will be done, to know what are the needed dimensions. Then the two array will be designed and it will be verified that the solution chosen, put a helix within the other, is possible physically. Afterward with some computer simulations, this design will be checked and modified if necessary to obtain the final design.

3.3.1 Individual design

In section 3.1 it has been discussed that the best radiating mode for this situation is the axial mode. When the helix is working in this mode, the circumference length of the imaginary cylinder where the helix is wounded at are around one wavelength.

The design parameters of an axial mode helix are the circumference C, the center frequency f_c, the pitch angle α, the number of turns n and the total axial length A. These parameters are represented in figure 3.1.

The circumference takes the value of λ, the spacing between turns S is set to $\lambda/4$, what defines the pitch angle with the relation $arctan(\frac{S}{\pi D})$, and the number of turns has been found in 3.2.2, and it is equal to 9.

In table 3.2, the principal characteristics are summed up

center frequency	**148.98 MHz**	**437.305 MHz**
Circumference C (m)	0.686	2.07
Pitch angle α	14 $^\circ$	14 $^\circ$
Space between turns S (m)	0.172	0.517
Axial length A (m)	1.55	4.65

Table 3.2: Design parameters of helix antennas.

From the equations in 3.1 some theoretical results can be found. The expected radiating resistance is, from 3.6 equal to $140C_\lambda$. The relation that allows to find the beam-width is 3.7, $\Delta\theta_{-3dB} = \frac{52}{(C_\lambda)\sqrt{NS_\lambda}}(^\circ)$. The directivity can be estimated with the expression 3.8, $D = 12NC_\lambda^2 S_\lambda$ (expression found in [8]). The calculated values are expressed in the table:

center frequency	**148.98 MHz**	**437.305 MHz**
Resistance R_r (ω)	140	140
Beam-width $\Delta\theta_{-3dB}$ ($^\circ$)	34 $^\circ$	34 $^\circ$
Directivity D (dB)	14.3	14.3

Table 3.3: Principal calculated parameters for each helix antenna.

Since the expressions do not depend on the center frequency, both antenna have the same parameters. The beam-width is rather big, as usual in helix antennas. The gain is good enough, here it is calculated with the most pessimistic expression $D = 12NC_\lambda^2 S_\lambda$ ([8]) instead of $D = 15NC_\lambda^2 S_\lambda$ ([1] or [11]).

But it can be seen that the resistance is 140 Ω, so it is not matched. And it does not depend on the design parameters listed before. It will be necessary to do some extra design to solve this inconvenient. A possible solution is found in [9]. Where it is mentioned that it is easy to adjust the impedance at 50 ω value by increasing the conductor size close to the feed point at the ground plane. It can be done by bond a thin metal strip to the helix conductor between the feed point and the beginning of the helix. In the simulations this solution will be checked and if suitable it will be implemented.

For both the antennas the ground plane is designed as a square with a side equal to the corresponding wavelength.

3.3.2 Array design

Each helix in the two arrays will have the parameters listed in table 3.2. Each array is made with a squared ground plane with a side equal to two times λ.

The feeding point for each helix has to be decided after the simulations or practical matters. When mounting the helix in the array it has to be assured that all the helix has the feeding point in the same point, so the polarization of the antenna does not change.

There are two possible configurations when including one of the arrays within the other as seen in figure 3.4.

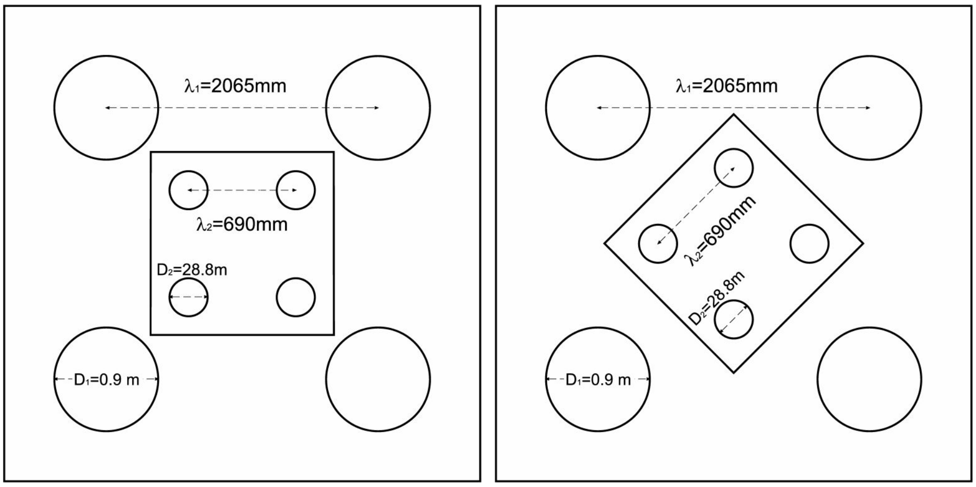


Figure 3.4: Two possible configurations in the array design.

The second option is better because all the helix are at the maximum distance from each other, therefore the influence between the big and the small array will be less.

Chapter 4

Simulations and final Design

In the previous chapter a first design has been developed. The present chapter shows the computer simulated data results. Them will help to verify if the antenna behaves as expected. Therefore several computer simulations have been done. The main results obtained in these simulations, and the inferred conclusions are explained below.

For the antennas design WIPL-D has been used ([6]). It is a powerful an easy-to-use computer program for fast and accurate simulation and design of antennas and other devices that radiate electromagnetic waves into free space. As it is the main tool for the simulation here a basis overview of the program can be found.

4.1 Simulation Software Description

WIPL-D simulates circuits with built-in or user defined components. The circuit analysis is based on the s-parameter of components that are computed on-the-fly during circuit simulation.

This program is based on the method of moments. This method has been developed into a very powerful tool for the analysis of wire structures that interact with electromagnetic waves when immersed in free space. This method was extended by Kolundzija, [7]

This method allows to model structures with arbitrary shapes using basic elements, like wires and plates. It is not necessary to know precisely these techniques in order to use the program effectively, nevertheless is advisable to know the basis, so that it is possible to know the limitations and interpret the results properly. Thus, some theory about the method of moments is included.

4.1.1 Numerical Methods

The method of moments is a numeric method that allows to obtain the solution of Maxwell equations with the boundary conditions that the antenna imposes.

An analytic solution is only possible in some very particular geometries. Due to most of the antennas do not fit this kind of geometry, it is not achievable to find an accurate analytic solution and it becomes necessary to turn to a numerical solution. This solution is usually done by the following steps:

1. Electromagnetic problem definition: in general, the starting point are the Maxwell equations, the wave equation or any other integral or differential equations related to them.
2. Discretization of the mathematical formulation: it is required to discretize every function and the results of applying the integral or differential operators to the functions, in a numerical vector. Therefore, a functional equations system becomes in a finite algebraic equations system, that allows the computational resolution.
3. Discretization of the boundary conditions: It is only possible to impose exactly the boundary conditions when the problem geometry is the canonical geometry. In general, it will be necessary to discretize the surface, and also to impose, approximately, the boundary conditions in the model.
4. The fields have to comply with the Sommerfeld radiation condition. This condition says that fields have to propagate from the source to the exterior, and not the other way round. The energy radiated must scatter to infinity. It is impossible to discretize the whole free space to the infinity, so indirect methods have to be used to discretize the space as well.

There are several types of numerical methods, depending, among other characteristics, on the equation type they solve. Integral methods, that solve integral equations, lie in the calculation of the radiated fields. The fields are radiated by the currents that flow in the object interior or surface. These currents are unknown and in general are the problem variables.

A Green function that takes into consideration the object presence, has to be used when calculating the current radiation integrals. Since that is very difficult, the original problem is not analyzed, but an equivalent situation. In this situation the real currents that radiate in the presence of the object, are replaced by equivalent currents that radiate the same field but in the free space, without any object.

A general integral equation in antenna problems can be written as follows

$$LX = Y \tag{4.1}$$

where L is a lineal operator, either L_E or L_H, the function X is the problem variable (equivalent currents), and the function Y is the independent term (incident field).

In order to solve the equation 4.1 the functions and operators are discretized. Then it is possible to turn the functional equation into a matrix equation.

First of all, the unknown function X is expressed as a lineal combination of base functions x_j. That is an approximation of X

$$X_N = \sum_j^N a_j x_j \approx X \tag{4.2}$$

where the N coefficients a_j are the X samples and represent the variables in the numerical problem that is going to be solved.

When replacing 4.2 in 4.1 we get

$$\sum_j^N a_j L x_j = Y_N \approx Y \tag{4.3}$$

that is also a functional equation, but now with N numerical unknown a_j. Now it is necessary a lineal combination of the functions Lx_j that approach the Y function. It has to be possible to represent the field with the basis $\{Lx_j\}$.

Since that is an approximation, it will be an error. The error in the contour condition or residue is

$$R = Y - Y_N = Y - \sum_j^N a_j L x_j. \tag{4.4}$$

To turn the functional equation 4.3 into a M equation with N unknowns system, the residue is cancelled poised with M weight functions W_i

$$\langle W_i, R \rangle = 0 \qquad i = 1 \dots M \tag{4.5}$$

where the product is the Hilbert inner product

$$\langle f, g \rangle = \int_{D_{(L)}} f * (\vec{r}) \cdot g(\vec{r}) d\vec{r} \tag{4.6}$$

Therefore, the resulting linear system is

$$\langle W_i, Y\rangle = \sum_{j}^{N} a_j \langle W_i, Lx_j\rangle \qquad i = 1 \ldots M \tag{4.7}$$

that can also be written in the matrix formulation

$$Aa = b \tag{4.8}$$

Here, A is the MxN matrix $A_{ij} = \langle W_i, Lx_j\rangle$, a is a vector with the elements a_j, and b is also a vector $b_j = \langle W_i, Y\rangle$.

4.2 Simulations of the Antennas Individually

The goal of this chapter is to analyze the antenna behaviour. It is wanted to know the behaviour of the final device. But first, in order to improve the design, it is needed to do some simulations of each antenna individually, and then the influence between the two frequencies will be analyzed.

The first step is done with the theoretical parameters found in the previous chapter. The first antenna that will be analyze is the VHF-antenna. In the figure it is shown its WIPL-D design

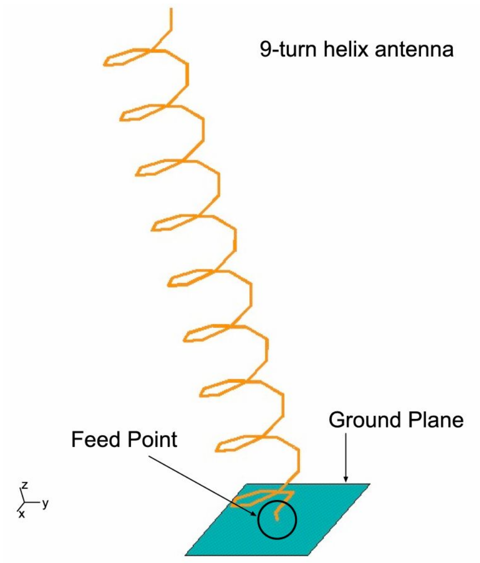


Figure 4.1: 9-turn center fed helix antenna with ground plane.

In that figure it can be seen the design of a 9-turn helix with a square ground plane with dimension equal to λ. When designing the feeding there are two possibilities. Helix antennas can have the feed point in the center (center-fed), or in the cylinder surface where the helix is turned. In this very first design the feed point is placed in the center, and it is linked to the rest of the helix with a straight wire parallel to the ground plane.

This image shows the VSWR, and its value is below 2, as wanted. But the central frequency in the graphic is not the designed main frequency, there are other frequencies with a better matching.

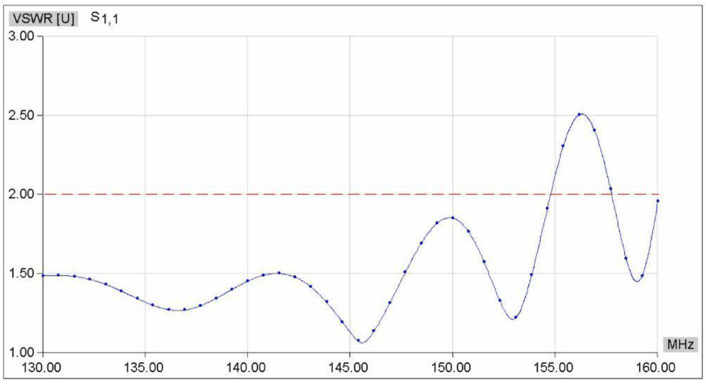


Figure 4.2: Simulated VSWR of the first design

In the image 4.3 it is noticed that 14 dB with only 9 turns are achievable. But, as in the previous image, it also shows that there are other frequencies that have a better behaviour, because actually, the maximum gain is achieved by a lower frequency, and inclusively it is seen that the designed main frequency has a very lower value, only 8 dB. Therefore, it can be said the number of turns is enough, but the other helix parameter have to be changed. The circumference dimension will be changed progressively, by respecting the conditions 3.2, in order to make that the design frequency becomes the central frequency.

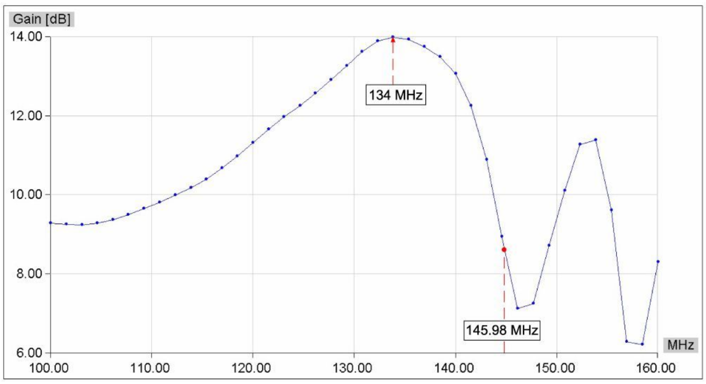


Figure 4.3: Simulated Radiation of the first design

The final parameters are those that offer the best directivity and impedance matching to the design frequency. Those parameters are $C = 1.24\lambda = 2.56m$ and $S = 0.3\lambda = 0.62m$, and the results can be seen in the figure 4.4.

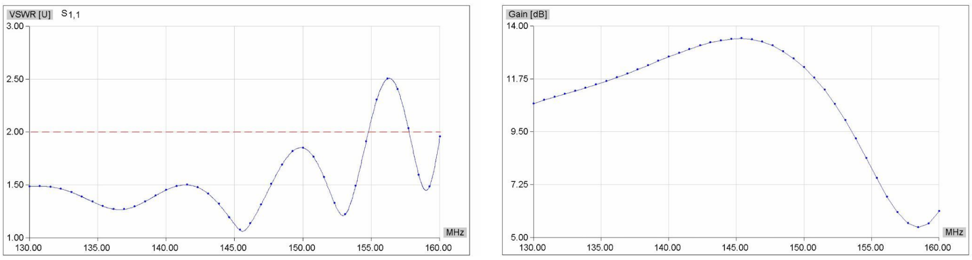


Figure 4.4: VSWR (left) and Radiation (right) of the VHF antenna final design.

The process is done again for the UHF-antenna. In that case, the number of turns are again 9, and the circumference and spacing have to be changed again. With the same procedure as before, the final found parameters are $C = 0.85m$ and $S = 0.2m$. The results in this case are plotted in figure 4.5.

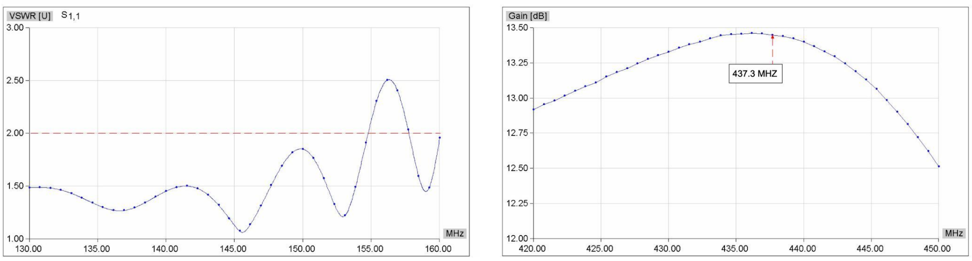


Figure 4.5: VSWR (left) and Radiation (right) of the UHF antenna final design.

The figure shows that the maximum gain is lower than 14 dB, but it is known, theoretically, that this value can be achieve with the specified dimensions. That effect can be due to the software limitation. The program works with wires and plates, therefore, to simulate a helix a lot of little wires are needed so to have a good shape. That produces two problems, one is that the helix is not perfect, and the other is that the program is not able no calculate parameters with the maximum accuracy.

In order to check if the gain actually can be the wanted gain another program is used. That is a MATLAB code that is available with [1].

This program considers axial helix as an ordinary axial array or a Hansen-Woodyard array. In this case the simulations have been done as a Hansen-Woodyard array, since the design conditions were done with that hypothesis and the number of turns is high enough.

The results given by that program are acceptable, since the directivity is 14.33 dB. Then it could be possible to achieve this directivity. It has to be proved latter in practice. The radiation pattern given by that program is plotted in figure 4.6.

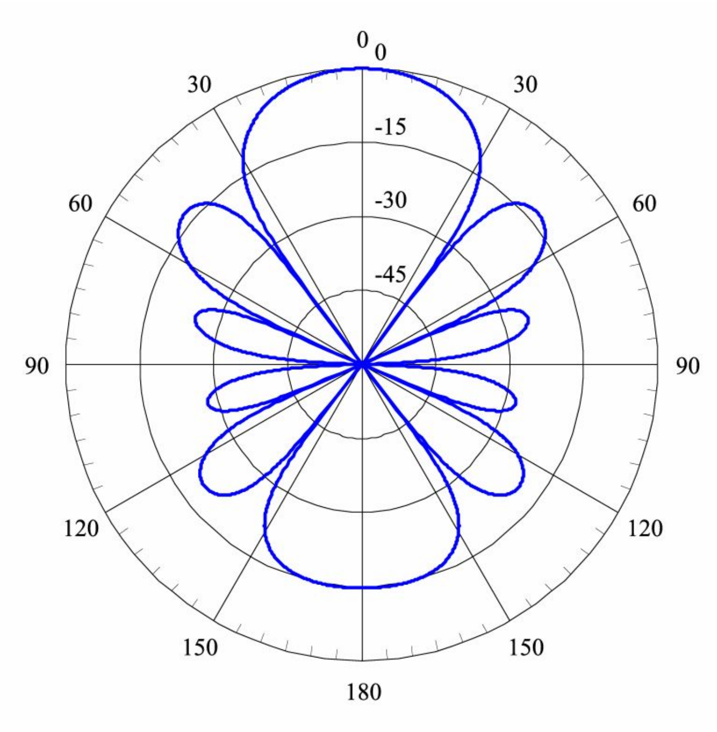


Figure 4.6: Radiation Pattern given by the Matlab program.

The obtained numerical results with that simulation are:

1. Impedance: 173.6 ω
2. Axial ratio: 1.055
3. 3dB Beam width: 25.7 degrees
4. Directivity: 14.5 dB

The individual simulations say that the gain is around 14 dB, that the Beam width is around 25-30 degrees and that the impedance is not well matched at all, then that some matching work has to be done.

4.3 Whole Antenna Simulation

Once the individual antenna are been designed, it has to be seen what is the behaviour of all the device together. It will be seen what is the influence between one antenna and the other when they are working at the same time. The problem in this case is again the available software, that is not capable to simulate both arrays together. Then, only one antenna of each array will be simulated but not all the 8 helix.

There two possible solutions in this case. One is to include both helix es in the same ground plane. The figure 4.7 shows the sketch of this solution.

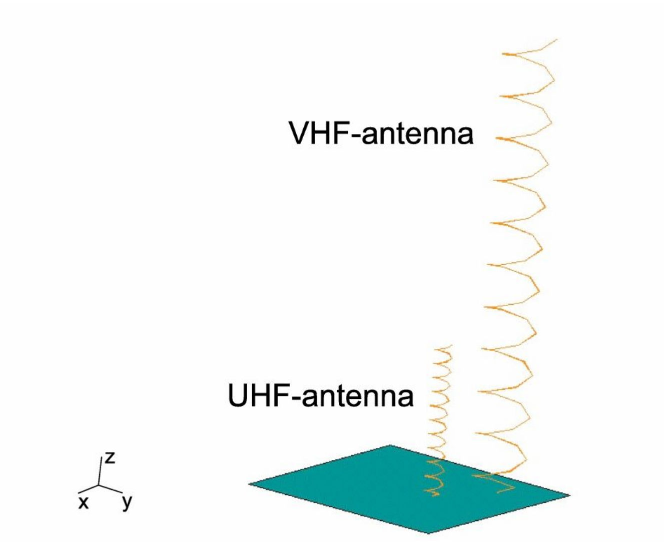


Figure 4.7: Two different helix included in the same ground plane.

As seen in that figure the small helix seems to be very disturbed by the big one. The simulations revealed that in fact both the radiation pattern and the impedance are affected by the big antenna. That is because the dimensions of the big antenna are too much large and the radiation that the small antenna emits is modified by the turns in the big antenna. in order to avoid that problem it is decided to put the small array in a higher position so all the antennas are aligned in the above part as seen in the figure 4.8.

In that case the small helix seems to avoid the influence of the big antenna. But now it could be happening the opposite situation, that is that the small antenna influences the big one. In the image 4.9 it can be seen that the maximum radiation is a little bit lower than before, and the bandwidth has decrease as well, but not very significantly.

4.4 Conclusion and Final Design

The simulations have checked that the wanted design is possible and that the parameters requested are achievable.

The final design will be two arrays 2x2 where the radiant element is a helix antenna with 9 turns. In order to preserve the polarization all the he-

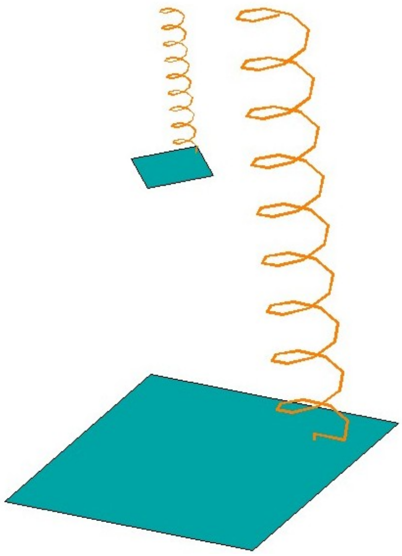


Figure 4.8: Two different helix aligned at the above part.

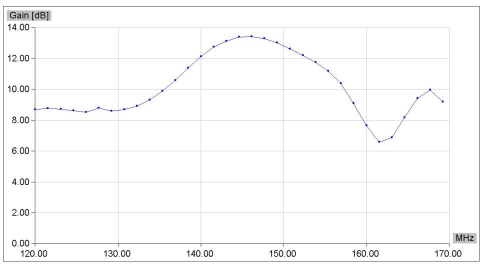


Figure 4.9: Radiation of the VHF-antenna with the UHF-antenna influence.

lix in both the arrays must have the feed point in the same position. It is important to have circular polarization, but it does not matter if the polarization is right or left. But it is very important that all the helix have the same polarization, then they have to be turned in the same direction. The VHF-array will work at 145.98 MHz and the UHF-array at 437.305 MHz. Each array will have a square ground plane with a dimension equal to 2λ. The helix dimensions are shown in next table.

center frequency	**145.98 MHz**	**437.305 MHz**
Circumference C (m)	2.57	0.85
Space between turns S (m)	0.62	0.21
Axial length A (m)	5.58	1.89

Table 4.1: Final design parameters of helix antennas.

The simulations have given some correct results. But those results have to be checked in practice. The antenna, since is working in VHF and UHF frequency has large dimensions. It would be not very easy to build it and verify how it actually behaves. Then it is decided to built a prototype in a smaller scale. The main frequency will change as well. The final parameters are set out in the next table:

center frequency	**2.1 GHz**	**6.3 GHz**
Circumference C (mm)	178	59
Space between turns S (mm)	43	14.5
Axial length A (mm)	387	130

Table 4.2: Scaled design parameters of helix antennas.

And it will be this prototype what will be measured in the next chapter. Once this prototype is built and improved as wanted the real antenna with the big dimensions will have to be built and included in the ground station.

But first there is still another problem, the impedance in the antenna. As seen in figure 4.10 the simulated impedance is the theoretical, then it is not matched. Here it can be seen the S11-parameter, that is the entrance impedance, and it shows that the antenna is not matched, and the real part value is around 3 times the reference impedance. If the reference impedance is 50 ω the impedance is around 150 ω, value found theoretically before. Then, in practice, some modification will be needed so to match properly the antenna.

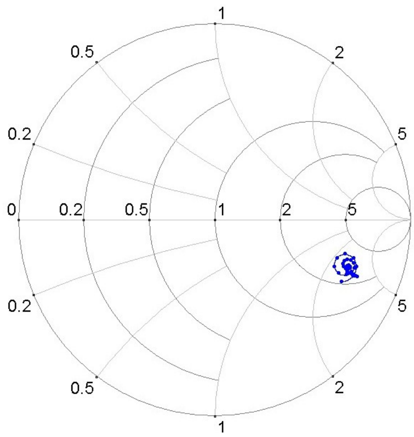


Figure 4.10: Smith diagram of the antenna S11-parameter.

Chapter 5

Antenna Measurements

In previous chapters the antenna design has been done. In chapter 4 several simulations have been done as well. But these simulations are not exempt from approximations and also, some parameters are not easy to simulate. Therefore it is needed to measure the actual characteristics of the antenna once it is built in order to check and verify the theoretical predictions.

The measurements carried out are either about the radiation pattern and the input impedance. The results have shown the direction of maximum radiation, the beam-width, the polarization and input return losses for the antennas.

These measurements were carried out in the antenna laboratory at NTNU, where we could have access to the anechoic chamber and to an Automatic Network analyzer, ANA - HP 8720C, so to measure the different S-parameters in the antenna. The setup consisted on the Network Analyser, the Newport Model MM4005 Motion Controller and the Hewlett-Packard Model 83017A amplifier to excite the transmitter antenna.

The transmitting antenna is a double-ridge horn antenna, set in the aperture in the chamber. Inside the chamber, the antenna under test is placed. To measure both radiation planes, first the antenna is placed in one way, and the second time it is rotated 90 degrees.

The first problem that the practice has to solve is the entrance impedance. When the match in impedance is absent an impedance-matching system must be constructed. In this case, in order to know what was the impedance matching, a unique antenna helix has been built and measured. The helix does not have a well matched impedance so a matching may be included. This modification, suggested in [9], will be an additional metal strip near the feed point as seen in figure 5.1. This strip has a width equal to 70 mm, and it is bended progressively around the helix cylinder being parallel to the ground plane at the end.

In figure 5.2 the impedance measurements with and without the strip are shown. There, it can be seen that actually the strip improves the antenna

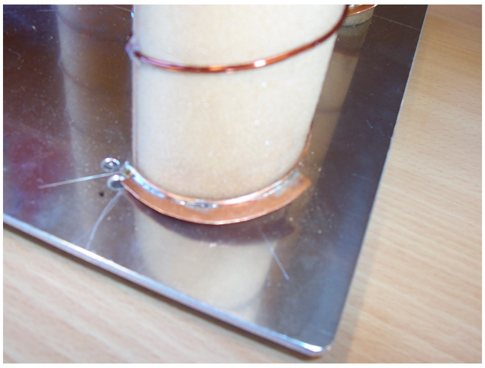


Figure 5.1: Metal strip included in the feed point to match the antenna impedance.

matching.

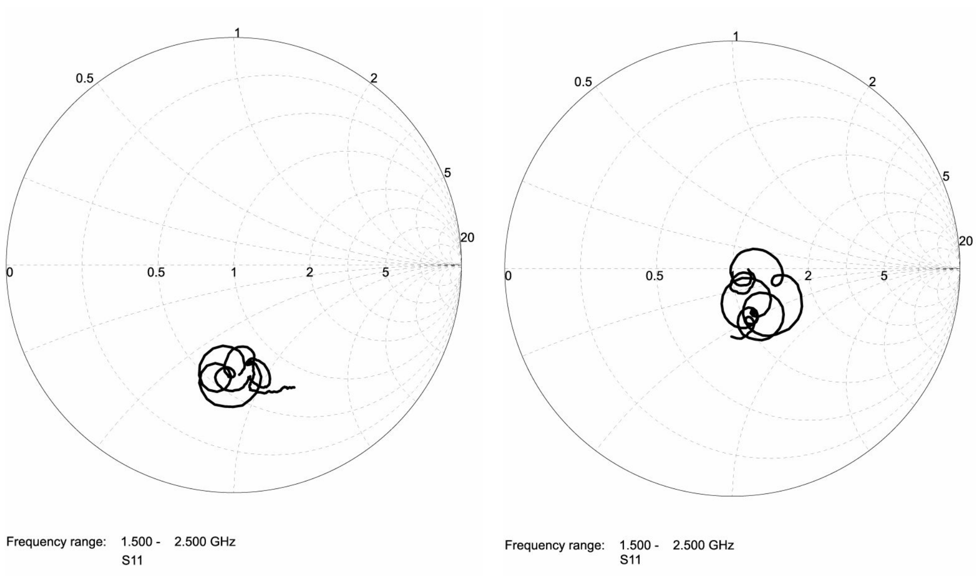


Figure 5.2: Measured impedance of a helix antenna without matching (right) and with a metal strip added (left).

With the parameters found in previous chapter and with these new considerations the antenna prototype is built. The antennas are built with wire with a diameter equal to 1.5 mm. The wires are bounded around a cylinder until the 9 turns are completed, and are fixed to the cylinder by glue. The cylinder is a solid mass and it is built with a porous and insulating material in order to not influence the antenna radiation.

The matching is only included in the big helix because of the difficulty to include it in the small ones.

In order to facilitate the manufacturing, and given that it does not have too much influence in the radiation, it is decided to change the feeding point. It will be placed on the cylinder surface instead of being in the center. This point must be in the same place in every helix, in order to preserve the polarization.

The prototype can be seen in the figure 5.3

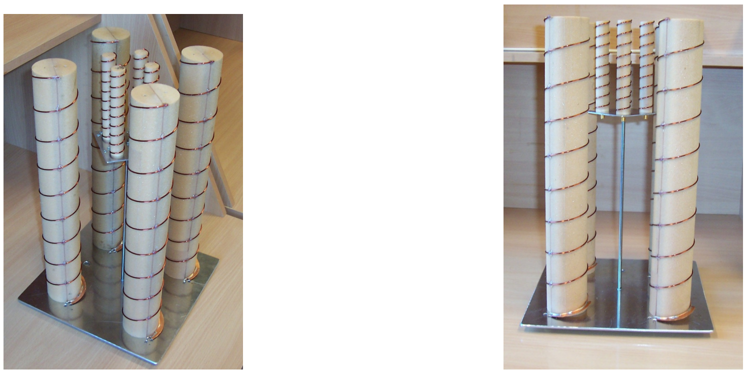


Figure 5.3: Antenna prototype

5.1 Radiation Pattern and Beam-width

The radiation pattern is a graphical representation of the radiation properties of an antenna expressed as a space direction function, with a constant distance.

Radio waves are built by two fields, electric and magnetic. These two fields are orthogonal. Then, the representation can be either with the electric or the magnetic field. It is usually expressed by the electric field. The representation can be 3Dimensional or it can be with a plane cut.

The 3dB-Beam-width ($\Delta\theta_{-3db}$) is the angular range where the radiation patten has half the maximum value.

The antenna directivity D is defined as the relation between the radiated power density in one direction an at a one distance, and the power density that an isotropic antenna with the same power would radiate at the same distance. The directivity can be approximately calculated with the equation 5.1 ([1]):

$$D = \frac{4\pi}{\Omega_e} = \frac{4\pi}{\Delta\theta_1 \cdot \Delta\theta_2} \tag{5.1}$$

In the radiation pattern measurements, another antenna is used. This second antenna, the transmitter antenna, is kept fixed in the its place and the antenna under measure is rotated with a positioning system. The pattern is the same when the antenna is either the receiver or the transmitter due to the reciprocity property.

The transmitter antenna sends a plane wave in a determined space direction. The answer to this wave is proportional to the radiation pattern of the antenna under measure in this space direction.

The best way to measure antennas is avoiding reflexions. That is the reason to use an anechoic chamber, where the walls in the room will absorb this reflexions thanks to an absorbent material, carbon black. By measuring in the chamber, there is no external influence.

A horn antenna is used to generate the plane wave, as seen in figure 5.1. Its polarization is lineal

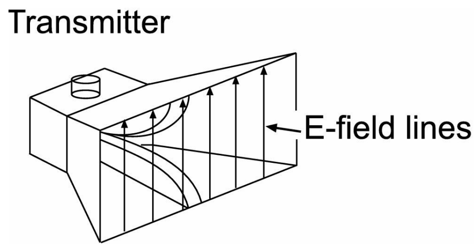


Figure 5.4: Field generated in the horn antenna's aperture

When measuring the radiation pattern, several experiments were carried out. It was pretended to check the behaviour of one of the antennas alone, and then see the influence between them both. and also to see what is the final radiation pattern at both frequencies.

In first place, the 2 GHz antenna was measured in both cases with and without the presence of the small array. In the image 5.5 the radiation pattern in both situations are plotted.

In the first diagram, there is the radiation pattern without the small array. Here there are plotted 3 frequencies. As seen in the figure, the maximum of radiation is well oriented to 0 degrees in every frequency.

Since the frequencies are very closed from each other, it can be said that the equipment affects equally all of them, then, although no absolute value for the gain can be found, it is possible to have the actual normalized radiation pattern. Then, by the figure it can be said that the better frequency, that has the highest gain, is actually the design frequency 2.1GHz. But the other frequencies still have a similar behavior. The greatest beam-width is also present in the main frequency. The secondary lobes are not very big, so they will no affect the transmission.

In the other figure the situation has changed, now the small array is present. Then, it is possible to see the influence between the both antenna by comparing this two plots. The first thing that can be seen is that the

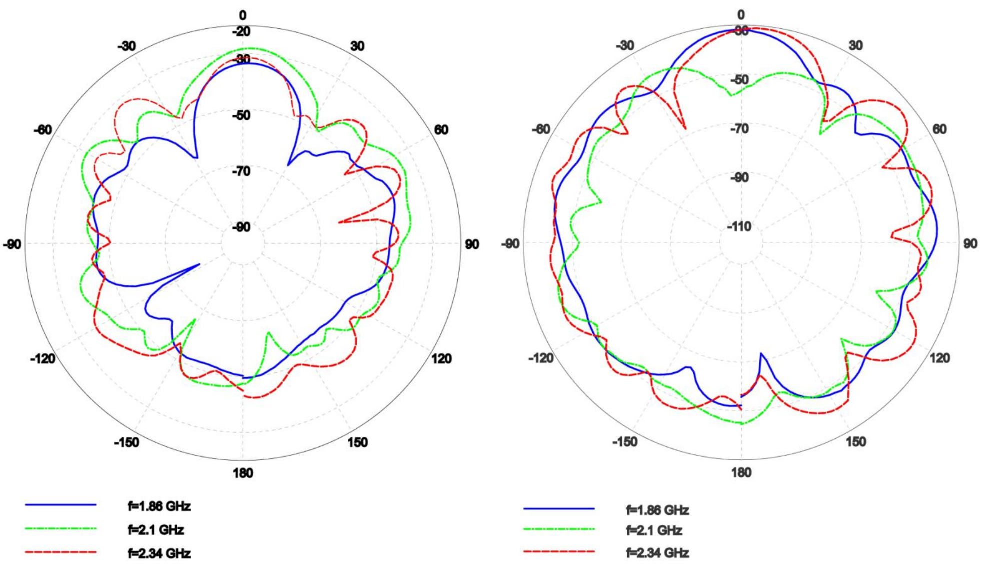


Figure 5.5: 2 GHz Antenna's radiation Pattern with and without the small array presence.

behaviour at the main frequency is not good at all. On the other hand, at all the other frequencies, it seems that the small array does not affect that much the big antenna.

The main frequency pattern is not centered at the 0 degrees direction any longer, where it has almost a minimum of radiation. And the relation between principal and secondary lobe has decreased a lot. This phenomenon has to be studied in the future, and it may be due to some unknown theory.

The other frequencies seem to have a good response, and the influence of the small antenna is not so critical.

The beamwidth observed in those diagrams are narrower than the theoretical beamwidth calculated in previous chapters.

It is not possible to measure the value of the directivity, the diagrams only show the behaviour but not the antenna gain. Thus, the directivity must be estimated by the equation 5.1. The beamwidth in both directions are almost the same. The maximum beamwidth occurs at the frequency of 2.2 GHz. In one direction it is observed a beamwidth equal to 18 $^{\circ}$ and 17 $^{\circ}$ in the other direction. Then, the estimated beamwidth is $D = 21.3dB$.

The same procedure is used to measure the small array. Figure **??** shows the radiation pattern. It can be seen that in this case the design main frequency seems to have the better features.

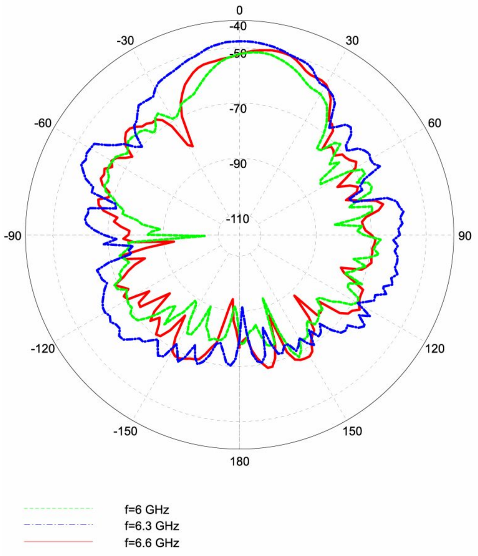


Figure 5.6: Small array radiation pattern

5.2 Polarization measurement

The electric field has a field vector different in every space point, depending on the position and on the time. Polarization is an indication about the field vector orientation in a fixed point along the time. The antenna polarization in one direction is the radiated wave polarization in that direction. A wave polarization is the geometric shape described by the electric field vector. An antenna can have lineal, circular or elliptical polarization. The polarization required of these antenna is the circular polarization, that means that the antenna has to be the same behaviour in every radiation plane.

To check if the polarization is circular or not, two orthogonal plans will have to measured. Keeping the transmitting antenna in the same orientation, it is possible to measure the two principal planes by changing the orientation of the antenna 90 degrees (always oriented towards the transmitter antenna).

Figure 5.7 shows the radiating pattern in the two orthogonal planes:

As can be seen in the images, the two plots are similar. That effect shows that the polarization is circular, or near it. For the three representative frequencies plotted here, the beamwidth is more or less the same in both planes, and so is the maximum radiation direction. The secondary lobes are a bit different, but the values are not very high in either cases.

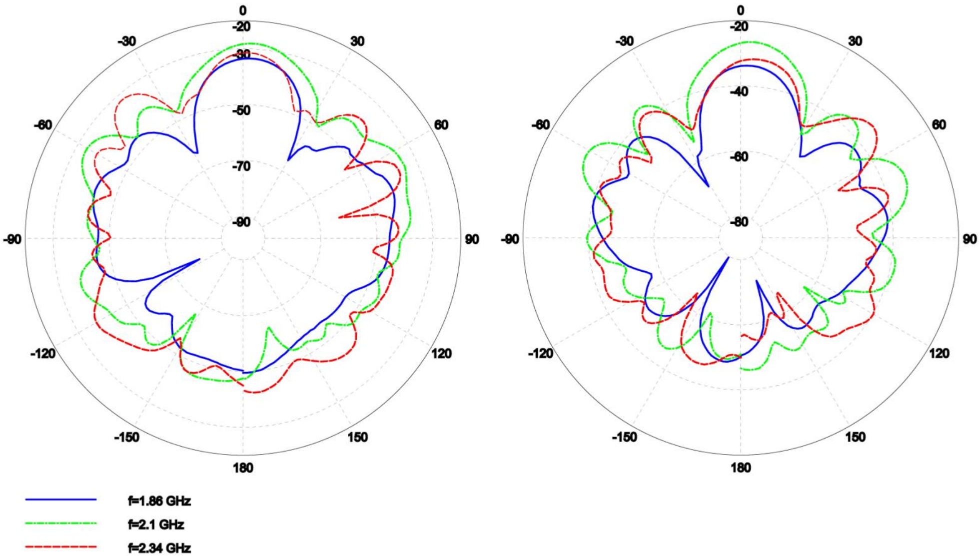


Figure 5.7: 2 GHz Antenna's radiation Pattern in two different planes.

5.3 Antenna Impedance

The antenna impedance has to be matched in order to maximize the power transfer and minimize reflections from the load. The matching can be measured with the reflection coefficient (relation between the incident and the reflected wave):

$$\gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{5.2}$$

where Z_0 is the transmission line impedance and Z_L is the antenna impedance. The match can be described as well by the voltage standing wave ration:

$$VSWR(f) = \frac{1 + |\gamma|}{1 - |\gamma|} \tag{5.3}$$

When the impedance is matched $Z_0 = Z_L$ and then the reflection coefficient becomes equal to 0. VSWR is always greater than 1, and equal to 1 when the impedance is perfectly matched. But a perfect matching is impossible to achieve, accepted VSWR values are those below 2, when the power absorption is equal to 90

Bandwidth is defined as the range of frequencies within which some antenna characteristic does not exceed a specified limit. For instance, as in this case, the bandwidth can be specified as the range frequencies within which the VSWR is below 2. The impedance measurements are affected by the environment in the laboratory, so it is necessary to isolate the antenna as much as possible to have conditions similar to the real conditions when the antenna is working.

The impedance is measured with an net analyzer (ANA), where in fact it measures the S parameters in the access device. Several ANA measurements were done to see the different effects between the helix present in the whole antenna. The aim of these measurements is to see which is the input impedance of the antenna, and see if it is well matched. It is necessary to see also the influence between two helix. The previous design was done with only one helix antenna and the matched was correct, but it has to be checked the matched with the presence of other helix, and the mutual impedance.

First the s-parameter in the big array are measured, without the influence of the small array. In the first measurement it is been used as "port 1" in the network analyzer, one of the big helix, and as "port 2" another one. Then parameter S11 is measuring the input impedance in the first helix, S22 in the second helix, and S12 and S21 measures the mutual impedance between this helix. The results can be seen in the figure 5.3, where both the parameter in Smith-chart representation and the VSWR diagram are plotted.

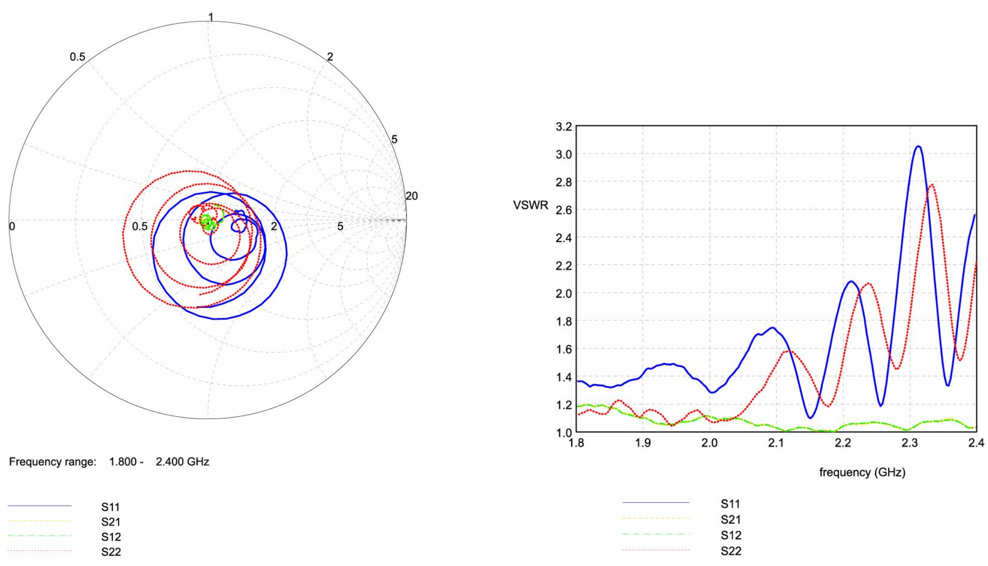
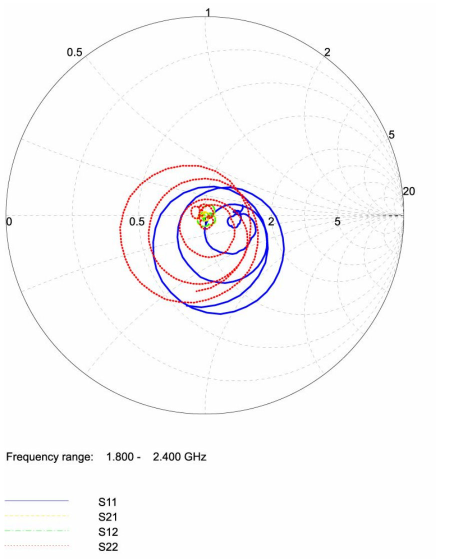


Figure 5.8: Measured impedance of the big helix array without the small array.

In this image it can be seen that the mutual impedance (S12 and S21) is very low. The central frequency, 2.1 GHz has a VSWR with a value below 2, then the impedance is as desired. But as the figures show S11 and S22 are different. That means that the impedance in one helix is different from the impedance in other helix. That is because the feeding point. All the helix antennas have the feeding at the same position in order to preserve the polarization. But that implies that the position of the other antennas respect the feed point is different in every case, then the impedance is also a little bit different. But in both cases the results are acceptable.

Then, once the impedance in the array has been analyzed, the measurement is repeated but with the small array included. The results are shown in figure 5.9.



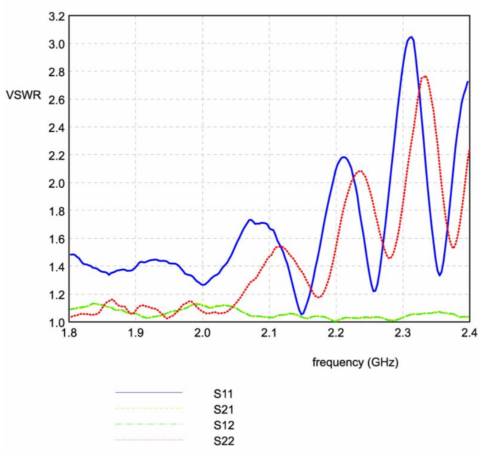


Figure 5.9: Measured impedance of the big helix array with the small array included.

In this case, it can be seen that the presence of the small does not mainly vary the impedance. But an important aspect is that the main frequency, 2.1 GHz, although be in the required range it is not the best frequency.

Finally, the same measures are carried out for the high frequency case (6.3 GHz), and the results are plotted in figure 5.10

As seen in that figure, the impedance is not well matched at all. This array has been built without the additional metal strip because of the small dimensions in these helix. When the final model with the real dimensions is constructed it will have to include the matching to avoid the unwanted behaviour.

5.4 Results Overview

In next table it can be seen an overview of all the measurements carried out. It shows the results for the design main frequency and the results in

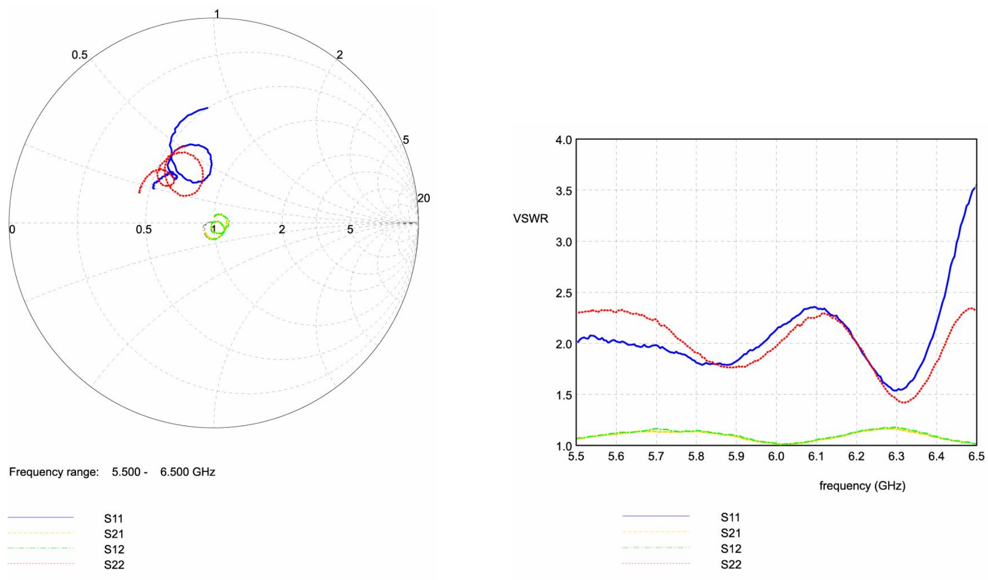


Figure 5.10: Measured impedance of the small array.

the better case.

Frequency	2.1 GHZ	1.98 GHz	6.3 GHz
$HPBW_1$	22 °	18 °	24 °
$HPBW_2$	20 °	17 °	22 °
Directivity	19.7 dB	21.3 dB	18.9 dB
Return Loss	12.5 dB	16.7 dB	13.5 dB
VSWR	1.7	1.3	1.6
Bandwidth	100MHz	200MHz	100MHz

Table 5.1: Measured results overview

These results show that for the big antenna, the main frequency is not the best choice, but for the small array the main frequency has the best behaviour although it could be improved. In fact, as seen before, the directivity has to be measured in practice so to determine if it necessary to improve it or not, at least in the high frequency when the budget is more tight.

Chapter 6

Conclusions and Future Work

With this chapter this document is concluded. Working in that project gave me very valuable experience working with a satellite project in general and with antennas in particular.

The aim of this project was to begin with the design of a student satellite ground station. But this project needs further work to be done over the next semesters to successfully design the satellite and its ground station itself.

6.1 Conclusions

An antenna design was successfully designed, optimized and simulated, and finally a small prototype was built and measured. The antenna consist of two helix array that will provide circular polarization what was desirable.

The design was done so to the final antenna will be feasible, as the final dimensions showed.

The measured antenna has an approximate gain around 20 dB, although the high frequency seems not to achieve exactly this value but a few lower one (19 dB). In the future it will have to be weigh up if it necessary or not to improve this feature, because this link is the most weak and it could need more gain. The link budget was done bearing in mind that it was necessary to have some margin, and the high frequency link has a lower margin.

The antenna need some impedance matching. As the measurements done during this project demonstrate, this matching can simply be an extra thin metal strip added near the feed point.

As seen in the previous chapter as well, the rejection between both antennas are good, so it will be no interference between both the frequencies.

6.2 Future Work

During the measurements a problem seems to appear. It is the mentioned effect that can be seen in figure 5.5. The effect is that the main frequency seems to have a very bad behaviour. This problem has to be studied in the future to found a possible explanation to it. But it can be avoided by choosing another frequency as the center one since the only frequency that has that problem is actually the 2.1 GHz. Then, scaling with the new possible frequency, the dimensions for the final antenna can be found instead of those determined before.

Only the antenna system has been studied. Some other projects will have to work in the design of the other devices at the ground station.

As said, only a prototype was built. In the future the final antenna will have to be built, when the resources will be enough to start building the ground station. Once the antenna is built some features will have to be checked, as the actual gain that was determined theoretically or the antenna factor of merit that is difficult to predict because of the antenna temperature. As the frequencies used, 145.98 MHz and 437.305 MHz are amateur frequencies, students will be able to check the antenna with real transmissions before the satellite is launched.

Also some improvements on the satellite antenna will have to be done, as for example the impedance matching that as measured it was not done.

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Appendix A

Link Budgets

On the following pages the link budgets can be found. These sheets are used in Chapter 2.

Downlink Budget for TT&C

Parameter	***Value (Best Case)***	***Value (Worst Case)***	***Unit***
Speed of light	300000000,00	300000000,00	m/s
Frequency	145980000,00	145980000,00	Hz
Wavelength	2,06	2,06	m
Boltzmann's Constant	0,00	0,00	J/K
	-228,60	-228,60	dBW/K/Hz
Earth Radius	6378000,00	6378000,00	m
Orbit parameters			
Elevation angle	90,00	20,00	degrees
Orbit Height	400000,00	800000,00	m
Distance Ground-Satellite	400000,00	1768000,00	m
Ground Station			
Transmitter Power Output	1,00	1,00	W
	0,00	0,00	dBW
	30,00	30,00	dBm
Transmission Line Loosses	4,00	4,00	dB
Antenna Gain	2,00	2,00	dB
EIRP	-2,00	-2,00	dBW
Uplink Path			
Polarization Loss	3,00	3,00	dB
Path Loss	127,77	140,68	dB
Atmospheric Loss	1,00	1,00	dB
Ionospheric Loss	5,00	5,00	dB
Received Signal	-138,77	-151,68	dBW
Spacecraft			
Antenna Gain	20,00	20,00	dB
Effective Noise Temperature	700,00	700,00	K
Figure of Merit	-8,45	-8,45	dB/K
Signal to Noise power density	81,38	68,47	dBHz
System desired data rate	9600,00	9600,00	bps
	39,82	39,82	dBHz
Eb/N0	41,56	28,65	dB
Minimum receiver Eb/N0	12,00	12,00	dB
Eb/N0 Margin	29,56	16,65	dB

Downlink Budget for Payload

Parameter	Value (Best Case)	Value (Worst Case)	Unit
Speed of light	300000000,00	300000000,00	m/s
Frequency	437305000,00	437305000,00	Hz
Wavelength	0,69	0,69	m
Boltzmann's Constant	0,00	0,00	J/K
	-228,60	-228,60	dBW/K/Hz
Earth Radius	6378000,00	6378000,00	m
Orbit parameters			
Elevation angle	90,00	20,00	degrees
Orbit Height	400000,00	800000,00	m
Distance Ground-Satellite	400000,00	1768000,00	m
Ground Station			
Transmitter Power Output	1,00	1,00	W
	0,00	0,00	dBW
	30,00	30,00	dBm
Transmission Line Loosses	3,50	3,50	dB
Antenna Gain	2,00	2,00	dB
EIRP	-1,50	-1,50	dBW
Uplink Path			
Polarization Loss	3,00	3,00	dB
Path Loss	137,30	150,21	dB
Atmospheric Loss	1,00	1,00	dB
Ionospheric Loss	4,00	4,00	dB
Received Signal	-146,80	-159,71	dBW
Spacecraft			
Antenna Gain	20,00	20,00	dB
Effective Noise Temperature	700,00	700,00	K
Figure of Merit	-8,45	-8,45	dB/K
Signal to Noise power density	73,35	60,44	dBHz
System desired data rate	18000,00	18000,00	bps
	42,55	42,55	dBHz
Eb/N0	30,80	17,89	dB
Minimum receiver Eb/N0	10,00	10,00	dB
Eb/N0 Margin	20,80	7,89	dB

Uplink Budget for TT&C

Parameter	Value (Best Case)	Value (Worst Case)	Unit
Speed of light	300000000,00	300000000,00	m/s
Frequency	145980000,00	145980000,00	Hz
Wavelength	2,06	2,06	m
Boltzmann's Constant	0,00	0,00	J/K
	-228,60	-228,60	dBW/K/Hz
Earth Radius	6378000,00	6378000,00	m
Orbit parameters			
Elevation angle	90,00	20,00	degrees
Orbit Height	400000,00	800000,00	m
Distance Ground-Satellite	400000,00	1768000,00	m
Ground Station			
Transmitter Power Output	10,00	10,00	W
	10,00	10,00	dBW
	40,00	40,00	dBm
Transmission Line Loosses	4,00	4,00	dB
Antenna Gain	20,00	20,00	dB
EIRP	26,00	26,00	dBW
Uplink Path			
Polarization Loss	3,00	3,00	dB
Path Loss	127,77	140,68	dB
Atmospheric Loss	1,00	1,00	dB
Ionospheric Loss	5,00	5,00	dB
Received Signal	-110,77	-123,68	dBW
Spacecraft			
Antenna Gain	2,00	2,00	dB
Effective Noise Temperature	290,00	290,00	K
Figure of Merit	-22,62	-22,62	dB/K
Signal to Noise power density	95,21	82,30	dBHz
System desired data rate	9600,00	9600,00	bps
	39,82	39,82	dBHz
Eb/N0	55,39	42,48	dB
Minimum receiver Eb/N0	12,00	12,00	dB
Eb/N0 Margin	43,39	30,48	dB

Uplink Budget for Payload

Parameter	Value (Best Case)	Value (Worst Case)	Unit
Speed of light	300000000,00	300000000,00	m/s
Frequency	437305000,00	437305000,00	Hz
Wavelength	0,69	0,69	m
Boltzmann's Constant	0,00	0,00	J/K
	-228,60	-228,60	dBW/K/Hz
Earth Radius	6378000,00	6378000,00	m
Orbit parameters			
Elevation angle	90,00	20,00	degrees
Orbit Height	400000,00	800000,00	m
Distance Ground-Satellite	400000,00	1768000,00	m
Ground Station			
Transmitter Power Output	10,00	10,00	W
	10,00	10,00	dBW
	40,00	40,00	dBm
Transmission Line Loosses	4,00	4,00	dB
Antenna Gain	20,00	20,00	dB
EIRP	26,00	26,00	dBW
Uplink Path			
Polarization Loss	3,00	3,00	dB
Path Loss	137,30	150,21	dB
Atmospheric Loss	1,00	1,00	dB
Ionospheric Loss	5,00	5,00	dB
Received Signal	-120,30	-133,21	dBW
Spacecraft			
Antenna Gain	2,00	2,00	dB
Effective Noise Temperature	290,00	290,00	K
Figure of Merit	-22,62	-22,62	dB/K
Signal to Noise power density	85,68	72,77	dBHz
System desired data rate	18000,00	18000,00	bps
	42,55	42,55	dBHz
Eb/N0	43,13	30,22	dB
Minimum receiver Eb/N0	12,00	12,00	dB
Eb/N0 Margin	31,13	18,22	dB