Early Breast Tumor Detection Using a Microwave Imaging System

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Declaration
I declare that this document is an original work of my own authorship and it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa
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Well, it is the end of this six year journey. What a marathon it was. This accomplishment would not have been possible without the help of those who surround me.

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Secondly, my family was extremely important for me during this period. They always knew what to say and when to say it in order to prevent me from giving up. Therefore, I want to thank and give a big kiss to my father, João Fernandes, my mother Teresa Bastos, and my siblings Carolina Fernandes and Afonso Fernandes for all the love, care and strength they have always given me.

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Resumo

O cancro da mama é o que afeta mais as mulheres. Existem diversos métodos que permitem a detecção do tumor, mamografia, RM ou ultrassons.

De forma a ultrapassar as dificuldades destes métodos, a imagem por microondas está em desenvolvimento e existem protótipos que já foram experimentados em ensaios clínicos. Assim, no Instituto de Telecomunicações (IT), grupo de Antenas e Propagação em Lisboa tem trabalhado a fim de fabricar um protótipo que permita a detecção do tumor usando um setup seco, ou seja, sem a utilização de um meio de acoplamento. O setup é constituído por um anel de antenas, uma estrutura que imita os tecidos, uma câmara, dois raspberryPi e um VNA. A parte de software do setup é responsável pela sua automatização.

Um dos maiores objectivos deste setup é reconstrução das estruturas internas da mama através da soma da fase das ondas reflectidas. A parte mais desafiante corresponde à eliminação das reflexões das paredes da pele visto que têm uma magnitude muito superior comparando com as do tumor. O algoritmo pode utilizar dois tipos de calibração para a sua remoção: a Ideal e a Decomposição em Vectores Singulares (DVS). A segunda é mais relevante tendo em conta que é aquela que será utilizada em ensaios clínicos.

Os resultados foram obtidos, apenas para uma altura para um plano horizontal e outro vertical. Estes foram promissores, visto que foi possível detectar o tumor para ambos os planos. No entanto, como apenas foi utilizada uma altura, a resolução da imagem foi pobre.

Palavras-chave: Cancro da mama, microondas, calibração, setup
Abstract

Breast cancer is the most frequent type of cancer that affects women. There are several methods that allow the detection of tumors, like x-ray mammography, MRI or ultrasound.

To overcome the shortfalls of these methods, microwave imaging has been under development and some setups have already been submitted to clinical trials. Therefore, at Instituto de Telecomunicações (IT), the Antennas and Propagation group in Lisbon has been working towards the fabrication of a MWI prototype that allows the detection of tumors using a dry setup, meaning, without coupling medium. The setup has a ring of antennas, a phantom, a camera, two RaspberryPi and a VNA. The software part of the setup, the Graphical User Interface (GUI), is responsible for automating it.

One of the main purposes of this setup is the internal reconstruction of the breast by summing the phase of the reflected waves. The most challenging part is the artifact removal, since these reflections are a lot higher when compared to the tumor ones. The algorithm can use two calibration methods to remove these early time reflections: the Ideal and the Singular Vector Decomposition (SVD). The second is more relevant since it is the one that can be used in clinical trials.

The results were obtained, for only one height, using both calibration methods for an horizontal and a vertical plane. They were promising since it was possible to detect the tumor for both planes. However, as only height was used, the resolution of the images was poor.

Keywords: Breast cancer, Microwave Imaging, SVD Calibration, Setup Antennas
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Nomenclature

Greek symbols

χ  Dissipation Losses.
ε  Relative Permitivity.
Γ  Reflection Coefficient.
v  Light Speed.

Roman symbols

d  Distance.
E  Electric Field.
I  Reflected Power.
k  Wave Number.
n  Refractive Index.
S  Antennas Coefficient.
T  Transmission Coefficient.
V  Volume.

Subscripts

a  Antenna.
f  Frequency.
x, y, z  Cartesian Components.

Superscripts

*  Conjugated.
H  Hermitian.
T  Transpose.
# Acronyms

<table>
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<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>CABAVA</td>
<td>Circular Array Balanced Antipodal Vivaldi Antenna</td>
</tr>
<tr>
<td>CST</td>
<td>Computer Simulation Technology</td>
</tr>
<tr>
<td>GPIO</td>
<td>General Purpose Input/Output</td>
</tr>
<tr>
<td>IDFT</td>
<td>Inverse Discrete Fourier Transform</td>
</tr>
<tr>
<td>MARIA</td>
<td>Multistatic Array Processing for Radiowave Image Acquisition</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>MU</td>
<td>McGill University</td>
</tr>
<tr>
<td>MWI</td>
<td>Microwave Imaging</td>
</tr>
<tr>
<td>PEC</td>
<td>Perfect Electric Conductor</td>
</tr>
<tr>
<td>PLA</td>
<td>Polyactic Acid</td>
</tr>
<tr>
<td>SVD</td>
<td>Singular Value Decomposition</td>
</tr>
<tr>
<td>TSAR</td>
<td>Tissue Sensing Adaptive Radar</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wide Band</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyzer</td>
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Chapter 1

Introduction

1.1 Motivation

Breast cancer is the type of cancer that affects women the most. It corresponds to the second cause of death by cancer [1]. In 2018, the estimation of the number of new cases, worldwide, was approximately 266 000. Moreover, the number of deaths caused by breast cancer was about 40 000 [1]. Although these numbers are worrisome, statistics show that, if this type of cancer is diagnosed in an early stage the survival rate, 5 years after detection, is greater than 90% [2].

Technological evolution brought more reliable techniques to detect breast cancer. These evaluation methods must be sensitive and specific, in order to detect the presence of a tumor in an early-stage and also to distinguish between benign and malignant lesions [3]. The most used screening modalities are the X-ray mammography, the magnetic resonance imaging (MRI) and the ultrasound. X-ray mammography is an imaging modality based on the attenuation coefficient contrast between healthy and cancerous tissues [4, 5]. X-ray mammography benefits from the photoelectric effect, which enhances the contrast referred above. This screening modality presents false positive and false negative rates of 70% and 4-34%, respectively, essentially in patients with high density breasts [6] because the identification of tumors without distinct mass or calcifications is quite difficult. For the purpose of improving the quality of the image, digital techniques can be used in order to enhance the vascularity of the tissues [7]. Even with these improvements in the quality of the image, 10-15% of the tumors are still undetectable. Besides the results, patient compliance should also be taken into account, as the exam requires breast compression, which is often very painful. X-Ray mammography also exposes patients to ionizing radiation that may cause health problems, as the cell structure can be damaged by high-energy radiation [6]. As the X-ray mammography entails some problems regarding the quality of the image, in order to improve it, tomosynthesis was created [7]. This method consists on a series of sequential X-rays taken around the breast. It reduces the masking effect caused by the superposition of breast tissue, improving the quality of the image when compared with an image from X-ray mammography. However, tomosynthesis is more expensive and requires a longer interpretation of the results by the physician [7]. Figure 1.1 represents a patient taking a X-ray mammography.
MRI is a method that exploits the variation in the magnetic field that is captured. Normally, a contrast agent is administrated to the patient in order to enhance these variations. Thus, with an electromagnetic impulse, it is possible to disturb the spin of hydrogen atoms in the body, and then, reconstruct an image of the tissues using image reconstruction algorithms based on the resulting magnetic oscillation. After observing test results, it is possible to conclude that MRI has a good contrast between fibroglandular tissue and adipose tissue [9, 10]. This method has the advantage of having good resolution. In addition, MRI is non-invasive as the patient is examined laying with the belly down, prone position, with the breast inside a coil [10, 11]. However, this method entails some issues. Firstly, MRI cannot distinguish between benign and malignant tumors, secondly this method cannot image calcifications [11]. Moreover, this method is extremely time-consuming and expensive. Figure 1.2 represents a patient taking a MRI examination.

Ultrasound imaging is used, primarily, to evaluate abnormalities found in a breast by other imaging methods, like x-ray mammography or MRI [13]. This technique uses sound waves that are sent to the breast in order to display tissue in real-time without superposition [14]. The power emitted by the ultrasound is really low in order not to heat the skin of the breast, since the heat can cause lesions. This type of exam is non-invasive and the used radiation is non-ionizing. However, ultrasound entails some difficulties. The exam is time-consuming and the resolution of the image is not very good. Moreover, the examiner influences the obtained image since the examiner may perform the exam incorrectly [14]. Figure 1.3 represents a patient taking a ultrasound examination.
In order to overcome the shortfalls of these methods, microwave imaging (MWI) is being investigated as a complementary imaging modality. Contrarily to X-ray mammography, MRI and ultrasound, MWI exploits the differences from the dielectric constant of healthy and cancerous tissues. This technique uses an ultra-wideband microwave pulse to illuminate the breast tissue with antennas distributed around the breast. In MWI, the work frequencies vary between 1 to 10 GHz, which correspond to a wavelength interval from 300 mm to 30 mm. The reflectivity map of the breast tissues is built based on the scattered waves, due to the echoes originated by the dielectric contrast between healthy and unhealthy tissues. This recent method enables 3D imaging, is non invasive and uses non-ionizing radiation. Despite these advantages, MWI does not provide the same resolution as X-rays or MRI. In particular, for dense breasts it becomes increasingly difficult to detect small tumors. After many studies, it was concluded that a tumor has a higher dielectric constant (permittivity), because it has a higher water content, in comparison with the breast’s adipose tissue which has low dielectric constant (permittivity), due to its low water content [16]. However, the use of the dielectric constant as a comparative arises another challenge. Besides the adipose tissue, there is glandular tissue in a breast. This type of tissue has a high water content, so its dielectric constant (permittivity) is only 10-30% lower than the cancerous tissue constant. Therefore, if the tumor appears in the middle of glandular tissue, it could be masked by a clutter, making its detection more difficult.

1.2 Objectives

At Instituto de Telecomunicações (IT), the Antennas and Propagation group in Lisbon has been working towards the fabrication of a MWI prototype system to be submitted to clinical trials. The setup comprises a camera that takes snapshots of the breast, a ring of 8 antennas that goes up and down in order to take the measurements and a Vector Network Analyzer (VNA). Moreover, the group has already developed adequate signal processing algorithms to cope with the inherent challenges that MWI faces. More details will be given in section 4.1. Within this framework, the goals of this Master thesis are:

- Automation and synchronization of the setup. The automation is referred to the data acquisition and signal processing, since this allows lower time-consuming measurements.
• Incorporation of the 8 antennas in the setup. This step entails some challenges. Firstly, the
antennas have to be incorporated in a reduced space and at the same time the coupling between
them has to be low. Secondly, the measurements have to be made for all the antennas and the
Vector Network Analyzer (VNA) only can take 4 at the time. Therefore, two switches are going to
be necessary in order to use all the antennas in the measurements.

• Adapt heritage signal processing algorithms to multistatic systems, in order to overcome the an-
tenna coupling and inherent propagation challenges (e.g. multipath)

• Finish the Graphical User Interface (GUI), which interacts with the setup. This application allows
the user to communicate with the setup using only a computer. A part of the interface was devel-
oped by the previous work [17].

1.3 State of the Art

In the last few decades, several microwave breast imaging setups have been developed and some
of which have already been submitted to clinical trials. Most of these systems favour an examination
posture with the patient lying in prone position. The coupling medium is used by some setups in order
to stabilize and maintain the breast immobile. Moreover, this liquid reduces the contrast between the
skin and the air, and consequently, reduces the reflections from the breast skin. Besides this, it helps
to miniaturize the antennas since the surrounding environment is more dense, hence, it has a larger
permittivity comparing to the air. In MWI, there are, also, dry setups which do not use a coupling
medium [16]. In the next subsection, some setups are going to be presented and described.

1.3.1 Experimental Laboratory Setups

The Bristol Centre for Communications Research, Department of Electrical and Electronic Engineer-
ing fabricated an experimental setup to test the detection of a tumor embedded in an heterogeneous
phantom, meaning, containing fibroglandular tissues [18]. As far as the breast phantom is concerned,
it is heterogeneous, thus it contains materials that simulate the fibroglandular tissues. The phantom is
fabricated with high dielectric constant materials. On the outside, there is a homogeneous skin (2mm
thickness and 86mm radius) located at 20mm from the antennas array. This material has relative permi-
ttivity of 35. The tumor is made of a material with a relative permittivity of 50. Finally, the fibroglandular
tissues have a relative permittivity of 27 [18]. The setup has an array of 31 antennas and it is a multistatic
system, so the antennas send and receive energy. The chosen antenna to constitute the array was a
wide-slot Ultra Wide Band (UWB), which is a low profile antenna with great transient characteristics and
has a stable radiation pattern throughout the frequency [19]. Series of switches connect the array to
the VNA in order to perform the measurements. During the measurements the array is immersed in
a matching liquid that simulates the dielectric properties of the adipose tissue (dielectric constant with
value 10). Finally, the exam duration is 80 seconds.
1.3.2 Clinical Trial Setups

Dartmouth college built one of the first setups for microwave imaging breast cancer detection in human patients [20]. In this setup, the patient is laying down in prone position. The breast is inside a coupling fluid with 0.9% of salinity. The array takes 7 acquisition levels at different heights with 16 antenna excitations. Regarding the antenna array, it has 32 channels and all the antennas can transmit or receive in order to maximize the number of measurements. The antennas used in this setup are monopoles. Although this type of antenna has some disadvantages, it works well in lossy environments because the resistive loading reduces the dissipated energy in the liquid. The monopole antenna, usually, is characterized for having a straight shaped conductor [21]. The measurements were made for 7 frequencies with values between 500 and 900 MHz. The Dartmouth college setup uses an absorptive switch, which is a matched switch that does not allow the re-radiation of a signal when an antenna is non-active. Finally, each exam takes 10-15 minutes. This value is quite large, which may lead to errors caused by patient movement. In the clinical trials, 5 patients, with an age between 48 and 76 years, took the exam.

Multistatic Array Processing for Radiowave Image Acquisition (MARIA®) is other one of these setups that aim to detect breast cancer with microwaves [16]. Figure 1.4 represents the setup created by MARIA®. To perform MARIA®, the patient has to be in prone position, where the patient lays in the examination table which has a hole where the breast is inserted. This is done in order to examine the breast from different locations so that various transmission pathways are obtained. MARIA® is integrated in an unit which slides under the examination table in order to ease the breast sizing and cleaning. To secure the pendant breast, it is placed in a coupling shell of a biocompatible material. The use of a coupling shell requires a certification that the contact between the shell and the breast is adequate. The breast can also be put in a surface which is in direct contact with the antennas.

![Figure 1.4: MARIA® Setup taken from [16].](image-url)

As far as antenna arrays design is concerned, MARIA® uses an hardware set which consists in individual antennas that are static. However, the set can be rotated in order to obtain various scans for an skin-artifact removal. This kind of set ensures the pendant breast safety because, as it does not have moving parts, there is not the risk of collisions. However, the set's calibration is quite difficult because of the high number of antennas and the rotation that the removal artifact requires. The antennas used by MARIA® are cavity-backed slot antennas. This type of antenna is a rectangular cube with metallic walls and a cavity inside. MARIA® uses the frequency domain to acquire the data with the use of the stepped
frequency sine wave. This setup requires 1770 channels and the work frequency bandwidth varies from 3 to 8GHz [16]. A fast scan is really important in order to mitigate errors from patient breathing or movement. The hardware set is fast, but, as it is necessary to rotate it to obtain different angles, the time rises up a little. In this setup the total scan is done in about one minute. By analyzing the results of this method in a population of 223 patients it is possible to verify that MARIA® allows to detect breast abnormalities.

Another setup that is being studied in ongoing clinical trials [22, 23, 24] is Tissue Sensing Adaptive Radar (TSAR) [16]. Figure 1.5 represents the setup created by TSAR. In order to perform this method, the patient needs to be in the same position as in MARIA®’s setup. The hole has a diameter of 130mm and the tip of the sensor is located 70mm from the center of the hole. The breast is immersed in a coupling medium tank, so its surface is deformed by the medium. The liquid has a permittivity value of 2.5 and a conductivity value of 0.04S/m [25]. As far as the antenna array is concerned, TSAR uses a synthetic array. This type of array has an antenna that moves during the scan in order to create a full synthetic array [16]. Synthetic arrays have less antennas which facilitates the calibration. However, a concern in this kind of arrays is the breast safety. As TSAR’s system has moving parts, it cannot have calibration errors in order to avoid collisions with the breast. TSAR uses only one antenna, that is rotating. It can analyze 200 different positions that are situated around the breast. The scan region varies from 24mm to 141mm under the top of the surface where the patient is lay down. The antennas used in TSAR are antipodal Vivaldi antennas [26]. This kind of antennas are coplanar and broadband. To acquire the data, TSAR uses the frequency domain with the stepped frequency sine wave. In this technique the number of channels needed is 140 and the work frequency bandwidth varies from 1.3 to 7.7GHz.

This setup uses Magnetic Resonance (MR) images in the reconstruction algorithm in order to compensate for the breast shape changes that the coupling liquid provokes [25]. The calibration of the algorithm is done by taking measurements in two phases. In the first one, the breast is inside the tank and the reflections of the breast are captured. In the second, the tank is empty in order to cut out the environment reflection. The received signals from both phases are subtracted. One of the problems with this method is that it requires about 30 minutes to be finished. TSAR biggest trial was done with 8
patients. In the results, it was possible to find suspicious areas in the breast. It is important to refer that before taking this exam all the patients were submitted to an MRI, for comparison.

Another alternative setup was developed in McGill University (MU) [16]. Figure 1.6 represents the setup created by MU. It integrates all the hardware in a bra, which is worn by the patient. The bra is undersized in order to ensure good contact between the breast and the antennas. The exam is done with the patient seated down. This method has acquisition and excitation hardware all in the same unit. Moreover, the antennas are also integrated in this unit. However, as the bra is small, it does not totally cover the breast which may lead to errors during the monitoring of the signals. Monitoring consists on comparing the signals over time in order to detect differences. MU uses a stationary array, which is characterized for not having moving parts. Although this array is simpler, it requires more antennas which makes the calibration more difficult. The antennas that MU use are flexible microstrip that has a PCB with a flexible substrate used to route the signal. To acquire the data, MU uses backscattered data in the time domain. This method uses 120 channels and its work frequency bandwidth varies from 2 to 4GHz.

![Figure 1.6: MU Setup taken from [16].](image)

The time to take the exam is about 5 minutes. Trials using MU were done in 13 healthy patients, which have demonstrated some influence of the patient positioning on the results. The MU resulted scan showed potential as far as microwave imaging monitoring is concerned.

The most recent advance in MWI was made by the setup Wavelia, which was implemented in the Galway University Hospital in Ireland [27]. Figure 1.7 represents the Wavelia setup. This setup was primarily tested in a phantom, which was constructed based on MRI images [28]. The phantom is constituted by an outer breast recipient to simulate the breast, fibroglandular tissues with 2mm thick and a tumor with a diameter of 14mm designed using several Gauss random spheres. Inside the breast recipient and the fibraglandular tissues there are liquids that simulate the structures of the breast [29]. The relative permittivity of the breast liquid and the fibroglandular tissues are 5 and 36 respectively. Both these structures were made in plastic. Moreover, the breast recipient was coated with a skin made with graphite, carbon black and urethane. This mixture was slightly adjusted in order to match the dieletric constant of the real breast skin [30]. The tumor was made by the same mixture as the phantom.
skin and has a relative permittivity of 52. After some positive results from the tests made with the phantom, this setup was experimented in humans. In Wavelia, the patient takes the exam in the prone position with the breast inside a cavity. The cavity, incorporated in the examination table, is filled with a coupling medium that was created with specific dielectric properties in order to favor the penetration of the microwaves. The antennas used by the Wavelia setup are wideband Vivaldi [26]. This setup has a set of 18 antennas with an horizontal and circular configuration. The ring of antennas has an up and down movement controlled by 6 sensors. This movement allows that several measurements are taken through the vertical plane, hence, increasing the spatial resolution [27, 31]. To acquire the data, Wavelia uses the frequency domain. This method uses 18 channels and the work frequency is comprehended in the interval between 0.5 and 4.1GHz approximately [31].

![Wavelia Setup](image)

Figure 1.7: Wavelia Setup taken from [27].

An examination using Wavelia takes about 10 minutes. Only one patient was submitted to an exam. Regarding the results, they were encouraging since it was possible to detect a lesion.

### 1.4 Breast Anatomy

In order to study the breast cancer, it is relevant to understand the anatomy of this organ. During puberty, the production of hormones such as estrogen and progesterone promote the growth and development of the breast. During pregnancy and the menstrual cycle, this organ also suffers some changes due to growth in hormone production. The overall anatomy of the breast is presented in Figure 1.8.
The adipose tissue is the main constituent of the female breast. This type of tissue is formed by adipocytes which are cells whose function is to store energy. Moreover, the adipose tissue contains a stromal vascular fraction which is formed by fibroblasts, vascular endothelial cells and immune cells. Regarding the location of this type of tissue, it reaches an area from the collarbone to the armpit [33].

Another essential structure in the female breast are the lobes. There are about 12-20 lobes in a woman breast. This structure is an aggregate of smaller lobules. This set corresponds to the mammal gland that produces milk during the nursing phase of a woman. The lobes and lobules are linked to milk ducts which are tubes that bring the milk in order to reach the nipple. In the areola, a lactiferous sinus exists in each duct, this structure dilates in order to store milk. To expel the fluids, the female breast has myoepithelial cells, which are muscle cells, that contract and expand [32]. In Figure 1.9 it is possible to observe the mammal gland and the ducts.
The lymphatic and blood systems, respectively, take part in the protection and irrigation of the organs, in this specific case, the breast. The first system is spread through the breast with lymphatic nodes and vessels while the second one resorts to blood vessels. Along with these, the adipose tissue, also have ligaments, nerves and fibrous connective tissues, which correspond to muscle fibers. The lymphatic systems distributes lymphocytes, which are disease fighting cells, and fluids through the body using the lymphatic vessels. The lymphatic nodes clean the fluids in case of abnormal cells are found [35]. Figure 1.10 represents the network of vessels in a breast.

![Figure 1.10: Lymphatic and Blood Systems, Muscle Tissue, Ligaments and Nerves [34].](image)

1.5 Thesis Structure

This masters thesis is divided into five chapters. The first one has already been presented.

Chapter 2 is dedicated to the analytical formulation and problem description. It encompasses four subsections. The first has a small setup description. The second describes the inverse problem formulation, where a description of the theoretical solution to the problem in hand is going to be made. The third explains the artifact removal algorithm, where the solution for the skin reflections are presented. The fourth is related to the image reconstruction algorithm, where the method to analyze the signals is explained.

Chapter 3 describes the comparison between several simulated results in order to determine the optimal outcome for the setup's ring of antennas. The results presented are related to the antennas' substrate, FR4 or teflon, and to the number of rings, one or two.

Chapter 4 is divided in three sections. The first one is dedicated to a complete description of the setup. The second one describes the application built to establish the communication between the computer and the setup. Finally, the third one is related to the presentation and analysis of the results obtained from measurements taken with teflon and FR4 antennas. The results that are going to be presented were obtained using two calibration types.

Chapter 5 is dedicated to the conclusion and future work.
Chapter 2

Analytical Formulation

This section presents the formulation of the artifact and image reconstructions algorithms. The artifact removal algorithm is in charge of removing the early-time reflections. These reflections correspond to the interface between the air and the breast, meaning the breast skin. The image reconstruction algorithm determines the reflection field in each point in space. The reflected field is related to phase sum of the microwaves radiated by the antennas.

2.1 Setup Introduction

In the problem formulation, it is important to take into account the setup configuration and patient posture during an examination. In this setup, the patient is in the prone position with the breast pendant inside a cavity. Since the setup does not use any coupling medium, it is considered a dry setup. In figure 2.1 it is possible to see a scheme of the patient's position during the exam.

![Figure 2.1: Sketch of the patient's position during the exam.]

The signals are radiated by a ring of 8 antennas distributed around the patient's breast, in a circular way. However, the distance between each antenna and the phantom is not the same due to the irregularity of the phantom that was built. A scheme of the phantom and antennas' ring is presented in figure 2.2.
Another topic with extreme relevance for this project is the dielectric properties. Any dielectric material is characterized by its complex permittivity. The real part is also known as the dielectric constant and relates the interaction of the material with the electric field. As for the imaginary part, it accounts for losses in the material. The dielectric constant corresponds to the ratio between the permittivity of a material comparing to the free-space permittivity and defines the capacity of a material to concentrate electric flux [36].

One of the main purposes of the setup, that has been built, is the elimination of the early-time reflections without the use of a coupling medium, since it turns the setup more complex, less hygienic and less comfortable to the patient. These reflections have a high magnitude because they correspond to skin reflections.

As far as this work is concerned, the dielectric constant is essential in order to distinguish the malignant tumor from the surrounding tissue.

2.2 Inverse Problem Formulation

The image reconstruction algorithm chosen to approach this problem is a radar-based technique whose name is matched filter. Usually, radar-based techniques measure the round trip time that the wave takes to reflect in the scatterer and come back to its origin. This algorithm works in the frequency-domain and uses the reflected waves to reconstruct the image. The matched filter algorithm accounts for the phase difference between all the reflected waves. This algorithm consists on the calculation of the reflective power for a specific sweep point in order to determine the position of the scatterer. By multiplying several values of the S-parameters and summing this contribution for each position of the antenna, it is possible to build a reflectivity map for all the sweep points.

In order to characterize a wave, it is important to explain its route. The wave propagates through the air and reaches the scatterer, where the wave is reflected back due to the dielectric contrast, thus
travelling back towards the antenna. The electric field of this phenomenon is described as in equation 2.1. We note that the argument of the exponential designates the phase of the travelling wave, whereas its magnitude, including radial spread and losses in the medium, is comprised in the factor $E_0$.

$$E(x, y, z, f) = E_0 e^{-jk(f)(n_1d_1 + n_2(f)d_2)}$$

(2.1)

The variable $k$ is function of the frequency and corresponds to the wave number. The values $d_1$ and $d_2$ correspond to the distances that the wave goes through in the air and in a dielectric medium, like the breast, respectively. Finally, the values $n_1$ and $n_2$ correspond to the refractive indexes of both mediums.

The distances in the air and in the breast are given by the Euclidian distance, represented in equation 2.2.

$$\begin{cases} d_1 = \sqrt{(x_b - x)^2 + (y_b - y)^2 + (z_b - z)^2} \\ d_2 = \sqrt{(x_p - x_b)^2 + (y_p - y_b)^2 + (z_p - z_b)^2} \end{cases}$$

(2.2)

Figure 2.3 illustrates a sketch that represent the microwave propagation in different mediums.

Figure 2.3 describes two types of systems, monostatic, $T_x$, and multistatic, $R_x$. In the monostatic system, the reflected electric field received by an antenna results from the field radiated from that same antenna. Therefore, the phase of the reflected is $-jk_2(f)(d_1 n_1 + d_2 n_2)$. The factor two represents the route that the wave goes through from the antenna to a specific sweep point, represented by the red line, and back to the antenna, represented by the green line. In the multistatic system, the reflected electric field received by an antenna results from the field radiated from other antenna. Therefore, the phase of the
reflected is $-jk(f)(n_1(d_{1Rx} + d_{1Tx}) + n_2(f)(d_{2Rx} + d_{2Tx})).$

In order to locate the reflected field, it is necessary to do a sweep in the three coordinates, $x$, $y$ and $z$. Moreover, this sweep is done for a specific position of the antenna. This procedure is important to localize the target, as it is going to be explained below. Also, in figure 2.3, it is possible to understand how the sweep is done.

The S-parameter defines the ratio between the received energy comparing to the incident energy. There are two types of coefficients. The reflection ones that characterize the monostatic system and the transmission ones that characterize the multistatic system. In MWI, based on these parameters, it is possible to infer the target’s existence and its position. The S-parameter is a value that varies for each frequency and depends on the position of the antenna.

The presented problem can be described by a linear model [37], as in equation 2.3 describes the problem.

$$g = Ar + w$$ (2.3)

The vector $g$ represents the coefficients (S-parameters), the matrix $A$ represents the wave reflections received by the antenna, the vector $r$ represents the reflectivity of human tissues and the matrix $w$ represents the noise. The latter accounts for perturbations in the system like the interference signal caused by the interface between the air and the breast skin, the skin reflections, variability of the permittivity of the tissues between people and the fact that the internal structure of the breast is unknown.

A coefficient, $s_a$, is defined for each position of the antenna, $N_a$ and is given by equation 2.4.

$$g = \begin{bmatrix} s_1^T & \ldots & s_a^T & \ldots & s_{N_a}^T \end{bmatrix}^T$$ (2.4)

The operator $(.)^T$ denotes the transpose of a matrix. For each position of the antenna, the reflection coefficient is also a matrix that has a value of the reflection coefficient for each frequency, $N_f$. Equation 2.5 presents vector $s_a$.

$$s_a = \begin{bmatrix} s_a(f_1) & \ldots & s_a(f_{N_f}) \end{bmatrix}$$ (2.5)

Finally, it is possible to conclude that the size of vector $g$ is $N_aN_f \times 1$.

The wave reflections received by the antenna are defined for each position of the antenna $N_a$ and are given by equation 2.6.

$$A = \begin{bmatrix} A_1 & \ldots & A_a & \ldots & A_{N_a} \end{bmatrix}^T$$ (2.6)

For each coordinate $x$, $y$ and $z$ there is a number of sweep points that are given by $N_x$, $N_y$ and $N_z$.
respectively. Moreover, each phase delay is calculated for each frequency. Given equation 2.1, it is possible to construct the matrix $A$ for each antenna position. Therefore, equation 2.7 represents this matrix.

$$A_a = \begin{bmatrix} E(x_1, y_1, z_1, f_1) & \cdots & E(x_N, y_N, z_N, f_1) \\ \vdots & \ddots & \vdots \\ E(x_1, y_1, z_{N_f}, f_1) & \cdots & E(x_N, y_N, z_N, f_{N_f}) \end{bmatrix}^T$$

(2.7)

In conclusion, it is possible to gauge that the size of the matrix $A$ is $N_a N_f \times N_x N_y N_z$.

The reflectivity of human tissues is different for each point of the space, since the human body has distinct types of tissues in each position. Taken into account figure 2.3, the sweep is done in the three coordinates, $x$, $y$ and $z$. Therefore, for each coordinate, the number of sweep points is given by $N_x$, $N_y$ and $N_z$. Equation 2.8 describes vector $r$.

$$r = \begin{bmatrix} r(x_1, y_1, z_1) & \cdots & r(x_1, y_1, z_{N_z}) & r(x_1, y_{N_y}, z_1) & \cdots & r(x_{N_x}, y_{N_y}, z_{N_z}) \end{bmatrix}^T$$

(2.8)

In conclusion, it is possible to deduct that the size of the matrix $r$ is $N_x N_y N_z \times 1$.

### 2.3 Artifact Removal Algorithm

The solution that is proposed, in order to use a dry setup and eliminate the artifact, is the Singular Value Decomposition (SVD) [37]. The SVD is an arithmetic tool that calibrates the measurements using factorization. The SVD decomposes the signals into different sets of reflections allowing the elimination of some reflection components without changing the tumor position. The main purpose of this algorithm is the elimination of the early time reflections, in order to enable the analysis of the breast interior. Therefore, the interface between the air and the breast skin must be clearly defined.

It is possible to use the SVD in the calibration in order to remove the skin reflections. However, it is necessary to assume that the front and back skin reflections are equal in all the points of the breast. This assumption is related to the fact that this method is based on a symmetry of the number of positions of the antenna that are considered.

By analyzing figure 2.4, it is possible to consider an antenna, $a$, and add the same number of neighbour antennas, $N_a$, on each side of the previously selected antenna.
Therefore, it is possible to build the matrix for the coefficients for the selected antennas in equation 2.9. This equation is a subset of equation 2.5

\[ S_a = \begin{bmatrix} s_{T_{a-N_n}}^T & \cdots & s_{T_a}^T & \cdots & s_{T_{a+N_n}}^T \end{bmatrix} \]

(2.9)

Since each coefficient is represented for all the frequencies, \( N_f \), it can be concluded that the size of matrix \( S_a \) is \( N_f \times 2N_n + 1 \).

The SVD is used to solve the filtering issue. This method works by factorizing matrices, as this algorithmic tool, generically, is described in equation 2.10.

\[ M = U\Sigma V^H \]

(2.10)

Before, explaining the origin of the matrices presented in equation 2.10, it is important to refer that the operator \( ()^H \) represents the Hermitian. Moreover, a singular value of a matrix \( M \), correspond to a eigenvalue of \( M^*M \). \( ()^* \) operator correspond to the conjugated.

Matrix \( \Sigma \) is a diagonal matrix defined by the singular values of the matrix \( M \). These singular values decrease in magnitude, through the matrix. The matrix \( U \) represents the singular vectors of \( MM^* \) and the matrix \( V \) represents the singular vectors of \( M^*M \) [38]. Considering the applications of the SVD, the optimal approximation for this method is presented in equation 2.11.

\[ M_q = \sum_{i=0}^{q} \sigma_i u_i v_i^H \]

(2.11)

The variable \( \sigma \) defines the \( q \) singular values that constitute the matrix \( \Sigma \) decreasingly ordered.

Taking into account the previous antenna’s analysis, presented in equation 2.9, it is possible to build a calibration matrix. This matrix is obtained by subtracting the contributions of the \( q \) scatterers that represent the skin. Equation 2.12 represents the calibration matrix, \( S_{a_{cal}} \).
\[ S_{a,cal}^{cal} = S_a - \sum_{i=0}^{q} \sigma_i U_i V_i^H \]  

(2.12)

According to the explanation presented above it can be concluded that the matrix \( S_{a,cal}^{cal} \) contains the response of the interior tissues of the breast for a specific position of the antenna.

Regarding the value of \( q \), it represents the number of coefficients that are erased from the S-parameter’s matrix, \( S_a \), in order to eliminate all the reflections from the skin, leaving only the coefficients that describe the tumor. The value of \( q \) varies from antenna to antenna because the skin reflections in each breast point and the distance from the tumor to the antenna are different. Therefore, depending on the magnitude of the reflections the value of \( q \) can be higher or lower.

The calculation of the \( q \) value is done by applying the inverse discrete Fourier transform (IDFT) to the time signals of matrix \( S_{a,cal}^{cal} \). This arithmetic tool transforms the signal from the frequency domain into the spatial domain. Thus, the new calibration matrix, that is obtained, depends of the roundtrip distance between the antenna and the initial breast skin. The maximum value for \( q \) is defined when the reflected signal obtained by the IDFT, \( s_{a,q}(d) \), is out of the breast, before the front skin, \( d_{sinit} \) and after the back skin \( d_{sback} \). The distance interval is defined by:

- \([d_{sinit} - \Delta d, d_{sinit} + \Delta d]\)
- \([d_{sinit} + n_{avg} d_{sback} - \Delta d, d_{sinit} + n_{avg} d_{sback} + \Delta d]\)

The variable \( \Delta d \) represents the range of the image resolution and is described in equation 2.13.

\[ \Delta d = \frac{v}{4 n_{avg}^2 \Delta f} \]  

(2.13)

The variable \( v \) represents the light speed and the variable \( \Delta f \) represents a frequency interval.

Therefore, to conclude, the calibration matrix is given by the calibrated coefficients in each position of the antenna. This matrix is presented in equation 2.14.

\[ S_{cal} = \begin{bmatrix} s_{T_1}^{T_{cal}} & \ldots & s_{T_{acal}}^{T_{cal}} & \ldots & s_{T_{N_{cal}}}^{T_{cal}} \end{bmatrix} \]  

(2.14)

To finalize, in order to calculate the reflectivity of the tissues in each space point it is possible to use the calibration matrices. This matrix is presented in equation 2.15.

\[ g_{cal} = A r + w_{cal} \]  

(2.15)

The matrix \( w_{cal} \) represents the calibrated noise after the removal of the air-skin transition.

The SVD allows a faster data computation which makes possible a real-time exam visualization. Moreover, this method does not introduce distortion in the tumor position and can detect tumors which distance for the skin is smaller than the image resolution.
2.4 Image Reconstruction Algorithm

The noise factor, $w_{\text{cal}}$, no longer accounts for the skin reflection. However, the noise can still appear since there are also some inconsistencies in the calculation of the distances due to the arrival angle, which changes because of the movement of the phase center depending on the frequency. Moreover, the internal tissues’ electric permittivity changes, and in the calculations this characteristic is considered to be equal throughout the tissues with the same properties. Besides these facts, the antenna phase center instability needs to be considered as well. However, after the elimination of the early-time reflections, the value of the noise can be neglected comparing to the vector $g$.

Taking into account matrix $A$, it can be concluded that the number of singular values is lower than the number of lines, $N_a \times N_f$, which makes the inversion of this matrix impossible. Furthermore, a common matrix inversion would maximize the noise, because its value is really low. In order to solve this last problem, it is necessary to resort to an approximation that is described in equation 2.16 [37]. In equation 2.16 the presented matrix is a general one.

$$M^{-1} \simeq M^H M \tag{2.16}$$

Adapting to the presented problem, it is possible to calculate the matrix that represents the reflectivity of the tissues in each point of the space. The calculation is presented in equation 2.17. To obtain equation 2.17 it is necessary to take into consideration equation 2.15.

$$\hat{r} \simeq A^H g_{\text{cal}} \tag{2.17}$$

Individually, each value of the vector $r$ is defined in equation 2.18.

$$\hat{r}_{a,f} = \frac{1}{N_a N_f} \sum_{a=1}^{N_a} \sum_{f=1}^{N_f} g_{\text{cal}}^{a,f} e^{2\pi i (d_1(a) n_1 + d_2(a) n_2(f))} \tag{2.18}$$

By analyzing equation 2.18, it is possible to conclude that a reflectivity map is formed under a form of a three dimensional matrix, where each coordinate $(x,y,z)$ has a value for the reflected electrical field. If the sum is coherent, which means that there is phase sum, the value of the electric field will be maximum. Therefore, a target is present in that specific synthetic focal point. On the other hand, if the sum is incoherent the phase sum is random and, therefore, the signals cancel each other. Thus, the value of the electric field will tend to zero. Hence, the target is not present in the sweep point under analysis.

Finally, it is possible to conclude that the matrix $r$, represented in space, is proportional to the reflected field in a specific point in space ($I(x,y,z)$). The proportion is presented in equation 2.19.

$$I(x,y,z) \propto \hat{r}^2 \tag{2.19}$$

In conclusion, this linear model can be used to represent the intensity of the electric field in a specific point in space.
Chapter 3

Numerical Assessment

In this section, it is going to be assessed the possibility of having two rings of antennas and if the FR4 substrate can produce adequate results, comparing to the teflon ones.

3.1 Setup and Simulation Description

In program Computer Simulation Technology (CST) Microwave Studio [39], five different setups were created for two types of substrates. In all five setups, a sphere, made with a material called perfect electric conductor (PEC), in order to ease the wave reflection, and radius 5mm, was located at coordinates (20,-15,-5)mm. The sphere, that represents the tumor, was inside a cylinder made with a material which relative permittivity was 4.2 in order to simulate the dielectric properties of the breast. The referred cylinder had a radius of 40mm and an height of 50mm, where half the length was located in the positive side of the z axis and the other half in the negative side of the z axis. The center of the cylinder was located at the origin of the referential. As far as the simulations are concerned, in all the setups, two simulations were made, one considering the sphere and one not considering the sphere, the second one to serve as calibration. The calibration method used was the ideal, thus it was made by subtracting the reflection coefficients from the calibration setup, the one without the sphere, to the setup considering the sphere. Figure 3.1 represents the sphere and the cylinder in a z plane and figure 3.2 illustrates the sphere and the cylinder in a y plane.

Figure 3.1: Cylinder and sphere in the z plane.
As far as the antennas are concerned, for both substrates, the chosen antennas were Circular Array Balanced Antipodal Vivaldi Antenna (CABAVA) because they are ultra wideband and slightly more directive than the average, they have a planar geometry, which allows measurements in different heights and their size can be adjusted according to the setup necessities without affecting its properties. The Vivaldi antennas are characterized for being in the travelling-wave category. This kind of antenna has metallizations where the electric current propagates. As the difference between both edges varies over the antenna, it can be resonant at multiple frequencies since the half wavelength condition is verified for different points of the antenna [26].

For the first type of substrate, teflon, all of the antennas distance 60mm from the center of the setup. The set of antennas, arranged in the shape of a ring, was constituted by 8 antennas which had an isolation factor of -8dB for the frequency that represents the worst case scenario. For the second type of substrate, FR4, which is a cheaper substrate, the distance between the center of the setup and the antennas was 65mm. The ring also had 8 antennas, but with an isolation factor of -10dB for the frequency that represents the worst case scenario. It is important to refer that in the setups with FR4 antennas, a connector in each antenna was introduced so that, these setups were similar to the experimental one.

Moreover, only the reflection coefficients were used to reconstruct the image, since these allowed to reach the intended conclusions. Figure 3.3 shows the ring of antennas for both types of antennas.

Figure 3.3: Ring of antennas for z=0mm. (a) Substrate made with teflon. (b) Substrate made with FR4.
As it is possible to verify from figure 3.3, the FR4 antennas are smaller. This was made in order to reduce the coupling between adjacent antennas and consequently reduce the isolation factor. The FR4 antennas reduce the coupling because they are not as close to each other as the teflon ones. This lack of proximity reduces the currents that flow between adjacent antennas, thus the power that is radiated to the setup is larger, making it easier to detect the sphere.

Before taking the simulations with the cylinder and the sphere, a free space measurement was made for each antenna type in order to determine the distance introduced by the antenna. This distance has to be taken into account in the image reconstruction because it is added to the position of the target’s response, causing an alteration in its position. To calculate the distance of the antenna it was necessary to know the distance between the antenna and the outside walls of the cylinder. In equation 3.1, it is possible to calculate this distance.

\[ d_{cyl} = d_{tot} - r_{cyl} \]  

The variable \( d_{cyl} \) correspond to the distance between the antenna and the outside walls of the cylinder, the variable \( d_{tot} \) defines the distance between the antenna and the center of the setup and the variable \( r_{cyl} \) corresponds to the radius of the cylinder. As the distance between the antenna and the center of the FR4 setup is 65mm and the cylinder radius is 40mm, with equation 3.1, it is possible to obtain the distance between the antenna and the outside walls of the metallic cylinder, which is 25mm.

By calculating the reflected power, the maximum value for the power corresponds to the position of the cylinder. Equation 3.2 presents the way to calculate the reflected power. It is important to refer that these simulations were made for an height of 0mm.

\[ E(d) = (S_{11cyl} - S_{11fs})e^{-j2k(f)(d)} \]  

The variable \( E_d \) the represents the reflected power, given in V/m, and the variables \( S_{11cyl} \) and \( S_{11fs} \) correspond to the reflection coefficient of the first antenna in the cylinder simulation and in free space respectively. They are subtracted in order to remove the influence of the surrounding environment since the only difference between both simulations referred above is the presence of the cylinder.

In order to determine the distance of the maximum reflected power it is necessary to build a graphic of the reflected power in function of the distance. This graphic is presented in figure 3.4.
By analyzing the graphic and with the help of computational tools, it is possible to conclude that the distance for the maximum, $d_{\text{max}}$ is located at 140mm. In conclusion, to calculate the distance of the antenna equation 3.3 is used.

$$d_{\text{ant}} = d_{\text{max}} - d_{\text{cyl}}$$  \hfill (3.3)

Finally, it is possible to conclude that the distance of the antenna is 115mm. For the teflon antennas the procedure was the same and the calculated distance was 120mm. The calculation of this distance is important because it influences the image reconstruction algorithm.

### 3.2 Simulation Results

The results that are going to be presented were obtained using the ideal calibration. The first setup had only one ring of antennas located at $z$ equal to 0mm and the second setup also had only one ring of antennas situated at $z$ equal to -10mm. The results for both these setups are presented in figure 3.5 for teflon substrate and in figure 3.6 for FR4 substrate.
Figure 3.5: Results for the plane $z=20\text{mm}$ using teflon substrate for plane $z$. (a) Antennas ring located at $0\text{mm}$. (b) Antennas ring located at $-10\text{mm}$.

Figure 3.6: Results for the plane $z=20\text{mm}$ using FR4 substrate for plane $z$. (a) Antennas ring located at $0\text{mm}$. (b) Antennas ring located at $-10\text{mm}$.

The results from figure 3.5 and 3.6 indicate that for each height, there is little clutter in the image, but it is possible to detect the sphere almost perfectly. For $z=0\text{mm}$, the intensity is higher comparing to the results for $z=-10\text{mm}$. The results with the maximum intensity are presented in the plane where $z$ is equal to $20\text{mm}$ which is different from the sphere position in the $z$ plane.

The results, in the $x$ plane for both setups, are presented in figure 3.7 for teflon substrate and in figure 3.8 for FR4 substrate.
By analyzing the results from figure 3.7 and 3.8 it is possible to conclude that the vertical resolution for both cases is really poor since the simulations were made only for one height.

Regarding the setups with two rings, they were made in order to improve the vertical resolution with less measurements. The third and fourth setups had two rings of antennas simultaneously. One located at \( z \) equal to 0mm and the other located at \( z \) equal to -10mm. In both these setups the lower ring had a rotation of \(-22.5^\circ\) comparing to the higher ring. In the third setup the lower ring had its ports in short circuit and in the fourth setup the higher ring had its ports in short circuit. The fifth setup also had two rings of antennas located at \( z \) equal to 0mm and \( z \) equal to -10mm. In this setup, the lower ring had a rotation of \(-22.5^\circ\) comparing to the higher ring. However, in this setup none of the rings had its ports in short circuit. The rotation is important because it allows the setup to increase the measured angles in the same perimeter improving the precision of the results. The images that will be presented can be compared because both have 16 reflection coefficients to reconstruct the image. The fifth setup measured 16 reflection coefficients and the third and fourth measured 8 reflection coefficients each.
because antennas in short circuit cannot measure any coefficients. Thus, the coefficients from the third and fourth setups were combined in order to have 16 coefficients.

The results for the fifth setup and for the combination of the reflection coefficients obtained for the third and fourth setups separately are presented in figure 3.9 for teflon substrate and in figure 3.10 for FR4 substrate.

![Figure 3.9](image1.png)

Figure 3.9: Results for the plane \(z=-20\) mm using teflon substrate for plane \(z\). (a) None of the antennas ring in short circuit. (b) Combination of the coefficients obtained for the higher ring in short circuit and the lower ring in short circuit separately.

![Figure 3.10](image2.png)

Figure 3.10: Results for the plane \(z=-20\) mm using FR4 substrate for plane \(z\). (a) None of the antennas ring in short circuit. (b) Combination of the coefficients obtained for the higher ring in short circuit and the lower ring in short circuit separately.

By analyzing Figure 3.9 and 3.10, it is possible to conclude that the sphere is located in the right position for the \(x\) and \(y\) coordinates and can be detected with little clutter for both cases. The results for the combination of the reflection coefficients obtained for the third and fourth setups separately are better because they have less clutter and a higher intensity. This can be explained because, in this case, the intensity of the currents flowing from the higher ring to the lower ring is smaller since they are in short circuit respectively at the time of the simulations. The fifth setup suffers from the coupling
problem between the antennas’ rings because they are active simultaneously.

The results, in the x plane, for the fifth setup and for the combination of the reflection coefficients obtained for the third and fourth setups separately, are presented in figure 3.11 for teflon substrate and in figure 3.12 for FR4 substrate.

![Figure 3.11: Results for the plane x=20mm using teflon substrate for plane x. (a) None of the antennas ring in short circuit. (b) Combination of the coefficients obtained for the higher ring in short circuit and the lower ring in short circuit separately.](image1)

![Figure 3.12: Results for the plane x=20mm using FR4 substrate for plane x. (a) None of the antennas ring in short circuit. (b) Combination of the coefficients obtained for the higher ring in short circuit and the lower ring in short circuit separately.](image2)

By the analysis of Figure 3.12, it is possible to conclude that the resolution for both cases is really poor. However, for the fifth setup the resolution is slightly better since the tumor is less spread through the cylinder mask. It can be concluded that even with two rings of antennas, the resolution did not improve that much.

Finally, comparing the results for one ring of antennas with the results for two rings of antennas, it is possible to conclude that the intensity is higher for one ring. This indicates that even with the short circuit in one of the rings, there are currents that go through to the other ring. Regarding the resolution in the
vertical plane, it is possible to gauge that it improves with the two ring setup. However, it is necessary to aggregate results from several heights in order to determine the importance of adding the second ring.

Comparing the results of the teflon antennas with the ones obtained for the FR4 antennas, it is possible to verify that the intensity is lower for the FR4 antennas. This result was expected since this type of antennas has more losses comparing to the teflon ones. The losses, measured by $\tan(\delta)$, are about $10^{-4}$ for the teflon substrate and $10^{-2}$ for the FR4 substrate. This means that the substrate of the FR4 antennas absorbs more energy comparing to the teflon antennas. In terms of clutter appearance and resolution the results are quite similar.

In conclusion, although the setup with two rings is less time consuming since it can take 16 measurements at the same time, it is more difficult to assemble and calibrate. Furthermore, it gives worse results comparing to the setup with only one antenna. As far as the substrate is concerned, despite having less losses, the teflon substrate is much more expensive. Therefore, the experimental setup is constituted by one ring of antennas made with FR4.
Chapter 4

System Development and Evaluation

This chapter consists in a description of the experimental setup and the developments on the experimental setup. Also in this chapter, there is going to be made an explanation about the Graphical User Interface, which describes the application that builds the bridge between the software and the setup. Finally, the measurements made with the experimental setup are going to be presented and analyzed.

4.1 Experimental Setup Description

The setup that is going to be described was built at Instituto de Telecomunicações (IT)-Instituto Superior Técnico [17].

It is divided into two different parts: the communication and the hardware.

The hardware part is divided in three types according to the role that a certain component has in the setup. The groups are: body simulation components, setup control components and radio-frequency measurements components. The structure of the setup consists of a plexyglas table were the other components are attached. The purpose of this model is to recreate a real examination of a breast. Thus, the patient would be in prone position with the breast inside the hole. The overall setup can be observed in Figure 4.1.
4.1.1 Breast Simulation Components

The structure is characterized by an acrylic board with a hole in the middle. The hole is for the phantom, which is a set of structures that emulates the structures of the breast. The phantom has an anthropomorphic container, which was built based on the structures referred in section 1.4. This container was made with polyactic acid (PLA), which is a material that has a much lower permittivity when compared with the breast skin. In order to test the microwave imaging technique, a target, that simulates a tumor, made also with PLA is set inside the container. To simulate the dielectric properties of these structures, both are filled with specific liquids [29]. In order to extend the research, fibroglandular tissues were made with the same material as the other structures of the phantom. The phantom can be classified in three different groups: one, two and three, according to adipose tissue content. The first one has a content between 0% and 30%, the second varies from 31% to 84% and finally, the third group has a content which interval goes from 85% to 100% [29]. As the adipose tissue content increases, the dielectric constant (permittivity) decreases, which should ease the tumor detection. However, it also provokes much more wave attenuation and that is why the tumor detection becomes more difficult. The phantom built to take the measurements belongs to the group three (G3). In order to simulate the dielectric properties of the tissues, according to Joachimowicz et al, the liquid Triton-X 100 (TX-100) is the best option. In order to simulate the adipose tissue, there is no need to dilute since the phantom belongs to G3, hence the concentration of the TX-100 is 100%. The liquid, that simulates the properties of the tumor and the fibroglandular tissues, consists on a mixture between TX-100 and salted water. The tumor has a
mixture with a TX-100 concentration of 20% and the fibroglandular tissues have a mixture with a TX-100 concentration of 25%. Equation 4.1 determines the permittivities of the mixtures [29].

\[
\epsilon_m = \epsilon_1 + \left[3V_2\epsilon_m \frac{\epsilon_2 - \epsilon_1}{2\epsilon_m + \epsilon_2}\right]
\]  

(4.1)

The variables \(\epsilon_m\), \(\epsilon_1\) and \(\epsilon_2\) represent the relative permittivities of the mixture, the TX-100 and the salted water respectively. The variable \(V_2\) represents the volume of salted water. In figure 4.2 it is possible to observe the model to represent the breast, the tumor and the fibroglandular tissues.

![Figure 4.2: Phantom components. (a) Breast container. (b) Tumor and glandular tissues.](image)

4.1.2 Setup Control Components

The setup control components are responsible for controlling the movements of the camera and the antennas’ ring. A Raspberry Pi0 v1.1 serves as a wireless controller that can be programmed to control devices, in this specific case, a camera and a motor. During the movement, the webcam takes several snapshots of the phantom, from different angles. The information contained in the pictures is used to build the breast mask. The reconstruction of the breast shape is essential since it defines the interface between the air and the breast skin, as it was presented in section 2.3. Regarding the motor, it is a servo one. This type of motor is characterized for an unidirectional communication with the Raspberry Pi. The technician, that programmed the Raspberry Pi, gives a certain amount of time and the motor makes the cart move, along the rails, a distance corresponding to a circumference arc with about 15°. It is important to refer that the Raspberry Pi is really small in order to facilitate the mobility and transport of the setup.

The automation of the setup required the incorporation of 2 microswitches. A microswitch is an electrical component that has 3 pins: NC, NO and COM. The connection NC-COM represents the minimum voltage which means that the microswitch is not activated, and the connection NO-COM represents the maximum voltage meaning that the microswitch is pressed. The detection of the microswitch activation is done using a Raspberry Pi. One microswitch was incorporated to stop and change the direction of the camera movement and the other microswitch was installed below the ring of antennas in order to stop its movement.
The image acquisition routine starts when the camera moves from its initial position to the end of the rail continuously. When it reaches the end of the rail, the microswitch is pressed and the camera changes the direction of its movement. In the second movement, the camera goes through a distance that is equivalent to an 15° arc and then it takes a snapshot of the phantom. This procedure is repeated until the camera reaches the initial position. Figure 4.6 schematizes this routine.

![Figure 4.3: Schematic of the camera movement routine.](image)

In the imaging setup, there is another motor, that controls bearings, which make the antennas’ ring platform move upwards and downwards. It is a stepper motor, which means that the relative position of the motor is inferred by keeping track of the number of steps taken. As the measurements with the antennas are more precise, this motor needs to know the exact distance that the platform needs to go through. The user defines a distance, that is converted automatically to a movement angle, and the motor makes the bearings move during a certain amount time in order to achieve the desired height. This motor is connected to another Raspberry Pi0 v1.1, which activates specific pins alternately in order to control the motor. Moreover, the stepper motor is fed by one voltage generator.

### 4.1.3 Radio-Frequency Measurements Components

The radio-frequency measurements components are responsible to radiate the waves as well as measure the S-parameters. The ring has 8 antennas, which do not have a perfect isolation due to the short distance that separates them. However, it is possible to separate the received signal from each antenna. The ring can go upwards and downwards, so it is possible to take several scans of the breast, at different heights. As the ring is around the breast, the scattered waves come from various locations. Therefore, with the received signals from each position, it is possible to reconstruct the breast interior and pinpoint the tumor. The antennas of this setup are Circular Array Balanced Antipodal Vivaldi Antenna (CABAVA) with the substrate made with FR4. The relation between image quality and price is good for this type of substrate. In figure 4.4 it is possible to observe the ring of antennas made with FR4. The numbers represent the position of that antenna in the measurements.
As the setup has 8 antennas and the VNA only has 4 ports, it is impossible to connect all the antennas to the VNA simultaneously. Therefore, it is necessary to incorporate switches in the setup. The switch has 4 ports, which means that it can take 4 antennas at the same time. Thus, since there are 8 antennas, 2 switches were incorporated. These switches are activated using 2 voltage generators, one per switch, to feed them. These switches are controlled by a Raspberry Pi. However, the maximum voltage that comes out of the Raspberry Pi output pin (GPIO) is 3.3V. Since the switches need a 24V voltage to work, it is necessary to use a voltage step-up. As all 4 pins of the switch will be connected to the Raspberry Pi, it is possible to define which pin is active at a certain moment. This is made via software. The activation of a pin allows the antenna to measure the selected coefficients. As it was already referred, 4 antennas are connected to each switch. With the purpose of reducing the coupling between the antennas, the antennas are connected to the switches in an alternate way, meaning the antennas 1, 3, 5 and 7 are connected to one switch and the antennas 2, 4, 6 and 8 are connected to the other. Figure 4.5 presents a scheme of the connection between each antenna and the switch.
The setup has a vector network analyzer (VNA). The VNA has the purpose of taking the measurements of the reflection and transmission coefficients regarding the antennas. This appliance is characterized for having a dynamic range of 123dB, which defines the amplitude level that is possible to measure. In order to analyze multiple networks the VNA has 4 ports that work until a frequency of 14GHz. The VNA has trace noise of 0.004dBrms at frequency of 70kHz. This characteristic allows the measurement of signal with a low amplitude level, since the noise is really low as well. [40].

The antennas routine starts with the upwards movement of the ring. When it goes through the distance defined by the technician, the VNA measures the antennas’ coefficients. This process repeats itself until the ring of antennas reach the maximum height, also defined by the technician. Then, the ring of antennas starts going down until the microswitch is pressed. When it is activated, the movement of the ring stops. The measurement process is done by alternating the switches. The first switch selects an antenna and the second switch goes through all the 4 antennas that are connected to it. When the measures are done, the first switch selects the next antenna and the second switch goes through all the antennas again. This process is terminated when the first switch reaches the last antenna. All the S-parameters are saved in different matrices.

![Figure 4.6: Schematic of the antennas’ ring and S-parameters measurement routine.](image)

The communication of the setup is responsible to control all the devices via PC in order to automate the setup. The PC has the code that controls them. A sketch of the setup communication is presented in Figure 4.7.
The communication is done in two distinct ways. In order to communicate with the PC, the VNA is connected to the computer via USB, so that the compatibility with the software code is assured. The other way to communicate, in the setup, is via Wi-Fi. The PC generates an Wi-Fi network and each Raspberry Pi of the setup connects to the PC using their own IP addresses. One Raspberry Pi controls the movement of the camera and the other controls the antennas’ movement, the microswitch activation and the synchronization of both switches.

### 4.2 Graphical User Interface

The Graphical User Interface (GUI) is an interface created in the software MATLAB, whose purpose is to establish a communication between the user and the breast setup. This application started being developed in the previous work [17].

#### 4.2.1 GUI Constitution

The GUI is divided in three main menus: Setup, Calibration and Exam. The menus designed for the technician are inside the red rectangle and the menu designed for the examiner is inside the blue rectangle. An overall tree of the application is shown in figure 4.8.
**Setup**

The menu Setup was designed for the technician. Its purpose is to define all the specifications regarding the devices that are involved in the breast setup. This menu is divided into four submenus: Antennas, Raspberry Pi, VNA and Wiring. The organization of this menu can be observed in figure 4.8.

Starting with the Antennas submenu, its function is to visualize the antennas’ orientation, so that the technician does not lose track of each antenna’s position.

The RaspberryPi submenu connects both RaspberryPi (camera and antennas’ motor) to the computer via Wi-fi. By knowing the IP address of both RaspberryPi, it is possible to connect them to the computer. The configuration menu of the camera RaspberryPi has other specifications related with the camera, like the rotation angle and the brightness. Regarding the antennas’ motor RaspberryPi configuration menu, it allows the user to define the vertical step of the ring, which corresponds to the distance that the platform goes through between measurements, the starting height, which defines the height of the first measurement and the maximum height, which indicates the height where the platform terminates the measurements and starts the downwards movement.

The VNA submenu is responsible for the connection, port calibration, disconnection and configuration, which involves the definition of the frequency range, the averaging, the number of points and the maximum power, of the VNA.

Finally, the Wiring menu’s purpose is to select the links between antennas that are going to be active during the measurements, which means, it selects the coefficients that are going to be measured.

**Calibration**

The Calibration menu was designed for the technician. This menu is related with the calibration of the antennas and the free space measurements. The Calibration menu is divided into two submenus: Free Space and Antenna Distance. The organization of this menu can be observed in figure 4.8.
The Free Space submenu was created in order to measure the free space coefficients. These coefficients are important in the SVD method which is a part of the image reconstruction algorithm.

The Antenna Distance submenu measures the S-parameters with a metal target in the middle. Then, it calculates the distance that is introduced by the antenna. This distance needs to be considered in the image reconstruction algorithm so that it can work with the right physical distances.

Exam

The Exam menu was designed to be used by the doctor. Its main function is related to the image reconstruction. Therefore, this menu is divided in three submenus: Target Shape, Scanning and Imaging. Moreover, this submenu allows the doctor to register a new patient in the system. The organization of this menu can be observed in figure 4.8.

The Target Shape submenu is responsible for the camera movement. While the camera is moving, it takes several snapshots and saves them. These snapshots are important to make a 3D model of the breast that is being examined. This model is necessary in order to build the mask that enters in the image algorithm.

The Scanning submenu controls the movement of the ring of antennas and takes the measurements of the S-parameters and saves them. This submenu is important since it builds the matrices that are going to be used in the image reconstruction algorithm.

The Imaging submenu has two functionalities. The first one allows the display of images previously saved by the doctor. It is possible to visualize them in three different planes: X-Y plane, X-Z plane and Y-Z plane. The other functionality is the calculation of new images using the image reconstruction algorithm.

4.2.2 GUI Developments

The first development made in the GUI was a generalization of the screen size. Therefore, now, it is possible to work in full screen in every device without the application being uncalled. This was done using a simple proportion since it is possible to acquire the screen size of any device via software.

As this application is destined to examine several patients, it is important to register them in order to save their data. This is important to organize and systematize the patient evolution through time. In figure 4.9 it is possible to observe the interface that is used to register a patient.
After finishing the registration, a folder and a text file are created. The folder has the purpose of saving all the exams of a certain patient. The text file contains the name and the identification number. If the patient has already been registered in the system, by loading this text file, the patient’s credentials will be inserted in the application.

In the calibration menu it is possible to take the free space or metal target measurements. This menu also allows the user to determine the distance introduced by the antenna. The interface of this menu is presented in figure 4.10.
By clicking in the button "Free Space" the scan starts, hence, the antennas’ ring goes up and takes the measurements according to the process described in section 4.1. After the measurements, the results are saved in a matrix form. In the end of the scan, a matrix for each height and a matrix combining all the heights are created. The button "Antenna Distance" takes only a measurement with a metal target in the middle of the setup. The button "Get Distance" sends an instruction to the GUI and, by subtracting the measurements from the metal target and free space, the antenna distance is calculated and saved in a specific matrix form in order to be used in the reconstruction algorithm. Finally, the button "Options" redirects the user to the antennas’ motor submenu of the Raspberry Pi.

The camera and antennas routines that describe the automation of the setup, presented in section 4.1, were implemented in GUI. In subsection Scanning, by using the button "Start Scan" the setup performs both routines sequentially. The menu "Automatic Scan" is presented in figure 4.11.
The button "Options", presented in the "Automatic Scan" menu, takes the user to the antennas submenu of the Raspberry Pi. This submenu allows the user to define the characteristics of the motor that controls the ring of antennas. The "Antennas RaspberryPi Options" is presented in figure 4.12.

The IP Address allows the GUI to connect to the Raspberry Pi. Therefore, it is possible to control the ring of the antennas through the application. As far as the ring's movement is concerned there were defined three different types of heights in order to control the ring. The start height defines the start
of the measurements, meaning, when the ring’s height is higher than this value the antennas start to measure. The maximum height determines the end of the measurements, and consequently reverses the direction of the ring. Finally, the vertical step corresponds to the distance that the ring goes through between measurements. During this process the files created by the VNA are automatically processed and the matrices are built in real time. Matrices only with one height and with all heights combined. In these matrices all the coefficients are presented, meaning, there are reflection and transmission coefficients.

Both the VNA files and the coefficients matrices are saved automatically under a certain format. The VNA files format includes the first letter of the name and surname, the identification number, the active antennas, the height of the measurement and the date. The matrices format includes the first letter of the name and surname, the identification number, the height of the measurement and the date. If the matrix joins all the heights, the height of the measurement does not appear in the format. Table 4.1 presents examples of the formats described above.

Table 4.1: Save formats for different types of files.

<table>
<thead>
<tr>
<th>File type</th>
<th>Save Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNA file</td>
<td>DF 12345678 Breast Exam for z = -35mm ant 1-4, 17/08/2019.s2p</td>
</tr>
<tr>
<td>Matrix one height</td>
<td>DF 12345678 Breast Exam for z = -35mm 17/08/2019.mat</td>
</tr>
<tr>
<td>Matrix all heights</td>
<td>DF 12345678 Breast Exam total 17/08/2019.mat</td>
</tr>
<tr>
<td>Image one height</td>
<td>DF 12345678 Image Reflection SVD for z = -35mm 17/08/2019.mat</td>
</tr>
<tr>
<td>Image all heights</td>
<td>DF 12345678 Image Reflection Ideal total 17/08/2019.mat</td>
</tr>
</tbody>
</table>

Regarding the image reconstruction, in the submenu Imaging, it is possible to obtain new results or load previous ones. The calculation of new results is done using the image reconstruction algorithm described in section 2.4 This submenu is presented in figure 4.13.

![Figure 4.13: Menu Imaging.](image-url)
By pressing the button “Calculate” the user needs to define how many heights are going to be analyzed. The next step is to load a file with the coefficients that were previously measured and organized into a matrix. After this procedure, the image matrix is saved in a certain format. Then, it is possible to display the image by pressing the buttons that select a specific plane. The format includes the first letter of the name and surname, the identification number, the type of coefficients, the type of calibration, the height of the measurement, and the date. If the matrix joins all the heights, the height of the measurement does not appear in the format. An example is also presented in table 4.1.

If the image matrix has already been calculated, it is possible to analyze it by pressing the button “Load”. This button opens a window that allows the user to choose a file previously saved. After the file selection, the image can be seen in different planes with the same procedure explained above.

The submenu “Options”, associated with the Imaging menu, allows the user to define the characteristics of the image reconstruction algorithm when the “Options” button is pressed. The “Imaging Options” is presented in figure 4.14.

![Figure 4.14: Menu Imaging Options.](image)

The pixel resolution and the number of points in x, y and z (n_x, n_y, and n_z) determine the reconstruction volume. The distance between planes defines the step in the slider that allows the user to control the plane in study. The calibration type indicates the type of calibration that is used in the algorithm. It can be ideal, which needs a calibration matrix or SVD. The plot type defines if the results are going to be shown in the energy form or power form. The difference resides in the fact that in the power type the image matrix is squared. Finally, the data type determines the type of coefficients that are going to be used. It is possible to choose only the reflection coefficients, only the transmission coefficients or both.
4.3 Experimental Assessment

The breast phantom used for the measurements was heterogeneous, thus contained the fibroglandular tissues. The tumor was not inside the fibroglandular tissues. As far as the tumor is concerned, three positions were used in these measurements. The first one had its center coordinates at (5, 35, -30)mm, the second one corresponded to (-10, -25, -30)mm and the third one was defined at (10, -30, -30)mm. Figure 4.15 represents the positions of the tumor in the phantom.

In order to mimic the dielectric properties of the breast the different containers were filled with liquids with specific characteristics. The phantom used in the experiment belonged to the group three (G3). The breast container was filled with TX-100 which has a relative permittivity of approximately 4.2, the fibroglandular and tumor containers were filled with a mixture of TX-100, distilled water and sodium chloride of different percentage of each ingredient [29]. The permittivities of the structures referred above are presented in figure 4.16.
In order to calibrate the results, two different methods were used: The ideal calibration and the SVD. The first calibration type is done by subtracting the results obtained with the tumor by the results obtained without the tumor. Therefore, the response presented in the reflection map would correspond only to the one provoked by the tumor. The second one is described in chapter 2.

As the ideal calibration cannot be used in real life diagnosis since it is not possible to obtain results from a measurement with tumor and without tumor, it is important to study a method that can enhance the tumor response in order to detect it. This calibration method is the SVD. As it was referred in section 2.3, the value for the variable $q$, described by equation 2.12, characterizes the number of signals that are eliminated, in order to reach the tumor signal. As the value of $q$ increases the power of the signal decreases, which means that, in the reconstruction of the image, the weight of this specific signal is going to be lower.

In the results, that are going to be shown, both calibration types were used. In each section, in the first set of results the antennas were made with a teflon substrate and in the second the antennas had a FR4 substrate.

The image reconstruction algorithm uses a 5mm distance between pixels and an average dielectric permittivity for the phantom of 4.2.

### 4.3.1 Ideal Calibration Results

The results that are going to be presented next were obtained using the ideal calibration. To take the measurements 4 antennas were used. The antennas were CABAVA with a substrate made of...
teflon. As the VNA has 4 ports, each antenna was connected to each port. A multistatic approach were used, therefore, these connections allowed the measurement of 4 reflection coefficients, one for each antenna (S11, S22, S33 and S44) and 12 transmission coefficients. However, as there are redundant transmission coefficients, only 6 were used (S12, S13, S14, S23, S24, S34).

As the setup only had 4 antennas, in order to simulate the eight antennas, towards getting the most information possible, the measurements were made with the phantom in a 0° and 180° orientation. This rotation simulated the other 4 antennas that were not in the setup. Thus, the number of reflection coefficients was 8 and the number of transmission coefficients was 12. Figure 4.17 represent the orientation of the antennas used to take the measurements. The numbers represent the position of an antenna in the measurements.

![Antennas Scheme](image)

Figure 4.17: Scheme of the antennas used in the measurements. (a) Rotation 0 degrees. (b) Rotation 180 degrees.

Regarding the measurements, the first step consisted in finding the distance of the antenna. Thus, the first measurement was in free space, meaning that there was nothing in the middle of the antennas, and the second one was with a metallic cylinder. It was important that the cylinder was metallic in order to reflect all the incident power. The procedure to determine the antenna distance was the same as the one described in section 3.1.

As the distance between the antenna and the center of the setup was 78mm and cylinder radius was 26.2mm, with equation 3.1, it was possible to obtain the distance between the antenna and the outside walls of the metallic cylinder, which was 51.8 mm.

It is important to refer that the measurements were made for an height of -29.8mm, considering the referential origin in the setup’s first level. The graphic for the reflected power is presented in figure 4.31.
The distance for the maximum is located at 163mm. In conclusion, to calculate the distance of the antenna equation 3.3 was used. The obtained value, for the antenna distance was 111.2mm.

After the measurements, to determine the antenna distance, the measurements with the phantom were made. These measurements encompassed 6 different heights: -29.8mm, -34.5mm, -39.5mm, -44.5mm, -49.5mm and -54.5mm. It was important to take measurements in several heights in order to eliminate the clutter that can appear, as it is going to be shown in the results.

For each height, 10 results were obtained, 5 for each phantom orientation. In the first, the setup did not have the phantom, thus it was a free space measurement. In the second, the setup had the phantom with the fibroglandular tissues, but no tumor. Finally, in the third, as the phantom has three different positions, as it is shown in figure 4.15, results for each tumor position were taken.

The first result corresponds to the one with the measurements for only one height, using only the reflection coefficients of the 8 antennas. Since the tumor was located at approximately -30mm, the chosen height to present the results is -29.8mm. The results for this case are presented for plane z in figure 4.19 and for plane x in figure 4.20.
As it is possible to verify, despite the detection of the tumor being achieved near the real position of the tumor, there is some clutter surrounding the area that can mask and lead to false results. This may happen due to the existence of the fibroglandular tissues, since they have a relatively similar dielectric constant comparing with the tumor’s one. For the x plane, it can be concluded that, with only one antenna, it is impossible to detect the tumor due to the low resolution of the image.

The next step, with the goal of reducing the surrounding clutter, was to obtain the results for all the 6 different heights. Theoretically, this means that these results were obtained with 48 antennas. The results for this case can be analyzed in figure 4.21 for plane z and in figure 4.22 for plane x.
Figure 4.22: Results for all heights using only the reflection coefficients for plane x. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.

By observation of figure 4.21, it is possible to conclude that the results did not improve so much. Although the tumor intensity rose, the clutter intensity rose as well. Thus, the clutter was not eliminated. This happens because, for all the different heights, the antennas detected the clutter in the same place. Therefore, the phase sum was coherent in those specific places elevating the intensity of the clutter. For the plane x, it is possible to conclude that the results improved. The tumor intensity rose and, with the 6 measurements, the resolution increased, which made possible the appearing of an ellipse to characterize the tumor. However the resolution is still relatively low.

Since the monostatic approach did not produce satisfactory results, the next step was to gauge the importance of the transmission coefficients. Therefore, the next results were obtained by a multistatic system.

In the first place, in order to observe the differences that the transmission coefficients could cause, the next results were obtained using only this type of coefficients. The first result was obtained using measurements from only one height. Since the tumor is located at approximately -30mm, the chosen height to present the results is -29.8mm. The results, for this case, can be analyzed in figure 4.23 for plane z and in figure 4.24 for plane x.

Figure 4.23: Results for one height (z=-29.8mm) only with the transmission coefficients for plane z. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.
In figure 4.23, it is possible to verify that the tumor can be detected, but there is some clutter spread in the image. In figure 4.24, it is possible to verify that the tumor cannot be detected because the resolution of the image is really low. Comparing to the results in figure 4.20 the intensity decreased and more clutter appeared. This means that the transmission coefficients alone do not add much information to the image as far as the x plane is concerned.

The next step was to obtain the results combining all the measurements from the 6 heights, using only the transmission coefficients. Theoretically it means that 72 antennas were used. The results are presented in figure 4.25 for plane z and in figure 4.25 for plane x.

As it is possible to verify the results with the transmission coefficients for the 6 heights show a reduction
of the clutter in the image. However, it is still possible to detect some inconsistencies regarding the tumor size and position. This means that, these results may lead to a tumor detection in a wrong position. For plane x, the results show an increase of the resolution of the image. However, comparing to figure 4.24, these results did not add anything since the intensity is practically the same. This comparison reinforce the fact that the transmission coefficients are not as strong as the reflection ones, since the intensity is practically the same and the number of transmission coefficients was much larger than the number of reflection coefficients.

To finalize, the last set of the results was obtained using both reflection and transmission coefficients. The first result correspond to the one with the measurements for only one height. Since the tumor is located at approximately -30mm, the chosen height to present the results is -29.8mm. The results for this case are presented in figure 4.27 for plane z and in figure 4.28 for plane x.

![Figure 4.27](image1.png)

**Figure 4.27:** Results for one height (-29.8mm) using both reflection and transmission coefficients for plane z. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.

![Figure 4.28](image2.png)

**Figure 4.28:** Results for one height (-29.8mm) using both reflection and transmission coefficients for plane x. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.

By analyzing figure 4.27, it is possible to conclude that the clutter has reduced comparing with figure 4.19. The combination of both reflection and transmission coefficients made almost all the clutter disappear since the sum is incoherent and the reflected power, in a position previously with clutter, is now practically zero. For the plane x, it is possible to conclude that the resolution has not increased comparing with figure 4.20. The combination of both reflection and transmission coefficients only increased the intensity of the results. This shows that even using all the coefficients available, the resolution did not improve.

In order to increase the intensity and to eliminate the remaining clutter, a combination of all the 6
heights for the multistatic system was made. Theoretically, 120 antennas were used. The results can be observed in figure 4.29 for the plane z and in figure 4.30 for plane x.

![Figure 4.29: Results for all heights using both reflection and transmission coefficients for plane z. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.](image)

![Figure 4.30: Results for all heights using both reflection and transmission coefficients for plane x. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.](image)

As it is possible to verify, almost all the clutter was eliminated and the tumor can be identified perfectly for each tumor position. However, the detected tumor is always a little deviated from its original position. This can be explained by the rotation of the phantom which was not exact, leading to a little deviation. For the plane x, the resolution is better, but not satisfactory. The ellipse has decreased in size, but it is still to big comparing with size of the PLA tumor. This resolution may mislead the exam performer regarding the position of the tumor.

The results that are going to presented next were obtained using the setup described in section 4.1. As the VNA only has for 4 ports and there were 8 antennas, they were connected to two switches according to figure 4.5. A multistatic approach were used hence, these connections allowed the measurement of 8 reflection coefficients, one for each antenna (S11, S22, S33, S44, S55, S66, S77 and S88) and 32 transmission coefficients. However, as there are redundant transmission coefficients, only 16 were used (S12, S14, S16, S18, S32, S34, S36, S38, S52, S54, S56, S58, S72, S74, S76, S78). These are the coefficients used since it is impossible to measure transmission coefficients between antennas that are connected to the same switch. This happens because in a switch only one antenna is active in each measurement.

Regarding the measurements, the first step consisted in finding the distance of the antenna, as it was done for the teflon antennas. Thus, the first measurement was in free space, meaning that there was
nothing in the middle of the antennas and the second one was with a metallic cylinder. It was important that the cylinder was metallic in order to reflect all the incident power. The procedure to determine the antenna distance was the same as the one described in section 3.1. It is important to refer that the procedure was made for all of the antennas and the one that is presented was for antenna one.

As the distance between the antenna and the center of the setup is 64.34mm and cylinder radius is 26.28mm, with equation 3.1 it is possible to obtain the distance between the antenna and the outside walls of the metallic cylinder, which is 38.06mm.

It is important to refer that these measurements were made for an height of -30mm, considering the referential origin in the first level of the setup. The graphic for the reflected power is presented in figure 4.31.

![Figure 4.31: Electric field’s magnitude reflected by the metallic target in function of the distance, for FR4 antennas.](image)

The distance for the maximum is located at 139mm. In conclusion, to calculate the distance of the antenna equation 3.3 is used. The obtained value, for the antenna one distance, is 100.9mm. The value used in the reconstruction algorithm corresponded to the media of the values for all the 8 antennas, hence, the considered antenna distance was 101.25mm.

The measurements with the FR4 antennas were made only for one height, which was -30mm since it is the vertical position of the tumor. At the time of the measurements, the electronic circuit that controls both switches were not available, thus, the measurements had to be made manually. The procedure to do the measurements for only one height took a lot of time, hence, it was decided not to take the measurements for other heights.

The first result corresponds to the one using only the reflection coefficients of the antennas. The results for this case are presented for plane z in figure 4.32 and for plane x in figure 4.33.
Figure 4.32: Results for one height (z=-30mm) using only the reflection coefficients for plane z. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.

As it happens for the teflon antennas, the tumor is detected near the theoretical position. However, there is some clutter surrounding the tumor. This may happen because the fibroglandular tissue has a similar dielectric constant comparing with the tumor one, as it happened for the teflon antennas. For the vertical plane, it is impossible to identify the tumor since the resolution of the results is really poor.

To study the effect of the multistatic system, as it was done for the teflon antennas, the next step consists in the determination of the influence that the transmission coefficients have in the final reconstructed image. The results, for this case, can be analyzed in figure 4.34 for plane z and in figure 4.35 for plane x.

Figure 4.33: Results for one height (z=-30mm) using only the reflection coefficients for plane x. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.

Figure 4.34: Results for one height (z=-30mm) only with the transmission coefficients for plane z. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.
Figure 4.35: Results for one height (z=−30mm) only with the transmission coefficients for plane x.  (a) Tumor 1.  (b) Tumor 2.  (c) Tumor 3.

As it is possible to verify from the pictures, the tumor is detected in the right place with little clutter in the image.  Regarding the plane x, the resolution is not satisfactory using only measurements from one height as it was concluded for the teflon antennas.  Although the results for the transmission coefficients have a higher intensity comparing to the reflection coefficients, the difference is not much significant.  Therefore, it is possible to conclude that the reflection coefficients carry more energy comparing to the transmission ones, as 8 reflection coefficients have almost the same energy as 16 transmission coefficients.  This happens because the route of the transmission coefficients is larger, so the losses in the air are higher.

The final step combines both types of coefficients, allowing to study the complete multistatic system.  The results for this case are presented in figure 4.36 for plane z and in figure 4.37 for plane x.

Figure 4.36: Results for one height (z=−30mm) using both reflection and transmission coefficients for plane z.  (a) Tumor 1.  (b) Tumor 2.  (c) Tumor 3.
Figure 4.37: Results for one height (z=-30mm) using both reflection and transmission coefficients for plane x. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.

From the observation of the pictures, it can be concluded that the tumor can be detected with almost no clutter present, but a little deviated from the theoretical position. As far as the plane x is concerned, the results did not improve after the combination of both types of coefficients. Thus, it can be concluded that adding more coefficients, from the same height, does not rise the resolution.

Throughout the results for both z and x planes, regarding the two types of substrate, the tumor in the position two (-10,-25,-30)mm is always the one with the most clutter and less tumor intensity. This happens because this position is the one which is closest to the side of the phantom that is curve. Thus, this curvature influences the propagation of the microwaves since it provokes a refraction. Furthermore, the skin reflections are higher due to the phantom curvature. This leads to a reduction of the intensity and the appearance of more clutter since there are less power arriving at the tumor.

Regarding only the x plane, these results correspond to the section with the most intensity. As it is possible to observe, the sections for all the tumors are really close to its real position. However, for tumor one and two some inconsistencies in the section with the most intensity can be verified. This indicates that the results for the vertical plane are very sensible. The resolution was poor for all the results since the algorithm cannot restrict the tumor to a specified position, dragging it to all the extent of the breast mask. This leads to the conclusion that it is necessary to take measurements in more heights for the algorithm to converge to a good solution. Another important thing that has to be taken into account, is the fact that the tube that holds the tumor contributes for the reflection map because it also has the liquid that simulates the dielectric properties of the tumor. This factor may lead to a reduction of the resolution and the appearance of some clutter above the tumor.

The only result that is comparable, between the teflon and FR4 antennas, are the one obtained for the reflection coefficients, since the number of coefficients is the same. Regarding the detection of the tumor and the resolution, the results are quite similar. The difference resides in the intensity of the results. As it was verified in section section 3.1, the intensity for the teflon antennas was higher comparing to the FR4 antennas. By observing the results from the measurements, it is possible to verify that the intensities are much more similar, comparing to what was expected. Moreover, for the tumor position three, the intensity is higher for the FR4 antennas. This result was not expected since the FR4 substrate have more losses and besides this, the FR4 setup had switches and extra cables that provoked more losses. The similarity in the intensities may be explained by the coupling of the teflon antennas. As those antennas
were bigger, the coupling between adjacent antennas were bigger as well. Although this coupling was taken into account in the simulations, the way the antennas were assembled in the setup provoked a higher coupling comparing to the one that was expected.

4.3.2 SVD Calibration Results

The next results were obtained using the SVD as the calibration method. For the first set of results, the antennas used were made with teflon. Given the explanation in section 2.3, it can be concluded that the antennas that are near the tumor should have a lower $q$ since the power of the signal reflected by the tumor is bigger. Thus, the antennas that are near the tumor should be more decisive to reconstruct the image. By analyzing the tumor positions presented in figure 4.15, it is possible to determine which antennas, presented in figure 4.17, have more weight in the image reconstruction. Theoretically, for position number one the antennas with more weight would be 7 and 8, for position number two would be 3 and 4 and finally, for position number three would be 2 and 3.

It is important to refer that these results were obtained by analyzing each coefficient (S-parameter) individually, searching for the ideal $q$ value in order to gauge which signal corresponded to the tumor. This search was made manually, by trying several values for each antenna.

The first set of results were made using only the reflection coefficients of the 8 antennas.

For tumor position number one, the table 4.2 presents the values for $q$ for each one of the 8 antennas and for each one of the 6 heights.

Table 4.2: Values for $q$ in a monostatic system using all the 6 heights for tumor position one.

<table>
<thead>
<tr>
<th>Measurement height [mm]</th>
<th>z=-29.8</th>
<th>z=-34.5</th>
<th>z=-39.5</th>
<th>z=-44.5</th>
<th>z=-49.5</th>
<th>z=-54.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>q=2</td>
<td>q=3</td>
<td>q=2</td>
<td>q=3</td>
<td>q=3</td>
<td>q=4</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=1</td>
<td>q=1</td>
<td>q=2</td>
<td>q=4</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
</tr>
<tr>
<td>Antenna 4</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
</tr>
<tr>
<td>Antenna 5</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
</tr>
<tr>
<td>Antenna 6</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=1</td>
</tr>
<tr>
<td>Antenna 7</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=4</td>
</tr>
<tr>
<td>Antenna 8</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=4</td>
</tr>
</tbody>
</table>

As it is possible to confirm, save for a few exceptions, the antenna that has, consistently, the lower value for $q$ is the antennas 5. It is important to refer that the antennas 2, 3 and 6 also contributes a lot in the image reconstruction. This was not expected considering the real position of the tumor. After combining all this values, the obtained results are presented in figure 4.38.
Figure 4.38: Results for all heights, for tumor position one using a monostatic system and the SVD as the calibration method. (a) plane z. (b) plane x.

By the analysis of figure 4.38 (a), it is possible to verify that the tumor can be detected near the right position. However, there is a lot of strong clutter in the image that would mislead the examiner. In image (b), it can be realized that the resolution is really poor since the tumor is spread throughout the z plane instead of being restricted to its real size.

For position number two, the table 4.3 presents the $q$ values for each one of the 8 antennas and for each one of the 6 heights.

<table>
<thead>
<tr>
<th>Measurement height [mm]</th>
<th>z=-29.8</th>
<th>z=-34.5</th>
<th>z=-39.5</th>
<th>z=-44.5</th>
<th>z=-49.5</th>
<th>z=-54.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>q=4</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=3</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>q=2</td>
<td>q=1</td>
<td>q=2</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
</tr>
<tr>
<td>Antenna 4</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=3</td>
<td>q=3</td>
<td>q=4</td>
</tr>
<tr>
<td>Antenna 5</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
</tr>
<tr>
<td>Antenna 6</td>
<td>q=4</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=4</td>
</tr>
<tr>
<td>Antenna 7</td>
<td>q=3</td>
<td>q=2</td>
<td>q=2</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
</tr>
<tr>
<td>Antenna 8</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
</tr>
</tbody>
</table>

As it is possible to confirm, save for a few exceptions, the antenna that has the lower value for $q$ is the antenna 3. Moreover, antennas 2 and 8 have a strong influence in the final result as well. For antenna 8, this result was not expected compared to the $q$ values obtained for antenna 4. The relatively weak influence of antenna 4 may be caused by the wall of the phantom. In the zone of this antenna, the wall is a little more curved which cause a larger dissipation and an alteration of the route of the microwaves.

After combining all this values, the obtained results are presented in figure 4.39.
Figure 4.39: Results for all heights, for tumor position two using a monostatic system ant the SVD as the calibration method. (a) plane z. (b) plane x.

For image 4.39 (a), the same result is found comparing to position one. The tumor can nearly be identified close to the right position, but there is a lot of strong clutter present in the image. This result would, certainly, mislead the examiner. For image (b), the result is similar since the resolution is also really poor.

For position number three, the table 4.4 presents the \( q \) values for each one of the 8 antennas and for each one of the 6 heights.

Table 4.4: Values for \( q \) in a monostatic system using all the 6 heights for tumor position three.

<table>
<thead>
<tr>
<th>Measurement height [mm]</th>
<th>z=-29.8</th>
<th>z=-34.5</th>
<th>z=-39.5</th>
<th>z=-44.5</th>
<th>z=-49.5</th>
<th>z=-54.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna 1</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
</tr>
<tr>
<td>Antenna 2</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
</tr>
<tr>
<td>Antenna 3</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
</tr>
<tr>
<td>Antenna 4</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
</tr>
<tr>
<td>Antenna 5</td>
<td>q=2</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
<td>q=1</td>
<td>q=2</td>
</tr>
<tr>
<td>Antenna 6</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
</tr>
<tr>
<td>Antenna 7</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=3</td>
<td>q=3</td>
</tr>
<tr>
<td>Antenna 8</td>
<td>q=2</td>
<td>q=2</td>
<td>q=3</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
</tr>
</tbody>
</table>

As it is possible to confirm, save for a few exceptions, the antennas that have the lower values for \( q \) are the antennas 2 and 3. It is important to refer that the antenna 6 also contributes a lot for the final image. This result was not expected since the antennas, which are closer to the tumor position three, do not have much influence in the reconstructed image. After combining all this values, the obtained results are presented in figure 4.40.
Figure 4.40: Results for all heights, for tumor position three using a monostatic system and the SVD as the calibration method. (a) plane z. (b) plane x.

For image 4.40 (a), the tumor can be identified. Regarding the clutter, it is possible to verify that there is much less compared with the images for the other two tumor positions. For image (b), despite being also really poor, the resolution for this tumor position is better comparing to the other two.

In order to extend the research, the next step was to study the behaviour of the multistatic signals when submitted to the SVD. In this analysis, only the transmission coefficients from adjacent antennas were used since these are the ones that have the most influence. This happens because as the antennas are closer, the signal trip is shorter so the signal arrives at the target antenna less degraded. Following this explanation, the coefficients that were used were S12, S23, S34, S56, S67, S78. The 4 antennas of the used setup originate three coefficients from adjacent antennas as it is possible to observe in figure 4.17. The three other were obtained in the measurements made by rotating the antennas, as it was referred in the beginning of this section.

According to the positions of the tumor, for tumor position one the signal that is expected to contribute the most is S78, for tumor position two the signal is S34 and lastly, for tumor position three the signal is S23.

For position number one, the table 4.5 presents the \( q \) values for each one of the 6 signals and for each one of the 6 heights.

Table 4.5: Values for \( q \) using only the transmission coefficients for all the 6 heights for tumor position one.

<table>
<thead>
<tr>
<th>Measurement height [mm]</th>
<th>z=29.8</th>
<th>z=34.5</th>
<th>z=39.5</th>
<th>z=44.5</th>
<th>z=49.5</th>
<th>z=54.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antennas 1-2</td>
<td>q=3</td>
<td>q=4</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
<td>q=1</td>
</tr>
<tr>
<td>Antennas 2-3</td>
<td>q=1</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=4</td>
</tr>
<tr>
<td>Antennas 3-4</td>
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<td>q=4</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
</tr>
<tr>
<td>Antennas 5-6</td>
<td>q=1</td>
<td>q=3</td>
<td>q=4</td>
<td>q=2</td>
<td>q=4</td>
<td>q=2</td>
</tr>
<tr>
<td>Antennas 6-7</td>
<td>q=3</td>
<td>q=2</td>
<td>q=1</td>
<td>q=1</td>
<td>q=4</td>
<td>q=3</td>
</tr>
<tr>
<td>Antennas 7-8</td>
<td>q=3</td>
<td>q=4</td>
<td>q=4</td>
<td>q=3</td>
<td>q=3</td>
<td>q=3</td>
</tr>
</tbody>
</table>

As it is possible to confirm there is not a defined standard for the most influence signals since they
vary a lot from height to height. However, it is possible to affirm that the signal with the lower $q$ values is $S_{12}$. Moreover, it is important to refer that the signal $S_{78}$ almost does not contribute in the image reconstruction. This result does not go along with the expected one since the antennas seven and eight are the ones closer to the tumor. After combining all this values, the obtained results are presented in figure 4.41.

![Figure 4.41](image)

For image 4.41 (a), the tumor can barely be identified due to the lack of intensity. Regarding the clutter, it is possible to verify that there is some near the tumor position. For image (b), the result is similar since the resolution is also really poor.

For position number two, the table 4.6 presents the $q$ values for each one of the 6 signals and for each one of the 6 heights.

<table>
<thead>
<tr>
<th>Measurement height [mm]</th>
<th>$z=-29.8$</th>
<th>$z=-34.5$</th>
<th>$z=-39.5$</th>
<th>$z=-44.5$</th>
<th>$z=-49.5$</th>
<th>$z=-54.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antennas 1-2</td>
<td>$q=4$</td>
<td>$q=4$</td>
<td>$q=4$</td>
<td>$q=4$</td>
<td>$q=1$</td>
<td>$q=2$</td>
</tr>
<tr>
<td>Antennas 2-3</td>
<td>$q=2$</td>
<td>$q=2$</td>
<td>$q=2$</td>
<td>$q=3$</td>
<td>$q=3$</td>
<td>$q=1$</td>
</tr>
<tr>
<td>Antennas 3-4</td>
<td>$q=3$</td>
<td>$q=2$</td>
<td>$q=2$</td>
<td>$q=3$</td>
<td>$q=2$</td>
<td>$q=2$</td>
</tr>
<tr>
<td>Antennas 5-6</td>
<td>$q=4$</td>
<td>$q=2$</td>
<td>$q=2$</td>
<td>$q=2$</td>
<td>$q=2$</td>
<td>$q=4$</td>
</tr>
<tr>
<td>Antennas 6-7</td>
<td>$q=3$</td>
<td>$q=4$</td>
<td>$q=4$</td>
<td>$q=3$</td>
<td>$q=4$</td>
<td>$q=4$</td>
</tr>
<tr>
<td>Antennas 7-8</td>
<td>$q=4$</td>
<td>$q=3$</td>
<td>$q=4$</td>
<td>$q=4$</td>
<td>$q=4$</td>
<td>$q=4$</td>
</tr>
</tbody>
</table>

As it happened in tumor position one, the dominant signals vary a lot from height to height. In tumor position two, the one which is consistently the strongest is $S_{23}$. This does not go according to what was expected. However, the signal $S_{34}$ also contributes a lot to the reconstruction of the image, since the antennas 3 and 4 are the one closest to the tumor. After combining all this values, the obtained results are presented in figure 4.42.
Figure 4.42: Results for all heights, for tumor position two with SVD as the calibration method using only the transmission coefficients. (a) plane z. (b) plane x.

For image 4.42 (a), the tumor can be identified with almost no clutter. For image (b), the result is similar to the one presented, for position one, since the resolution is also really poor.

For position number three, the table 4.7 presents the $q$ values for each one of the 6 signals and for each one of the 6 heights.

Table 4.7: Values for $q$ using only the transmission coefficients for all the 6 heights for tumor position three.

<table>
<thead>
<tr>
<th>Measurement height [mm]</th>
<th>z=-29.8</th>
<th>z=-34.5</th>
<th>z=-39.5</th>
<th>z=-44.5</th>
<th>z=-49.5</th>
<th>z=-54.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antennas 1-2</td>
<td>q=2</td>
<td>q=2</td>
<td>q=3</td>
<td>q=2</td>
<td>q=2</td>
<td>q=2</td>
</tr>
<tr>
<td>Antennas 2-3</td>
<td>q=2</td>
<td>q=3</td>
<td>q=4</td>
<td>q=2</td>
<td>q=4</td>
<td>q=3</td>
</tr>
<tr>
<td>Antennas 3-4</td>
<td>q=3</td>
<td>q=3</td>
<td>q=2</td>
<td>q=1</td>
<td>q=1</td>
<td></td>
</tr>
<tr>
<td>Antennas 5-6</td>
<td>q=2</td>
<td>q=3</td>
<td>q=3</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
</tr>
<tr>
<td>Antennas 6-7</td>
<td>q=1</td>
<td>q=3</td>
<td>q=4</td>
<td>q=3</td>
<td>q=2</td>
<td>q=2</td>
</tr>
<tr>
<td>Antennas 7-8</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
<td>q=4</td>
<td>q=3</td>
<td></td>
</tr>
</tbody>
</table>

For tumor position three, the values of $q$ also vary a lot from height to height. In this case, the signal that contributes the most to the image reconstruction is S12. The antennas 1 and 2 are near the tumor, so this result was expected. However, the signal that should be the strongest, which is S23, almost does not contribute to the final result. It is important to refer that signal S34 also takes a big part in the image reconstruction. After combining all this values, the obtained results are presented in figure 4.43.
Figure 4.43: Results for all heights, for tumor position three with SVD as the calibration method using only the transmission coefficients. (a) plane z. (b) plane x.

For image 4.42 (a), the tumor can be identified with some clutter around. For image (b), the result is similar comparing with the other tumor positions since the resolution is also really bad.

By analyzing the tables, it is possible to conclude that for each tumor position the \( q \) values for the same antenna differ from height to height. This is more clear in the transmission coefficients. The variation of the height makes the path of the microwaves different. Thus, depending on the position of the antenna, the waves focus on different places and can reflect the tumor with more intensity in some cases and less intensity in other cases. This demonstrates the sensibility of this calibration method.

As it was already referred, the tumor is located at a \( z \) coordinate of -30mm and the results that are presented are obtained using that same plane. However, as it is possible to verify, the intensity of the tumor, shown in the images from the \( z \) plane, is not very high. This is related to the fact that the poor resolution spreads the tumor and the highest intensities can be observed in lower heights. Regarding, the images taken from plane \( x \), in the monostatic system, it can be observed that for position one the \( x \) plane with the highest intensity is 10mm, for position two is -20mm and for position three is 10mm. For the transmission coefficients, in the \( x \) plane, for position one with the highest intensity is 10mm, for position two is -10mm and for position three is 10mm. Taking into account that the real position for tumors one, two and three are 5mm, -10mm and 10mm respectively, it is possible to conclude that there was a considerable deviation from the real position of the tumor in position one and two. This deviation can be seen in the images from plane \( z \) since the position of the detected tumor are not exactly equal to the real position.

As far as the intensity of the image is concerned, the monostatic system has much higher intensities since it has more coefficients and their energy is larger. Specifying for each tumor position, the lowest is for position two since this position is the closest one from the curved wall as it was already referred. This result goes along with the one that was expected. Furthermore, the intensity of the tumor in position three in the monostatic system is really high. By analyzing table 4.4, it is possible to verify that the values for \( q \) are mostly one and two. Therefore, as there are less values eliminated until the tumor response is found, the intensity should be really high. This happens because position three is the one that is closest
to the center, meaning, the tumor is less close to the phantom wall. Since the SVD calibration method works by eliminating signals, the possibility of the power reflected by the tumor being mixed with the one reflected by the phantom wall is lower. Therefore, it is easier to separate the tumor signal from the wall signal. However, for the transmission signals this does not happen.

The results that are going to be presented next were obtained with the measurements using the FR4 antennas. The method to obtain these results was equal to the one described for the teflon antennas.

The first set of results were made using only the reflection coefficients of the 8 antennas.

The table 4.8 presents the \( q \) values for tumor position one for the 8 antennas. The values are presented for only one height, \( z=-30\text{mm} \).

Table 4.8: Values for \( q \) in a monostatic system using one height \((z=-30\text{mm})\) for tumor position one.

<table>
<thead>
<tr>
<th>Antenna Number</th>
<th>( z=-30\text{mm} )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>q=1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>q=4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>q=2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>q=2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>q=1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>q=2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>q=4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>q=1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As it is possible to gauge the antennas 1 and 8 have a lot of influence in the reconstruction of the image, as it was expected. However, antenna 7, which should have a lot of influence, since it is near the tumor, almost does not contribute to the reconstruction of the image. On the other hand, antenna 5 has a lot of influence, which was not expected, given its position in the antennas’ ring. After combining all the values for \( q \), the resultant image is presented in figure 4.44

![Figure 4.44: Results for one height \((z=-30\text{mm})\), for tumor position one using a monostatic system and the SVD as the calibration method. (a) plane \( z \). (b) plane \( x \).](image)

By the analysis of the results in the \( z \) plane, picture (a), it is possible to conclude that it is possible to detect the tumor, but there is some clutter in the image that may mislead the examiner. For the plane \( x \), picture (b), it can be verified that the resolution is really poor, since the tumor is spread through the \( z \) axis.

For tumor position two, table 4.9 presents the \( q \) values for the 8 antennas. The measurement was taken only for one height, \( z=-30\text{mm} \).

63
Table 4.9: Values for $q$ in a monostatic system using one height ($z=-30\text{mm}$) for tumor position two.

<table>
<thead>
<tr>
<th>Antenna Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z=-30\text{mm}$</td>
<td>$q=3$</td>
<td>$q=1$</td>
<td>$q=2$</td>
<td>$q=3$</td>
<td>$q=3$</td>
<td>$q=2$</td>
<td>$q=3$</td>
<td>$q=3$</td>
</tr>
</tbody>
</table>

From table 4.9, it is possible to verify that the antenna with more influence is the antenna 2, but the antennas 3 and 4 do contribute a lot as well for the reconstruction of the image. This result is somehow expected, since these are the antennas that are closer to the tumor position two. However, it was expected that antenna 4 had more influence than antenna 2. After combining these values for $q$, the result which was obtained is presented in figure 4.45.

![Figure 4.45](image)

Figure 4.45: Results for one height ($z=-30\text{mm}$), for tumor position two using a monostatic system and the SVD as the calibration method. (a) plane $z$. (b) plane $x$.

After the analysis of the images, it can be concluded that, for the plane $z$, picture (a), the tumor can be detected. However, the tumor is slightly deviated from its theoretical position and there is some clutter present in the image. For the plane $x$, picture (b), the resolution is really bad as it can be verified.

For position number three, the table 4.10 presents the $q$ values for each one of the 8 antennas. The result is presented for one height, $z=-30\text{mm}$.

Table 4.10: Values for $q$ in a monostatic system using one height ($z=-30\text{mm}$) for tumor position three.

<table>
<thead>
<tr>
<th>Antenna Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z=-30\text{mm}$</td>
<td>$q=1$</td>
<td>$q=1$</td>
<td>$q=4$</td>
<td>$q=2$</td>
<td>$q=3$</td>
<td>$q=4$</td>
<td>$q=4$</td>
<td>$q=4$</td>
</tr>
</tbody>
</table>

According to the values from table 4.10 the antennas that have more influence are 1, 2 and 5. Regarding these results, the $q$ values for antennas 1 and 2 are adequate comparing to what was expected. However, the values for antenna 3 and 5 were not expected. Antenna 3 is close to the tumor and has almost no influence in the reconstructed image. Antenna 5 is a little more away from the tumor and has a lot of influence. In figure 4.46, it is possible to observe the results for the combination of the $q$ values.
Figure 4.46: Results for one height (\(z=-30\text{mm}\)), for tumor position three using a monostatic system and the SVD as the calibration method. (a) plane \(z\). (b) plane \(x\).

From this figure, it is possible to conclude that for plane \(z\), picture (a), there is a spot that may represent the tumor near its theoretical position. However, it cannot be detected since the intensity of the clutter is almost equal to the one from the tumor, which would mislead the examiner. For the plane \(x\), picture (b), the resolution is also really poor for this position tumor.

As well as it was made for the teflon antennas, in order to extend the research the transmission coefficients were also analyzed with the SVD. The only transmission signals used to reconstruct the images were the ones that come from adjacent antennas, as it was explained before. For the FR4 antennas, the setup had a ring of 8 antennas, contrary to the teflon antennas. Therefore, the used signals were the S18, S12, S32, S34, S54, S56, S76 and S78.

The signals that should have more influence in the reconstruction of the image are equal to the ones referenced for the teflon antennas. For tumor position one the signal is S78, for tumor position two the signal is S34 and finally, for tumor position three the signal is S23.

For the tumor position one, table 4.11 shows the \(q\) values for the 8 antennas. The measurements were made only for one height, \(z=-30\text{mm}\).

<table>
<thead>
<tr>
<th>Adjacent Antennas Numbers</th>
<th>1-8</th>
<th>1-2</th>
<th>3-2</th>
<th>3-4</th>
<th>5-4</th>
<th>5-6</th>
<th>7-6</th>
<th>7-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>(z=-30\text{mm})</td>
<td>q=4</td>
<td>q=1</td>
<td>q=2</td>
<td>q=4</td>
<td>q=1</td>
<td>q=1</td>
<td>q=4</td>
<td>q=4</td>
</tr>
</tbody>
</table>

After analyzing table 4.11, it is possible to conclude that the results were not expected. The signals that were supposed to have a higher \(q\) values, S78 and S18, almost do not contribute to the signal reconstruction. On the other hand, signals that should have lower \(q\) values, like S54 and S56, have high values leading to a strong influence in the final image. Figure 4.47 presents the results after combining these values.
Figure 4.47: Results for one height (z=-30mm), for tumor position one with SVD as the calibration method using only the transmission coefficients. (a) plane z. (b) plane x.

As it is possible to verify, for plane z, picture (a), the detection of the tumor cannot be achieved, since there is a lot of clutter with the same intensity as the tumor in the image. For the plane x, picture (b), the resolution is really poor for the transmission coefficients as well.

Table 4.12 presents the \( q \) values of tumor position two for the 8 antennas, using one height, z=-30mm.

Table 4.12: Values for \( q \), for one height (z=-30mm), in a multistatic system using only the transmission coefficients for tumor position two.

<table>
<thead>
<tr>
<th>Adjacent Antennas Numbers</th>
<th>1-8</th>
<th>1-2</th>
<th>3-2</th>
<th>3-4</th>
<th>5-4</th>
<th>5-6</th>
<th>7-6</th>
<th>7-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>z=-30mm</td>
<td>q=4</td>
<td>q=2</td>
<td>q=1</td>
<td>q=2</td>
<td>q=2</td>
<td>q=3</td>
<td>q=4</td>
<td>q=3</td>
</tr>
</tbody>
</table>

As it is possible to confirm from this table, the results are somehow expected. However the signal S34, which is the one that joins the antennas that are closer to the tumor in position two, should have the highest influence in the image reconstruction. Moreover, the signal S32 was expected to have a little less influence in the final image, lower influence comparing to the signal S34. Figure 4.48, combines all the values presented in table 4.12.
For tumor position two, the results are quite similar to the ones obtained for tumor position one. For the plane z, picture (a), it is not possible to detect the tumor since there is clutter with the same intensity comparing to the tumor, in the image. For plane x, picture (b), the resolution is bad as well.

For position number three, the table 4.13 presents the $q$ values for each one of the 8 signals and for one height, $z=-30\text{mm}$.

Table 4.13: Values for $q$, for one height ($z=-30\text{mm}$), in a multistatic system using only the transmission coefficients for tumor position three.

<table>
<thead>
<tr>
<th>Adjacent Antennas Numbers</th>
<th>1-8</th>
<th>1-2</th>
<th>3-2</th>
<th>3-4</th>
<th>5-4</th>
<th>5-6</th>
<th>7-6</th>
<th>7-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z=-30\text{mm}$</td>
<td>$q=3$</td>
<td>$q=2$</td>
<td>$q=2$</td>
<td>$q=4$</td>
<td>$q=2$</td>
<td>$q=2$</td>
<td>$q=4$</td>
<td>$q=3$</td>
</tr>
</tbody>
</table>

As far as tumor position three is concerned, these results were expected in a certain way since the signals from the antennas that are nearer to the tumor have high values for $q$. However, signals from antennas that are a little further away also have a lot of influence, like S54 and S56. Figure, 4.49 presents the combination of the values from table 4.13.
After analyzing figure 4.49, it is possible to conclude that for plane z, picture (a), it is impossible to detect the tumor. The image seems to have only clutter. For the plane x, picture (b), the resolution is still quite poor.

Regarding the images taken from plane x, in the monostatic system, in the x plane, it can be observed that for position one the highest intensity is for 5mm, for position two is for 0mm and for position three is for 5mm. For the transmission coefficients, for position one the highest intensity is for 20mm, for position two is for -15mm and for position three is for 15mm. Taking into account that the real position for tumors one, two and three is 5mm, -10mm and 10mm respectively, it is possible to conclude that there is a considerable deviation from the real position of the tumor in position two and three. This deviation can be seen in the images from plane z since the position of the detected tumor are not exactly equal to the real position.

As far as the intensity is concerned, as it was verified for the teflon antennas, the monostatic results have a higher intensity. This happens since the reflection coefficients have more energy due to their shorter routes. As the transmission coefficients go through the air more time, the signal loses more power because of the air attenuation. Continuing in the monostatic system, tumor two is the one with less intensity. This was expected due to curvature of the phantom as it was already explained in other occasions. For the multistatic system, using only the transmission coefficients, the results were not expected, since tumor position three is the one with the less intensity. This is explained since there are no $q$ values that are one. Therefore, most of the intensity is eliminated as the $q$ value decreases.

The results for the FR4 antennas are not much significative since they were obtained using only one height. In the heterogeneous model, the results for each height are irregular due to the similarity between the dielectric properties of the tumor and the fibroglandular tissues. Therefore, it is necessary to analyze several heights in order to make the signals converge to a certain position and eliminate the surrounding clutter.

The last step is to obtain the results with the full multistatic system. It is important to refer that the analysis of the neighbours for this system was separated in reflection coefficients and transmission
coefficients. This means that, although all the coefficients were analyzed simultaneously, the reflection coefficients' neighbours were reflection coefficients and the transmission coefficients' neighbours were transmission coefficients.

The results of the combination of the coefficients from the tables of the reflection and the transmission coefficients, using teflon antennas, are presented below. In figure 4.50, it is presented the reconstruction of the image for each tumor position in the plane z and in figure 4.51 the same result is shown, but for the plane x.

![Figure 4.50](image1)

Figure 4.50: Results for all heights using a multistatic system in plane z with SVD calibration with teflon antennas. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.

![Figure 4.51](image2)

Figure 4.51: Results for all heights using a multistatic system in plane x with SVD calibration with teflon antennas. (a) Tumor 1. (b) Tumor 2. (c) Tumor 3.

As it is possible to verify, it is possible to detect the tumor with some clutter around for plane z. Regarding the plane x, the resolution did not improve so much.

The results of the combination of the coefficients from the tables of the reflection and the transmission coefficients, using FR4 antennas, are presented below. In figure 4.52, it is presented the reconstruction of the image for each tumor position in the plane z and in figure 4.53 the same result is shown, but for the plane x.
After analyzing the image, the tumor can be detected for each position. However, there is some clutter surrounding the tumor. As far as the plane x is concerned, the combination of the coefficients did not improve the resolution.

Since the monostatic system was predominant comparing to the transmission coefficients, given the discrepancy in the intensity between the results, it was expected that the results for the multistatic system should be similar to the ones obtained for the monostatic setup. By comparing the images from the z plane, it is possible to verify this. However, as the images obtained from the transmission coefficients have clutter in different areas and the tumor in the same place, when both types of coefficients are combined the clutter is attenuated, and the tumor is enhanced. As far as the x plane is concerned, the resolution did not improve much in the multistatic setup. Thus, it can be concluded that it is necessary to take measurements in several heights in order to restrict the tumor to its real position.

Relatively to all the results obtained with the SVD, it is important to refer that this method is still imprecise. Sometimes, using a certain value for $q$, the signal would appear in the theoretical position of the tumor. However, it is impossible to know, if that specific signal corresponds to the tumor or, by coincidence, the signal reflected from the fibroglandular tissues happened to appear in that position. Other times, none of the signals appeared in the tumor position, which could mean that a certain value of $q$ that meant to eliminate the reflected signal from the fibroglandular tissues or the phantom wall, could have eliminated the signal reflected from the tumor as well. For an homogeneous model, tests were already made and the detection of the tumor was really easy to obtain, which means that this
algorithm works well. However, it is important to overcome the difficulty introduced by the fibroglandular tissues.

Finally, regarding all the results presented above, it is important to say that some inconsistencies might have influenced the final results. The distance between the antennas and the phantom were not totally right since the phase center of the antennas vary from antenna to antenna and also vary with the frequency. Besides, the distance introduced by each antenna is different. Both these factors were not taken into account.
Chapter 5

Conclusion and Future Work

5.1 Conclusions

Microwave imaging for breast detection is increasing the quality and the confidence in this imaging method is becoming higher. There are a lot of setups for this end, and Instituto de Telecomunicações (IT)-Instituto Superior Técnico build his own as well.

The setup and its automation is almost finished since the measurements can be made using the Graphical User Interface. After this step, IT’s setup might be used in clinical trials.

Regarding the measurements, it was possible to conclude that is possible to detect the tumor using both types of calibration. Moreover, the combination of both types of coefficients is important in order to nullify the clutter and enhance the tumor response.

5.2 Future Work

Regarding the future work, there are a lot of steps to be taken in order to conclude the project. In the first place, it is necessary to add, to the setup, the electronic circuit that connects the GPIO pin of the Raspberry Pi to the switch. This is the final step to full automate the setup. As far as the measurements with the FR4 antennas are concerned, it is necessary to take them in several heights in order to improve the resolution in the x plane. Moreover, it would be interesting to put the tumor inside the fibroglandular tissues to gauge if it is possible to detect it. Finally, the algorithm to reconstruct the image using the SVD calibration should be capable of choosing, automatically, the value for $q$, which resulting signal, represents the tumor.
Bibliography


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