ANALYSIS OF THE OVERALL PERFORMANCE OF ANTENNA ARRAYS FOR THE MANCHESTER UNIVERSITY STUDENT TELESCOPE (MUST)

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LIST OF ABBREVIATIONS

MUST: Manchester University Students Telescope.

SKA: Square Kilometre Array.

ASKAP: Australian Square Kilometre Array Pathfinder.

CSIRO: Commonwealth Scientific and Industrial Research Organization.

FWHM: Full Width between Half Maximum.

XPOL: Cross polarization.

LNA: Low Noise Amplifier.

GUI: Graphical User Interface.
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ABSTRACT

In this project some programs capable to describe the performance of an antenna array are developed as a part of the Manchester University Student Telescope (MUST) project. The goal of this work is to analyze the tradeoff between some technical factors like: the amounts of elements in an antenna array (or in a cluster of antenna arrays), the type of antenna used in such arrays, the noise temperature factor of the entire array, and the geometrical distribution (sensitivity) of the array. All the analysis will be done taking into account the radiation pattern, the directivity and the gain of the array. Basically the project will cover the following stages: The development of a set of programs capable to describe the performance of a Yagi antenna array (taking into account the mathematical description of the antenna’s directivity), the performance of the antenna array taking into account real parameters of the antenna used in the project, the analysis of the performance of the radiation pattern field of the antenna array and finally the optimization of the antenna array taking into account the geometrical distribution of the array.
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DEDICATION

To my mother María Cañar…

“If one day I go to a desert island I’ll just need a picture of you and I will survive!”
ACKNOWLEDGEMENT

“First of all thank you God!” Thank you for the precious gift of the life because with your love, the love of your son Christ and the guide of mother Mary I can do whatever I want.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

The use of antenna arrays for the reception of signals from the space in this century is increasing in importance mainly for the amount of products that can be obtained from this kind of configuration, but the technical challenges related to the implementation of arrays for astronomy is still high. Bearing that in mind the University of Manchester is developing a new and innovative project called MUST.

The Manchester University Student Telescope (MUST) is being developed taking into account the need of implement cheaper and effective ways to inspect the sky and to analyze the pulsars and elusive transient events produced in the deep space. This project consists in the implementation of a cluster of 100 arrays of Yagi antennas that is going to be located on the Jodrell Bank Observatory site [2]. Nowadays the project is developed with many collaborative parties that belong to the University of Manchester and to external institutions.

The goal of the project as it was said before is to implement a low cost radio telescope capable to track a big portion of the sky, with this aim in mind some factors should be taken into account e.g. Losses in the system, noise temperature, antenna noise, temperature of the sky and sensitivity among others.

Taking into account the information detailed in the last paragraphs the project: “Analysis of the overall performance of antenna arrays for the Manchester University Student Telescope (MUST)” has been proposed.

The project is divided in 6 stages: 1) Introduction, 2) Antenna and Antenna array Theory, 3) Antenna and Antenna array modeling in MATLAB®, 4) Validation of the results and optimization of the geometry, 5) Graphical User Interface in MATLAB® and 6) Conclusions and recommendations.

1.2 Objectives

1.2.1 General Objective

Study of the overall performance of antenna arrays for the Manchester University Student Telescope (MUST)

1.2.2 Specific Objectives

- Analyze the theoretical background related to antennas and antenna arrays.
- Compile all the information related to the antenna array in relation with the astronomy and with previous work carried out for the MUST project.
- Modeling of the radiation pattern of the antenna used for the MUST project.
• Generate advanced computer algorithms in order to understand in a better way the behavior of the antennas arrays (modeling) and determine in a deeper way the effect of the losses and the noise temperature.
• Analyze the geometry of the antenna array in order to analyze and improve the overall sensitivity of the array.
• Analyze the performance trade-offs of the array.

1.3 Importance of the project for future research

Nowadays there are two projects that are implementing arrays of antennas: The Square Kilometre Array (SKA) and the Australian Square Kilometre Array Pathfinder (ASKAP). It is necessary to say that in both cases the most used antenna for reception of signals is the parabolic dish. This type of antenna usually is expensive and difficult to build. In the other hand the use of Yagi antennas in a cluster of arrays is “relatively” cheap but it hasn’t been developed in deep during the last two decades. It implies that much research should be done to enjoy of the benefits of the antenna arrays.

In order to be capable to use a cluster of antenna array to scan bigger portions of the space first a deep analysis of the losses in the system, noise temperature, antenna noise temperature, gain and sensitivity should be done. It means that the analysis presented in this dissertation is not just useful for the present project (MUST) but for future application as well.

It can be said that all the dissertation projects related with the implementation of the MUST project are the open door to establish a pathway to follow by other institutions that are doing research in the short and long future.
CHAPTER 2: ANTENNA & ANTENNA ARRAY

With the aim of determine the theoretical background related to this project the following literature is presented as a starting point in the collection of information:

2.1 Antenna Theory

2.1.1 Radiation Intensity

As it reads in [6] the radiation pattern intensity is the amount of radiation power that an antenna is emitting per unit solid angle. Taking into account that the radiation power is a far field parameter the radiation intensity can be found analyzing the radiation density per the square distance.

\[ U = r^2 W_{\text{rad}} \], (ref. [6] eq. 2-12) \hspace{1cm} (2.1)

Where:

- \( U \): Radiation intensity (W/unit solid angle).
- \( W_{\text{rad}} \): Radiation intensity (W/m²).

Bearing in mind that the radiation intensity occurs in the electric field it can be written that:

\[ U(\theta, \phi) = \frac{r^2}{2\eta} |E(r, \theta, \phi)|^2 \approx \frac{r^2}{2\eta} \left[ |E_{\theta}(r, \theta, \phi)|^2 + |E_{\phi}(r, \theta, \phi)|^2 \right] \]

\[ \approx \frac{1}{2\eta} \left[ |E_{\theta}(r, \theta, \phi)|^2 + |E_{\phi}(r, \theta, \phi)|^2 \right], \text{(ref. [6] eq. 2-12a)} \hspace{1cm} (2.2)\]

Where:

- \( E(r, \theta, \phi) \): Antenna intensity in the far electric field. \( E(r, \theta, \phi) = E(\theta, \phi) e^{-jkr} \)
- \( E_{\theta} = E_{\phi} \): Components of the far electrical field of the antenna.
- \( \eta \): Intrinsic impedance of the medium.

2.1.2 Radiation Power Density

In order to find the power radiated by an antenna is necessary analyze the power emitted in the electrical \( E \) and magnetic \( H \) fields [6]. With this goal in mind a poynting vector formed with the radiation in the fields \( E \) and \( H \) is built.

\[ W_{\text{total}} = E \times H \], (ref. [6] eq. 2-3) \hspace{1cm} (2.3)

Where:
\( W_{\text{total}} \): Instantaneous poynting vector (W/m²)

\( E \): Instantaneous Electric field intensity (W/m)

\( H \): Instantaneous Magnetic field intensity (W/m)

It can be said that the poynting vector is a power density therefore the total power radiated by the antenna can be obtained integrating the vector over a closed surface (in this case a sphere with constant radius).

\[
P_{\text{total}} = \iiint_S W_{\text{total}} ds = \iiint_S W_{\text{total}} \cdot \hat{n} \, da, \quad \text{(ref. [6] eq. 2-4)} \tag{2.4}
\]

Where:

\( P_{\text{total}} \): Instantaneous total power (W)

\( \hat{n} \): Unit vector normal to the surface

\( da \): Infinitesimal area of the sphere (m²)

With the aim of determine the radiated power (average power radiated) the time average poynting vector can be written as:

\[
W_{av}(x,y,z) = [W_{\text{total}}(x,y,z;t)]_{av} = \frac{1}{2} \text{Re}[E \times H^*], \quad \text{(ref. [6] eq. 2-8)} \tag{2.5}
\]

The value of \( \frac{1}{2} \) appears because of \( E \) and \( H \) fields are peak values. This value can be omitted for RMS values.

\[
P_{\text{rad}} = \frac{1}{2} \iiint_S \text{Re}(E \times H^*) \, ds = \iiint_S W_{av} \cdot \hat{n} \, da = \iiint_S W_{\text{rad}} \, ds, \quad \text{(ref. [6] eq. 2-9)} \tag{2.6}
\]

\[
P_{\text{rad}} = \int_0^{2\pi} \int_0^{\pi} W_{\text{rad}}(r,\theta,\phi) r^2 \sin(\theta) \, d\theta d\phi \tag{2.7}
\]

Taking into account the eq. 2.1 the last expression can be reduced to:

\[
P_{\text{rad}} = \int_0^{2\pi} \int_0^\pi U(\theta,\phi) \sin(\theta) \, d\theta d\phi, \quad \text{(ref. [6] eq. 2-13)} \tag{2.8}
\]

### 2.1.3 Directivity & Gain

As it is presented in [6] and [7] the relation between the power density of an antenna (in the maximum radiation pattern) and the radiation pattern of an Isotrope is described as the directivity of the antenna. Namely it describes how directional is the radiation pattern of the antenna eq. 2.9. It is described to be measured at a distance \( r \) in the far-field region.
\[
D = \frac{U}{U_0} = \frac{4\pi U}{P_{rad}} = \frac{4\pi U(\theta, \phi)}{\int_{0}^{2\pi} \int_{0}^{\pi} U(\theta, \phi) \sin(\theta) \, d\theta \, d\phi}, \quad \text{(ref. [6] eq. 2-16)} \tag{2.9}
\]

Where:
- \(D\) : Directivity
- \(U\) : Radiation intensity of non isotropic antenna (W/unit solid angle)
- \(U_0\) : Radiation intensity of isotropic antenna (W/unit solid angle)
- \(P_{rad}\) : Radiated power (W)

The gain is the ratio between the intensity of the antenna emitted in a specific direction and the radiation intensity emitted by an isotropic antenna operating with the same power input of the antenna in analysis.

\[
G = 4\pi \frac{U(\theta, \phi)}{P_{in}}, \quad \text{(ref. [6] eq. 2-46)} \tag{2.10}
\]

### 2.2 Antenna Array Theory

#### 2.2.1 Linear Array

Again as it is described in the ref. [6] chapter 6, the shape and amplitude of the antenna array field is controlled by the position of each element in relation with the rest of the elements in the array. The analysis of Isotrope antennas is the easy starting point to describe the behavior of an antenna array. As it is shown in [7] firstly it in a uniform antenna array (Fig. 1) the Isotrope antennas are equally spaced, second are feed with the same current amplitude and finally show a progressive phase shift \((\delta)\).

![Uniform Isotrope antenna array. [7]](image)

In this array the feeding current for each element is:

\[
I_i = I_0 e^{j(\delta)}, \quad \text{(ref. [7] chapter 6.3)} \tag{2.11}
\]
Taking into account that the total electric field for the array is the sum of the electric field of each element of the array and assuming that all the analysis is going to be done in relation with a common point. The total electric field can be written as follows:

\[ E = \frac{A}{r_0} \left( e^{-jkr_0} + e^{-j(k_1-\delta)} + e^{-j(k_2-2\delta)} + \ldots + e^{-j(k_{n-1}-(n-1)\delta)} \right), \quad \text{(ref. [7] eq. 71)} \] (2.12)

Where:

\[ r_0 = r_1 = r_2 = \ldots = r_{n-1} : \text{ Distance term.} \]

\[ \delta : \text{ Phase shift between elements.} \]

Applying a geometrical solution for the array and doing some substitutions the electrical field can be described as follows:

\[ E = \frac{A}{r_0} e^{-jkr_0} e^{j\left(\frac{n-1}{2}\Psi\right)} \left( \sin \left( \frac{n}{2} \Psi \right) \right) = \frac{nA}{r_0} e^{-jkr_0} e^{j\left(\frac{n-1}{2}\Psi\right)} \left( \frac{\sin \left( \frac{n}{2} \Psi \right)}{n\sin \left( \frac{\Psi}{2} \right)} \right) \] (2.13)

Again the total electric field of an array is determined by \( n \) times the field of a single element multiplied by the array factor:

\[ E = n \left[ E \left( \text{Single element at centre} \right) \right] \times \left[ \text{array factor} \right] \] (2.14)

And \( E \) has a spatial distribution of:

\[ \frac{\sin \left( \frac{n}{2} \Psi \right)}{n\sin \left( \frac{\Psi}{2} \right)} \] (2.15)

With a maximum value at \( \Psi = 0 \):

\[ \left| E \right|_{\text{max}} = \frac{nA}{r_0} = n |E_0| \] (2.16)

Finally the array factor is:

\[ AF = \frac{\sin \left( \frac{n}{2} \Psi \right)}{n\sin \left( \frac{\Psi}{2} \right)} \] (2.17)

Where:

\[ \Psi = kd \cos(\phi + \delta) \] (2.18)

With \( k = \frac{2\pi}{\lambda} \).
### 2.2.2 Planar Array

A planar array basically has a grid of elements that can be located taking into account the distribution for \( \theta \) and \( \phi \) respect to the point of analysis in the space (Fig. 2).

![Planar antenna array. [7]](image)

The array in the Fig. 2 can be modeled analyzing the distribution of the elements in each axis of the planar array as follows:

\[
S_{xm} = \sum_{m=1}^{M} I_{m1} e^{j(m-1)(kd_x \sin \theta \cos \phi + \beta_x)} , \text{ (ref. [6] eq. 6-84)} \tag{2.19}
\]

\[
S_{yn} = \sum_{n=1}^{N} I_{1n} e^{j(n-1)(kd_y \sin \theta \sin \phi + \beta_y)} , \text{ (ref. [6] eq. 6-84)} \tag{2.20}
\]

Where:

- \( I_{m1} \): Excitation coefficient of each element in the \( x \) axis.
- \( d_x \): Spacing between each element in the \( x \) axis.
- \( \beta_x \): Progressive phase shift between each element in the \( x \) axis.
- \( I_{1n} \): Excitation coefficient of each element in the \( y \) axis.
- \( d_y \): Spacing between each element in the \( y \) axis.
- \( \beta_y \): Progressive phase shift between each element in the \( y \) axis.

Taking into account that the radiation pattern of the array is going to be the product of \( S_{xm} \) and \( S_{yn} \) then the array factor can be written in the following way:
\[ AF = S_{xm}S_{yn}, \text{ (ref. [6] eq. 6-85)} \]  
\[ AF = I_{mn} \sum_{m=1}^{M} e^{j(m-1)k d_x \sin \theta \cos \phi + \beta_x} \sum_{n=1}^{N} e^{j(n-1)k d_y \sin \phi \sin \phi + \beta_y}, \text{ (ref. [6] eq. 6-87)} \]

Where \( I_{mn} \) is the product of \( I_m I_n \).

Following the same process in 2.2.1 the array factor can be written as follows:

\[ AF_n(\theta, \phi) = \frac{\sin\left(\frac{M \Psi_x}{2}\right) \sin\left(\frac{N \Psi_y}{2}\right)}{M \sin\left(\frac{\Psi_x}{2}\right) N \sin\left(\frac{\Psi_y}{2}\right)} \]  

Where:

\[ \Psi_x = k d_x \sin \theta \cos(\phi + \beta_x), \text{ (ref. [6] eq. 6-88a)} \]  
\[ \Psi_y = k d_y \sin \theta \sin(\phi + \beta_y), \text{ (ref. [6] eq. 6-88b)} \]

### 2.3 Noise Analysis Theory

#### 2.3.1 Analysis of Temperature

The starting point for the analysis of the noise in the antenna array is the brightness temperature \( (T_B) \) that is defined as the equivalent temperature of the radiated energy from an object. The brightness temperature in combination with the relation between the antenna Gain and the directivity gives raise to the Antenna temperature \( (T_A) \) [6].

\[ G(\theta, \phi) = \eta_{total} \ast D(\theta, \phi) \]  

Where:

- \( \eta_{total} \): Radiation efficiency\(^1\).
- \( G(\theta, \phi) \): Antenna gain.
- \( D(\theta, \phi) \): Antenna Directivity.

\(^1\) The radiation efficiency represents the amount of energy in percentage that is radiated out from the antenna namely to the space. There are two possible points for observation of the radiated power: the antenna and the system (taking into account the losses in the system).
\[
T_A = \frac{\int_{0}^{\pi} \int_{0}^{2\pi} T_B(\theta, \phi) G(\theta, \phi) \sin(\theta) d\theta d\phi}{\int_{0}^{\pi} \int_{0}^{2\pi} G(\theta, \phi) \sin(\theta) d\theta d\phi}, \text{(ref. [6] eq. 2-144)}
\] (2.27)

In order to determine the radiation efficiency \( \eta_{total} \) the losses of the system by matching, cable, combiners and filter can be combined as follows:

\[
L_{ref} = (1 - S_{11})
\] (2.28)

Where:
- \( L_{ref} \): Losses by reflected power (Matching).
- \( S_{11} \): S parameter (in power ratio).

\[
\eta_{total} = L_{total}^2
\] (2.29)

Where:
- \( \eta_{total} \): Radiation efficiency\(^3\).
- \( L_{total} \): Total amount of Losses (in dB) in the system.

Once the temperature of the antenna and the radiation efficiency are known then the temperature of the entire system can be calculated.

\[
T_{sys} = \eta_{total} * T_A + (1 - \eta_{total}) T_{amb} + T_{LNA}
\] (2.30)

Where:
- \( T_{sys} \): Temperature of the system.
- \( T_{amb} \): Room temperature.
- \( T_{LNA} \): Temperature of the LNA (Low Noise Amplifier).

\(^2\) For a detailed analysis of losses see eq. 4.8.

\(^3\) In this project the radiation efficiency is represented as the total amount of losses in the system. This is done because of the effective energy radiated to the space is reduced by the losses by: matching (not perfect), cables, combiners and filters.
2.3.2 Sensitivity

In a similar way the Sensitivity can be determined as follows[20]:

\[
S = \frac{A_{\text{eff}}}{T_{\text{sys}}} = \frac{\lambda^2 \eta_{\text{total}} D(\theta, \phi)}{4\pi} = \frac{\lambda^2 \eta_{\text{total}} D(\theta, \phi)}{4\pi T_{\text{sys}}}
\]  

(2.31)

Where:

\( S \) : Sensitivity.

\( A_{\text{eff}} \) : Effective aperture.
CHAPTER 3: ANTENNA AND ANTENNA ARRAY MODELING IN MATLAB®

3.1 Yagi antenna

3.1.1 Frequency operation of the Yagi Antenna

In order to analyze the frequency operation of the antenna it is necessary to analyze the technical data for the Yagi antenna given by the antenna provider (Blake Antennas) and the data obtained from real measurements (network analyzer).

First the technical data from the vendor [17] is the following:

Centre frequency: 590 MHz
Bandwidth: +/- 25 MHz (total 50 MHz)
Gain: 15 dB.
FWHM⁴ ≈ 30°

Second the data obtained from the network analyzer (Agilent Technologies E5071B– Network Analyzer – 300 kHz to 8.5 GHz) is the following (see Fig. 3):

![Fig. 3. Measurements of frequency operation for the Yagi antenna.](image)

⁴ Full Width between Half Maximum points (FWHM) is the angular width of the main beam of the Yagi antenna. In this work it is assumed to be located at -10 dB from the maximum gain achievable.
The measurements of the S11 response (Fig. 3.) are not totally precise because of them were done in the open space of the microwave laboratory (receiving many reflections) and not in an isolated chamber. This was done mainly for the mechanical length of the antenna (approximately 236 cm). Despite of the inaccuracy in the measurements the parameter S11, these measurements are useful to understand the behavior of the antenna.

It can be said then that the lowest values for the S-parameter are located at 518.2 MHz and 526.4 MHz with -24.69 dB and -24.46 dB respectively; and approximately -17 dB at a frequency of 590 MHz (expected operational frequency of the antenna). Additionally it can be seen a usable bandwidth (-10 dB) approximately from 460 MHz to 644 MHz.

3.1.2 Radiation pattern of the Yagi Antenna

The base technique described in the Chapter 2 of this project consists in the use of mathematical formulas for the implementation of the Array factor in MATLAB®. This array factor is multiplied by the electrical field of the antenna in order to get the electrical field of the entire array. The goal in this section is define the correct radiation pattern that will be entered in the program for the simulation of the array. Bearing that in mind two options can be proposed to get radiation pattern and enter it in MATLAB®: 1) simulate the antenna in CST Microwave Studio® or 2) enter the data from the real measurements of the radiation pattern of one Yagi antenna directly in MATLAB®.

3.1.2.1 Modelling of the Radiation pattern with CST Microwave Studio®

With the aim of find the electrical field of the Yagi antenna the software CST Microwave Studio® was used as the first approximation to get the radiation pattern of the Yagi antenna. The goal with this software is to build the antenna considering its mechanical dimensions. These dimensions are described in the Table I and in the Fig. 4.

<table>
<thead>
<tr>
<th>Element</th>
<th>Length of the element</th>
<th>Spacing from driven element</th>
<th>Spacing from boom position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boom position</td>
<td>0</td>
<td>-491</td>
<td>0</td>
</tr>
<tr>
<td>Reflector</td>
<td>236</td>
<td>-219</td>
<td>272</td>
</tr>
<tr>
<td>Driven element</td>
<td>210</td>
<td>0</td>
<td>491</td>
</tr>
<tr>
<td>Director 1</td>
<td>209.5</td>
<td>57</td>
<td>548</td>
</tr>
<tr>
<td>Director 2</td>
<td>209.5</td>
<td>57.5</td>
<td>605.5</td>
</tr>
<tr>
<td>Director 3</td>
<td>209.5</td>
<td>63.5</td>
<td>669</td>
</tr>
<tr>
<td>Director 4</td>
<td>198</td>
<td>93.5</td>
<td>762.5</td>
</tr>
<tr>
<td>Director 5</td>
<td>198</td>
<td>93</td>
<td>855.5</td>
</tr>
<tr>
<td>Director 6</td>
<td>198.5</td>
<td>100</td>
<td>955.5</td>
</tr>
<tr>
<td>Director 7</td>
<td>198.5</td>
<td>105</td>
<td>1060.5</td>
</tr>
<tr>
<td>Director 8</td>
<td>199</td>
<td>121</td>
<td>1181.5</td>
</tr>
<tr>
<td>Director 9</td>
<td>198.5</td>
<td>140</td>
<td>1321.5</td>
</tr>
</tbody>
</table>
With the information showed in the Table I and the Fig. 4 the antenna Yagi was simulated in the software CST Microwave Studio® (Fig. 5).

The maximum value for the Gain in this scenario was 14.09 dB. In order to make an early validation of data a comparison of the data obtained from CST with real data has been done. In this case some measurements\(^5\) (real data) from the group of Research of the School of Physics & Astronomy from the University of Manchester have been used (see Fig. 6 and Fig. 7).

\(^5\) The measurements of the antenna pattern were done in Jodrell Bank Centre for Astrophysics. This data was obtained with the use of one antenna performing as transmitter (connected to a signal generator) and one antenna performing as receiver(s) (connected to a spectrum analyzer).
In this case the outcome from MATLAB® from the program “program_3_9.m” with M=1 and N=1; and additionally the outcome from MATLAB® (for the data from CST Microwave Studio®) uses the function “directivity_file.m” into the program “program_3_9.m”.

Clearly it can be seen that the radiation pattern from CST Microwave Studio® is not adjusting to the real measurements done in the field. It can be said that the erroneous behavior of the antenna in
CST Microwave Studio® probably is related to the use of a folded dipole (driven element in the Yagi antenna) that even now is suffering some upgrading in this software. As a consequence this radiation pattern cannot be used to work in further simulations of the antenna array.

Talking about the frequency response (analysis of the S11 parameter) another analysis to contrast the correct operation of the simulation was done (Fig. 8). In this case the information from the network analyzer (chapter 3.1.1) and the information from CST were contrasted.

![Comparison of data (S11)](image)

**Fig. 8.** Comparison of the S11 parameter for the Yagi antenna. In red the data from the network analyzer in green the data from CST Microwave Studio® (shifted)

In the Fig. 8 the signal from CST Microwave Studio® was shifted because of the absence of the imaginary component in the impedance of the antenna in the simulation program. The Yagi antenna uses a balun that change the impedance of the antenna to 50 \( \Omega \). The real impedance of the antenna can be obtained short circuiting the terminals of the antenna but for question of time and objectives this wasn’t done. The value for the input impedance for the antenna was assumed to be 190 \( \Omega \) in the simulation (purely resistive). The comparison done previously shows a relatively similar behavior for the data from the real measurement and the outcome of the simulation.

### 3.1.2.2 Radiation pattern modeling with real data

Again in order to find the electrical field in this case data collected by the group of Research of the School of Physics & Astronomy from real measurements of one Yagi antenna was used. The data from the measurements of Directivity (every 5 degrees) of the Yagi antenna (Antenna “A” at 590 MHz) was entered in MATLAB®.

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6 Outcome for Matlab from the program “S11_comparison.m”.
Basically the data is interpolated taking into account the polarization of the antenna. For the horizontal polarization the data for plotting is obtained when Phi is 0° (with Theta between 0° to 180°) and 180° (with Theta between -180° to 0°). For the vertical polarization the data for plotting is obtained when Phi is 90° (with Theta between 0° to 180°) and 270° (with Theta between -180° to 0°). This data is assumed to be an initial vector of 5 elements specifying the directivity at 0°, 90°, 180°, 270° and 360°. The interpolation is applied to have a final vector of 361 elements namely from 0° to 360° in steps of 1°. Finally a matrix of 361 by 181 elements was built. This distribution of elements in this matrix is related to the directivity in Phi (0° to 360°) and Theta (0° to 180°) every 1 degree.

The MATLAB® program that generate the interpolation mentioned before is “directivity_file_2.m”. There are 2 files that contain the data with the real measurements: “directivity_antenna_horizontal” (for a Yagi antenna with horizontal polarization) and “directivity_antenna_vertical” (for a Yagi antenna with vertical polarization).

![Image of radiation pattern comparison](image)

Fig. 9. Comparison of the radiation pattern of the Yagi Antenna. In blue the real data and in red the data from MATLAB® (Horizontal Polarization). Both radiation patterns are identical so are overlapped.
When the process of integration was done in MATLAB® it gave a value of Directivity of approximately 16 dB. That can be considered as the real value of directivity of the Yagi antenna.

The outcome from MATLAB® of the signal is described in the Fig. 9 and Fig. 10. Both radiation patterns are overlapped so it can be said that the interpolation works properly.

### 3.1.3 Radiation pattern of the array of Yagi Antennas

In this stage of the project it is necessary to implement in MATLAB® the mathematical expression for the antenna array (see section 2.2.2). The equation 2.23 has been implemented as the core of the array analysis and it is compiled in the function “pattern_array.m” (see Annex 2). This function processes the angular distribution every 0.1 degree for the angle in elevation and in azimuth. This is done basically to be accurate in the calculation of the Radiated power, which is integrated as is described in the equation 2.9 (see Annex 1).

For the MUST project the distribution of the Yagi antennas in the antenna array proposed by the group of Research of the School of Physics & Astronomy is related to an array of 16 by 4 antennas (see Fig. 11). This array is going to be built with antennas working in Horizontal and Vertical

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7 Outcome for MATLAB® from the program “program_3_9.m” with M=1 and N=1.
polarization. The array comprises a separation of 0.9 m between the antennas with the same polarization and 0.45 m between antennas with a different polarization (see chapter 4.1.2 for further information).

Fig. 11. Distribution of antennas in the array.

The antennas working with similar polarization are not going to be affected by the antennas with different polarization (see section 4.1.1.2). Therefore the analysis in MATLAB® of the radiation pattern can be done separately for the horizontal polarization (Fig. 12 and Fig. 13) and for the vertical polarization (Fig. 14 and Fig. 15), namely one array of 8 by 4 antennas with horizontal polarization and another one with 8 by 4 antennas with vertical polarization.

Fig. 12. Radiation pattern of a Yagi antenna array (8 by 4 elements) with Horizontal polarization.

The letter \( H \) represents “Horizontal polarization” and \( V \) represents vertical polarization.

Outcome from MATLAB® from the program “program_3_9.m” with \( N=8 \) and \( M=4 \) for radiation patterns. Distance equal to 0.9 meters. Horizontal polarization.

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8 The letter \( H \) represents “Horizontal polarization” and \( V \) represents vertical polarization.

9 Outcome from MATLAB® from the program “program_3_9.m” with \( N=8 \) and \( M=4 \) for radiation patterns. Distance equal to 0.9 meters. Horizontal polarization.
Fig. 13. Radiation pattern of a Yagi antenna array (8 by 4 elements) with Vertical polarization\textsuperscript{10}.

\textsuperscript{10} Outcome from MATLAB\textsuperscript{®} from the program “program_3_9.m” with N=8 and M=4 for radiation patterns. Distance equal to 0.9 meters. Vertical Polarization.
CHAPTER 4: VALIDATION OF THE RESULTS AND OPTIMIZATION OF THE GEOMETRY

4.1 Validation of data

4.1.1 Validation of the Radiation pattern for the array of Yagi Antennas

In this stage a first approach to the validation of data is done comparing the outcome of the program developed in this work (for the antenna array) against real measurements done in the field.

4.1.1.1 Radiation pattern of an array of 2 by 1 antennas

Fig. 14. Radiation pattern\(^{11}\) of an array of 2 Yagi antennas with Horizontal polarization (In blue the real measurements - in red the outcome from Matlab\(^\text{®}\))\(^{12}\).

Fig. 15. Radiation pattern of an array of 2 Yagi antennas with Vertical polarization (In blue the real measurements - in red the outcome from Matlab\(^\text{®}\)).

\(^{11}\) Outcome for MATLAB\(^\text{®}\) from the program “program_3_9.m” (separation of 0.9 meters).

\(^{12}\) The outcome of the program “program_3_9.m” originally consist of a distribution of the radiation pattern every 0.1° for the process of integration and 1° for plotting. But because of the data from the real measurements was done every 5° the outcome from the program was down-sampling to 5° just to make the comparison of the radiation pattern.
In this case the information from the group of Research of the School of Physics & Astronomy was used again. There are two scenarios for the analysis. The first scenario consists in the use of two antennas with horizontal polarization at a frequency of 590 MHz (Fig. 14) and the second scenario is related to the use of two antennas with vertical polarization (Fig. 15). Both scenarios were compared against the outcome of the program working with the same characteristics. Clearly it can be seen that in both cases the outcome from the program is close to the real pattern. So it can be said that in this stage of the project the approach assumed in the program (planar array see section 2.2.2) is correct.

4.1.1.2 Analysis of Cross-polarization of antennas (Radiation pattern)

With the aim of determine the effect of the use of antennas with a different polarization (in the same frame for antenna array) again real measurements were compared against the outcome from Matlab®. In this case the scenario consists in 2 antennas with vertical polarization installed in the same frame with one antenna with horizontal polarization in the middle of them “Cross-polarization” (Xpol) see Fig. 16. The separation between antennas in this case is 0.45 meters.

![Fig. 16. Analysis of Radiation pattern (cross-polarization) normalized in the three cases.](image)

Taking into account the information of the Fig. 16 it can be said that the radiation pattern obtained with the cross polarization is approximately the same for the radiation pattern obtained with just two antennas operating with a similar polarization. Therefore it can be concluded that the use of antennas with different polarization (one after another) in the same frame for the array won’t affect the work of the array in each polarization.

4.1.2 Validation of the distance between elements in the array of Yagi Antennas

In the MUST project the separation between every antenna in the array is 0.9 m (for 2 antennas with a same polarization) and it was defined by the group of Research of the School of Physics &

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13 Outcome from Matlab from the program “program_3_12.m” (xpol) and the program “program_3_9.m” (2 by 1 array).
Astronomy. This distance is the outcome of the use of an approximate technique that take into account the gain in function of the antenna beam and the relation between the effective aperture and the wavelength as follows:

\[ D = \frac{4\pi}{\Omega_A} \]  
(4.1)

Where:

\( D \): Directivity of the Yagi antenna.

\( \Omega_A \): Beam solid angle\(^{14}\).

\[ A_{\Omega} = \frac{\lambda^2 G}{4\pi} = \frac{\lambda^2 (\eta D)}{4\pi} = \frac{\lambda^2 \left( \frac{\eta 4\pi}{\Omega_A} \right)}{4\pi} = \frac{\lambda^2 \eta}{\Omega_A} \]  
(4.2 a)

Where:

\( A_{\Omega} \): Effective aperture of the Yagi antenna.

\( G \): Antenna Gain.

\( D \): Directivity of the Antenna.

\( \eta \): Radiation Efficiency of the Antenna.

\( \Omega_A \): Antenna beam.

\( \lambda^2 \): Wavelength of operation.

The assuming radiation efficiency equals to 1 the equation 4.2 a, is reduced to:

\[ A_{\Omega} = \frac{\lambda^2}{\Omega_A} \]  
(4.2 b)

Bearing in mind that the Directivity of the antenna is 15 dB (approximately 32 in power ratio) and combining the equations 4.1 and 4.2 b, then it can written that the effective aperture is:

\[ A_{\Omega} = \frac{\lambda^2}{\Omega_A} = \frac{\lambda^2}{4\pi} = \frac{0.508^2}{4\pi} = 0.64 \text{ m}^2 \]  
(4.3)

Assuming that the pattern of the effective aperture is described by a circle it can be said that:

\[ A_{\Omega} = \frac{\pi D_{\text{eff}}}{4} \]  
(4.4)

\(^{14}\) If the radiation intensity in one antenna is irradiated with a same magnitude (as a maximum value of radiation intensity) in all the angles, then it can be said that this angle is a beam solid angle.
Where:

\[ D_{\text{eff}} \] : Effective Diameter for the aperture of the Yagi antenna.

Then solving the equation to find the diameter of the circle it can be written that:

\[
D_{\text{eff}} = \sqrt{\frac{4 \ A_{\text{eff}}}{\pi}} = \sqrt{\frac{4 \times 0.64}{\pi}} \approx 0.9 \ m \quad (4.5)
\]

From 4.5 it can be said that there should be a spacing of 0.9 meters (0.5085 wavelengths at a frequency of 590 MHz) between every antenna operating with the same polarization in the array.

In order to contrast the information from the last approach and the outcome from MATLAB® (see section 3.1.3) the following analysis is done. First the maximum distance between the antennas is defined with the maximum Directivity achievable (Figs. 17 (a) and 17 (b)).

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\[ \text{Fig. 17. (a). Directivity vs spacing (in wavelengths) Horizontal polarization}^{15}. \]

\[ \text{Fig. 17. (b). Directivity vs spacing (in wavelengths) Vertical polarization}^{16}. \]

\[ ^{15} \text{Outcome from Matlab from the program “program_3_7_2.m” with horizontal polarization.} \]
It can be seen that in both cases the array factor is predominant in the pattern of the antenna array for that reason the outcome “Directivity vs Spacing” for horizontal polarization is almost the same for the vertical polarization.

It can be said from the outcome from MATLAB® that the maximum gain (32.17 dB in horizontal polarization and 32.18 dB in vertical polarization) can be reached with a separation of 1.3729 meters or 2.7 wavelengths (with a frequency of operation of 590 MHz). It can be said that in both cases the 2 polarizations show a similar behavior. If a separation of 0.9 meters is assumed then a gain of 30.54 dB is achieved. With the aim of expand the landscape to make a better comparison of the directivity reached, two distances more were simulated: 0.64 meters (0.9 m - lambda/2) and 1.16 meters (0.9 m + lambda/2). The maximum directivity achievable for a separation of 0.64 meters is 28.28 dB and 31.73 dB for a separation of 1.16 meters (see Fig. 18).

From the simulation it can be seen that the more increase the separation between antennas the most closely the side lobes will be. But in a similar manner the more increase the separation between antennas the shorter angle for FWHM (see section 3.1.1) will be, namely the smaller the beam the higher the directivity because in this case the side lobes are not high. For the cases of 0.9 and 1.37 meters there is a difference of amplitude between the main lobe and the first side lobe of around 13

---

16 Outcome from Matlab from the program “program_3_7_2.m” with vertical polarization.

17 Outcome for Matlab from the program “program_3_9.m” with M=4 by N=8 and dx=dy={0.64,1.16, 1.37, 0.9}.
dB. Additionally for the case of 0.9 meters the highest side lobe is separated from the main lobe in around 34 degrees. In as similar way for a separation of antennas of 1.16 and 1.37 meters the separation between lobes will be approximately 24 and 20 degrees respectively. It can be seen that a low contribution of side lobes and a good value of FWHM at -10 dB is achieved with a separation of 0.9 meters between Yagi antennas, but it can be noticed as well that there is a decrement in gain of approximately 1.63 dB with respect to the gain achieved with a separation of 1.37 meters. The value of FWHM is expected to be around of 6° for the case of 0.9 meters and 4° in the case of the 1.37 meters.

4.2 Optimization of the Array’s Geometry (Analysis of spacing between antennas)

4.2.1 Optimization of the geometry for the array of Yagi Antennas

Taking into account the analysis of the separation between antennas done in the section 4.1.2 it can be said that a high portion could be lost when a separation between Yagi antennas of 0.9 meters is used instead of a separation of 1.37 meters. Having that in mind and taking into account the mechanical dimensions of the structure for the antenna array the following analysis of the spacing between antennas can be done.

The mechanical dimension of the frame for the antenna array has being designed taking into account a distance of 0.9 meters between antennas (Fig. 19). Bearing that in mind and with the distance of 1.37 meters the size of the array is reduced to an array of 5 by 3 Yagi antennas.

In this case the new directivity is 28.83 dB, it means that around 1.71 dB are lost in comparison with the directivity reached with a distance of 0.9 meters (30.54 dB) because of the smaller number of elements that can fit on the frame.
Another approach consists in keep the separation between antennas of 0.9 meters in the columns and change the separation to 1.37 meters in the case of the rows in the array and vice versa (1.37 meters in the columns and 0.9 in the rows). In the first case a directivity of 29.84 dB is reached but it is still 0.7 dB below the standard Directivity reached with a distance of 0.9 meters. In the case of the variation in the columns a directivity of 29.14 dB is reached namely 1.4 dB below the expected directivity of the array with a separation of 0.9 m.

Bearing in mind this analysis at a first stage it is recommended that in order to get a better value of directivity for the array using the same number of antennas the mechanical dimensions of the array should be changed at least to 10.3 by 4.2 meters.

4.2.2 Optimization of the geometry for the cluster of Yagi Antenna arrays

The Must Project implies the construction of a cluster of antenna arrays (around 100 arrays of Yagi antenna arrays). The Cluster of arrays is made of Yagi antenna arrays each array is mounted on a frame with fixed mechanical dimension as shown in sections: 3.1.3, 4.2.1. For this analysis each array has 32 elements in each polarization (namely 64 Yagi antennas in total) separated by 0.9 m (see section 3.1.3).

In order to develop a good geometry for this cluster the following analysis is proposed:
1) The cluster is inspected using 5 geometries 100 by 1, 50 by 2, 25 by 2, 20 by 5 and 10 by 10. In every case the maximum separation between arrays will be determined finding the maximum directivity for the cluster. The outcome has been written in the Table II and depicted in the Fig. 20.

![Comparison of radiation pattern for 5 different sizes of arrays](image)

**Fig. 20.** Comparison of radiation pattern for 5 different sizes of arrays\(^\text{18} \).\n
\(^{18}\) Outcome for MATLAB® from the program “program_3_11_a.m”.\n
26
TABLE II. DIRECTIVITY FOR THE CLUSTER OF ARRAYS WITH A SPACING OF 7.6271 METERS BETWEEN ARRAYS

<table>
<thead>
<tr>
<th>Size of the array</th>
<th>Maximum Directivity (dB)</th>
<th>Spacing (in lamda)</th>
<th>Spacing (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 by 1</td>
<td>50.2</td>
<td>15</td>
<td>7.6271</td>
</tr>
<tr>
<td>50 by 2</td>
<td>50.53</td>
<td>15</td>
<td>7.6271</td>
</tr>
<tr>
<td>25 by 4</td>
<td>50.79</td>
<td>15</td>
<td>7.6271</td>
</tr>
<tr>
<td>20 by 5</td>
<td>50.84</td>
<td>15</td>
<td>7.6271</td>
</tr>
<tr>
<td>10 by 10</td>
<td>50.91</td>
<td>15</td>
<td>7.6271</td>
</tr>
</tbody>
</table>

2) Now the maximum separation between arrays is determined with the help of the equations 4.3 and 4.5 and then this information will be contrasted against the data from the 5 geometries proposed for the first step. With this analysis the separation between arrays is approximately 5.11 meters. The outcome has been written in the Table III and depicted in the Fig. 21.

![Comparison of radiation pattern for 5 different geometries of cluster](image)

Fig. 21. Comparison of radiation pattern for 5 different geometries of cluster\(^{19}\).

TABLE III. DIRECTIVITY FOR THE CLUSTER OF ARRAYS WITH A SPACING OF 5.11 METERS BETWEEN ARRAYS

<table>
<thead>
<tr>
<th>Size of the array</th>
<th>Maximum Directivity (dB)</th>
<th>Spacing (in lamda)</th>
<th>Spacing (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 by 1</td>
<td>49.57</td>
<td>10.05</td>
<td>5.11</td>
</tr>
<tr>
<td>50 by 2</td>
<td>49.49</td>
<td>10.05</td>
<td>5.11</td>
</tr>
<tr>
<td>25 by 4</td>
<td>49.79</td>
<td>10.05</td>
<td>5.11</td>
</tr>
<tr>
<td>20 by 5</td>
<td>49.89</td>
<td>10.05</td>
<td>5.11</td>
</tr>
<tr>
<td>10 by 10</td>
<td>50.02</td>
<td>10.05</td>
<td>5.11</td>
</tr>
</tbody>
</table>

\(^{19}\) Outcome from Matlab from the program “program_3_11_a.m”.
3) Finally the best geometry in the last two cases will be compared in order to define the appropriate separation between arrays. It can be seen that in the both cases (5.11 m and 7.63 m) that the squarer is the array the higher side lobes will appear. Then the best option is the array of 50 by 2 arrays. This because of the low size of the side lobes. Bearing that in mind the both results now are showed in the Fig 22.

![Comparison of radiation pattern for a cluster of 50 by 2 arrays.](image1)

(b) Geometry proposed

4.3 Optimization of the Array’s Geometry (Analysis of Temperature of the System & Sensitivity)

The analysis of the noise temperature of the system is fundamental (see section 2.3). In order to find this noise temperature a program for computing the system temperature and sensitivity has been developed taking into account the information detailed in [18] (see Fig. 23).

---

20 Outcome for Matlab from the program “program_3_11_a.m” with N=50 by M=2 for 2 different distances 5.11 and 7.62 meters.
In the Fig. 23 the variation of the sky temperature during a complete day (24 hours) is depicted. The procedure implemented in [18] implies the conversion of the data mentioned before in information that can show the variation of the temperature (every degree) in azimuth in elevation. This conversion takes into account: the geographical coordinates of the place from where the sky is going to be observed, the date (hours, day, month and year) for the analysis of a date in the past or for a forecast, and finally, the operational frequency to scanning of the sky.

In this case the information of the sky temperature and the program for conversion of the information of the sky temperature (Fig. 23) to a two dimensional map was provided by A. El-Makadema [18]. The data obtained is related to: the forecast of the sky for the 1 of January of 2014\textsuperscript{21}, the coordinates of the sky are related to the position of Jodrell Bank (53°14'01.89''N, 2°18'11.93''W) and a frequency of operation of 590 MHz. The data from the sky temperature is stored in the file “T_sky.xls”.

Finally the measurements of the losses (see ref. [17], section 2.3 and Annex 3) are entered in the program “program_3_16_noise_temperature.m” as well. These losses were obtained from real measurements done in field by the provider of the antennas for the project and are described in the Table IV.

The array of antennas described in the Fig. 11 in practice is divided in two arrays (Tile #1 and Tile #2) of 8 by 4 antennas each one (4 by 4 antennas in horizontal polarization and 4 by 4 antennas

\textsuperscript{21} This date has been selected to being in accordance with the proposed dates for the start of operation of the MUST project.
with vertical polarization). This is done for a post-processing of information but for the simulation is still being one array (see Fig. 24).

![Diagram of antennas distribution](image)

**Fig. 24.** Distribution of the antennas in the array for post-processing (- horizontal polarization, | vertical polarization). [17]

Taking into account the mechanical dimensions of the frame and the distribution of the antennas, then here are two possible ways to improve the MUST system: optimization of the MUST system increasing or decreasing the amount of antennas.

### 4.3.1 Optimization of the MUST system (Increasing the number of antennas)

In this stage 7 geometries for the array are proposed with the aim of improve the behavior of the array. This is done in order to analyze the effect of an increase in the number of Yagi antennas but maintaining the mechanical dimensions of the frame for the antenna array. Bearing that in mind 7 different geometries for the tile are analyzed: 4 by 4 antennas, 5 by 5 antennas, 6 by 6 antennas, 7 by 7 antennas, 8 by 8 antennas, 9 by 9 antennas and 10 by 10 antennas.

At this point is necessary to talk about the losses in the system. The insertion of the losses in the program is done bearing in mind every set of 16 Yagi antennas see Figs. 25 (a) to (g). The following losses are taken into account: losses by cable, losses by combiner (16 ways combiner see ref [17] and Annex 3), losses by filter and losses by LNA.

<table>
<thead>
<tr>
<th>Element</th>
<th>Losses (dB)</th>
<th>Temperature of the losses (°K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNA Noise Figure</td>
<td>0.4</td>
<td>28</td>
</tr>
<tr>
<td>Cable loss</td>
<td>0.2</td>
<td>14</td>
</tr>
<tr>
<td>Combiner loss</td>
<td>0.7</td>
<td>14</td>
</tr>
<tr>
<td>Filter loss</td>
<td>0.2</td>
<td>14</td>
</tr>
</tbody>
</table>
Fig. 25. Distribution of the elements in the antenna array for the analysis of the losses. (a) tile of 4 by 4 antennas, (b) tile of 5 by 5 antennas.

Fig. 25. (c) Distribution of the elements in the antenna array for a tile of 6 by 6 antennas. (d) Distribution of the elements in the antenna array for a tile of 7 by 7 antennas.

Fig. 25. (e) Distribution of the elements in the antenna array for a tile of 8 by 8 antennas.
Having in mind the information mentioned before the following equation for the losses is written:

\[ L_{\text{cable}} = (2.20m \times 0.2\, \text{dB}) + (\text{extra cable} \times 0.2\, \text{dB}) \]  

(4.6)

Where:

- \( L_{\text{cable}} \): Losses by cable.
- \( \text{extra cable} \): Amount of cable (in meters) used to interconnect the combiners with the filters and with the LNA.

The losses in the cable take into account 2.20 meters of cable per each antenna (provided by the manufacturer) and 1 extra meter for interconnection between the array and the filter; and between the filter and the LNA (see Figs. 25 (a) to (g)). The losses per every meter of cable are assumed to be 0.2 dB (see ref [17]). The losses per combiner are 0.7 dB, per filter 0.2 dB and per LNA 0.2 dB. See ref [17] and Annex 3 (Datasheets for power splitters/combiners).

Now bearing in mind the value of the parameter S11 from the section 3.1.1 (-17 dB or 0.0199 (in power ratio) at 590 MHz), the equations 2.33, 2.34 and the information in the TABLE IV then the radiation efficiency can be determined as follows:

\[ L_{\text{ref}} = (1 - S_{11}) = 1 - 0.0199 = 0.98 = -0.0877\, \text{dB} \]  

(4.7)

\[ \eta_{\text{total}} = L_{\text{total}} = L_{\text{ref}} + L_{\text{cable}} + L_{\text{combiner}} + L_{\text{filter}} \]  

(4.8)
With the information described before a first approach to analyze the Sensitivity of the array taking into account the separation between Yagi antennas has been done. In this case the mechanical dimensions of the frame for the array are the limit for the size of the array (see Fig. 19). Having that in mind 7 different sizes of antenna array have been selected for the analysis of the Sensitivity and for every array the elements that produce losses have been included (see TABLE V).

### TABLE V. NOISE FIGURE OF AN ARRAY OF 4x4 ANTENNAS [17], FRAME CONSTANT AND DECREASING THE NUMBER OF ANTENNAS

<table>
<thead>
<tr>
<th>Size of array</th>
<th>Tile</th>
<th>Distance between antennas (meters)</th>
<th>Number of combiners</th>
<th>Number of filters</th>
<th>Number of LNA</th>
<th>Cable Losses per Tile (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 by 4</td>
<td>4 by 4</td>
<td>0.9</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.84</td>
</tr>
<tr>
<td>10 by 5</td>
<td>5 by 5</td>
<td>0.7</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1.04</td>
</tr>
<tr>
<td>12 by 6</td>
<td>6 by 6</td>
<td>0.57</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1.04</td>
</tr>
<tr>
<td>14 by 7</td>
<td>7 by 7</td>
<td>0.48</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1.04</td>
</tr>
<tr>
<td>16 by 8</td>
<td>8 by 8</td>
<td>0.42</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1.04</td>
</tr>
<tr>
<td>18 by 9</td>
<td>9 by 9</td>
<td>0.35</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1.04</td>
</tr>
<tr>
<td>20 by 10</td>
<td>10 by 10</td>
<td>0.315</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1.04</td>
</tr>
</tbody>
</table>

4.3.1.1 Analysis in horizontal polarization

Bearing in mind the structure depicted in the Figs. 25 (a) to (g) and the efficiency of the system then the following outcome is obtained:

### TABLE VI. ANALYSIS OF SENSITIVITY AND DIRECTIVITY PER ARRAY

<table>
<thead>
<tr>
<th>Size of array</th>
<th>Tile</th>
<th>Distance between antennas (meters)</th>
<th>Peak Sensitivity (dB)</th>
<th>Peak Directivity(^{22}) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 by 4</td>
<td>4 by 4</td>
<td>0.9</td>
<td>-26.5567</td>
<td>27.6084</td>
</tr>
<tr>
<td>10 by 5</td>
<td>5 by 5</td>
<td>0.7</td>
<td>-32.1267</td>
<td>27.7781</td>
</tr>
<tr>
<td>12 by 6</td>
<td>6 by 6</td>
<td>0.57</td>
<td>-34.0806</td>
<td>28.8625</td>
</tr>
<tr>
<td>14 by 7</td>
<td>7 by 7</td>
<td>0.48</td>
<td>-35.6804</td>
<td>28.0325</td>
</tr>
<tr>
<td>16 by 8</td>
<td>8 by 8</td>
<td>0.42</td>
<td>-35.5126</td>
<td>28.1157</td>
</tr>
<tr>
<td>18 by 9</td>
<td>9 by 9</td>
<td>0.35</td>
<td>-39.9935</td>
<td>27.6420</td>
</tr>
<tr>
<td>20 by 10</td>
<td>10 by 10</td>
<td>0.315</td>
<td>-41.6140</td>
<td>27.6556</td>
</tr>
</tbody>
</table>

\(^{22}\) The degradation in the Directivity is the outcome of the addition of losses in the system. The Directivity in this case comes from the directivity of one Tile multiplied by 2 (Tile#1 + Tile#2).
Fig. 26. (a). Expected Sensitivity for 7 different spacing between Yagi antennas with a fixed mechanical dimension in the array (Tile #1 + Tile #2)

In this case it can be seen clearly that the increment of antennas doesn’t implies an increment in the sensitivity of the array. This phenomenon appears because of the insertion of more losses by the combiners required for the interconnection of antennas.

Fig. 26. (b). Expected Directivity for 7 different spacing between Yagi antennas with a fixed mechanical dimension in the array (Tile #1 + Tile #2)

---

23 Outcome from MATLAB® (Figs. 26 (a)) from the program “program_3_16_noise_temperature.m”.

24 Outcome from MATLAB® (Figs. 26 (b)) from the program “program_3_16_noise_temperature.m”.

34
In the Fig. 26. (b), it can be seen that the value of directivity increases (in all the cases slightly higher than the value reached for a separation of 0.9 m between antennas) mainly for the increase of Yagi antennas in the array. Taking into account that the separation between antennas in the array decreases when the number of antennas increases it can be said that higher values of directivity cannot be reached (see section 4.1.2 Figs. 17 (a) and (b)) because of an optimal separation to get a high directivity is not reached.

Fig. 26. (c) Expected Sensitivity vs distance between Yagi antennas in the array (Tile #1 + Tile #2)

Fig. 26. (d) Expected noise Temperature vs losses in the tile\textsuperscript{25}.

\textsuperscript{25} Outcome from MATLAB\textsuperscript{®} (Figs. 26 (c) and (d)) from the program “program_3_16_noise_temperature.m”.
The losses described in the Fig. 26. (c) are related to one Tile not with the entire array. This was done to show the effect of the losses in a single tile. It can be seen clearly that the sensitivity decrease with the insertion of losses almost independently from the spacing between antennas.

The noise temperature of the system is showed in the Fig. 26. (d). It can be seen that there is a high variation of the noise temperature in the system (around 128°K). This value is reached for the increment in the size of the array, mainly for the insertion of losses by cable and power splitters/combiners in the system.

4.3.1.2 Analysis in Vertical polarization

Again as it was mentioned in the section 4.3.1.1 and having in mind the structure depicted in the Figs. 25 (a) to (g) the following outcome was obtained for the array with vertical polarization:

<table>
<thead>
<tr>
<th>Size of array</th>
<th>Tile</th>
<th>Distance between antennas (meters)</th>
<th>Sensitivity (dB)</th>
<th>Directivity (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 by 4</td>
<td>4 by 4</td>
<td>0.9</td>
<td>-26.5504</td>
<td>27.6082</td>
</tr>
<tr>
<td>10 by 5</td>
<td>5 by 5</td>
<td>0.7</td>
<td>-32.1229</td>
<td>27.7772</td>
</tr>
<tr>
<td>12 by 6</td>
<td>6 by 6</td>
<td>0.57</td>
<td>-34.0761</td>
<td>27.8616</td>
</tr>
<tr>
<td>14 by 7</td>
<td>7 by 7</td>
<td>0.48</td>
<td>-35.6788</td>
<td>28.0323</td>
</tr>
<tr>
<td>16 by 8</td>
<td>8 by 8</td>
<td>0.42</td>
<td>-35.5126</td>
<td>28.1156</td>
</tr>
<tr>
<td>18 by 9</td>
<td>9 by 9</td>
<td>0.35</td>
<td>-39.9937</td>
<td>27.6419</td>
</tr>
<tr>
<td>20 by 10</td>
<td>10 by 10</td>
<td>0.315</td>
<td>-41.6142</td>
<td>27.6556</td>
</tr>
</tbody>
</table>

Fig. 27. (a). Expected Sensitivity for 7 different spacing between Yagi antennas with a fixed mechanical dimension in the array (Tile #1 + Tile #2)
Again as it was said before it can be seen clearly that the increment of antennas doesn’t implies an increment in the sensitivity of the array. The losses play an important role in the value of the sensitivity.

Fig. 27. (b). Expected Directivity for 7 different spacing between Yagi antennas with a fixed mechanical dimension in the array (Tile #1 + Tile #2)  

Again it can be seen that the value of directivity increases slightly mainly for the increase of Yagi antennas in the array.

Fig. 27. (c) Expected Sensitivity vs distance between Yagi antennas in the array (Tile #1 + Tile #2)

Outcomes from MATLAB® (Figs. 27 (a) and (b)) from the program “program_3_16_noise_temperature.m”.

---

26 Outcome from MATLAB® (Figs. 27 (a) and (b)) from the program “program_3_16_noise_temperature.m”.
It can be seen clearly that the sensitivity decrease with the insertion of losses in the system.

Finally the noise temperature of the system is showed in the Fig. 27. (d).

Fig. 27. (d) Expected noise Temperature vs losses in the tile\textsuperscript{27}.

Again it can be seen that the maximum variation of the noise temperature in the system is around 128\textdegree K same as in the case of horizontal polarization.

### 4.3.2 Decreasing the number of antennas and incrementing the spacing between antennas

Another analysis can be done if the amount of antennas is reduced but the separation between them is increased. In this case there is no variation in the amount of combiners in the array but indeed the losses per combiners tend to decrease (see Annex 3). The equations 4.6, 4.7 and 4.8 have been used again for the calculations. In this case four geometries for the array have been proposed and for every array the elements that produce losses have been included as well (see TABLE VIII).

#### TABLE VIII. NOISE FIGURE OF AN ARRAY OF 4X4 ANTENNAS [17]

<table>
<thead>
<tr>
<th>Size of array</th>
<th>Tile#1</th>
<th>Tile#2</th>
<th>Distance between antennas (meters)</th>
<th>Number of combiners</th>
<th>Number of filters</th>
<th>Number of LNA</th>
<th>Cable Losses Tile 1 (dB)</th>
<th>Cable Losses Tile 2 (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 by 4</td>
<td>4 by 4</td>
<td>4 by 4</td>
<td>0.9</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>6 by 3</td>
<td>3 by 3</td>
<td>3 by 3</td>
<td>1.16</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>5 by 3</td>
<td>3 by 2</td>
<td>2 by 3</td>
<td>1.37</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.84</td>
<td>0.84</td>
</tr>
<tr>
<td>5 by 2</td>
<td>3 by 2</td>
<td>2 by 2</td>
<td>1.87</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.84</td>
<td>0.84</td>
</tr>
</tbody>
</table>

\textsuperscript{27} Outcome from MATLAB\textsuperscript{®} (Figs. 27 (c) and (d)) from the program “program_3_16_noise_temperature.m”.

38
In this case the losses per every meter of cable are assumed to be 0.2 dB (see ref [17]). The losses per combiner are 0.7 dB (array 4 by 4 and 3 by 3) and 0.35 dB (array 3 by 2 and 2 by 2); per filter 0.2 dB and per LNA 0.2 dB (see ref [17] and Annex 3 (Datasheets for power splitters/combiners)).

4.3.2.1 Analysis in horizontal polarization

Having in mind the structure depicted in the Fig. 25 (a) and the efficiency of the system then the following outcome was obtained for the horizontal polarization:

![Sensitivity vs elevation for Tile#1 + Tile#2](image1)

(a)

![Directivity vs elevation for Tile#1 + Tile#2](image2)

(b)

Fig. 28. (a). Expected Sensitivity and (b) expected Directivity, for 4 different spacing between Yagi antennas with a fixed mechanical dimension in the array (Tile #1 + Tile #2)\(^{28}\).

\(^{28}\) Outcome from MATLAB® from the program “program_3_16_a_noise_temperature.m”.
<table>
<thead>
<tr>
<th>Size of array</th>
<th>Tile#1</th>
<th>Tile#2</th>
<th>Distance between antennas (meters)</th>
<th>Sensitivity (dB)</th>
<th>Directivity (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 by 4</td>
<td>4 by 4</td>
<td>4 by 4</td>
<td>0.9</td>
<td>-26.5567</td>
<td>55.2169</td>
</tr>
<tr>
<td>6 by 3</td>
<td>3 by 3</td>
<td>3 by 3</td>
<td>1.16</td>
<td>-29.3134</td>
<td>52.4629</td>
</tr>
<tr>
<td>5 by 3</td>
<td>3 by 2</td>
<td>2 by 3</td>
<td>1.37</td>
<td>-32.6878</td>
<td>47.7011</td>
</tr>
<tr>
<td>5 by 2</td>
<td>3 by 2</td>
<td>2 by 2</td>
<td>1.87</td>
<td>-34.3364</td>
<td>47.0466</td>
</tr>
</tbody>
</table>

In the Fig 28. (a), a decrement of the sensitivity can be seen. This decrement in the sensitivity is related to the decrement of antennas in the array when the separation between antennas is increased (mechanical dimensions of the frame for the array).

Again in the Fig. 28 (b), like in the case of the sensitivity a decrement of the directivity can be seen as well. This decrement in the directivity is related to the decrement of antennas in the array when the separation between antennas is increased.

![Sensitivity vs spacing between Yagi antennas for Tile#1 + Tile#2](image)

Fig. 28. (c) Expected Sensitivity vs distance between Yagi antennas in the array (Tile #1 + Tile #2)

In the Fig. 28 (c) it can be seen clearly that the sensitivity decrease with the decreasing of antennas in the array despite the reduction of the losses by power splitter/combiners. Finally the noise temperature of the system is showed in the Fig. 28. (d).
Fig. 28. (d) Expected noise Temperature vs losses in the tile. In this case a variation of noise temperature of 13°K can be seen. The points are coincident basically for the losses assumed per combiner (0.7 dB (array 4 by 4 and 3 by 3) and 0.35 dB (array 3 by 2 and 2 by 2)).

4.3.2.2 Analysis in Vertical polarization

Having in mind the analysis done in the section 4.3.2.2 now the outcome for the array in vertical polarization is showed:

<table>
<thead>
<tr>
<th>Size of array</th>
<th>Tile#1</th>
<th>Tile#2</th>
<th>Distance between antennas (meters)</th>
<th>Sensitivity (dB)</th>
<th>Directivity (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 by 4</td>
<td>4 by 4</td>
<td>4 by 4</td>
<td>0.9</td>
<td>-26.5504</td>
<td>55.2163</td>
</tr>
<tr>
<td>6 by 3</td>
<td>3 by 3</td>
<td>3 by 3</td>
<td>1.16</td>
<td>-29.3013</td>
<td>52.4610</td>
</tr>
<tr>
<td>5 by 3</td>
<td>3 by 2</td>
<td>2 by 3</td>
<td>1.37</td>
<td>-32.6848</td>
<td>47.6963</td>
</tr>
<tr>
<td>5 by 2</td>
<td>3 by 2</td>
<td>2 by 2</td>
<td>1.87</td>
<td>-34.3283</td>
<td>47.0491</td>
</tr>
</tbody>
</table>

29 Outcome from MATLAB® from the program “program_3_16_a_noise_temperature.m”.

41
Again in the Fig 29 (a) a decrement of the sensitivity can be seen and is related to the decrement of antennas in the array, and in a similar way in the Fig 29. (b) a decrement in the directivity can be seen and it is related to the decrement of antennas in the array.

30 Outcome from MATLAB® from the program “program_3_16_a_noise_temperature.m”.

---

Fig. 29. (a) Expected Sensitivity (b) expected directivity, for 4 different spacing between Yagi antennas with a fixed mechanical dimension in the array (Tile #1 + Tile #2).
It can be seen clearly that the sensitivity decrease with the decreasing of antennas in the array despite the reduction of the losses by power splitter/combiners.

Finally the noise temperature of the system is showed in the Fig. 29. (d).

4.3.3 Expected Sensitivity for the array of arrays (100 Yagi antenna arrays)

Now bearing in mind the expected behavior for each array of Yagi antennas now the expected sensitivity is presented. The value in this case is the outcome of an approximation. The approximation consists in the direct multiplication of the expected sensitivity for a single Yagi

31 Outcome from MATLAB® (Figs. 29 (c) and (d)) from the program “program_3_16_a_noise_temperature.m”.

43
antenna array (32 antennas in each polarization) by the amount of arrays expected to be used in the project. For this case the losses by cable and for the devices used to interconnect the arrays is not included. Having that in mind the following outcome was obtained (see Fig. 22 (b)).

![Graph showing expected sensitivity for the array of arrays.](image1)

Fig. 30. Expected Sensitivity for the array of arrays (horizontal polarization).

![Graph showing expected sensitivity for the array of arrays.](image2)

Fig. 31. Expected Sensitivity for the array of arrays (vertical polarization).\(^{32}\)

It can be seen that for the array of Yagi antenna arrays the expected peak sensitivity is around \(-2.6657 \times 10^3\) dB and \(-2.6650 \times 10^3\) dB for the horizontal polarization and vertical polarization respectively.

Finally it is necessary to say that the analysis so far has assumed the beam is pointing to zenith. However it is of interest to study the scenario when the main beam is tilted away from zenith in

\(^{32}\) Outcome from MATLAB® from the program “program_3_16_b_noise_temperature.m”.

44
order to compare the behavior of the array for different elevation angles a comparison between the sensitivity was carried out keeping a variation of angle of 10° (see Table XI). This is planned to be done mechanically, namely each array is tilted see Fig. 32.

<table>
<thead>
<tr>
<th>Elevation angle (°)</th>
<th>Sensitivity (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>-2.6557 x 10³</td>
</tr>
<tr>
<td>80</td>
<td>-2.6632 x 10³</td>
</tr>
<tr>
<td>70</td>
<td>-2.6578 x 10³</td>
</tr>
<tr>
<td>60</td>
<td>-2.6517 x 10³</td>
</tr>
<tr>
<td>50</td>
<td>-2.6511 x 10³</td>
</tr>
<tr>
<td>40</td>
<td>-2.6512 x 10³</td>
</tr>
<tr>
<td>30</td>
<td>-2.6469 x 10³</td>
</tr>
<tr>
<td>20</td>
<td>-2.6457 x 10³</td>
</tr>
<tr>
<td>10</td>
<td>-2.6450 x 10³</td>
</tr>
<tr>
<td>0</td>
<td>-2.6433 x 10³</td>
</tr>
</tbody>
</table>

It can be seen that in the outcome of the program there is no significant variation in the sensitivity when there is a change in the elevation. This happen basically because the variation of the temperature of the environment (temperature of from buildings, external emissions, etc) is not included in the program. This can be included but it was not the aim in this dissertation project.

Fig. 32. Array tilted.

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Outcome from MATLAB® from the program “program_3_16_2_a_noise_temperature.m”.  

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CHAPTER 5: GRAPHICAL USER INTERFACE IN MATLAB®

The Graphical User Interface (GUI) has been developed to allow the users of the programs developed in this work to change the different parameters required for each program. No previous knowledge about programming in Matlab® is required.

With the aim of create the graphical user interface the MATLAB® Graphical User Interface Development Environment (GUIDE) has been used. In order to access to GUIDE the command “guide” can be entered in the prompt of MATLAB® or directly opening the corresponding file that contains the layout for the GUI (MATLAB® Figure) see Fig. 32.

GUIDE consists in the use of a Layout Editor that allows the allocation of the different buttons, images, etc that is part of the graphical interface.

![GUIDE Layout Editor](image)

Fig. 33. GUIDE Layout Editor [19].

The Layout Editor has a first Menu that allows the creation, the opening and the saving of a project. In a similar way allows the opening of the M-file editor for the implementation of the code in MATLAB®. Additionally the Layout editor allows the easy insertion of: buttons, links, images and selectors, using the palette located at the left of the layout (see Fig. 32). The insertion of these interfaces (buttons, images, etc) generates a section of code (functions) that allows the programmer assign the inputs and outputs for the code in MATLAB® (see Fig. 37).
When a layout is created (MATLAB® Figure) then a file (MATLAB® M-File) automatically is generated. The MATLAB® M-File will contain the code that is used for the simulations.

Bearing in mind the basic concepts mentioned before three GUIs have been developed: “directivity_vs_distance”, “Directivity_Yagi_antenna_array” and “noise_analysis”. The GUIs can be accessed in the folder “graphic interface” (see Fig. 34).

The file that contains the GUI as the extension “MATLAB M-file” the file “Matlab Figure” contains just the structure of the frame therefore is not the correct file.
CHAPTER 6: CONCLUSIONS AND DISCUSSIONS

6.1 Conclusions

From the analysis in the section 3.1.1 it can be said that the lowest values for the S-parameter are located at 518.2 MHz and 526.4 MHz with -24.69 dB and -24.46 dB respectively; and approximately -17 dB at a frequency of 590 MHz (expected operational frequency of the antenna). Additionally it can be seen a usable bandwidth (at -10 dB) approximately from 460 MHz to 644 MHz.

From the analysis carried out in the section 4.1.1.2 it can be said that the radiation pattern obtained with the cross polarization is approximately the same for the radiation pattern obtained with just two antennas operating with a similar polarization. Therefore it can be concluded that the use of antennas with different polarization (one after another) in the same frame for the array won’t affect the work of the array in each polarization.

From the analysis carried out in the section 3.1.2.2 it can be concluded that the value of Directivity of the Yagi antenna is approximately 16 dB. This number is the outcome of the process of integration over a solid angle (0° to 180° for elevation and 0° to 360° for azimuth per every degree) done in MATLAB®.

From the analysis carried out in the section 4.1.2 of this work it can be concluded that the separation between Yagi antennas of 0.9 meters defined previously for the MUST (by the group of Research of the School of Physics & Astronomy) is definitely good for the operation of the array but not optimal. The optimal distance recommended for this project is 1.37 meters not just because of the gain (32.17 dB for 1.37 meters and 30.5 dB for 0.9 meters) but for the FWHM (approximately 6° for the case of 1.37 meters and 4° for the case of 0.9 meters) as well.

From the analysis done in the sections 4.3.1.1 and 4.3.1.2 of this dissertation it can be concluded that an increment of antennas keeping the mechanical dimensions of frame for the array (see Fig. 11) doesn’t implies an increment in the sensitivity of the array. This phenomenon appears because of the insertion of more losses by the combiners required for the interconnection of antennas. Despite of that it can be said as well that the value of directivity increases (in all the cases slightly higher than the value reached for a separation of 0.9 m between antennas) mainly for the increase of Yagi antennas in the array. Taking into account that the separation between antennas in the array decreases when the number of antennas increases it can be said that higher values of directivity cannot be reached (see section 4.1.2 Figs. 17 (a) and (b)) because of an optimal separation to get a
high directivity is not reached. Finally it can be seen clearly that the sensitivity decrease with the insertion of losses almost independently from the spacing between antennas.

From the analysis in the sections 4.3.2.1 and 4.3.2.2 it can be concluded that there is a decrement in the sensitivity if the separation between antennas is increased (amount of antennas is reduced). This decrement in the sensitivity is related to the decrement of antennas in the array when the separation between antennas is increased (mechanical dimensions of the frame for the array). In a similar way a decrement of the directivity can be seen as well. Again this decrement in the directivity is related to the decrement of antennas in the array. It can be seen as well that the sensitivity decrease with the decreasing of antennas in the array despite the reduction of the losses by power splitter/combiners. Finally with the decrease of antennas a variation of noise temperature of 13°K can be seen. The points of analysis are coincident basically for the losses assumed per combiner (0.7 dB (array 4 by 4 and 3 by 3) and 0.35 dB (array 3 by 2 and 2 by 2)).

It can be concluded that the expected peak sensitivity for the cluster of arrays will be around \(-2.6657 \times 10^3\) dB and \(-2.6650 \times 10^3\) dB for the horizontal polarization and vertical polarization respectively.

### 6.2 Discussions & Recommendations

From the analysis carried out in the chapter 3.1.2 of this dissertation it can be seen that the values obtained from CST Microwave Studio® are not matching with the real values measured by the group of Research of the School of Physics & Astronomy. This error possibly is related with the use of a folded dipole (driven element in the Yagi antenna) in CST® that even now is suffering some upgrading in this software. In the same way there is a shifting error (see Fig. 8). This error is related to the imaginary component of the antenna impedance that is produced for the matching of the antenna and the balun that is not perfect but it works.

From the analysis done in the section 4.2.1.1 it can be concluded that with the mechanical dimensions assumed for the frame for the array nowadays it is no possible to reach a better Directivity and Sensitivity. It is recommended that in order to get a better value of directivity for the array using the same number of antennas (64 antennas, 32 with horizontal polarization and 32 with vertical polarization) the mechanical dimensions of the array should be changed at least to 10.3 by 4.2 meters.

Bearing in mind the analysis done in the section 4.2.2 it is suggested that the distance between arrays of Yagi antennas would be 7.62 meters using geometry of 50 by 20 arrays.
REFERENCES


ANNEX 1: APPROXIMATION FOR THE DOUBLE INTEGRAL

As is described in the ref [6] chapter 2.7, the starting point for the simulation approach is done taking into account the theoretical concepts. An approach to the simulation of the directivity for an antenna array can be done basically analyzing the eq. 2.9, eq. 2.2 and eq. 2.23. Bearing in mind that the eq. 2.9 implies the analysis of a double integral initially a numerical technique should be proposed.

Bearing in mind that the electrical field of an antenna and its radiation intensity can be described as the multiplication of two functions $f(\theta)$ and $g(\phi)$. Its radiated power can be written as follows:

$$P_{rad} = \int_{0}^{\pi} \int_{0}^{\pi} f(\theta)g(\phi)\sin(\theta) \ d\theta d\phi$$

(1)

Grouping terms it can be said that:

$$P_{rad} = \int_{0}^{\pi} g(\phi)\left[\int_{0}^{\pi} f(\theta)\sin(\theta) \ d\theta\right] d\phi$$

(2)

Analyzing the series approximation of an integral it can be said that the expression in brackets can be written in the following way:

$$\int_{0}^{\pi} f(\theta)\sin(\theta) \ d\theta = \sum_{i=1}^{N} [f(\theta_i)\sin(\theta_i)] \Delta\theta_i$$

(3)

$$\theta_i = i \left(\frac{\pi}{N}\right), \ i = 1, 2, 3, ..., N$$

Where:

$$\Delta\theta_i = \frac{\pi}{N}$$: The angle analyzed over the interval $\pi$ for N uniform divisions.

Doing the same analysis for $\phi$ and replacing the equations the following expression can be written:

$$P_{rad} = \left(\frac{2\pi}{M}\right) \left(\frac{\pi}{N}\right) \sum_{j=1}^{M} \left[ g(\phi_j) \left[ \sum_{i=1}^{N} f(\theta_i)\sin(\theta_i) \right] \right]$$

(4)
ANNEX 2: PROGRAMS

**program_3_9.m**

clear all; close all; clc
f=590e6;
lamda = 3e8/f; 
length=lamda/2; % calculate the length of the antenna
current=1; %
r=1e5;
N=5 % elements in the x-axis 
M=4 % elements in the y-axis
k=2*pi/lamda;

% ploting radiation pattern
pol=90;
theta=(0:0.1:180).*pi/180;
phi=(0:0.1:360).*pi/180;
dtheta=theta(2)-theta(1);
dphi=phi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);
beta=0;
direc= xlsread('directivity_antenna_horizontal.xls');
% direc= xlsread('directivity_antenna_vertical.xls');
directivity_dB_one_yagi=max(max(direc));
D=10.^(directivity_dB_one_yagi/10);
power=1; % as a reference to get the value of Radiation intensity (U)
Prad=10.^(power/10);
U=D.*Prad./(4*pi);
eta=120*pi;
k=2*pi/lamda;

% dx=1.37;
% dy=1.37;
dx=0.9;
dy=0.9;
spacing=dx/lamda;
Et = pattern_array(THETA, PHI, lamda, current, spacing, dx, dy, beta, M, N, k, r);
Ep=0;
eta = 120*pi; % intrinsic impedance (in ohms)
U = r^2*((abs(Et).*Et1).^2 + abs(EP).^2)/(2*eta); % eq. 2.2
Prad=sum(sum(U.*sin(THETA).*dtheta.*dphi)); % integration
D1=4*pi*U./Prad;% Direcivity
DdB1=10*log10(D1);% directivity in dB
Maximum_directivity_dB=max(max(DdB1))
% interpolating to show data because dB1 is heavy for the integration every 0.1 degrees
% to excel
escalal=0:1:180;
escala2=-180:1:0;
DdB_plot=DdB;
DdB_90=DdB_plot(90,:)';
% a = downsample(DdB_90, 5); % downsampling used just to compare data from simulation with real data that was taken every 5 degrees
a = [DdB_90 escalal']
xlswrite('vertical polarization (1 to 180).xls', a)
DdB_270_1=DdB_plot(270,:)'
for a=0:180;
    DdB_270(a+1,1)=DdB_270_1(181-a,1);
end
% b = downsample(DdB_270, 5);
b = [DdB_270 escalal2']
xlswrite('vertical polarization (-180 to 0).xls', b)
% to excel
DdB_0=DdB_plot(1,:)'
% c = downsample(DdB_0, 5);
c = [DdB_0 escalal']
xlswrite('horizontal polarization (1 to 180).xls', c)
DdB_180_1=DdB_plot(180,:)'
for a=0:180;
    DdB_180(a+1,1)=DdB_180_1(181-a,1);
end
% d = downsample(DdB_180, 5);
d = [DdB_180 escalal2']
xlswrite('horizontal polarization (-180 to 0).xls', d)

pattern_array.m

function [E_thetha_phi]=pattern_array(the, ph, lamda, current, spacing, dx, dy, beta, M, N, k, r);
% antenna array factor
psix=k*dx.*sin(the+1e-5).*cos(ph+beta+1e-5); % eq. 2.29
psiy=k*dy.*sin(the+1e-5).*sin(ph+beta+1e-5); % eq. 2.30
AF1=(sin(N*(psix+1e-5)/2))./(N*sin((psix+1e-5)/2)); % eq. 2.28 (part N)
AF2=(sin(M*(psiy+1e-5)/2))./(M*sin((psiy+1e-5)/2)); % eq. 2.28 (part M)
AFn=AF1.*AF2; % eq. 2.28
Et=N*M*AFn.*ones(size(the)); % electric field
E_thetha_phi = Et;
**S11_comparison.m**

```matlab
%% comparison of data from CST and the spectrum analyzer (S11)
clear all; close all; clc
A = xlsread('CST.xls');
B = xlsread('spectrum2.xls');
n=100; % amount of shift for the CST curve
x=0:0.22:220;
xi=0:1.75:221.75;
yi = interp1(xi,B(:,2)',x)';
mod=[zeros(n,1); A(:,2)]; % omitting the imaginary component of impedance
t1=480:(700-480)/(1000+n):700;
plot(t1',mod,'g')
hold on
yi2=[yi; zeros(n,1)];
plot(t1',yi2,'r')
title('Comparison of data (S11)')
xlabel('MHz')
ylabel('Magnitude of the S parameter dB')
h = legend('Data from CST (without imaginary)','Data from the network analyzer',2);
set(h,'Interpreter','none')
grid on
```

**program_3_10.m**

```matlab
clear all; close all; clc
f=590e6;
lamda = 3e8/f;%
length=lamda/2; %calculate the length of the antenna
current=1; %
r=1e5;
N=4 %elements in the x-axis
M=8 %elements in the y-axis
k=2*pi/lamda;
% Ploting radiation pattern
theta=(0:0.1:180).*pi/180;
phi=(0:0.1:360).*pi/180;
dtheta=theta(2)-theta(1);
dphi=phi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);
beta=0;
t=1:181:181*359+1;
direc= xlsread('directivity_antenna_horizontal.xls');
% direc= xlsread('directivity_antenna_vertical.xls');
directivity_db_one_yagi=max(max(direc));
D=10.^(direc)./10);
power=1;% as a reference to get the value of Radiation intensity (U)
```
Prad = 10.^(power./10);
U = D.*Prad./(4*pi);
eta = 120*pi;
k = 2*pi/lamda;
Et_in = sqrt(U.*(2*eta))./r^2;
theta1 = (0:1:180).*pi/180; % 5 degrees to compare with the
data from the MUST people
phi1 = (0:1:360).*pi/180;
[THETA1, PHI1] = meshgrid(theta1, phi1);
Et1 = interp2(THETA1, PHI1, Et_in, THETA, PHI);
%
d = 0.9;
% d = 1.4746;
spacing = d/lamda;
dx = d;
dy = d;
Et = pattern_array(THETA, PHI, lamda, current, spacing, dx, dy, beta, M, N, k, r);
Ep = 0;
eta = 120*pi; % intrinsic impedance (in ohms)
U = r^2*((abs(Et).*Et1).^2 + abs(Ep).^2)/(2*eta); % eq. 2.2
Prad = sum(sum(U.*sin(THETA)*dtheta*dphi)); % integration
D1 = 4*pi*U./Prad; % Direcivity
DdB1 = 10*log10(D1); % directivity in dB
Maximum_directivity_db = max(max(DdB1))
%
DdB = interp2(THETA, PHI, DdB1, THETA1, PHI1); % interpolating to
show data because dB1 is heavy
DdB2 = DdB;
% radiation pattern in 3D (dB)
figure
X3 = sin(THETA1).*sin(PHI1);
Y3 = sin(THETA1).*cos(PHI1);
Z3 = DdB2;
h = surf(X3, Y3, Z3);
colormap(flipud(jet));
colorbar
set(h, 'edgecolor', 'none')
title(['Directivity (in dB) of N = ', num2str(N), ' by M = ', num2str(M), ' elements and d = ', num2str(d), ' meters'])
xlabel('sin(THETA)*sin(PHI)')
ylabel('sin(THETA)*cos(PHI)')
zlabel('Directivity in dB')

program_3_12.m

clear all; close all; clc
f = 590e6;
lamda = 3e8/f; %
length = lamda/2; % calculate the length of the antenna
current = 1; %
r = 1e5;
k=2*pi/lamda;

%% Ploting radiation pattern
pol=90;
theta=(0:0.1:180).*pi/180;
phi=(0:0.1:360).*pi/180;
dthetatheta=theta(2)-theta(1);
dphiphilphi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);
beta=0;
direc= xlsread('directivity_antenna_horizontal.xls');
D=10.^((direc)./10);
power=1; % as a reference to get the value of Radiation intensity (U)
Prad=10.^((power./10);
U=D.*Prad./(4*pi);
eta=120*pi;
k=2*pi/lamda;
Et_in=sqrt(U.*(2*eta))./r^2;
theta1=(0:1:180).*pi/180; % 5 degrees to compare with the data from the MUST people
phi1=(0:1:360).*pi/180;
[THETA1,PHI1]=meshgrid(theta1,phi1);
Et1 = interp2(THETA1,PHI1,Et_in,THETA,PHI);
direc2= xlsread('directivity_antenna_vertical.xls');
D2=10.^((direc2)./10);
power2=1; % as a reference to get the value of Radiation intensity (U)
Prad2=10.^((power2./10);
U2=D2.*Prad2./(4*pi);
Et_in2=sqrt(U2.*(2*eta))./r^2;
Et2 = interp2(THETA1,PHI1,Et_in2,THETA,PHI);
%
d=0.45;
EV1=Et2.*exp(-1i*k*(2*d*cos(THETA)));
EV2=Et2.*exp(-1i*k*(-2*d*cos(THETA)));
EH=Et1;
Ep=0;
eta = 120*pi; % intrinsic impedance (in ohms)
U = r^2*((abs(EV1+EV2+EH)).^2 + abs(Ep).^2)/(2*eta); % eq. 2.2
Prad=sum(sum(U.*sin(THETA+1e-5)*dtheta*dphi)); % integration
D1=4*pi*U./Prad;% Direcivity
DdB1=10*log10(D1);% directivity in dB
Maximum_directivity_dB=max(max(DdB1))
%
DdB = interp2(THETA,PHI,DdB1,THETA1,PHI1); % interpolating to show data because dB1 is heavy
%% to excel
DdB_plot=DdB;
DdB_90=DdB_plot(90,:)
% a = downsample(DdB_90,5); %downsampling used just to compare data from simulation with real data that was taken every 5 degrees
a = [DdB_90 escalal1];
program_3_7_2.m

%% program_3_7_2 calculate the maximum directivity in dB, spacing
%% (in wavelengths) and distance between radiators with a precision of 0.1 degrees and sketch the directivity vs the spacing between radiators

clear all; close all; clc
f=590e6;
lamda = 3e8/f;%
length=lamda/2; %calculate the length of the antenna

N=8 %elements in the x-axis
M=4 %elements in the y-axis
k=2*pi/lamda;

%% Ploting radiation pattern
theta=(0:0.1:180).*pi/180;
phi=(0:0.1:360).*pi/180;
dtheta=theta(2)-theta(1);
dphi=phi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);

beta=0;
t=1:181:181*359+1;
direc= xlsread('directivity_antenna_horizontal.xls');

D=10.^(directivity_db_one_yagi=max(max(direc)))

power=1;%max value of power from the file power_pattern.txt from CST
Prad=10.^(power./10);
U = D.*Prad./(4*pi);
eta = 120*pi;
k = 2*pi/lamda;
Et_in = sqrt(U.*(2*eta))./r^2;
theta1 = (0:1:180).*pi/180;
phi1 = (0:1:360).*pi/180;
[THETA1, PHI1] = meshgrid(theta1, phi1);
Et1 = interp2(THETA1, PHI1, Et_in, THETA, PHI);

%%
i = 4;
a = 1;
points = 40; % number of points in the plot
escale = 0:i/points:i+(i/points);
for count = 0:i/points:i
a = a + 1;
spacing = count;
d = lamda*spacing;
dx = d;
dy = d;
Et = pattern_array(THETA, PHI, lamda, current, spacing, dx, dy, beta, M, N, k, r);
Ep = 0;
eta = 120*pi; % intrinsic impedance (in ohms)
U = r^2*((abs(Et).*Et1).^2 + abs(Ep).^2)/(2*eta); % eq. 2.2
Prad = sum(sum(U.*sin(THETA)*dtheta*dphi)); % integration
D = 4*pi*U./Prad; % Directivity
D0 = max(max(D)); % higher value of Directivity
D0_dB(1, a) = 10*log10(D0); % directivity in dB
end
%%
lim1 = size(escale);
lim2 = size(D0_dB);
plot(escale(1:lim1(1,2)-1), D0_dB(2:lim2(1,2)));
axis([0 i 0 40])
grid on
title(['Directivity vs spacing with N = ', num2str(N), ' by M = ', num2str(M)]);
xlabel('Spacing in wavelengths');
ylabel('Directivity in dB');
[Directivity_dB, I] = max(D0_dB);
Directivity_dB
D0p(1,:) = D0_dB;
Directivity_lin = 10^(max(D0p)/10);
spacing = escale(1, I-1)
spacing_in_wavelengths = spacing;
d_meters = spacing*lamda

program_3_11_a.m

clear all; close all; clc
f = 590e6;
lamda = 3e8/f; %
length=la\lambda/2; \text{ %calculate the length of the antenna}
current=1; \%
r=1e5;
N=50 \text{ %elements in the x-axis}
M=2 \text{ %elements in the y-axis}
k=2*\pi/\lambda;

\text{\% Ploting radiation pattern}
pol=90;
theta=(0:0.1:180).*\pi/180;
phi=(0:0.1:360).*\pi/180;
dtheta=theta(2)-theta(1);
dphi=phi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);
beta=0;
t=1:181:181*359+1;
% direc=directivity_file(t); \text{ % calling function to build matrix 361 x 181}
% direc=direc-14.09;
direc= xlsread('directivity_array_true.xls');
directivity\_dB\_one\_yagi=max(max(direc));
D=10.^(\text{directivity\_dB\_one\_yagi})/10;
power=1; \text{ % as a reference to get the value of Radiation intensity (U)}
Prad=10.^(\text{power}/10);
U=D.*Prad./(4*\pi);
etab=120*\pi;
k=2*\pi/\lambda;
Et\_in=sqrt(U.*(2*\eta))/r^2;
fac=2
thetab=(0:1:180).*\pi/180; \text{ % 5 degrees to compare with the data from the MUST people}
phib=(0:1:360).*\pi/180;
[THETAb,PHIb]=meshgrid(thetab,phib);
Et1 = interp2(THETAb,PHIb,Et\_in,THETA,PHI);
%%
% d=7.62
d=5.11
spacing=d/\lambda
dx=d;
dy=d;
Et = pattern\_array(THETA, PHI, \lambda, current,spacing,dx,dy,\beta,M,N,k,r);
Ep=0;
etab = 120*\pi; \text{ % intrinsic impedance (in ohms)}
U = r^2*((abs(Et).*Et1).^2 + abs(Ep).^2)/(2*\eta); \text{ % eq. 2.2}
Prad=sum(sum(U.*sin(THETA)*dtheta*dphi)); \text{ % integration}
D1=4*\pi/U./Prad; \text{ % Directivity}
DdB1=10*log10(D1); \text{ % directivity in dB}
Maximum\_directivity\_dB=max(max(DdB1))

%%
DdB = interp2(THETA,PHI,DdB1,THETAb,PHIb); \text{ % interpoling to show data because dB1 is heavy}
%% to excel
% DdB_plot=direc;
escalal=0:0.1:180;
escalal2=-180:0.1:0;
DdB_plot=DdB1;
DdB_90=DdB_plot(900,:);'
% a = downsample(DdB_90,5); %downsampling used just to
cmpare data from simulation with real data that was taken
every 5 degrees
a = [DdB_90 escala1'];
xlswrite('vertical polarization (1 to 180).xls', a)
DdB_270_1=DdB_plot(2700,:);

% for a=0:180;
%     DdB_270(a+1,1)=DdB_270_1(181-a,1);
% end
DdB_270=flipud(DdB_270_1');
% b = downsample(DdB_270,5);
b = [DdB_270' escala2'];
xlswrite('vertical polarization (-180 to 0).xls', b)

%% to excel
% DdB_0=DdB_plot(10,:);'
% c = downsample(DdB_0,5);
c = [DdB_0 escala1'];
xlswrite('horizontal polarization (1 to 180).xls', c)
DdB_180_1=DdB_plot(1800,:);
% for a=0:180;
%     DdB_180(a+1,1)=DdB_180_1(181-a,1);
% end
DdB_180=flipud(DdB_180_1');
% d = downsample(DdB_180,5);
d = [DdB_180' escala2'];
xlswrite('horizontal polarization (-180 to 0).xls', d)

directivity_file.m

function [dir]=directivity_file(t);
load directivity.txt %loading the file with the data from CST
direct=directivity(:,3); % radiation in dBi
directivity_dB=max(direct);
t=1:181:181*359+1;
for rep=1:1:360;
    dir1(rep,:)=direct(t(1,rep):t(1,rep)+180,1);
end
dir=[dir1;dir1(1,:)];

directivity_file_2.m
clear all; close all; clc
ndata = xlsread('antenna_A_590_horizontal.xls'); % reading data in horizontal polarization
ndata = xlsread('antenna_A_590_vertical.xls'); % reading data in vertical polarization
Yin = ndata';
% interpolating in theta (0 to 180)
Y1 = Yin(2,1:37); % copying the vector to have 4 rows to interpolate axis -x,x,-y,y
a = 1;
for rep = 0:1:35;
    Y21(1,a) = Yin(2,73 - rep);
a = a + 1;
end
Y2 = [0 Y21];
Y3 = Yin(4,1:37);
a = 1;
for rep = 0:1:35;
    Y41(1,a) = Yin(4,73 - rep);
a = a + 1;
end
Y4 = [0 Y41];
Y = [Y1' Y3' Y2' Y4' Yin'];% generating an array of linear vector to interpolate data in the 4 axis
x = 0:90:360;
x1 = 0:1:360;
for rep = 1:1:37;
    y(rep,:) = interp1(x,Y(rep,:),xi);
end
part1 = y';% vector part1 contains the info of the pattern with a precision of 361x73 (360 degrees (in steps of 1 degree) in phi and 180 in theta (in steps of 5 degrees))
% interpolating in phi (from 0 to 360)
x = 0:5:180;
x1 = 0:1:180;
for rep = 1:1:361;
    yf(rep,:) = interp1(x,part1(rep,:),xi);
yfin(a,:) = yf(a,:);
a = a + 1;
end
xlswrite('directivity_antenna_horizontal.xls', yfin)
xlswrite('directivity_antenna_vertical.xls', yfin)

program_3_16_noise_temperature.m

clear all;
close all;
clc
f = 590e6;
lamda = 3e8/f; %

length=lamda/2; %calculate the length of the antenna
current=1; %
r=1e5;
arrays=1;%amount of arrays of antennas
k=2*pi/lamda;
%%% Entering data from real measurements
theta=(0:0.1:180).*pi/180;
phi=(0:0.1:360).*pi/180;
dtheta=theta(2)-theta(1);
dphi=phi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);
beta=0;
t=1:181:181*359+1;
% direc= xlsread('directivity_antenna_horizontal.xls');
direc= xlsread('directivity_antenna_vertical.xls');
directivity_dB_one_yagi=max(max(direc));
D=10.^((direc)./(10);
power=1;
Prad=10.^(power./10);
U=D.*Prad./(4*pi);
eta=120*pi;
k=2*pi/lamda;
Et_in=sqrt(U.*(2*eta))./r^2;
theta1=(0:1:180).*pi/180;
phi1=(0:1:360).*pi/180;
[THETA1,PHI1]=meshgrid(theta1,phi1);
Et1 = interp2(THETA1,PHI1,Et_in,THETA,PHI);
%%% Calculating the brightness temperature
TB_in= xlsread('T_sky.xls'); %data from the reference [18]
matrix of 360 by 90 elements
TB_pro=[TB_in(:,1) TB_in]; %converting to a matrix of 360 by 91
TB_pro_1=[TB_pro fliplr(TB_pro(:,1:90))];%converting to a matrix of 360 by 181
Tsky=[TB_pro_1(360,:);TB_pro_1];%converting to a matrix of 361 by 181
TB = interp2(THETA1,PHI1,Tsky,THETA,PHI);
%%% Calculating the radiation intensity of the array and the
directivity
data=[4 5 6 7 8 9 10; 4 5 6 7 8 9 10; 0.9 0.7 0.57 0.48 0.42
0.35 0.315; 1 3 4 5 5 7 8; 0.84 1.04 1.04 1.04 1.04
1.04];
for count=1:1:7
N=data(1,count);
M=data(2,count);
d=data(3,count);
dx=d;
dy=d;
comb=data(4,count);
spacing=dx/lamda;
Et = pattern_array(THETA, PHI, lamda,
current,spacing,dx,dy,beta,M,N,k,r);
Ep=0;
eta = 120*pi; % intrinsic impedance (in ohms)
% Calculation of the Antenna temperature
losses_cable=data(5,count);
n_ef=(-0.0877)+(-(losses_cable)+(comb*(-0.7))+(-0.2));
n_eff=10^(n_ef/10);
G=n_eff*D1;
G_norm=G./(max(max(G)));
TA_num=sum(sum(TB.*G.*sin(THETA)*dtheta*dphi)); % integration
TA_den=sum(sum(G.*sin(THETA)*dtheta*dphi)); % integration
TA=TA_num./TA_den;
TA_count(count)=TA;

%% Calculating the System temperature, Sensitivity
Tamb=273+20;%assuming temperature of 20 degress Celsius
TLNA=28;
Tcable=14;
Tcombiner=14;
Tfilter=14;
Tsys=((n_eff*(TA+Tcable+(comb*Tcombiner)+Tfilter))+((1-n_eff).*Tamb)+TLNA);%2 Tcombiner per each tile
Tsys_tile(count)=Tsys;
S1=((lamda^2)*n_eff.*D1)./(4*pi*Tsys); %sensitivity
S = interp2(THETA,PHI,S1,THETA1,PHI1); % interpoling to show data because dB1 is heavy
SdB=10.*log10(S).*arrays;%multiplied by because the array (horizontal) of 8 by 4 has two arrays of 4 by 4
Stotal(count,:)=[fliplr(SdB(1,:)) SdB(180,:)];
% losses(count) = (losses_cable*M*N)+(comb*0.7)+0.2; %cable losses+combiner losses+filter losses
losses(count)=n_ef;
Dir_db = interp2(THETA,PHI,DdB1,THETA1,PHI1); % interpoling to show data because dB1 is heavy
Dtotal(count,:)=[fliplr(Dir_db(1,:)) Dir_db(180,:)];
end

%% Sensitivity vs elevation
SdB_K=max((2*Stotal)')
TA_count;
plot(2*Stotal(1,92:272),'r')
hold on
plot(2*Stotal(2,92:272),'m')
hold on
plot(2*Stotal(3,92:272),'c')
hold on
plot(2*Stotal(4,92:272),'y')
hold on
plot(2*Stotal(5,92:272),'g')
hold on
plot(2*Stotal(6,92:272),'b')
hold on
plot(2*Stotal(7,92:272),'k')
ggrid on
% Sensitivity vs elevation for Tile#1 + Tile#2
xlabel('Degrees in elevation (Being 90° the direction of the zenith)
ylabel('Sensitivity (dB, meter/°K)'

h = legend('d=0.9 m (32 antennas)','d=0.7 m (50 antennas)','d=0.57 m (72 antennas)','d=0.48 m (98 antennas)','d=0.42 m (128 antennas)','d=0.35 m (162 antennas)','d=0.315 m (200 antennas)',7);
set(h,'Interpreter','none')

%% Directivity vs elevation

DdB_K=max(Dtotal')
figure
plot(Dtotal(1,92:272),'r')
hold on
plot(Dtotal(2,92:272),'m')
hold on
plot(Dtotal(3,92:272),'c')
hold on
plot(Dtotal(4,92:272),'y')
hold on
plot(Dtotal(5,92:272),'g')
hold on
plot(Dtotal(6,92:272),'b')
hold on
plot(Dtotal(7,92:272),'k')
grid on
title('Directivity vs elevation for Tile#1 + Tile#2')
xlabel('Degrees in elevation (Being 90° the direction of the zenith)')
ylabel('Directivity (dB)')

h = legend('d=0.9 m (32 antennas)','d=0.7 m (50 antennas)','d=0.57 m (72 antennas)','d=0.48 m (98 antennas)','d=0.42 m (128 antennas)','d=0.35 m (162 antennas)','d=0.315 m (200 antennas)',7);
set(h,'Interpreter','none')

%% Sensitivity vs spacing

figure
plot(data(3,:)/lamda,SdB_K/2)
grid on
title('Sensitivity vs spacing between Yagi antennas for one Tile (including losses per point)')
xlabel('Spacing between Yagi antennas in wavelengths')
ylabel('Sensitivity (dB, meter/°K)')

hold on
wave=data(3,:)/lamda;
plot(wave,SdB_K/2,'x','MarkerEdgeColor','k','MarkerFaceColor','k','MarkerSize',8);
for count=1:1:7
  text(wave(count),SdB_K(count)/2,...
       ['   losses = ',num2str(losses(count)),' dB'],...
       'HorizontalAlignment','left');
end

%% Temperature vs losses

figure
plot(abs(losses),Tsys_tile)
grid on
title('Temperature of one Tile vs Losses (including number of antennas per point)')
xlabel('Losses (dB)')
ylabel('Temperature (°K)')
hold on
wave=abs(losses);
plot(wave,Tsys_tile,'x','MarkerEdgeColor','k','MarkerFaceColor','k','MarkerSize',8);
am_antennas=[32 50 72 98 128 168 200];
for count=1:1:7
text(wave(count),Tsys_tile(count),...
    ['   ',num2str(am_antennas(count)),' antennas'],...
    'HorizontalAlignment','left');
end

program_3_16_a_noise_temperature.m

clear all;
close all;
clc
f=590e6;
lamda = 3e8/f;/*
length=lamda/2; %calculate the length of the antenna
current=1; %
r=1e5;
arrays=1;%amount of arrays of antennas
k=2*pi/lamda;
% Entering data from real measurements
theta=(0:0.1:180).*pi/180;
phi=(0:0.1:360).*pi/180;
dtheta=theta(2)-theta(1);
dphi=phi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);
beta=10;
t=1:181:181*359+1;
% direc= xlsread('directivity_antenna_horizontal.xls');
direc= xlsread('directivity_antenna_vertical.xls');
directivity_dB_one_yagi=max(max(direc));
D=10.^((direc)./10);
power=1; % as a reference to get the value of Radiation intensity (U)
Prad=10.^((power./10));
U=D.*Prad./(4*pi);
eta=120*pi;
k=2*pi/lamda;
Et_in=sqrt(U.*(2*eta))./r^2;
theta1=(0:1:180).*pi/180;
phi1=(0:1:360).*pi/180;
[THETA1, PHI1] = meshgrid(theta1, phi1);
Et1 = interp2(THETA1, PHI1, Et_in, THETA, PHI);

%% Calculating the brightness temperature
TB_in = xlsread('T_sky.xls'); %data from the reference [18]
matrix of 360 by 90 elements
TB_pro = [TB_in(:, 1) TB_in]; %converting to a matrix of 360 by 91
TB_pro_1 = [TB_pro fliplr(TB_pro(:, 1:90))]; %converting to a matrix of 360 by 181
Tsky = [TB_pro_1(360,:); TB_pro_1]; %converting to a matrix of 361 by 181
TB = interp2(THETA1, PHI1, Tsky, THETA, PHI);

%% Calculating the radiation intensity of the array and the
directivity
data1 = [4 3 3 3; 4 3 2 2; 0.9 1.16 1.37 1.87; 1 1 1 1; 0.84 0.84 0.84 0.84; 0.7 0.7 0.35 0.35]; %tile 1
data2 = [4 3 2 2; 4 3 2 2; 0.9 1.16 1.37 1.87; 1 1 1 1; 0.84 0.84 0.84 0.84; 0.7 0.7 0.35 0.35]; %tile 2

%% Tile#1
for count = 1:1:4
    N = data1(1, count);
    M = data1(2, count);
    d = data1(3, count);
    dx = d;
    dy = d;
    comb = data1(4, count);
    spacing = dx / lamda;
    Et = pattern_array(THETA, PHI, lamda, current, spacing, dx, dy, beta, M, N, k, r);
    Ep = 0;
    eta = 120 * pi; % intrinsic impedance (in ohms)
    U = r^2 * ((abs(Et) .* Et1).^2 + abs(Ep).^2) / (2 * eta); % eq. 2.2
    Prad = sum(sum(U .* sin(THETA) .* dtheta .* dphi)); % integration
    D1 = 4 * pi^2 * U ./ Prad; % Directivity
    DdB1 = 10 * log10(D1); % directivity in dB
    Maximum_directivity_db = max(max(DdB1));
end

%% Calculating the Antenna temperature
losses_cable = data1(5, count);
n_ef = (-0.0877) + ((- losses_cable) + (comb * (-data1(6, count))) + (-0.2));
n_eff = 10^(n_ef/10);
G = n_eff * D1;
G_norm = G ./ (max(max(G)));
TA_num = sum(sum(TB .* G .* sin(THETA) .* dtheta .* dphi)); % integration
TA_den = sum(sum(G .* sin(THETA) .* dtheta .* dphi)); % integration
TA = TA_num ./ TA_den;
TA_count1(count) = TA;

%% Calculating the System temperature, Sensitivity
Tamb = 273 + 20; % assuming temperature of 20 degrees Celsius
TLNA = 28;
Tcable = 14;
Tcombiner = 14;
Tfilter = 14;
\[ T_{sys} = (n_{eff} \times (T_A + T_{cable} + (comb \times T_{combiner}) + T_{filter})) + ((1 - n_{eff}) \times T_{amb}) + TLNA; \] % 2 T-combiner per each tile

\[ T_{sys\_tile}(count) = T_{sys}; \]

\[ S_1 = \left( \frac{(\lambda^2 \times n_{eff} \times D_1)}{4\pi \times T_{sys}} \right); \] % sensitivity

\[ S = \text{interp2} (\theta, \phi, S_1, \theta_1, \phi_1); \] % interpolating to show data because dB1 is heavy

\[ S_{dB} = 10 \times \log_{10}(S) \times \text{arrays}; \] % multiplied by because the array (horizontal) of 8 by 4 has two arrays of 4 by 4

\[ \text{Stotal}(\text{count}, :) = \text{flip} \left( \text{SdB}(1, :) \right), \text{SdB}(180, :); \]

\[ \% \text{Stotal}(\text{count}, :) = \text{flip} \left( \text{SdB}(285, :) \right), \text{SdB}(285, :); \]

\[ \% \text{SdB\_zenith}(\text{count}) = \text{max}(\\text{Stotal}); \]

\[ \text{losses}(\text{count}) = n_{ef}; \]

\[ \text{Dir\_dB} = \text{interp2} (\theta, \phi, D_{dB1}, \theta_1, \phi_1); \] % interpolating to show data because dB1 is heavy

\[ \text{Dtotal}(\text{count}, :) = \text{flip} \left( \text{Dir\_dB}(1, :) \right), \text{Dir\_dB}(180, :); \]

\[ \% \text{Tile\#2} \]

\[ \text{for} \text{ count} = 1:1:4 \]

\[ N = \text{data2}(1, \text{count}); \]

\[ M = \text{data2}(2, \text{count}); \]

\[ d = \text{data2}(3, \text{count}); \]

\[ dx = d; \]

\[ dy = d; \]

\[ \text{comb} = \text{data2}(4, \text{count}); \]

\[ \text{spacing} = dx / \lambda; \]

\[ \text{Et} = \text{pattern\_array}(\theta, \phi, \lambda, \text{current}, \text{spacing}, \text{dx}, \text{dy}, \beta, M, N, k, r); \]

\[ \text{Ep} = 0; \]

\[ \eta = 120 \pi; \] % intrinsic impedance (in ohms)

\[ U = r^2 * ((\text{abs}(\text{Et}) \times \text{Et1})^2 + \text{abs}(\text{Ep})^2) / (2 \times \eta); \] % eq. 2.2

\[ \text{Prad} = \text{sum} (\text{sum}(U \times \text{sin}(\theta) \times d\theta \times d\phi)); \] % integration

\[ D_1 = 4 \pi U / \text{Prad}; \] % Direcivity

\[ \text{DdB1} = 10 \times \log_{10}(D_1); \] % directivity in dB

\[ \text{Maximum\_direcivity\_dB} = \text{max}(\text{max}(\text{DdB1})); \]

\[ \% \text{Calculating the Antenna temperature} \]

\[ \text{losses\_cable} = \text{data2}(5, \text{count}); \]

\[ n_{ef} = (-0.0877) + ((\text{losses\_cable} + (\text{comb} \times \text{data1}(6, \text{count})) + (-0.2)); \]

\[ n_{ef} = 10^{(n_{ef}/10)}; \]

\[ \text{G} = n_{eff} \times D_1; \]

\[ \text{G\_norm} = \text{G} / \text{(max(G))}; \]

\[ \text{T}_A\_num = \text{sum} (\text{sum}(\text{TB} \times \text{G} \times \text{sin}(\theta) \times d\theta \times d\phi)); \] % integration

\[ \text{T}_A\_den = \text{sum} (\text{sum}(\text{G} \times \text{sin}(\theta) \times d\theta \times d\phi)); \] % integration

\[ \text{T}_A = \text{T}_A\_num / \text{T}_A\_den; \]

\[ \text{T}_A\_count2(\text{count}) = \text{T}_A; \]

\[ \% \text{Calculating the System temperature, Sensitivity} \]

\[ \text{T}_\text{amb} = 273 + 20; \% \text{assuming temperature of 20 degrees Celsius} \]

\[ \text{TLNA} = 28; \]

\[ \text{T}_{\text{cable}} = 14; \]

\[ \text{T}_{\text{combiner}} = 14; \]

\[ \text{T}_{\text{filter}} = 14; \]

\[ \text{T}_{\text{sys}} = (n_{\text{eff}} \times (\text{T}_A + \text{T}_{\text{cable}} + (\text{comb} \times \text{T}_{\text{combiner}}) + \text{T}_{\text{filter}})) + ((1 - n_{\text{eff}}) \times \text{T}_{\text{amb}}) + \text{TLNA}; \% 2 \text{T-combiner per each tile} \]

\[ \text{T}_{\text{sys\_tile}}(\text{count}) = \text{T}_{\text{sys}}; \]
\[ S_1 = \frac{(\lambda^2 \cdot n_{\text{eff}} \cdot D_1)}{(4\pi T_{\text{sys}})}; \]  
% sensitivity

\[ S = \text{interp2} \left( \theta, \phi, S_1, \theta_1, \phi_1 \right); \]  
% interpolating to show data because dB1 is heavy

\[ S_{\text{dB}} = 10 \cdot \log_{10}(S) \cdot \text{arrays}; \]  
% multiplied by because the array (horizontal) of 8 by 4 has two arrays of 4 by 4

\[ \text{Stotal2}(\text{count}, :) = \left[ \text{flip} \left( S_{\text{dB}}(1, :) \right) S_{\text{dB}}(180, :) \right]; \]  
% losses

\[ \text{Dir}_{\text{dB}} = \text{interp2} \left( \theta, \phi, D_{\text{dB}1}, \theta_1, \phi_1 \right); \]  
% interpolating to show data because dB1 is heavy

\[ \text{Dtotal2}(\text{count}, :) = \left[ \text{flip} \left( \text{Dir}_{\text{dB}}(1, :) \right) \text{Dir}_{\text{dB}}(180, :) \right]; \]  
% end

\[ \text{Stotal} = \text{Stotal1} + \text{Stotal2}; \]

\[ \text{Dtotal} = \text{Dtotal1} + \text{Dtotal2}; \]

\% Sensitivity vs elevation

\[ S_{\text{dB}}_{K} = \max(\text{Stotal}'); \]  
% TA_count;

\[ \text{plot}(\text{Stotal}(1, 92:272), 'r'); \]
hold on

\[ \text{plot}(\text{Stotal}(2, 92:272), 'b'); \]
hold on

\[ \text{plot}(\text{Stotal}(3, 92:272), 'k'); \]
hold on

\[ \text{plot}(\text{Stotal}(4, 92:272), 'g'); \]
grid on

title('Sensitivity vs elevation for Tile#1 + Tile#2')

\% Directivity vs elevation

\[ D_{\text{dB}}_{K} = \max(\text{Dtotal}'); \]
figure

\[ \text{plot}(\text{Dtotal}(1, 92:272), 'r'); \]
hold on

\[ \text{plot}(\text{Dtotal}(2, 92:272), 'b'); \]
hold on

\[ \text{plot}(\text{Dtotal}(3, 92:272), 'k'); \]
hold on

\[ \text{plot}(\text{Dtotal}(4, 92:272), 'g'); \]
grid on

title('Directivity vs elevation for Tile#1 + Tile#2')

\% sensitivity vs spacing

figure
plot(data1(3,:)/lamda,SdB_K)
grid on
title('Sensitivity vs spacing between Yagi antennas for Tile#1 + Tile#2')
xlabel('Spacing between Yagi antennas in wavelengths')
ylabel('Sensitivity (dB, meter/°K)')
hold on
wave=data1(3,:)/lamda;
plot(wave,SdB_K,'x','MarkerEdgeColor','k','MarkerFaceColor','k','MarkerSize',8);
for count=1:1:4
    text(wave(count),SdB_K(count),'
    ' , num2str(losses(count)), ' dB'],...
    'HorizontalAlignment','left');
end

%% temperature vs losses
figure
plot(abs(losses),Tsys_tile)
grid on
title('Temperature of Tile#1 vs Losses (including number of antennas per point)')
xlabel('Losses (dB)')
ylabel('Temperature (°K)')
hold on
wave=abs(losses);
plot(wave,Tsys_tile,'x','MarkerEdgeColor','k','MarkerFaceColor','k','MarkerSize',8);
am_antennas=[16 9 6 6];
for count=1:1:4
    text(wave(count),Tsys_tile(count),...
    ' , num2str(am_antennas(count)),' antennas' ],...
    'HorizontalAlignment','left');
end

program_3_16_b_noise_temperature.m

clear all;
close all;
clc
f=590e6;
lamda = 3e8/f; %
length=lamda/2;  %calculate the length of the antenna
current=1;  %
r=1e5;
arrays=100;%amount of arrays of antennas
k=2*pi/lamda;
% Entering data from real measurements
theta=(0:0.1:180).*pi/180;
phi=(0:0.1:360).*pi/180;
dtheta=theta(2)-theta(1);
dphi=phi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);
beta = 0;
t = 1:181:181*359+1;
% direc = xlsread('directivity_antenna_horizontal.xls');
direc = xlsread('directivity_antenna_vertical.xls');
directivity_dB_one_yagi = max(max(direc));
D = 10.^((direc)./10);
power = 1;
Prad = 10.^((power./10));
U = D.*Prad./(4*pi);
eta = 120*pi;
k = 2*pi/lambda;
Et_in = sqrt(U.*(2*eta))./r^2;
theta1 = (0:1:180).*pi/180;
phi1 = (0:1:360).*pi/180;
[THETA1, PHI1] = meshgrid(theta1, phi1);
Et1 = interp2(THETA1, PHI1, Et_in, THETA, PHI);

%% Calculating the brightness temperature
TB_in = xlsread('T_sky.xls'); % data from the reference [18]
matrix of 360 by 90 elements
TB_pro = [TB_in(:,1) TB_in]; % converting to a matrix of 360 by 91
TB_pro_1 = [TB_pro flipr(TB_pro(:,1:90))]; % converting to a matrix of 360 by 181
Tsky = [TB_pro_1(360,:); TB_pro_1]; % converting to a matrix of 361 by 181
TB = interp2(THETA1, PHI1, Tsky, THETA, PHI);

%% Calculating the radiation intensity of the array and the directivity
data = [4 5 6 7 8 9 10; 4 5 6 7 8 9 10; 0.9 0.7 0.57 0.48 0.42 0.35 0.315; 1 3 4 5 7 8; 0.84 1.04 1.04 1.04 1.04 1.04 1.04 1.04];
for count = 1:1:2
N = data(1,count);
M = data(2,count);
d = data(3,count);
dx = d;
dy = d;
comb = data(4,count);
spacing = dx/lambda;
Et = pattern_array(THETA, PHI, lambda, current, spacing, dx, dy, beta, M, N, k, r);
Ep = 0;
eta = 120*pi; % intrinsic impedance (in ohms)
U = r^2*((abs(Et).*Et1).^2 + abs(Ep).^2)/(2*eta); % eq. 2.2
Prad = sum(sum(U.*sin(THETA)*dtheta*dphi)); % integration
D1 = 4*pi*U./Prad; % Directivity
DdB1 = 10*log10(D1); % directivity in dB
Maximum directivity dB = max(max(DdB1));
%% Calculating the Antenna temperature
losses_cable = data(5,count);
n_ef = (-0.0877) + (-losses_cable) + (comb*(-0.7)) + (-0.2);
n_eff = 10^(n_ef/10);
G = n_eff.*D1;
G_norm = G./(max(max(G)));
TA_num=sum(sum(TB.*G.*sin(THETA)*dtheta*dphi)); % integration
TA_den=sum(sum(G.*sin(THETA)*dtheta*dphi)); % integration
TA=TA_num./TA_den;
TA_count(count)=TA;

%% Calculating the System temperature, Sensitivity
Tamb=273+20;%assuming temperature of 20 degress Celsius
TLNA=28;
Tcable=14;
Tcombiner=14;
Tfilter=14;
Tsys=((n_eff*(TA+Tcable+(comb*Tcombiner)+Tfilter))+((1-n_eff).*Tamb)+TLNA);%2 Tcombiner per each tile
Tsys_tile(count)=Tsys;

%% Sensitivity vs elevation
SdB_K=max((2*Stotal)'');
TA_count;
plot(2*Stotal(1,92:272),'r')
grid on
title('Sensitivity vs elevation for the array of arrays')
xlabel('Degrees in elevation (Being 90° the direction of the zenith)')
ylabel('Sensitivity (dB, meter/°K)')
h = legend('3200 antennas',1);
set(h,'Interpreter','none')

%% Directivity vs elevation
DdB_K=max(Dtotal)''
figure
plot(Dtotal(1,92:272),'r')
hold on
grid on
title('Directivity vs elevation for the array of arrays')
xlabel('Degrees in elevation (Being 90° the direction of the zenith)')
ylabel('Directivity (dB)')
h = legend('3200 antennas',1);
set(h,'Interpreter','none')

program_3_16_2_a_noise_temperature.m

clear all;
close all;
clc
f=590e6;
lamda = 3e8/f;%
length=lamda/2; %calculate the length of the antenna
current=1; %
r=1e5;
darrays=100;%amount of arrays of antennas
k=2*pi/lamda;
% Entering data from real measurements
theta=(0:0.1:180).*pi/180;
phi=(0:0.1:360).*pi/180;
dtheta=theta(2)-theta(1);
dphi=phi(2)-phi(1);
[THETA,PHI]=meshgrid(theta,phi);
beta=0;
t=1:181:181*359+1;
direc= xlsread('directivity_antenna_horizontal.xls');
% direc= xlsread('directivity_antenna_vertical.xls');
directivity_dB_one_yagi=max(max(direc));
D=10.^((direc)./10);
power=1; % as a reference to get the value of Radiation intensity (U)
Prad=10.^((power.)/10);
U=D.*Prad./(4*pi);
eta=120*pi;
k=2*pi/lamda;
Et_in=sqrt(U.*(2*eta))./r^2;
theta1=(0:1:180).*pi/180;
phi1=(0:1:360).*pi/180;
[THETA1,PHI1]=meshgrid(theta1,phi1);
Et1 = interp2(THETA1,PHI1,Et_in,THETA,PHI);
% Calculating the brightness temperature
TB_in= xlsread('T_sky.xls'); %data from the reference [18]
matrix of 360 by 90 elements
TB_pro=[TB_in(:,1) TB_in]; %converting to a matrix of 360 by 91
TB_pro_1=[TB_pro fliplr(TB_pro(:,1:90))];%converting to a matrix of 360 by 181
Tsky=[TB_pro_1(360,:);TB_pro_1];%converting to a matrix of 361 by 181
ve=1;
for count=0:1:9
a=[Tsky fliplr(Tsky(:,2:181))];
rot=count*10;
if (rot == 0)
    Tsky2=Tsky;
else
    for co=0:1:rot
        b = [a(:,2:361) a(:,1)];
        a=b;
    end
end
Tsky2=a(:,1:181);
TB = interp2(THETA1,PHI1,Tsky2,THETA,PHI);
Calculating the radiation intensity of the array and the directivity

\[
data = [4 \ 5 \ 6 \ 7 \ 8 \ 9 \ 10; \ 4 \ 5 \ 6 \ 7 \ 8 \ 9 \ 10; \ 0.9 \ 0.7 \ 0.57 \ 0.48 \ 0.42 \ 0.35 \ 0.315; \ 1 \ 3 \ 4 \ 5 \ 5 \ 7 \ 8; \ 0.84 \ 1.04 \ 1.04 \ 1.04 \ 1.04 \ 1.04 \ 1.04];
\]

\[
N = data(1,1);
\]

\[
M = data(2,1);
\]

\[
d = data(3,1);
\]

\[
dx = d;
\]

\[
dy = d;
\]

\[
comb = data(4,1);
\]

\[
spacing = dx / lamda;
\]

\[
Et = pattern_array(THETA, PHI, lamda, current, spacing, dx, dy, beta, M, N, k, r);
\]

\[
Ep = 0;
\]

\[
eeta = 120 * pi; \quad \% \text{intrinsic impedance (in ohms)}
\]

\[
U = r^2 * ((abs(Et) * Et1) * (2 + abs(Ep))) / (2 * eta); \quad \% \text{eq. 2.2}
\]

\[
Prad = sum(sum(U .* sin(THETA) * dtheta * dphi)); \quad \% \text{integration}
\]

\[
D1 = 4 * pi * U / Prad; \quad \% \text{Directivity}
\]

\[
DdB1 = 10 * log10(D1); \quad \% \text{directivity in dB}
\]

\[
Maximum_{directivity}_{dB} = max(max(DdB1));
\]

Calculating the Antenna temperature

\[
losses_{cable} = data(5,1);
\]

\[
n_{ef} = (-0.0877) + (-\text{losses}_\text{cable}) + (\text{comb} * (-0.7)) + (-0.2);
\]

\[
n_{eff} = 10^{(n_{ef}/10)};
\]

\[
G = n_{eff} * D1;
\]

\[
G_{norm} = G / (max(max(G)));
\]

\[
TA_{num} = sum(sum(TB.*G.*sin(THETA)*dtheta*dphi)); \quad \% \text{integration}
\]

\[
TA_{den} = sum(sum(G.*sin(THETA)*dtheta*dphi)); \quad \% \text{integration}
\]

\[
TA = TA_{num} / TA_{den};
\]

\[
TA_{count}(ve) = TA;
\]

Calculating the System temperature, Sensitivity

\[
Tamb = 273 + 20; \quad \% \text{assuming temperature of 20 degrees Celsius}
\]

\[
TLNA = 28;
\]

\[
Tcable = 14;
\]

\[
Tcombiner = 14;
\]

\[
Tfilter = 14;
\]

\[
Tsys = ((n_{eff} * (TA + Tcable + (comb * Tcombiner) + Tfilter)) + ((1 - n_{eff})*Tamb) + TLNA); \quad \% \text{2 combiner per each tile}
\]

\[
Tsys_{tile}(ve) = Tsys;
\]

\[
S1 = ((lamda^2 * n_{eff} * D1) / (4 * pi * Tsys)); \quad \% \text{sensitivity}
\]

\[
S = interp2(THETA, PHI, S1, THETA1, PHI1); \quad \% \text{interpoling to show data because dB1 is heavy}
\]

\[
SdB = 10 * log10(S) * 2 * arrays; \quad \% \text{multiplied by because the array (horizontal) of 8 by 4 has two arrays of 4 by 4}
\]

\[
Stotal(ve,:) = [fliplr(SdB(28,:)) SdB(208,:)];
\]

\[
losses(ve) = n_{ef};
\]

\[
ve = ve + 1;
\]

end

\[
SdB_{K} = max(Stotal)';
\]

\[
TA_{count};
\]
ANNEX 3: DATASHEETS FOR POWER SPLITTERS/COMBINERS
16 ways Power splitter/Combiner
Coaxial Power Splitter/Combiner

ZB16PD-72+

Maximum Ratings
- Operating Temperature: -55°C to 100°C
- Storage Temperature: -55°C to 100°C
- Power Input (as a splitter): 10W max.
- Internal Dissipation: 2W max.

Permanent damage may occur if any of these limits are exceeded.

Coaxial Connections
- SUMPORT S
- PORT 1, 2, 3,.....16

Features
- Low insertion loss, 0.7 dB typ.
- Excellent input VSWR, 1.10:1 typ.
- Excellent output VSWR, 1.05:1 typ.
- Very high isolation, 30 dB typ.

Applications
- UHF TV/DTV
- CDMA
- GSM

Electrical Specifications

<table>
<thead>
<tr>
<th>FREQ. RANGE (MHz)</th>
<th>ISO. (dB)</th>
<th>INSERTION LOSS (dB) ABOVE 12 dB</th>
<th>PHASE UNBALANCE (Degrees)</th>
<th>AMPLITUDE UNBALANCE (dB)</th>
<th>VSWR S</th>
<th>VSWR OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-700</td>
<td>1.4</td>
<td>8</td>
<td>0.6</td>
<td>11.0</td>
<td>1.6</td>
<td>1.05</td>
</tr>
</tbody>
</table>

1. Total Loss = Insertion Loss +12dB splitter loss.

Typical Performance Data

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Total Loss' (dB)</th>
<th>Amplitude Unbalance (dB)</th>
<th>Isolation (dB)</th>
<th>Phase Unbalance (deg.)</th>
<th>VSWR S</th>
<th>VSWR OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>400.00</td>
<td>12.68</td>
<td>0.42</td>
<td>25.02</td>
<td>24.04</td>
<td>2.57</td>
<td>1.48</td>
</tr>
<tr>
<td>420.00</td>
<td>12.64</td>
<td>0.23</td>
<td>29.43</td>
<td>27.87</td>
<td>2.65</td>
<td>1.42</td>
</tr>
<tr>
<td>440.00</td>
<td>12.58</td>
<td>0.13</td>
<td>38.18</td>
<td>34.59</td>
<td>2.86</td>
<td>1.33</td>
</tr>
<tr>
<td>460.00</td>
<td>12.54</td>
<td>0.17</td>
<td>36.71</td>
<td>38.65</td>
<td>2.93</td>
<td>1.22</td>
</tr>
<tr>
<td>480.00</td>
<td>12.53</td>
<td>0.29</td>
<td>29.48</td>
<td>30.86</td>
<td>2.98</td>
<td>1.12</td>
</tr>
<tr>
<td>500.00</td>
<td>12.55</td>
<td>0.35</td>
<td>26.03</td>
<td>26.96</td>
<td>3.84</td>
<td>1.06</td>
</tr>
<tr>
<td>520.00</td>
<td>12.58</td>
<td>0.35</td>
<td>24.14</td>
<td>24.85</td>
<td>5.03</td>
<td>1.06</td>
</tr>
<tr>
<td>540.00</td>
<td>12.60</td>
<td>0.26</td>
<td>23.12</td>
<td>23.71</td>
<td>6.03</td>
<td>1.09</td>
</tr>
<tr>
<td>560.00</td>
<td>12.60</td>
<td>0.20</td>
<td>22.68</td>
<td>23.18</td>
<td>6.44</td>
<td>1.12</td>
</tr>
<tr>
<td>580.00</td>
<td>12.60</td>
<td>0.18</td>
<td>22.65</td>
<td>23.09</td>
<td>6.43</td>
<td>1.14</td>
</tr>
<tr>
<td>600.00</td>
<td>12.59</td>
<td>0.24</td>
<td>22.97</td>
<td>23.35</td>
<td>5.92</td>
<td>1.14</td>
</tr>
<tr>
<td>620.00</td>
<td>12.59</td>
<td>0.29</td>
<td>23.59</td>
<td>23.90</td>
<td>6.03</td>
<td>1.11</td>
</tr>
<tr>
<td>640.00</td>
<td>12.59</td>
<td>0.34</td>
<td>24.50</td>
<td>24.71</td>
<td>4.74</td>
<td>1.11</td>
</tr>
<tr>
<td>660.00</td>
<td>12.58</td>
<td>0.38</td>
<td>25.65</td>
<td>25.69</td>
<td>4.55</td>
<td>1.10</td>
</tr>
<tr>
<td>700.00</td>
<td>12.55</td>
<td>0.45</td>
<td>27.60</td>
<td>26.84</td>
<td>4.97</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Notes:
1. Performance and quality attributes and conditions not expressly stated in this specification sheet are intended to be excluded and do not form a part of this specification sheet.

+ RoHS compliant in accordance with EU Directive (2002/95/EC)

The +Suffix has been added in order to identify RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications.
6 ways Power splitter/Combiner
Coaxial
Power Splitter/Combiner

ZB6PD-17
6 Way-0°  50Ω  600 to 1700 MHz

Maximum Ratings
- Operating Temperature: -55°C to 100°C
- Storage Temperature: -55°C to 100°C
- Power Input (as a splitter): 10W max.
- Internal Dissipation: 0.875W max.

Permanent damage may occur if any of these limits are exceeded.

Coaxial Connections
SUM PORT S
PORT 1,2,3,4,5,6

Outline Drawing

Outline Dimensions (inch mm)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.50</td>
<td>3.00</td>
<td>.63</td>
<td>.130</td>
<td>3.380</td>
<td>1.50</td>
</tr>
<tr>
<td>88.90</td>
<td>76.20</td>
<td>16.00</td>
<td>3.30</td>
<td>88.85</td>
<td>38.10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>G</th>
<th>H</th>
<th>J</th>
<th>K</th>
<th>wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>.125</td>
<td>1.75</td>
<td>.32</td>
<td>.500</td>
<td>grams</td>
</tr>
<tr>
<td>3.18</td>
<td>44.45</td>
<td>8.13</td>
<td>12.70</td>
<td>180</td>
</tr>
</tbody>
</table>

Features
- Wideband: 600 to 1700 MHz
- Low Insertion loss: 0.35 dB typ.
- Good isolation: 25 dB typ.
- Excellent output VSWR: 1.1:1 typ.
- Rugged, shielded case
- Up to 10W power input as splitter

Applications
- VHF
- Cellular
- PCN
- Instrumentation

Electrical Specifications

<table>
<thead>
<tr>
<th>FREQ. RANGE (MHz)</th>
<th>ISO.</th>
<th>INSERTION LOSS (dB)</th>
<th>PHASE UNBALANCE (Degrees)</th>
<th>AMPLITUDE UNBALANCE (° dB)</th>
<th>VSWR (:1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600-1700</td>
<td>5</td>
<td>18</td>
<td>0.35</td>
<td>0.9</td>
<td>7</td>
</tr>
</tbody>
</table>

Typical Performance Data

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Total Loss¹</th>
<th>Amplitude Unbalance (° dB)</th>
<th>Phase Unbalance (Degrees)</th>
<th>VSWR S</th>
<th>VSWR 1</th>
<th>VSWR 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>600.00</td>
<td>8.14</td>
<td>8.20</td>
<td>8.10</td>
<td>0.17</td>
<td>24.86</td>
<td>21.42</td>
</tr>
<tr>
<td>650.00</td>
<td>8.11</td>
<td>8.17</td>
<td>8.08</td>
<td>0.17</td>
<td>28.02</td>
<td>23.40</td>
</tr>
<tr>
<td>700.00</td>
<td>8.07</td>
<td>8.14</td>
<td>8.05</td>
<td>0.16</td>
<td>33.38</td>
<td>26.20</td>
</tr>
<tr>
<td>750.00</td>
<td>8.06</td>
<td>8.14</td>
<td>8.04</td>
<td>0.17</td>
<td>44.76</td>
<td>30.67</td>
</tr>
<tr>
<td>800.00</td>
<td>8.06</td>
<td>8.12</td>
<td>8.04</td>
<td>0.16</td>
<td>35.26</td>
<td>30.67</td>
</tr>
</tbody>
</table>

1. Total Loss = Insertion Loss + 7.8dB splitter loss.

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4 ways Power splitter/Combiner
1. Over -55°C to +55°C. Derate linearly to 20% of rating at 90°C.

2. As a combiner of non-coherent signals, max. power per port is power rating divided by number of ports.

---

**Coaxial Connections**

<table>
<thead>
<tr>
<th>SUM PORT</th>
<th>S</th>
<th>PORT 1</th>
<th>1</th>
<th>PORT 2</th>
<th>2</th>
<th>PORT 3</th>
<th>3</th>
<th>PORT 4</th>
<th>4</th>
</tr>
</thead>
</table>

**Outline Drawing**

**Outline Dimensions** (inch/mm)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.06</td>
<td>3.13</td>
<td>1.00</td>
<td>250</td>
<td>1.430</td>
<td>5.030</td>
<td>6.810</td>
<td>.250</td>
</tr>
<tr>
<td>179.32</td>
<td>79.50</td>
<td>25.40</td>
<td>6.35</td>
<td>36.32</td>
<td>143.00</td>
<td>172.97</td>
<td>6.35</td>
</tr>
<tr>
<td>J</td>
<td>K</td>
<td>L</td>
<td>M</td>
<td>N</td>
<td>P</td>
<td>wt</td>
<td>grams</td>
</tr>
<tr>
<td>2.875</td>
<td>.156</td>
<td>3.53</td>
<td>.44</td>
<td>.73</td>
<td>1.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73.03</td>
<td>3.96</td>
<td>89.66</td>
<td>11.18</td>
<td>18.54</td>
<td>35.56</td>
<td>810</td>
<td></td>
</tr>
</tbody>
</table>

---

**High Power Combiner Electrical Specifications**

<table>
<thead>
<tr>
<th>FREQ. RANGE (MHz)</th>
<th>ISO (dB)</th>
<th>INSERTION LOSS (dB) ABOVE 6.0 dB</th>
<th>PHASE UNBALANCE (Degrees)</th>
<th>AMPLITUDE UNBALANCE (dB)</th>
<th>POWER INPUT (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-700</td>
<td>25</td>
<td>0.35</td>
<td>0.6</td>
<td>4.0</td>
<td>0.1</td>
</tr>
<tr>
<td>425.00</td>
<td>27.11</td>
<td>0.21</td>
<td>1.29</td>
<td>1.14</td>
<td>1.15</td>
</tr>
<tr>
<td>450.00</td>
<td>31.65</td>
<td>0.10</td>
<td>1.19</td>
<td>1.13</td>
<td>1.14</td>
</tr>
<tr>
<td>475.00</td>
<td>35.74</td>
<td>0.11</td>
<td>1.13</td>
<td>1.12</td>
<td>1.13</td>
</tr>
<tr>
<td>500.00</td>
<td>39.89</td>
<td>0.12</td>
<td>1.11</td>
<td>1.11</td>
<td>1.10</td>
</tr>
<tr>
<td>525.00</td>
<td>44.04</td>
<td>0.13</td>
<td>1.10</td>
<td>1.08</td>
<td>1.10</td>
</tr>
<tr>
<td>550.00</td>
<td>48.19</td>
<td>0.14</td>
<td>1.08</td>
<td>1.06</td>
<td>1.07</td>
</tr>
<tr>
<td>575.00</td>
<td>52.33</td>
<td>0.15</td>
<td>1.06</td>
<td>1.03</td>
<td>1.08</td>
</tr>
<tr>
<td>600.00</td>
<td>56.48</td>
<td>0.16</td>
<td>1.04</td>
<td>1.03</td>
<td>1.09</td>
</tr>
<tr>
<td>625.00</td>
<td>60.63</td>
<td>0.17</td>
<td>1.01</td>
<td>1.02</td>
<td>1.10</td>
</tr>
<tr>
<td>650.00</td>
<td>64.77</td>
<td>0.18</td>
<td>1.00</td>
<td>1.03</td>
<td>1.11</td>
</tr>
</tbody>
</table>

---

**Features**

- high power, up to 10W input power
- low insertion loss, 0.35 dB typ.
- good isolation, 25 dB typ.
- good sum-port VSWR, 1.14 typ.
- good VSWR at ports 1-4, 1.10 typ.

---

**Applications**

- UHF-TV/DTV
- communication receivers & transmitters

---

**Notes:**

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---

**Cases & Configurations**

- **PORT 1:** 4 Way-0°
- **PORT 2:** 50Ω
- **PORT 3:** 400 to 700 MHz

---

For detailed performance specs & shopping online see web site minicircuits.com
ANNEX 4: FEASIBILITY STUDY REPORT
Feasibility Study Report

Project Title: Analysis of the overall performance of antenna arrays for the Manchester University Student Telescope (MUST)

Student Name: Ricardo LLugsi

Student Number: 8415698

Project Supervisor: Professor Anthony Brown

Submission Date: 09 – 05 – 2013
ABSTRACT

In this project a program capable to describe the performance of an antenna array will be developed as a part of the Manchester University Student Telescope (MUST) project. The goal of this work is to analyze the tradeoff between some technical factors like: the amounts of elements in an antenna array (or in a cluster of antenna arrays), the type of antenna used in such arrays, the noise temperature factor of the entire array, and the geometrical distribution (sensitivity) of the array. All the analysis will be done taking into account the radiation pattern, the directivity and the gain of the array. Basically the project will cover the following stages: The development of a program capable to describe the performance of an ideal antenna array (taking into account the mathematical description of the antenna’s directivity), the performance of the antenna array taking into account real parameters of the antenna used in the project, the analysis of the performance of the radiation pattern field of the antenna array and finally the optimization of the antenna array taking into account the geometrical distribution of the array.
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I. INTRODUCTION

The use of radio telescopes for astronomy is a technique that has been used since the 1930’s with the aim of analyze a huge area of the space. Something that is not possible to achieve with optical telescopes. One of the most famous radio telescopes around the world is the University of Manchester’s Lovell Telescope located in Jodrell Bank. This is a radio telescope capable of collect information from an area of 4560 m² using a dish with a diameter of bowl of 76.2 m [1].

Despite the high potential for the analysis that can be obtained with this kind of radio telescopes the construction of big dishes is complicated and expensive. Additionally the need to analyze bigger areas of the space is becoming more and more important.

Nowadays the interest related to the use of antenna arrays for the reception of signals coming from the space is still increasing and is evolving in different technological approaches that allow the reception of the signals with high precision. One of these approaches consists in the use of antenna arrays. This approach is getting importance mainly because many antenna arrays can be used instead of just one big dish. It implies as well that with the use of a huge antenna arrays bigger portions of the space can be analyzed.

To accomplish with the requirement mentioned above The Manchester University Student Telescope (MUST) is being developed. The MUST is a project that involves the construction of a radio telescope for astronomy with the use of Yagi antenna arrays. This telescope is going to be used as a teaching aid and to observe pulsars and elusive transient events produced in the deep space and is going to be located on the Jodrell Bank Observatory site [2]. Basically there are three main stages in the project that involve: First the construction of a single tippable panel outfitted with an array of 60 TV-type Yagi antennas. Second the construction of five similar panels that are going to be located at the Jodrell Bank Observatory, and finally the implementation of a big array of arrays that is going to cover an area of 3000 m² [2] of the sky.

Taking into account the information of the last paragraph a correct analysis of the losses and the noise temperature in the array is fundamental. In a similar way it is necessary to determine what the best geometry of the array is in order to improve the array’s sensitivity. With the aim of achieve the goals mentioned before is necessary to study the Yagi antenna arrays for astronomy and implement a simulation program. In order to accomplish this need the project: “Analysis of the overall performance of antenna arrays for the Manchester University Student Telescope (MUST)” has been proposed.

In this project 5 main stages can be determined: 1) Antenna concepts; 2) Antenna array development; 3) Implementation of algorithms in Matlab®; 4) Validation of the results and optimization of the geometry; and 5) Developing of the Graphical User Interface in Matlab®. Each of these stages comprises a detailed analysis of the technical requirements for the MUST apart of course from the study of the state of the art. Each stage implies a strategy of documentation of the results as well.
II. OBJECTIVES

2.1 General Objective
Study of the overall performance of antenna arrays for the Manchester University Student Telescope (MUST)

2.2 Specific Objectives
- Analyze the theoretical background related to antennas and antenna arrays.
- Compile all the information related to the antenna array in relation with the astronomy and with the previous work carried out for the MUST project.
- Modeling of the radiation pattern of the antenna used for the MUST project.
- Generate advanced computer algorithms in order to understand in a better way the behavior of the antennas arrays (modeling) and determine in a deeper way the effect of the losses and the noise temperature.
- Analyze the geometry of the antenna array in order to analyze and improve the overall sensitivity of the array.
- Analyze the performance trade-offs of the array.

III. IMPORTANCE OF THE PROJECT FOR FUTURE RESEARCH

The use of antenna arrays is becoming a normal practice for the astronomy centres. Two main projects can be mentioned: The Square Kilometre Array (SKA) and the Australian Square Kilometre Array Pathfinder (ASKAP). The first case is still in the implementation stage but it takes into account the construction of thousands of receptors. These receptors are interlinked between them with the aim of cover an area of a million square metres of the sky [3]. This array for astronomy is going to be located in Australia and Southern Africa [4]. In the second case a radio telescope array has been implemented thanks to the support of the Commonwealth Scientific and Industrial Research Organization (CSIRO). It is designed to cover an area of 4000 square metres of the sky with the use of 36 antennas [5]. The projects mentioned before use antenna dishes as a focal point of the array implementation. This type of antenna is expensive and sometimes difficult to build. But there is another alternative in the field of antennas: “The Yagi antenna”. The Yagi antenna is cheap and easy to implement something that is valuable at the moment of the budget planning of a project. For that reason the use of antenna arrays based in Yagi antennas becomes a key factor. The study of the Yagi antenna arrays for astronomy is crucial because of there is no project before that has used this type of antenna for astronomy. It means that this analysis is not just useful for the present development but for future application as well. The analysis of losses in a Yagi antenna array; the analysis of noise temperature and the determination of the array’s geometry to achieve a high sensitivity are fundamental topics for future research.
IV. LITERATURE

With the aim of determine the background related to this project the following literature is presented as a starting point in the collection of information.

4.1 Radiation Pattern

As it reads in [6] and [7] the radiation pattern is the spatial description of the radiation properties of an antenna. Depending on the desired output the radiation pattern can be expressed as:

a. Field pattern: This is the magnitude of the electric or magnetic field in linear scale.

b. Power pattern: This is square of the magnitude of the electric or magnetic field in linear scale.

c. Power pattern: This is the magnitude of the electric or magnetic field in dB scale.

The radiation pattern is usually described as mathematical functions with a normalized form. The normalized field (1) and power (2) patterns can be written as follows:

\[ F_n(\theta, \phi) = \frac{|E(r, \theta, \phi)|}{|E(r, \theta, \phi)|_{\text{max}}} \]  
\[ P_n(\theta, \phi) = \frac{S_{av}(r, \theta, \phi)}{S_{av, \text{max}}} \]

4.2 Antenna Array

Again as it is described in [6] the shape and amplitude of the antenna array field is controlled by the position of each element in relation with the rest of the elements in the array. The analysis of Isotrope antennas is the easy starting point to describe the behavior of an antenna array. As it is shown in [7] firstly it in a uniform antenna array (Fig. 1) the Isotrope antennas are equally spaced, second are feed with the same current amplitude and finally show a progressive phase shift (\( \delta \)).

![Fig. 1. Uniform Isotrope antenna array. [7]](image-url)
In this array the feeding current for each element is:

\[ I_i = I_0 e^{j(i\delta)} \]  

(3)

Taking into account that the total electric field for the array is the sum of the electric field of each element of the array and assuming that all the analysis is going to be done in relation with a common point. The total electric field can be written as follows:

\[ E = \frac{A}{r_0} \left( e^{-jk_0} + e^{-j(k_1-\delta)} + e^{-j(k_2-2\delta)} + \ldots + e^{-j(k_{n-1}-(n-1)\delta)} \right) \]

(4)

Where:

- \( r_0 = r_1 = r_2 = \ldots = r_{n-1} \) : Distance term.
- \( \delta \) : Phase shift between elements.

Applying a geometrical solution for the array it is possible to find a relation between the different distances in the following way:

\[ r_i = r_0 - id \cos \phi \]

(5)

Therefore the following substitution can be done:

\[ E = \frac{A}{r_0} e^{-jk_0} \left( 1 + e^{j\Psi} + e^{j2\Psi} + \ldots + e^{j(n-1)\Psi} \right) \]

(6)

Where:

- \( \Psi = kd \cos \phi + \delta \)

(7)

Multiplying the eq.4 by \( e^{j\Psi} \); then the eq.4 can be written as follows:

\[ Ee^{j\Psi} = \frac{A}{r_0} e^{-jk_0} \left( e^{j\Psi} + e^{j2\Psi} + \ldots + e^{jn\Psi} \right) \]

(8)

Subtracting eq.6 from eq. 4 yields:

\[ E(1 - e^{j\Psi}) = \frac{A}{r_0} e^{-jk_0} \left( 1 - e^{jn\Psi} \right) \]

(9)

Rearranging eq.7 yields:

\[ E = \frac{A}{r_0} e^{-jk_0} \left( \frac{1 - e^{jn\Psi}}{1 - e^{j\Psi}} \right) = \frac{A}{r_0} e^{-jk_0} \frac{e^{j(n\Psi)/2}}{e^{j\Psi/2}} \frac{e^{jn\Psi/2} - e^{-jn\Psi/2}}{e^{j\Psi/2} - e^{-j\Psi/2}} \]

(10)
Replacing the exponent for the equivalent $\sin$ function and taking into account the additional phase, $e^{j\frac{n-1}{2}\Psi}$ (that can be omitted if the first element is on the centre of the array). Then the following equation can be written:

$$E = \frac{A}{r_0} e^{-jk_0} e^{j\frac{n-1}{2}\Psi} \left( \frac{\sin\left(\frac{n}{2}\Psi\right)}{\sin\left(\frac{\Psi}{2}\right)} \right) = \frac{A}{r_0} e^{-jk_0} e^{j\frac{n-1}{2}\Psi} \left( \frac{\sin\left(\frac{n}{2}\Psi\right)}{n\sin\left(\frac{\Psi}{2}\right)} \right)$$  \hspace{1cm} (11)

Again the total electric field of an array is determined by $n$ times the field of a single element multiplied by the array factor:

$$E = n [E \text{ (Single element at array centre)}] \times [\text{array factor}] \hspace{1cm} (12)$$

And $E$ has a spatial distribution of:

$$\sin\left(\frac{n}{2}\Psi\right) / n\sin\left(\frac{\Psi}{2}\right)$$  \hspace{1cm} (13)

With a maximum value at $\Psi = 0$:

\[ |E|_{\text{max}} = \frac{AE_0}{r_0} = n|E_0|  \hspace{1cm} (14) \]

Finally the array factor is:

$$AF = \frac{\sin\left(\frac{n}{2}\Psi\right)}{n\sin\left(\frac{\Psi}{2}\right)}$$  \hspace{1cm} (15)

### 4.3 Directivity & Gain

Again as it is presented in [7] the relation between the power density of an antenna (in the maximum radiation pattern) respect to the radiation pattern of an Isotrope is described as the directivity of the antenna. Namely it describes how directional is the radiation pattern of the antenna eq. 16. It is described to be measured at a distance $r$ in the far-field region.

\[ D = \frac{S_{av.\max} ^{P_{rad}}}{4\pi} = \frac{4\pi r^2 S_{av.\max} ^{S_{av.\max}}}{\int_0^{2\pi} \int_0^\pi S_{av}(r,\theta,\phi)r^2 \sin(\theta) d\theta d\phi} \]
Analysis of the overall performance of antenna arrays for the Manchester University Student Telescope (MUST)

Ricardo LLugsi
Profesor Anthony Brown

\[
\frac{4\pi r^2}{\int_0^\infty \int_0^{\pi} S_{av}(r, \theta, \phi) \sin(\theta) d\theta d\phi} = \frac{4\pi r^2}{\int_0^\infty \int_0^{\pi} P_n(\theta, \phi) \sin(\theta) d\theta d\phi}
\] (16)

Additionally taking into account that the gain of the antenna is a parameter that is related to the antenna’s input power it can be said that:

\[
D = \frac{S_{av,\max}}{P_{in}}
\] (17)

And

\[
P_{rad} = \eta P_{in}
\] (18)

Therefore

\[
G = \eta D
\] (19)

4.4 Simulation Approaches

The basic starting point for the simulation approach is done taking into account the theoretical concepts. For instance in Fig. 2 an approach to the simulation of the radiation pattern for a dipole antenna array is done. In this case basically the eq. 12 and eq. 15 are analyzed. Additionally the radiation pattern for a dipole antenna is described in [7].

Fig. 2. Radiation Pattern of a 5 dipole antenna array.
The last approach is basically the most comprehensive but there are other approaches that have been released in the past years and are valid too. One of the easiest ways to simulate the radiation pattern emitted by an antenna array is presented in [8] and [9]. In this analysis a comparison between the mathematical definition of the antenna array factor of \( N \) isotropic points (eq. 16) and the frequency response of a Finite Impulse Response (FIR) filter (eq. 17) is done.

\[
AF = w_0 + w_1 e^{j\Psi} + w_2 e^{j2\Psi} + \ldots + w_{n-1} e^{j(n-1)\Psi}
\]  

(16)

Where:
- \( \Psi \): Is described in eq. 7
- \( w_n \): Is the current excitation of each element in the array.

\[
H(j\omega) = h_0 + h_1 e^{-j\omega} + h_2 e^{-j2\omega} + \ldots + h_{n-1} e^{-j(n-1)\omega}
\]  

(17)

As it can be seen both eq. 16 and eq. 17 are similar except for the minus sign in the exponential components. Taking into account the last conclusion the FIR filter can be used for the simulation of the antenna array Fig. 2.

![Radiation Pattern of a 5x5 uniform rectangular array.](image)

**Fig. 3.** Radiation Pattern of a 5x5 uniform rectangular array. [8]

It can be said that the method is very simple and it presents a good approach for analysis and can be useful for the research carried out in the project.

### 4.5 Simulation Approaches for noise Temperature and Sensitivity

The use of simulation programs for astronomy taking into account the effects of the losses produced by cables and for noise temperature is crucial to achieve a high performance and reliability. In [10] an analysis of the array temperature of various antenna array configuration geometries is presented. In this document some antennas operating at a frequency of 100 MHz with different inter-element separations are studied. Thanks to the analysis of the noise temperature it could be concluded that there is a high impact on the array temperature.
in the presence of grating lobes. However this effect can be reduced if the side lobes are distributed randomly. As a consequence when the array spacing increases a smoother temperature profile is generated.

Additionally to the losses in the reception systems the analysis of the sensitivity is a very important factor as well. In [11] it can be concluded that for a large element separations, in an N element array, a high sensitivity can be achieved with the use of high directive elements.

As it can be seen the last approaches are very useful and can be used as a starting point for the analysis of the noise temperature and sensitivity in this research as well.

4.6 General Concepts

In order to have an overview and a summary of relevant research and theory related to the antenna array field some references can be mentioned. In [12] a deep analysis about the basic and advance aspects of the simulation procedure are described. The last reference can be used in conjunction with [13] and [14] because of in these books the basic aspects of the computational approach for antenna and antenna arrays are determined as well as the software Matlab® by itself.

Finally with the aim of collect more information for this project the technical meetings with the people in charge with the MUST project (Research - School of Physics & Astronomy) are crucial. Therefore the technical information from these meetings will be included as literature in the project.
V. METHODOLOGY

The research method proposed [15] for this project is described in the Table I.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Method</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Determination of the theory related to the antenna. Radiation pattern, Gain, radiated power, radiation intensity, radiated power density, noise temperature.</td>
<td>Theory of antennas</td>
</tr>
<tr>
<td></td>
<td>Literature review and development of initial research questions.</td>
<td>Online search, references</td>
</tr>
<tr>
<td></td>
<td>Analysis of the antennas previously developed for the Manchester University Student Telescope (MUST)</td>
<td>Case study evaluation</td>
</tr>
<tr>
<td></td>
<td>Initial summarization and transcription of information</td>
<td>Synthesis, transcripts analysis and content analysis</td>
</tr>
<tr>
<td>2</td>
<td>Review of the concepts related to antenna arrays, array factor, radiation pattern, linear arrays, broadside array, end fire array, phased array.</td>
<td>Theory of antenna array</td>
</tr>
<tr>
<td></td>
<td>Analysis of the technical requirements for MUST applications</td>
<td>Case study evaluation</td>
</tr>
<tr>
<td></td>
<td>Development of categories and flowcharts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial summarization and transcription of information</td>
<td>Transcript analysis, content analysis</td>
</tr>
<tr>
<td>3</td>
<td>Implementation of antenna radiation patterns</td>
<td>Case analysis, content analysis and transcription of the outcome</td>
</tr>
<tr>
<td></td>
<td>Implementation of isotropic antenna arrays</td>
<td>Case analysis, content analysis and transcription of the outcome</td>
</tr>
<tr>
<td></td>
<td>Determination of the radiation pattern for the antenna used in the MUST project</td>
<td>Analysis of the data from previous works in the MUST telescope. Modeling of the antenna’s radiation pattern.</td>
</tr>
<tr>
<td></td>
<td>Implementation of antenna array radiation pattern for the MUST project</td>
<td>Case analysis, content analysis and transcription of the outcome</td>
</tr>
<tr>
<td></td>
<td>Analysis of the sensitivity</td>
<td>Case analysis, content analysis and transcription of the outcome</td>
</tr>
<tr>
<td></td>
<td>Analysis of noise temperature</td>
<td>Case analysis, content analysis and transcription of the outcome</td>
</tr>
<tr>
<td>4</td>
<td>Validation of the results and optimization of the geometry</td>
<td>Content analysis</td>
</tr>
<tr>
<td></td>
<td>Comparison of results in relation to previous works</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Optimization of the array’s geometry in order to improve sensitivity</td>
<td>Case analysis, content analysis and transcription of the outcome</td>
</tr>
<tr>
<td>5</td>
<td>Developing of the Graphic User Interface in Matlab®</td>
<td>Theory</td>
</tr>
<tr>
<td></td>
<td>Graphic User Interface for Matlab® concepts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Developing of the Graphic User Interface for Matlab®</td>
<td>Case analysis, content analysis and transcription of the outcome</td>
</tr>
</tbody>
</table>
VI. PLANNING & MILESTONE CHART

The project is developed to be accomplished in the schedule showed in the Table II.

<table>
<thead>
<tr>
<th>Task</th>
<th>Month 1</th>
<th>Month 2</th>
<th>Month 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>1. Antenna concepts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 Determination of the theory related to the antenna</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation pattern, Gain, radiated power, radiation intensity, radiated power density, noise temperature.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1.2 Analysis of the antennas previously developed for the Manchester University Student Telescope (MUST)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 Transcription of the results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Antenna array development</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Review of the concepts related to antenna arrays, array factor, radiation pattern, linear arrays, broadside array, end fire array, phased array.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2 Analysis of the technical requirements for MUST applications</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2.3 Development of categories and algorithms</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2.4 Transcription of the results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Implementation of algorithms in Matlab®</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1 Implementation of antenna radiation patterns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2 Implementation of isotropic antenna arrays</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>3.3 Determination of the radiation pattern for the antenna used in the MUST project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4 Implementation of antenna array radiation pattern for the MUST project (100 antenna arrays)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5 Analysis of the sensitivity</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3.6 Analysis of noise temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.7 Transcription of the results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Validation of the results and optimization of the geometry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1 Comparison of results in relation to previous works</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2 Optimization of the array’s geometry in order to improve sensitivity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Developing of the Graphical User Interface in Matlab®</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1 Graphic User Interface for Matlab® concepts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.2 Developing of the Graphic User Interface for Matlab®</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.3 Transcription of the results</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Final structural design report</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1 Writing of the conclusions and discussions</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.1 Final report

Note: The milestone in the chart is represented by the symbol [ ].

VII. REVIEW OF PROJECT RISK

The project is developed correctly if the risks in the Table III are carried out properly.

TABLE III. ANALYSIS OF THE RISK

<table>
<thead>
<tr>
<th>Risk description</th>
<th>Consequences</th>
<th>Probability</th>
<th>Significance</th>
<th>Quantification of Risk</th>
<th>Risk treatment</th>
<th>Potential action for improvement</th>
<th>Control mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure to model the radiation pattern for the MUST antenna</td>
<td>Delaying in the start of the next stage</td>
<td>0.3</td>
<td>4</td>
<td>1.2</td>
<td>Predefined appointments with the people in the lab</td>
<td>Theoretical analysis of the radiation pattern for Yagi antenna</td>
<td>Milestone</td>
</tr>
<tr>
<td>Failure to implement the simulation programs</td>
<td>Delaying in the start of the next stage</td>
<td>0.3</td>
<td>4</td>
<td>1.2</td>
<td>Predefined appointments with the supervisor and lab assistants</td>
<td>Reorganization of time planning for stage</td>
<td>Milestone</td>
</tr>
<tr>
<td>Failure to comply with the deadlines</td>
<td>Delaying in the start of the next stage</td>
<td>0.2</td>
<td>3</td>
<td>0.6</td>
<td>Predefined meetings with the supervisor</td>
<td>Pre-allocation of tasks</td>
<td>Attendance record</td>
</tr>
<tr>
<td>Failure to met the lab assistants (antenna lab)</td>
<td>Delaying in the start of the next stage</td>
<td>0.2</td>
<td>3</td>
<td>0.6</td>
<td>Predefined meetings with the lab assistants</td>
<td>Pre-allocation of tasks</td>
<td>Attendance record</td>
</tr>
<tr>
<td>Lack of information (previous work related to antennas)</td>
<td>Delaying in the start of the next stage</td>
<td>0.1</td>
<td>2</td>
<td>0.2</td>
<td>Previous collection of the main information from the people in charge of the MUST project (School of Physics &amp; Astronomy)</td>
<td>Contact as soon as possible with the supervisor</td>
<td>Verification of the necessary information related to the algorithms</td>
</tr>
</tbody>
</table>

Note: Probability is in the range of 0 to 1. Significance is in the range of 0 to 5 (being 5 the worst scenario). The quantification of the risk is written from the highest to the lowest value.
VIII. REFERENCES


### General Risk Assessment Form

**Date:** (1) 09.05.2013  
**Assessed by:** (2)  
**Checked / Validated by:** (3)  
**Location:** (4) Library / E floor cluster  
**Assessment ref no:** (5)  
**Review date:** (6) 09.05.2013

**Task / premises:** (7)

Analysis of the overall performance of antenna arrays for the Manchester University Student Telescope (MUST)

<table>
<thead>
<tr>
<th>Activity (8)</th>
<th>Hazard (9)</th>
<th>Who might be harmed and how (10)</th>
<th>Existing measures to control risk (11)</th>
<th>Risk rating (12)</th>
<th>Result (13)</th>
</tr>
</thead>
</table>
| DSE work     | • Pain in the fingers, wrists, arms or shoulders  
               • tenderness  
               • feeling of heaviness in the arms/wrists  
               • swelling  
               • tingling sensation at the fingertips  
               • numbness  
               • joint restriction | The student | • adequate lighting  
               • adequate contrast, no glare or distracting reflections  
               • distracting noise minimised  
               • leg room and clearances to allow postural changes  
               • window covering if needed to minimise glare  
               • software – appropriate to the task, adapted to the user, providing feedback on the system status, no undisclosed monitoring  
               • screen – stable image, adjustable, readable, glare/reflection free  
               • keyboard – usable, adjustable, detachable, legible  
               • work surface – with space for flexible arrangement of equipment and documents, glare-free  
               • chair – stable and adjustable  
               • footrest if user needs one | Medium | A |

**Result:**  
T = trivial, A = adequately controlled, N = not adequately controlled, action required, U = unknown risk

*University risk assessment form and guidance notes. Revised Aug07*