Systems for Breast Tumor Detection Using Microwave Imaging

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
Dedicated to Cristina and Ricardo.
Acknowledgments

This work was hosted by Instituto de Telecomunicações that provided the conditions to develop this thesis, including the computational and laboratory resources.

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Abstract

Breast cancer is the most prevailing form of cancer among women. However, conventional preliminary diagnoses are harmful, painful, time consuming and money costly for mass population screening. These drawbacks motivated the research for alternatives for early detection of breast cancer. This thesis proposes and demonstrates a breast cancer detection system based on microwave radiation. The thesis includes two main correlated topics: de-embedding of dielectric properties of biological tissue samples, and microwave imaging. The first topic is based on the open-ended coaxial cable method. We numerically studied its sensitivity with well-known characterized samples, and experimentally measured the permittivity of animal tissues and some liquid mixtures that mimic the breast. Two of them have similar properties of tumor and fat, which constitute our breast phantoms for the second part of the work. The second topic concerns microwave imaging to extract the tumor response from the breast phantoms. To this end, a modified broadband Vivaldi antenna was designed and tested, both alone and in a circular array configuration. The experimental results corroborate the numerical results, which show an image improvement when using multiple antennas and selecting specific links between them. In order to ease the equipment handling, an user-friendly graphical interface was also developed to automate the measurement procedure. Also a switching circuit was designed and fabricated to allow multiple antenna management.

Keywords: Breast cancer, complex permittivity measurement, microwave imaging, broadband antenna, switching network, measurement setup.


**Resumo**

O cancro da mama é a forma mais prevalente de cancro entre as mulheres. No entanto, os diagnósticos preliminares convencionais são prejudiciais, dolorosos, demorados e caros para a maioria da população. Estas desvantagens motivaram a pesquisa de alternativas para a deteção precoce do cancro da mama. Esta tese apresenta um sistema de deteção de cancro da mama baseado em radiação microondas. A tese inclui dois tópicos principais correlacionados: extração das propriedades dielétricas das amostras, e imagens por microondas. O primeiro tópico prende-se ao estudo do método de cabo coaxial em aberto. Estudámos numericamente a sua sensibilidade com amostras bem caracterizadas e medimos experimentalmente a permitividade de tecidos animais e algumas misturas líquidas que simulam as propriedades da mama. Duas delas têm propriedades semelhantes às do tumor e da gordura, que constituem o modelo fictício da mama para a segunda parte do trabalho. O segundo tópico diz respeito a imagens por microondas para extrair a resposta do tumor da mama fictícia. Para isso, uma antena Vivaldi de banda larga modificada foi projetada e testada, tanto sozinha como numa configuração de matriz circular. Os resultados experimentais corroboram os resultados numéricos, que mostram uma melhoria da imagem ao utilizar múltiplas antenas e selecionar determinadas ligações entre elas. Para facilitar o manuseio do equipamento, uma interface gráfica intuitiva também foi desenvolvida para automatizar o processo de medição. Além disso, um circuito de comutação foi projetado e fabricado para permitir a gestão de várias antenas.

**Palavras-chave:** Cancro da mama, medição de permitividade complexa, imagens por microondas, antena de banda larga, rede de comutação, demonstrador de medida.
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Acronyms

**BAVA** Balanced Antipodal Vivaldi Antenna.

**CABAVA** Circular Array Balanced Antipodal Vivaldi Antenna.

**CST** Computer Simulation Technology.

**DAS** Delay and Sum.

**DC** Direct current.

**GUI** Graphical User Interface.

**MRI** Magnetic Resonance Imaging.

**MUT** Material Under Test.

**MWI** Microwave Imaging.

**OC** Open-circuit.

**PCB** Printed Circuit Board.

**PLA** Polylactide acid.

**RM** Reference material.

**SC** Short-circuit.

**SMA** SubMiniature version A.

**SUT** Sample under test.

**TSAR** Tissue Sensing Adaptative Radar.

**USB** Universal Serial Bus.

**UWB** Ultra Wide-Band.

**VNA** Vector Network Analyzer.
Chapter 1

Introduction

1.1 Motivation and Objectives

Breast cancer is the most prevailing type of cancer among women and the second cause of death by cancer [1]. It is estimated that about 266 000 new cases will have breast cancer and about 40 000 cases of death by breast cancer in 2018 [1]. However, if the tumor is detected in an early-stage, the relative survival rate in 5 years after diagnosis is more than 90% [2]. Thus, women are subjected to regular screening examinations, in order to detect breast cancer in an early-stage and initiate the treatments. Within this framework, screening technologies must ensure reliable and effective detection of the tumor.

Nowadays, the most used methods in breast cancer detection are x-ray mammography, magnetic resonance imaging and ultrasound [3], which are described in the following bullet points:

- Mammography: X-ray procedure that allows visualization of the breast internal structure. Although mammography is not time consuming, it requires compressing the breast, in order to improve the quality of the image. This procedure is quite painful and causes patient distress. Moreover, mammography exposes the patient to ionizing radiation, which increases the risk of developing cancer. For dense breast tissues, the tumor may be masked due to low contrast between malignant and normal tissues, leading to false-positive test results and follow-up examinations. Despite these characteristics, mammography is considered the only screening technique compatible with mass population screening.

- Magnetic Resonance Imaging (MRI): MRI uses magnetic fields to produce high resolution images of the breast. MRI is currently used as a complementary technique to mammography, since it offers optimum resolution. However, it is expensive and longstanding, making it inadequate as primary screening technology. In addition, for some patients it is necessary to inject an intravenous liquids, in order to improve contrast in the produced images. This contributes to further extend the time MRI takes.

- Ultrasound: This method uses sound waves to reconstruct the internal structure of the breast. It is a painless examination and does not expose the patient to radiation, but shows small resolu-
tion. Also, an ultrasound exam takes a long time and its effectiveness depends on the operator responsible for the exam. Similarly to MRI, ultrasound is used as a complementary technology to mammography in cases a suspect mass is detected.

The drawbacks of the aforementioned screening methods, motivated the research for complementary breast imaging technologies.

In the last decades, microwave imaging has been drawing the attention from investigators in the biomedical field, as an alternative to conventional preliminary diagnoses, particularly for its non ionizing and painless nature, which poses no health risk and avoids breast compression, as well as the low costs associated. Figure 1.1 illustrates the patient position during an examination. The patient lays prone on the bed, and the breast extends through a circular gap. The antennas are positioned around the breast, radiating microwave energy and recording the backscatters from within breast.

![Figure 1.1: Patient in prone position in the bed, with the breast pending in the circular gap and the antennas around it to examine the breast [4].](image)

Microwave Imaging (MWI) relies on the contrast between healthy tissues and the tumor. Several studies in the literature show an existing contrast between dielectric properties of malignant and surrounding tissues [5–7], which motivated the use of microwave radiation. Malignant tissues have higher density and water content than fat tissues. The difference in permittivity causes the backscattering of microwave energy that is picked up by sensors distributed around the breast. From these echoes and using adequate signal processing algorithms, it is possible to reconstruct an image of the breast tissues. Additionally, microwaves offers a good compromise between energy attenuation that can propagate through large breast volumes.

MWI is categorized as passive and active. The first [8], also called thermography, concerns the measurement of thermal radiation emitted by the breast and mapping the temperature distribution of the breast. By analyzing the thermal image of the breast, one may identify peak temperatures that are interpreted as large activity volumes corresponding to tumors. However, the power level emitted by tumor is low and hard to detect, and even the environment temperature can interfere with the radiometer.

Active MWI uses active antennas that radiate energy towards the breast and collect the signals originated inside it. In the field of MWI, it is common to categorize active MWI as tomography and radar-based.

Microwave tomography aims at reconstructing the breast profile based on dielectric properties, using non-linear inversion algorithms. Due to the non-linearity and ill-posedness of the problem, the inversion
algorithms are very time-consuming as well as heavy computationally, which limits their clinical utility as primary screening technology. Alternatively, radar-based MWI aims at the detection of significant scatterers (e.g. breast tumor). Contrarily to tomography, it involves a linear problem and much faster computational signal processing.

Radar is a technique first developed for military ground penetrating applications, and it has been proposed to medical imaging field approximately 20 years ago. Moreover, Ultra Wide-Band (UWB) radar microwave imaging overcomes the computational challenges of microwave tomography.

For these reasons, radar-based MWI is an attractive method for breast cancer detection, overcoming limitations of traditional detection methods.

The primary goal of this dissertation is to develop a complete functional demonstrator, resembling the envisioned examination posture. A further objective is to evaluate the sensitivity of a complex permittivity measurement technique, widely used for tissue characterization. In this context, the work comprehends the following tasks:

- Numerical design and study of a single antenna element for the breast scanning setup. Among the existing antennas for MWI, we aim at designing one with small dimensions, without degrading its performance;
- Numerical analysis of a circular distribution of 8 antennas around the breast. Increasing the number of antennas leads to an increase in mutual coupling, which we intend to minimize;
- Automation of the configuration and measurement procedure, which includes improving interaction with a Vector Network Analyzer (VNA), and designing a Printed Circuit Board (PCB) for switching between the antennas;
- Fabrication and experimental assessment of the demonstrator, including hardware components and signal processing;
- Development of a graphical interface that resembles the final application to be used by the medical team in a real examination. This code is intended to control the measurement procedure, data acquisition and signal processing.

In order to develop a complete functional demonstrator, we need to study the electromagnetic properties of tissues, since radar-based MWI is based on the difference between dielectric properties of malignant and surrounding tissues. Since we are performing the experiments in lab environment, we resort to breast phantoms to mimic the electromagnetic behaviour of breast tissues. Breast phantoms need to be characterized with a permittivity estimation method, which we chose to be the open-ended coaxial cable method [9]. Moreover, another goal of this dissertation is to gain experience with the open-ended coaxial cable method in order to measure dielectric properties of biological tissues. Thus, dielectric properties characterization involves the following procedures:

- Numerical and experimental study of the open-ended coaxial cable technique, with particular emphasis on the required tissue sample;
Implementation and validation of the signal processing that allows de-embedding the dielectric properties.

The development of the demonstrator for microwave breast imaging relies on the production and characterization of phantoms for experimental assessment. However, we will give emphasis to the study of the permittivity estimation method and, therefore, we will address both topics in different sections from this point onward.

1.2 State of the Art

1.2.1 Dielectric Properties of Tissues

There are two types of materials we are going to deal with: real tissues, and phantom mixtures. These mixtures mimic the dielectric properties of the tumorous and the normal tissues, which constitute our breast phantom. First, it is important to study the electrical properties of the real tissues, in order to characterize the phantom mixtures. The real tissues are semi-solid samples, while the phantom mixtures are liquids, and the methods for dielectric properties de-embedding need to be chosen accordingly to the types of samples.

Several research groups have studied the dielectric properties of breast tissues [5–7]. Malignant tissues show a higher relative permittivity relative to the normal tissues due to higher content of water. However, early studies used small samples of patients and a low frequency range. Later in 2007, Wisconsin University and Calgary University together have carried out a first large-scale study of dielectric properties of malign, benign and normal tissues, obtained from breast reduction surgeries [10, 11]. Both studies were performed with the open-ended coaxial probe method, in the measurement frequency range from 0.5 GHz up to 20 GHz.

Several methods are used in order to determine the complex permittivity of a sample, such as transmission/reflection line method [12], resonant method [13], open-ended coaxial probe method [14, 15] and free space method [16]. Each method presents its own advantages/disadvantages (e.g. frequency bandwidth) and should be chosen accordingly to the dimensions and physical state of the samples.

The transmission/reflection line method [12] uses coaxial lines or waveguides to measure the complex permittivity of samples. The sample is placed in a section of the coaxial line or waveguide and the input reflection and transmission coefficients are measured with a VNA. The Sample under test (SUT) requires prior preparation in order to avoid air gaps between the sample holder and the sample. This method is suitable for lossy and low loss solid SUTs, in order to fit tightly in the gap section, at the cost of being sensitive to air gaps between the sample and waveguide/coaxial line, which may induce errors in the measurements.

The resonant method [13] is one of the most accurate methods to measure permittivity of samples. There are several types of resonant techniques such as Fabry-Perot resonator, cavity resonator, split cylinder resonator and reentrant cavity. There are two types of resonant measurements: perturbation method, which is suitable for small samples with high loss materials, and low loss measurement method,
which requires larger samples with low loss material. Dielectric properties can be obtained by monitoring changes on quality factor and resonant frequency. This method is suitable for solid and non-solid samples. However, only a single frequency can be measured for each sample.

The open-ended coaxial probe method [14, 15] is widely used for liquid and semi-solid samples, such as real tissues. It requires submersing the tip of the cable and measuring the reflection coefficient from which we de-embed the permittivity of SUT. This method requires the calibration of the probe. This is achieved by measuring the $S_{11}$ in three different scenarios: free-space, short-circuit and reference liquid with well known dielectric properties, in the end of the probe. It presents many advantages, such as simple construction, single measurement point, and it is broadband. The main limitation of this method is the formation of air gaps between the probe and the sample.

Free space method [16] is non destructive, broadband and contactless. It uses two antennas facing each other and the sample holder is placed between them. Scattering parameters are measured with empty sample holder and then with the Material Under Test (MUT) inside the sample holder. As a 2-port network, it is possible to measure the $S_{11}$ and the $S_{21}$ in order to determine complex permittivity. However, this method requires large and thin samples, it is suitable for high temperature materials and shows diffraction effects on the edges of the sample.

Among these methods, we must choose one able to measure the permittivity of any type of tissues. Thus, the open-ended coaxial probe was chosen for the study of dielectric properties of samples in this dissertation.

The main common challenge to the variety of methods in measuring the dielectric properties is tissue heterogeneity which makes it difficult to determine the exact range of dielectric properties of tissues. Of course, this is inherent to the samples but the errors introduced by this heterogeneity need to be mitigated.

### 1.2.2 Microwave Imaging for Breast Cancer Detection

Several research groups have studied microwave imaging methods for medical applications, such as breast cancer diagnosis. In these systems, the antennas play a very important role and their influence has to be taken into account in the designing process and calibration.

Broadband antennas with compact size, stable end-fire radiation patterns, wide impedance bandwidth and high gain are suitable for radar based microwave imaging. We can find in the literature different types of antennas for medical microwave imaging such as as dipole-based [17] and bowtie [18], though they lack stable radiation characteristics with frequency (e.g. changes in the shape of radiation pattern and shifts in the phase center). Horn antennas [19, 20] are also used for medical MWI, but their size limits the number of probes around the breast. Monopole antennas offer a space advantage when using multiple receiving/transmitting antennas. However, its isotropic radiation pattern does not satisfy the requisites of microwave imaging systems. The antennas used by Bristol University are a Staked-Patch and Wide-Slot antennas [21]. The Wide-Slot antenna has smaller dimensions, thus allowing to maximize the number of antennas. The antenna used by Calgary University is a Balanced Antipodal
Vivaldi Antenna (BAVA) with a director [22] placed in the antenna aperture, which increases antenna directivity.

Vivaldi antenna was first proposed by P. J. Gibson in 1979 [23]. Vivaldi antennas are good candidates for medical MWI due to their compact dimensions and fairly directive radiation patterns. Vivaldi is like a travelling-wave type antenna and has an exponential tapered profile, which provides large bandwidth and end-fire radiation patterns. Also, its simple construction, compact design and low costs associated makes the Vivaldi antenna suitable for microwave imaging methods. However, its significant large size is a limitation to systems which require multiple antennas. Thus, decreasing its dimensions represents a challenge, maintaining the bandwidth.

Meaney et al. from Dartmouth University developed in 2000 a clinical prototype of 16 monopole antennas which radiates to the breast positioned in the center of the circular antenna configuration [24]. Figure 1.2 shows an exam to a patient in prone position, and the antennas illuminating the breast. Although they are very simple, monopole antennas are inadequate for microwave breast imaging, since they show narrow bandwidth. The system measures at seven different antenna heights. For each height, the 16 antennas emit and receive the signals reflected by the breast and the total acquisition time for one breast is from 10 up to 15 minutes. Years later [25, 26], the Dartmouth group presented the first 3D microwave tomographic images, through a new developed prototype, which lowered the total acquisition time for 2 minutes. The prototype was used also in chemotherapy treatment to monitor the tumor response. The Dartmouth group also uses a saline coupling medium where the breast is immersed. Besides of being uncomfortable and lacking of hygiene, the saline fluid can mask the internal structure of the breast, due to its high relative permittivity and considerable reflections from the skin. Also, tomography is not suitable for MWI due to its computationally heavy requirements.

Figure 1.2: Photographs of a microwave exam in session [24]. (a) Close-up view. (b) The breast in position within the center of the antenna array.

In [27], tomography MWI is also used in the setup, with 16 custom antennas. An outer Plexiglas cylinder is filled by an homogeneous mixture, and a plastic tube is also included, filled with a different mixture of higher relative dielectric permittivity, as target under test. They use Delay and Sum (DAS) [28, 29]
as the reconstruction algorithm. DAS advantages are the simplicity, robustness and short computation
time, although DAS imposes limitations such as low resolution and worse clutter rejection capability.
This experimental setup uses a switching network to commute between the antennas and to be able to
use every possible antenna pair combination. Two different switching boards (1:4 and 2:4) operate in a
frequency range from 10 MHz up to 8 GHz.

Bristol University initially developed, in 2008, a 16 stacked-patch antenna multistatic radar system
positioned in a 4 by 4 hemispherical matrix [30]. Each antenna is connected through coaxial cables to
a switch system, to commute between the pairs of antennas during signal acquisition. The 120 trans-
mittance coefficients are acquired in the frequency domain with a VNA and then converted to the time
domain with the Inverse Fast Fourier Transform method. The time domain signals allow to reconstruct
the image through focusing algorithms. However, they use a regular geometry for the breast phantom,
which does not match the real breast case scenario. Later, the Bristol group developed a 31 UWB wide-
slot antenna system which uses a 2-port VNA and takes 90 seconds to examine a patient [31]. Later,
the system was improved to 60 antennas and uses an 8-port VNA [32]. The total acquisition time was
reduced to 10 seconds. The setup is shown in figure 1.3. Although the new acquisition time represented
a significant progress, the biggest challenge was to ensure a good fit between the ceramic cup and the
breast, in an attempt to avoid air gaps [31].

![Figure 1.3: Bristol University setup [32]. (a) Switching network between VNA and the antenna array. (b) 60-element antenna array.](image)

Calgary University developed a prototype based in monostatic radar system, the Tissue Sensing
Adaptative Radar (TSAR), which uses one BAVA antenna to examine the breast [33]. Figure 1.4 shows
the TSAR setup. The patient lies prone on the bed and the breast extends through a hole to a cylindrical
tank filled with canola oil. The use of an immersion liquid aims to improve the matching between the
sensor and the breast, but lacks of hygiene and causes patient discomfort. The antenna exams the
breast by rotating around it with the help of a mechanical arm, which moves vertically as well. The
data acquired is calibrated in order to remove skin reflections. However, the breast phantom used in the
setup is a very simple model and does not mimic the dielectric properties from the breast. This way, this approach cannot be replicated in real cases, contributing to deteriorate the results.

Figure 1.4: TSAR prototype system with dimensions [33]. (a) Top view. (b) Side view.

1.3 Thesis Structure

This dissertation is organized in four chapters, and each chapter is divided in two sections, regarding the two main topics to be addressed:

- Dielectric properties of samples;
- Microwave breast imaging.

Chapter 2 presents the formulation used to measure dielectric properties of tissues and microwave breast imaging. It starts by explaining the open-ended coaxial cable method used to measure dielectric properties of samples, followed by the explanation of the radar-based wave migration algorithm for breast cancer detection, in the frequency domain.

Chapter 3 presents the numerical results for the two main topics and, once more, this chapter is divided in two sections. The first one addresses the study of dielectric properties of samples which include probe design and simulated results. It is important to have in consideration the proper features to satisfy the requisites of the coaxial probe method, and to ensure good measurements and error mitigation. The second section includes the study of microwave breast imaging, starting by the antenna design, study of a circular configuration of antennas and simulation results in several cases. It also addresses the analytical design of a PCB, which acts as a switching network in an attempt to use an 8-port system.

Chapter 4 starts by presenting the experimental characterization of biological tissues and liquid samples, followed by the description of the new automatic measurement system. This system includes the measurement setup, including the breast phantom, as well as a new Graphical User Interface (GUI). A
GUI was developed in order to simplify equipment handling and calibration, but also to make the measurement procedure less time consuming. It is used in lab controlled environment but we are attempting to turn the interface into an application destined for real case scenarios, where a quick clinical response is required. Then, MWI experimental results are presented with two different antennas, a 1-port and a 4-port antenna, with follow-up discussion.

Finally, Chapter 5 draws the main conclusions of the work, which includes future work description.
Chapter 2

Analytical Formulation

This chapter discusses the analytical background necessary in the course of the thesis. Firstly, it addresses the open-ended coaxial probe, which we used for dielectric measurement of biological tissues and liquids. Secondly, this chapter presents the formulation of the imaging algorithm for the reconstruction of the reflectivity map of breast tissues. The algorithm shares similarities with radar-based techniques, although it is implemented in the frequency-domain. Moreover, besides the basic focusing principle of the algorithm, we kept in mind other issues that have a huge impact on target detection, such as the equivalent electrical distance introduced by the antenna.

2.1 Open-ended Coaxial Probe Method

The goal of this work regards prior evaluation of permittivity of normal and malignant tissues, such as tumors or lymph nodes, since we need to integrate this characterization in the image reconstruction process. Although the literature contains a lot of information about several relevant tissues, it is necessary to verify whether the substitution materials used in lab to mimic the dielectric properties of those tissues (phantoms), match the real ones. That is the goal of the method analyzed bellow.

The open-ended coaxial probe method has been found to be the most used method to measure the dielectric properties of tissues, and its theory is very well established in the literature [9, 14, 15, 34]. Its non-invasive nature, simple construction and independence on sample shape and volume, make this method attractive for permittivity measurement of biological samples. For instance, it is intended to get insight on how small can be the sample and still provide good permittivity results, with the same probe, and see how varies the permittivity along the working frequency. The information and experience gathered about this method will be used in future work regarding permittivity measurement.

In order to characterize the electrical properties of the tissues, we immerse the tip of the probe in the MUT and measure the reflection coefficient using a VNA. The electromagnetic field is extremely focused on the tip of the probe. In fact, it may be viewed as an open-ended transmission line, which means the energy is almost entirely reflected back to the port. Hence, when we place the MUT in the tip of the probe, the measured $S_{11}$ is directly related to the permittivity of the material. Figure 2.1 shows the probe...
immersed into the MUT.

Figure 2.1: Probe tip immersed in MUT [9].

Prior to de-embedding the electromagnetic properties of the MUT, it is necessary to calibrate the probe. In this regard, three standard calibration loads are placed at the end of the probe: short-circuit (SC), open-circuit (OC) and a reference material (RM). The errors in measurements may arise from uncertainties such as air gaps, inadequate short-circuit, and inadequate characterization and selection of reference material used as standard for calibration. It is crucial that the reference material is well characterized with known dielectric properties, which may include taking into account the variability with temperature.

The de-embedding of the dielectric properties is obtained through the combination of the measured $S_{11}$ in the three calibration scenarios: $S_{11}^{OC}$, $S_{11}^{SC}$, and $S_{11}^{RM}$, respectively. To this end, we compute $A_1$, $A_2$ and $A_3$ coefficients [9], given by

$$A_1 = \frac{(S_{11}^{OC} - S_{11}^{SC}) + (S_{11}^{SC} - S_{11}^{RM})(\varepsilon_{RM}' - j\varepsilon_{RM}'')}{S_{11}^{RM} - S_{11}^{OC}}, \quad (2.1)$$

$$A_2 = \frac{S_{11}^{RM}(S_{11}^{OC} - S_{11}^{SC}) + S_{11}^{OC}(S_{11}^{SC} - S_{11}^{RM})(\varepsilon_{RM}' - j\varepsilon_{RM}'')}{S_{11}^{RM} - S_{11}^{OC}}, \quad (2.2)$$

$$A_3 = S_{11}^{SC}. \quad (2.3)$$

where $\varepsilon_{RM}'$ and $\varepsilon_{RM}''$ are the real and imaginary parts of permittivity of the reference material.

The input reflection coefficient measured with the MUT at the tip of the probe, $S_{11}^{MUT}$, is related to $A_1$, $A_2$ and $A_3$ through,

$$S_{11}^{MUT} = \frac{A_2 + A_3(\varepsilon_{r}' - j\varepsilon_{r}'')}{A_1 + (\varepsilon_{r}' - j\varepsilon_{r}'')}, \quad (2.4)$$

Rearranging expression 2.4, the complex permittivity can be de-embedded as

$$\varepsilon_{r} = \varepsilon_{r}' - j\varepsilon_{r}'' = \frac{S_{11}^{MUT}A_1 - A_2}{A_3 - S_{11}^{MUT}}, \quad (2.5)$$

with no need for sample preparation and high sensitivity.
2.2 Imaging Algorithm

This sub-chapter formulates the imaging algorithm. The presented method is based on wave migration, which "back-propagates" the wavefront. Contrarily to radar systems, which are based on time signals, this algorithm accounts for the phase-delay of the propagating wave. It is also very time-efficient, but presents the advantage of being compatible with dispersive media, as we will show.

The signal transmitted by the antenna travels through the medium and encounters scatterers that reflect the signal back to the same antenna (in monostatic systems) or to a different antenna (bi- or multistatic system). The electric field expression as it propagates through a dielectric medium transition between two media is given by equation 2.6.

\[ E = E_0 e^{-2jk(n_1d_1+n_2d_2)} \]  

The phase of the received wave is \(-2k(n_1d_1 + n_2d_2)\), where \(k\) is the free-space wave number, \(n_1\) and \(d_1\) correspond to the refractive index and distance between the antenna and the end of medium 1, respectively, and \(n_2\) and \(d_2\) to the refractive index and distance from the beginning of medium 2 to the scatterer. The two media have different refractive index values and, consequently, different propagation velocities. Fig. 2.2 illustrates the monostatic radar system, with media transition.

The imaging algorithm considers a search space which contains the target, as shown in Fig. 2.3. The search space may not be completely embedded in the second dielectric medium, but part of it. We only need to keep in mind that the path between the antenna and the focal point may include media transition.

The algorithm assumes each test point \((x, y, z)\) as a potential scatterer. The location of the target is inferred by multiplying the measured reflection/transmission coefficient by the phase of the travelling wave between the Tx antenna, test point and Rx antenna, given the different velocity in the corresponding dielectric medium.

Figure 2.2: Monostatic radar principle, with media transition. The antenna transmits a signal which travels a certain distance \(d_1\) in the first dielectric medium with refractive index \(n_1\) and then \(d_2\) with refractive index \(n_2\), until it reaches the scatterer. The reflected signal then travels the reverse way and it is received by the antenna.
The location of the target is unknown. Thus, from equation 2.6, the reflected wave from the target is

$$E = E_0 e^{-2jk(n_1d_{t1} + n_2d_{t2})},$$

where $d_{t1}$ and $d_{t2}$ are the unknown distances travelled by the signal in dielectric media 1 and 2, respectively.

In order to obtain a detection of the target, the algorithm consists in, for every point $p$ of the search space, multiplying the phase of the reflected wave by the frequency dependent S-parameters, for each position of the antenna $a$, as shown in Eq. 2.8.

$$v(p) = \sum_{p=1}^{t_p} \sum_{a=1}^{t_a} S(a) * e^{2jk(n_1d_{s1}(a,p) + n_2d_{s2}(a,p))}$$

where $t_p$ and $t_a$ are the total number of points in the search space and the total number of antenna positions, respectively. $d_{s1}$ and $d_{s2}$ represent the distance between the antenna and the searching scatter point. $v(p)$ contains the final reflectivity map.

This phase cancellation represents the comparison between the target distances, $d_{t1}$ and $d_{t2}$, and the scanning distances, $d_{s1}$ and $d_{s2}$. When both the distances become equal, the phases cancel and the electric field is maximum, resulting in target detection. If the distances are different, the phases sum, meaning that there is no detection of the target. Thus, the imaging algorithm used is extremely computationally efficient and it is robust enough to overcome errors during the measurements.

In order to guarantee that the algorithm processes uniquely the target reflections, it is necessary to subtract a calibration measurement, since there are two issues which compromises the effectiveness of the imaging algorithm. The first issue regards setup influence, where the skin reflections can be twice the intensity of received signal from the tumor, leading to its masking. We can find some skin-removal techniques in the literature [35], but it is out of the scope of this thesis. Also, lab environment may influence negatively the results, which is eliminated when we subtract the calibration measurement. The second issue concerns the effects introduced by the antenna, such as the additional length introduced by the coaxial cables and the antenna itself. When the antenna is excited, the electric currents propagate...
on the antenna structure, from the feeding port until the electromagnetic energy is radiated. Thus, the distance the signals travel includes the propagation on the antenna structure, which needs to be accounted in the imaging signal processing. The simplest way to extract the electric distance $d_a$ is to place a metallic plane in front of the antenna, and subtract the physical distance between the metallic plane and the antenna $d_{mp}$, to the total distance $d$ obtained from the matched filter algorithm (explained below), as expressed in equation 2.9. Fig. 2.4 illustrates the extraction method of the electrical distance of the antenna.

$$d_a = d - d_{mp}$$  \hspace{1cm} (2.9)

Figure 2.4: Antenna electric distance extraction. A metallic plane is placed in front of the antenna at a $d_{mp}$ distance, which is subtracted to the $d$ distance seen by the antenna in order to obtain the equivalent distance $d_a$ of the antenna.

The matched filter algorithm consists in attributing the intensity of the reflected signals from the scatterer, to the location points of a space interval, starting from the antenna and containing the scatterer. For each point, we multiply several reflection coefficients (measured for the same number of frequencies) by the phase of the received wave $2\pi kd_i$, where $d_i$ corresponds to each location point. Thus, the location point to which corresponds the maximum intensity value, is the same location of the scatterer. The remaining points will have smaller reflection intensity, ideally null.

Another important feature of the antenna to keep in mind, since we are under the near-field condition, regards the stability of its phase center, but it is out of the scope of this dissertation, and we will not give emphasis the subject.

The subtraction of a calibration measurement is called ideal calibration and mitigates the negative effects previously described, in order to improve algorithm performance and, consequently, have better imaging results. Although it cannot be put in practice in realistic examinations, the aim of this work is the antenna characterization and the setup for MWI, and not image inversion algorithms, which can be implemented in the future.
Chapter 3

Numerical Results

This chapter addresses the numerical results of permittivity estimation using the open-ended coaxial probe, and microwave breast imaging. It is divided in two sections. In the first section, we start by designing an adequate numerical model of the probe in Computer Simulation Technology (CST) [36] Studio Suite from the different coaxial cables we have available in our lab, followed by a numerical study of the sensitivity of the probe concerning the sample size and permittivity. The second section presents the numerical results for microwave breast imaging, which starts by describing the antenna optimization steps with focus on the challenges of designing a broadband and low-profile antenna for microwave breast imaging. Secondly, the antenna influence on the imaging results is described, such as the antenna electric distance to be compensated in the reconstruction algorithm, as well as the influence of multiple elements on a circular configuration. Also in the second section, we present the imaging results based on numerical signal processing, considering measurement scenarios, and different antenna configurations.

3.1 Open-ended Coaxial Probe Method

3.1.1 Coaxial Probe Design

We chose three coaxial probes with different sizes available in the lab, in order to understand the differences in the results of permittivity measurements. The main characteristics are listed in the table 3.1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>EZFlex 141</th>
<th>EZFlex 86</th>
<th>EZFlex 47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable length [cm]</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Inner conductor diameter [mm]</td>
<td>0.91</td>
<td>0.51</td>
<td>0.28</td>
</tr>
<tr>
<td>Dielectric diameter [mm]</td>
<td>2.95</td>
<td>1.68</td>
<td>0.91</td>
</tr>
<tr>
<td>Outer conductor diameter [mm]</td>
<td>3.58</td>
<td>2.18</td>
<td>1.19</td>
</tr>
<tr>
<td>Characteristic impedance [Ω]</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Dielectric relative permittivity</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 3.1: Probes parameters [37].
We simulated the three coaxial probes in CST using the full-wave microwave transient solver with an open end. The corresponding reflection coefficients are shown in Fig. 3.1 along the frequency range of 0.5-6 GHz. There is a ripple for the EZFlex 141, although not very concerning.

![Figure 3.1: Measured S11 from coaxial probes EZFlex 47, EZFlex 86 and EZFlex 141 in free-space.](image)

Figure 3.1: Measured $S_{11}$ from coaxial probes EZFlex 47, EZFlex 86 and EZFlex 141 in free-space.

Fig. 3.2 shows the electric field at the probe tip open to free-space, at 1 GHz. We observe that the probe EZFlex 141 and EZFlex 86 are the ones that confine the electromagnetic fields to a more limited space in the probe tip, which improves the results, even for small volumes, as we can see below. Thus, EZFlex 86 is suitable because it offers the best trade-off between submerging the probe and mechanical robustness. This means it is possible to submerge the probe tip without taking the risk of bending the probe.

![Figure 3.2: Electric field distribution at the probe tip in free-space, at 1 GHz. (a) EZFlex 141. (b) EZFlex 86. (c) EZFlex 47.](image)
3.1.2 Open-ended Coaxial Probe Method Numerical Results

As mentioned in chapter 2, in order to de-embed the EM properties of the MUT, it is necessary to calibrate the probe, which is accomplished in a three-stage procedure. As a result, we simulated the three probes in table 3.1 with the three terminations, as illustrated in Fig. 3.3. For open circuit, the material chosen was vacuum, for short-circuit perfectly electric conductor, and a third well-knows load Teflon. Given that we are under numerical conditions, we had to pay attention to the numerical mesh, in order to have coherent results.

![Fig. 3.3: Three standard terminations for probe calibration. (a) Open circuit. (b) Short-circuit. (c) Teflon.](image)

The same setup is used to study the influence of sample size on the results. To this end, we simulated a FR-4 ($\varepsilon_r = 4.4$, $\tan(\delta) = 0.018$) sample of volume 4x4x3 cm$^3$, as shown in Fig. 3.4. This material is widely used as a substrate for printed circuits. We successively reduced the original sample dimensions by 10% steps, until the smallest possible size that could provide satisfactory results of the permittivity.

![Fig. 3.4: MUT sample dimensions.](image)

Fig. 3.5 shows the permittivity results for FR-4 versus the variation of volume size, from 10% up to 100%, at 1 GHz, for the three probes. The expected permittivity of FR-4 is extracted from CST internal material data-base, thus it represents an approximate value just for the sake of comparison with the de-embedded values from CST simulation using Eqs. 2.4 and 2.5 from Section 2.1.
Figure 3.5: Permittivity results for FR-4 versus the percentage of the original sample volume, for the three probes. Solid curve represents the expected value of FR-4 permittivity, extracted from CST. Curves with symbols represent the results de-embedded from CST simulation, for the three probes.

We observe that permittivity values of FR-4 with EZFlex 141 and 86 are closer to the expected value than EZFlex 47, although the difference is about 1.5%. Moreover, for small volumes, permittivity values were expected to have the bigger discrepancy, and EZFlex 47 shows better performance measuring small samples than the other two probes, with a more consistent behaviour. Overall, the results show an error of about 1% given the expected value of permittivity of FR-4.

Fig. 3.6 shows the variation of permittivity along the frequency range, for a sample with 100% of its volume. Once more, permittivity results for EZFlex 47 show the major discrepancy given the expected permittivity of FR-4, and EZFlex 86 with better results.

Figure 3.6: Permittivity results for FR-4 versus the frequency range of 0.5 - 6 GHz, with three probes. Blue curve represents the expected values of permittivity of FR-4. Red curve represents the results obtained by simulation with CST. (a) EZFlex 141. (b) EZFlex 86. (c) EZFlex 47.

We can conclude this method is really sensitive to volume sample and probe size, but it is possible to reduce the sample size and still obtain useful results. The challenge faced by EZFlex 47 is that it is very thin which compromises its mechanical rigidity. When we press the probe against the sample to submerge the tip, the probe may easily bend, and produce errors in the measurements. However, EZFlex 47 is best for measure permittivity of small samples. Besides, it is important to maintain the probe stable. EZFlex 86 is the chosen probe for experimental measurements and it was fabricated.
3.2 Microwave Imaging Numerical Results

Before we individually describe the pieces which will be part of the setup, it is important to understand the final goal regarding the setup. We aim at using a supporting table with a circular gap carrying a breast phantom, which mimics the dielectric properties of the breast, simulating the prone posture in Fig. 1.1.

The antennas will be placed horizontally, in order to measure several coordinates along the z-axis, with several sets. We want the antenna set distributed in a circular configuration, with a maximum number of antennas which does not allow a significant energy to couple among them, in order to prevent cross-talk. Moreover, the internal radius of the circular configuration has to satisfy a minimum value of 6 cm, since we need the breast phantom to fit inside and we want the antennas as close as possible to the phantom. The internal radius should not exceed 8 cm because the antennas will be too far from the phantom to guarantee the quality of the results. The antenna set also needs to meet requirements regarding its size, since there are limitations in the manufacturing equipment, which does not allow to fabricate extremely large pieces.

3.2.1 Basic MWI setup

Fig. 3.8 illustrates the hardware components which integrate the MWI setup. The phantom will be scanned through a set of antennas placed around the phantom, connected to a 4-port VNA. Since we intend to use several antennas, it is possible that we could use a switching network to commute between the antennas. For image processing, the setup will also feature a Raspberry Pi, a webcam and a motor in order to obtain images of the breast phantom and, afterwards, building a complete profile to be used in signal processing, which will result in a reconstructed image shown in a computer.

Figure 3.7: MWI setup block diagram.
3.2.2 Antenna characterization

Among the several antennas for MWI, we opted for a Vivaldi antenna, which is comprised in the travelling-wave category. As such, as the electric current propagates through the metallizations, and the distance between both edges becomes larger, the radiating area adjusts to a larger bandwidth, allowing to improve it. Thus, the electromagnetic waves are radiated when the separation between both metallization edges is approximately half the wavelength. As a result, we can achieve very broadband designs, which are ideal for radar-based systems. Moreover, Vivaldi antennas may be relatively compact when miniaturization strategies are used, low cost and simple to fabricate. It also presents relatively high gain radiation patterns and optimum end-fire radiation pattern.

The final antenna design took several steps in order to achieve the maximum possible optimization. Fig. 3.8 shows antenna evolution, which is going to be carefully explained along this section, in order to achieve the circular configuration.

The initial Vivaldi antenna design is shown in Fig. 3.9, including its geometric parameters. It consists of a Balanced Antipodal Vivaldi Antenna (BAVA). The substrate used is a Rogers RT5880, with thickness 0.254 mm and dielectric properties $\varepsilon_r = 2.2$ and $\tan(\delta) = 0.0009$.

The set of geometric parameters from Fig. 3.9 are listed in table 3.2.

![Figure 3.8: Antenna evolution.](image)
In order to improve the performance of the BAVA, namely at the lower frequencies of the operational bandwidth, an ellipse was added to the "fins" of the BAVA, pointed by the red arrow in Fig. 3.9 (b).

The exponential profiles of the copper layers, $e_a$, $e_f$ and $e_t$, are defined by the Eq. 3.1, and its curvature parameters are presented in table 3.3.

$$z = \pm A_{a,f,t} e^{P_{a,f,t}(x-B_{a,f,t})} + C_{a,f,t}$$

<table>
<thead>
<tr>
<th>Curve</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_a$</td>
<td>$A_{a,f,t}$, $P_{a,f,t}$, $B_{a,f,t}$, $C_{a,f,t}$</td>
</tr>
<tr>
<td>$e_f$</td>
<td>0.08, 0.28, $L_t + L_{ts}$, $W_{a} - A_f$</td>
</tr>
<tr>
<td>$e_t$</td>
<td>-0.1, 0, $W_{ts} - A_t$</td>
</tr>
</tbody>
</table>

Table 3.3: Exponential parameters of the stand-alone BAVA after optimization.

A study of the phase center of BAVA was carried out in order to check its stability, and it is presented in Appendix A. Though the study was not accounted in the microwave imaging results to be presented ahead, the algorithm is sufficiently robust to small inaccuracies in the distance calculations, including the
variability of the phase center along frequency around the millimeters. Also, an intermediate numerical study of BAVA was performed in linear and circular configurations, and it is presented in Appendix B. With this study, it is intended to get insight on how the energy is coupled in both configurations.

The next step is to add a SubMiniature version A (SMA) connector to the feeding line, as illustrated in Fig. 3.10.

![Figure 3.10: BAVA with the connector. (a) Front view. (b) Back view.](image)

BAVA was simulated in CST with and without the connector, and the results for the $S_{11}$ are shown in Fig. 3.11. The results show a degradation of the $S_{11}$ with the inclusion of the connector since operational bandwidth decreases, from 4 GHz up to 10 GHz, defined by the threshold -10 dB. From this point onward, the simulation setup includes the SMA connector.

![Figure 3.11: Comparison between BAVA $S_{11}$ with and without the connector.](image)

Given that the purpose of the antenna is to be distributed around the breast, we can re-arrange its shape, in order to achieve the most compact design possible using the available space. To this end, we re-shaped the antenna substrate into a trapezoid. This polygon is compatible with the sought circular configuration. This modification allows to expand the ellipse size, which greatly influences the minimum operation frequency. The electric currents at the lower band are mostly concentrated on the top edge of the antenna, so enlarging these dimensions provides better impedance matching at these frequencies. Fig. 3.12 shows the final design. The geometry parameters of the antenna were re-tuned, in order to ensure adequate impedance matching. We emphasize that the antenna dimensions decreased from...

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110 x 67 mm² to 99 x 65 mm², which is quite more compact.

![Figure 3.12: BAVA with ellipse followed by a substrate extension. (a) Front view. (b) Back view.](image)

Fig. 3.13 illustrates the $S_{11}$ results for the simulated antenna with the modified antenna shape. Working frequency range is now from 2.12 GHz up to 10 GHz, while slightly reducing antenna dimensions. Besides proper impedance matching, the antenna should also maximize the energy coupling into the body. Since there is no standard near-field metric to evaluate this, we analyzed the radiation pattern of the antenna along frequency. Although it is a farfield figure-of-metric, it is common practice to use it as a first approximation in the antenna design. One should favor maximum energy radiation in the direction of the body and stable patterns along frequency. The radiation pattern is also shown in Fig. 3.14, at 2 GHz, 4 GHz, 6 GHz and 8 GHz.

The radiation pattern at higher frequencies is relatively directive. However, at 2 GHz the radiation pattern is significantly affected by the currents propagating on the edge of the ellipse. This phenomenon may be seen in Fig. 3.15.

![Figure 3.13: BAVA $S_{11}$ with ellipse and substrate extension, in a trapezoidal geometry.](image)
Figure 3.14: Radiation pattern of BAVA with ellipse extension at different frequencies. (a) 2 GHz. (b) 4 GHz. (c) 6 GHz. (d) 8 GHz.

In order to improve the directivity at lower frequencies, we added a slot at the edge of the ellipse, as shown in Fig. 3.16. The slot forces the currents to circulate around it and, therefore, minimize the radiation in non-intended directions, as shown in Fig. 3.18.
With the parameter sweep function, it is possible to check which position and size of the slot increases the most the antenna directivity without degrading its performance. Furthermore, we want to know if it is best to use one or multiple slots. We achieved the best solution with a single slot with $L_{\text{slot}} = 20.9 \, \text{mm}$ and $W_{\text{slot}} = 7 \, \text{mm}$, and the $S_{11}$ is shown in Fig. 3.17. Compared to the BAVA without the slot, the $S_{11}$ has approximately the same behaviour all over the frequency range. Operational frequency bandwidth is 1.98 GHz - 10 GHz. The inclusion of the slot only aims to increase antenna directivity, without degrading the $S_{11}$.

The results of Fig. 3.18 show a more directional pattern at 2 GHz. This is the final design that will be fabricated, and the final set of geometric parameters are listed in table 3.4. We call it Circular Array Balanced Antipodal Vivaldi Antenna (CABAVA).

Finally, we conclude the main challenge in designing an antenna for microwave imaging is increasing the operational bandwidth without increasing its size. Our CABAVA is still facing dimension issues, because aperture size is only 2 mm smaller than the initial design of BAVA, illustrated in Fig. 3.9. This aperture size determines the number of elements that can be arranged in the circular configuration of antennas but also to optimize the space necessary to accommodate the antennas.
Figure 3.18: Radiation pattern of BAVA with slot inclusion at different frequencies. (a) 2 GHz. (b) 4 GHz. (c) 6 GHz. (d) 8 GHz.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value [mm]</th>
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<tbody>
<tr>
<td>$L$</td>
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<tr>
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<tr>
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</tr>
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<tr>
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<td>0.7</td>
</tr>
<tr>
<td>$W_{ts}$</td>
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</tr>
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<td>$L_{slot}$</td>
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<tr>
<td>$W_{slot}$</td>
<td>47</td>
</tr>
<tr>
<td>$R_e$</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3.4: Geometric parameters of CABAVA.
3.2.2.1 Energy coupling between antennas in a circular configuration - 1 set of antennas

In order to increase the reconstructed image quality, we want to distribute the maximum possible number of antennas around the breast, in a circular configuration. However, the more the number of antennas, the larger the ring internal radius (the antennas become more distant from the breast), which hinders the tumor detection. The best trade-off is achieved with eight CABAVAs positioned in a circular configuration, with an inner radius of 7.8 cm, as illustrated in Fig. 3.19.

Figure 3.19: Circular configuration of 8 CABAVA, with internal radius 7.8 mm and external radius 17.8 cm.

First, it is important to know how the energy radiated is coupled among the antennas and Fig. 3.20 shows the antennas numbered to help in the perception of the following results. To this end, we analyzed the scattering matrix elements, which we represent in Fig. 3.21.

Figure 3.20: Numbered antennas in a circular configuration.

Comparing with $S_{11}$ measured with the CABAVA alone from Fig. 3.17, the input reflection of the antenna suffers a degradation which is shown in Fig. 3.21 (a). The scattering matrix elements in Fig. 3.21 (b) show an isolation of 15 dB between antenna 1 and 2, which increases slightly until antenna 5.
because they become more distant from antenna 1. However, given that in microwave breast imaging the tumor response is significantly low, it is desirable to place the antennas as close to the body as possible. Hence, we analyzed how much we could decrease the radius of the configuration without affecting the transmission coefficients between the antennas ($|S_{21}| \leq -15$ dB). To this end, since we cannot decrease the width of the antenna element (otherwise the reflection coefficient would deteriorate significantly), we slightly superimposed the antipodal "fins" of lateral elements. This has a great effect on the $S_{ij}$ coefficients since the electric currents couple more between antenna elements. The best trade-off was achieved for a radius of 60 mm, as illustrated in Fig. 3.22. The $S_{ij}$ results are shown in Fig. 3.23 (b). Additionally, we represent the input reflection coefficient of the final configuration in Fig. 3.23 (a).

Figure 3.21: S-parameters measured from circular configuration with 8 CABAVA. (a) $S_{ii}$ with $i = 1,2,3,4,5,6,7,8$. (b) $S_{ij}$ with $i = 1$ and $j = 2,3,4,5,6,7,8$. 

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Figure 3.22: Final circular configuration of 8 CABAVA, with internal radius 60 mm.

Figure 3.23: S-parameters measured from circular configuration with 8 CABAVA, with inner radius 60 mm. (a) $S_{ii}$ with $i = 1,2,3,4,5,6,7,8$. (b) $S_{ij}$ with $i=1$ and $j=2,3,4,5,6,7,8$.

The $S_{ii}$ exhibits slight deterioration, especially at around 4.8 GHz, where it reaches about -7 dB. However, we did not consider this effect to have any major consequence on the imaging performance of the system, given that the $S_{ii}$ is mostly below -10 dB across the rest of the frequency band of interest.
Regarding the scattering matrix elements, they are mostly below -15 dB, as intended. This is assumed to be a good trade-off between antenna separation and energy coupling.

Thus, this is the final circular configuration of 8 CABAVA to be used in microwave imaging measurements.

3.2.2.2 Electric current offset distance of CABAVA

CST Studio Suite only simulates antennas where waveguide ports are parallel to one of the main axes: x, y or z. Thus, in order to simulate antennas which make an angle of 45° with x-axis, they have to be bent of the same angle. First, the offset length distance of CABAVA and CABAVA with bend of 45° have to be calculated in order to be accounted in the microwave imaging algorithm.

To infer the electric current distance introduced by CABAVA, a metallic plane is placed in front of the antenna. We use a metallic plane instead of a metallic sphere due to its larger cross-section, leading to an easier detection of the reflected signals. The metallic plane distances 20 cm from the antenna, as shown in Fig. 3.24.

![Figure 3.24: Metallic plane placed in front of the antenna to extract the electric distance. (a) CABAVA. (b) CABAVA with bend of 45°.](image)

The location of the metallic plane detected by both antennas is shown in Fig. 3.25.

![Figure 3.25: Location of metallic plane detected by the antenna. (a) CABAVA. (b) CABAVA with bend of 45°.](image)
The electric distance introduced by the antenna is extracted through Eq. 2.4, represented once more in Eq. 3.2,

\[ d_a = d - d_{mp} \] (3.2)

where \( d_a \) is the wanted distance, \( d_{max} \) is the equivalent distance at which the target is detected and \( d_{mp} \) is the 20 cm physical separation between the antenna and the metallic plane. Table 3.5 shows the results for both antennas.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Intensity</th>
<th>Total distance [mm]</th>
<th>Electrical distance [mm]</th>
</tr>
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<tbody>
<tr>
<td>CABAVA</td>
<td>22.17</td>
<td>320</td>
<td>120</td>
</tr>
<tr>
<td>CABAVA 45°</td>
<td>22.76</td>
<td>320</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 3.5: Electrical distances introduced by CABAVA given the target position.

The electrical distance introduced is 12 cm for both antennas, which needs to be accounted in the imaging algorithm in order to produce the correct imaging results. Otherwise, the final image will not be properly focused, since we are accounting an incorrect distance travelled by the signals on the antenna structure.

3.2.3 Numerical Assessment of CABAVA

In this section we evaluate the imaging performance of the CABAVA in different scenarios. We start by considering a target in free-space, as to analyze the useful information we gather from the multistatic configuration. This information will be used in the design of the switching network. Secondly, we add a dielectric transition, that mimics the dielectric properties of the body. Lastly, we assess the useful information that we retrieve by using two levels of CABAVA around the body, in order to improve z-axis resolution. In this case, the S-matrix is composed of \((16^2)/2\) elements instead of \((8^2)/2\) elements, so one may expect the useful information about the target to be greater.

3.2.3.1 Metallic sphere suspended in the air - 1 set of antennas

The first imaging scenario is a metallic sphere of radius 5 mm, suspended in air, as shown in Fig. 3.22. In this case, the propagation velocity is well known, so this analysis should provide good insight on the information gathered by the multistatic system. The position of the metallic sphere, given the origin \((x_o, y_o, z_o) = (0, 0, 0)\) mm at the center of the circular configuration, is \((x_s, y_s, z_s) = (25, -15, 0)\) mm, as illustrated in Fig. 3.26.
The S-parameters were simulated using CST Studio Suite. Accounting the electric offset distance introduced by the antennas previously calculated with Eq. 2.4, the imaging algorithm was applied to the data, using Eq. 2.8. The measurement frequency range is 2 GHz - 7 GHz. Three scenarios were measured: first, only monostatic information is used to reconstruct the reflectivity map; second, bistatic information between adjacent antennas was added to the monostatic data; and last, all multistatic information was used to obtain the microwave imaging results. Adjacent antennas are side-by-side antenna pairs such as 1 and 2, or 2 and 3. Figs. 3.27, 3.28 and 3.29 illustrate those three scenarios.

Fig. 3.27 shows the results using only monostatic information, with a clear and correct detection of the metallic sphere. The results are improved by adding bistatic information, between the adjacent antennas, as shown in Fig. 3.28, eliminating some artifacts. With the addition of more information, it is expected a more clear detection of the target. However, it is possible to observe in Fig. 3.29 that using all the multistatic information available may not lead to useful results. In fact, we observe that some artifacts come up when we expand the useful data to the entire S-matrix.

We concluded that the bistatic information between radially opposite antennas (e.g. 1 and 5, or 2 and 6) adds ambiguity and degrades the imaging results. The ambiguity is a result of the symmetric distribution of the antennas around the body. To illustrate this ambiguity effect, we illustrate in Fig. 3.30 the imaging results that we obtained when using the bistatic information between opposite antennas only.

Finally, the low resolution along the z-axis shown in the reconstructed images is due to the fact that we use only one sampling level of antennas in that direction. However, this section does not intend to evaluate the influence of the number of antenna sets.
Figure 3.27: 2D images of slices through the inclusion at \((x, y, z) = (25, -15, 0)\) mm. Only monostatic information was accounted. (a) XY plane at \(z = 0\) mm. The white circle corresponds to the sphere location. (b) XZ plane at \(y = -15\) mm. (c) YZ plane at \(x = 25\) mm.
Figure 3.28: 2D images of slices through the inclusion at $(x, y, z) = (25, -15, 0)$ mm. Both monostatic and bistatic (between adjacent antennas) information were accounted. (a) XY plane at $z = 0$ mm. (b) XZ plane at $y = -15$ mm. (c) YZ plane at $x = 25$ mm.
Figure 3.29: 2D images of slices through the inclusion at \((x, y, z) = (25, -15, 0)\) mm. All multistatic information available was accounted. (a) XY plane at \(z = 0\) mm. (b) XZ plane at \(y = -15\) mm. (c) YZ plane at \(x = 25\) mm.
Figure 3.30: 2D images of slices through the inclusion at \((x, y, z) = (25, -15, 0)\) mm. Bistatic information from opposite antennas was accounted. (a) XY plane at \(z = 0\) mm. (b) XZ plane at \(y = -15\) mm. (c) YZ plane at \(x = 25\) mm.
3.2.3.2 Metallic sphere embedded in dielectric - 1 set of antennas

In this sub-section, we add a dielectric cylinder that represents the body in a first approach, with $\varepsilon_r = 4$ and $\tan(\delta) = 0.1$. The dielectric cylinder is centered in the origin, has length of 12 cm and 8 cm diameter. This scenario is more challenging than the previous one mainly due to two reasons: 1) we have to consider different propagation velocities according to the propagation material; 2) there is a large reflection of the air-body interface that hinders the detection of the target embedded in the body. We tackle the first challenge assuming that we know the shape and dimension of the dielectric. This information is accounted in the distance calculations, neglecting the refraction effect (which is common practice in near-field medical MWI). Regarding the strong backscattering at the interface, although there are some techniques to overcome the reflection, in this study we eliminate it by simulating the same setup with and without target, as we already discussed in Section 2.2 of Chapter 2. The reflection is then eliminated by subtracting both results, which should only keep the target response.

The metallic sphere location is changed from $(x_s, y_s, z_s) = (25, -15, 0)$ mm to $(x_s, y_s, z_s) = (15, -5, 0)$ mm, as shown in Fig. 3.31. The closer the target is to the wall of the dielectric body, the more distorted become the results. This phenomenon is illustrated in the results of Appendix C with a metallic cylinder as the target.

The MWI results were obtained and shown in Figs. 3.32 and 3.33. Fig. 3.32 represents the reconstructed image accounting only monostatic information and Fig. 3.33 monostatic and bistatic information between adjacent antennas. For both results, the metallic sphere is clearly detected in the correct position. Since accounting all the information provided by the S-matrix degrades the results, the images regarding all multistatic information are not included.

![Circular configuration of 8 CABAVA, with one metallic cylinder submersed in dielectric, at $(x_s, y_s, z_s) = (15, -5, 0)$ mm.](image)

Figure 3.31: Circular configuration of 8 CABAVA, with one metallic cylinder submersed in dielectric, at $(x_s, y_s, z_s) = (15, -5, 0)$ mm.
Figure 3.32: 2D images of slices through the inclusion at $(x, y, z) = (15, -5, 0)$ mm, submersed in dielectric medium. Only monostatic information was accounted. (a) XY plane at $z = 0$ mm. (b) XZ plane at $y = -5$ mm. (c) YZ plane at $x = 15$ mm.
Figure 3.33: 2D images of slices through the inclusion at \((x, y, z) = (15, -5, 0)\) mm, submersed in dielectric medium. Both monostatic and bistatic (between adjacent antennas) information were accounted. (a) XY plane at \(z = 0\) mm. (b) XZ plane at \(y = -5\) mm. (c) YZ plane at \(x = 15\) mm.

We conclude that the results improve significantly with the addition of bistatic information, by looking at the range of intensity values which increases from 250 to 1000. Moreover, Fig. 3.33 shows a 1:10
contrast between the target and the surrounding dielectric medium, as well as for the setup with the target suspended in the air.

Overall, the MWI results with one level of antennas show that even increasing the complexity of the problem (by immersing the target in a medium with twice the value of the refractive index of the air), we still have a clear detection of the target.

3.2.4 Circular configuration with two sets of CABAVA

In the previous section, we have considered a single set of CABAVA. However, we also evaluated the imaging results when two sets of antennas are used, as shown in Fig. 3.34. Both sets distance by 1 cm in z-axis. With two sets, we intend to improve vertical resolution, but also angular resolution because the second set is rotated by 22.5°.

Prior to the image reconstruction, the scattering matrix was measured, and the results are presented in Fig. 3.35. Between 2 GHz and 7 GHz the antenna coupling is again below -15 dB, while the $S_{11}$ is similar to the one in Fig. 3.23.

Figure 3.34: Two sets of 8 CABAVA distributed in a circular configuration.
Figure 3.35: S-parameters measured from circular configuration with 16 CABAVA, with inner radius 60 mm. (a) $S_{ii}$ with $i=1,2,3,4,5,6,7,8$. (b) $S_{ij}$ with $i=1$ and $j=2,3,4,5,6,7,8$. (c) $S_{ij}$ with $i=9$ and $j=10,11,12,13,14,15,16$. 
3.2.5 Microwave imaging results for circular configuration of 16 CABAVA - 2 antenna sets

3.2.5.1 Metallic sphere suspended in the air

A metallic sphere with 1 cm diameter is placed at \((x, y, z) = (25, -15, 0)\) mm, as shown in figure 3.36.

Figure 3.36: Two sets of 8 CABAVA distributed in a circular configuration, with one metallic sphere in the air, at \((x, y, z) = (25, -15, 0)\) mm.

Figs. 3.37, 3.38, 3.39 and 3.40 show the differences when accounting information between different levels. Resolution along the z-axis is still low, even with two sets of antennas with different heights. Fig. 3.38 shows the results only for bistatic information between the two sets, which degrades significantly the results. From this, we infer that a lot of energy is coupled among the levels, and it represents non useful information. Comparing with the range of values of the reconstructed images in section 3.2.3.1, intensity levels are significantly lower with the addition of a second set of antennas. We still have a correct detection of the target, but these results show the opposite of what is to be expected from adding another set of antennas.
Figure 3.37: 2D images of slices through the metallic sphere at $(x, y, z) = (25, -15, 0)$ mm, suspended in the air. Only monostatic information was accounted. (a) XY plane at $z = 0$ mm. (b) XZ plane at $y = -15$ mm. (c) YZ plane at $x = 25$ mm.
Figure 3.38: 2D images of slices through the metallic sphere at \((x, y, z) = (25, -15, 0)\) mm, suspended in the air. Bistatic information between the antennas of two sets. (a) XY plane at \(z = 0\) mm. (b) XZ plane at \(y = -15\) mm. (c) YZ plane at \(x = 25\) mm.
Figure 3.39: 2D images of slices through the metallic sphere at \((x, y, z) = (25, -15, 0)\) mm, suspended in the air. Monostatic plus bistatic information between the antennas of different levels. (a) XY plane at \(z = 0\) mm. (b) XZ plane at \(y = -15\) mm. (c) YZ plane at \(x = 25\) mm.
Figure 3.40: 2D images of slices through the metallic sphere at \((x, y, z) = (25, -15, 0)\) mm, suspended in the air. Monostatic plus bistatic information between the antennas of two sets, plus adjacent antennas. 
(a) XY plane at \(z = 0\) mm. (b) XZ plane at \(y = -15\) mm. (c) YZ plane at \(x = 25\) mm.
3.2.5.2 Metallic sphere submersed in dielectric

Once more, the metallic sphere is embedded in the same dielectric cylinder of Section 3.2.3.2. It is placed at \((x, y, z) = (15, -5, 0)\) mm. The study using a metallic cylinder as target is performed in Appendix C.2, and it represents complementary results with higher cross section than the metallic sphere.

![Figure 3.41](image)

Figure 3.41: Circular configuration of 16 CABAVA distributed by two levels, with one metallic sphere submersed in dielectric medium, at \((x, y, z) = (15, -5, 0)\) mm.

![Figure 3.42](image)

Figure 3.42: 2D image of XY plane, at \(z = 0\) mm, through the inclusion at \((x, y, z) = (15, -5, 0)\) mm. (a) Only monostatic information were accounted. (b) Monostatic plus bistatic information between the antennas of different levels, plus adjacent antennas.

Fig. 3.42 shows a clear detection of the target. Once more, comparing to the results of section 3.2.3.2, intensity level lowers with two sets of antennas. Also, YZ and XZ planes are not included since the results of the previous section revealed that the resolution along the z-axis did not improve with two antenna sets.

Finally, we conclude the results show a very clear detection of the target, even with medium transition, where the target is embedded in a more dense medium (higher relative permittivity than air). Moreover, we infer that the use of multiple sets of antennas produce unexpected results, by observing the spectrum of intensity values. The lower the maximum value, the lower the target response. Thus, we conclude
that there is no advantage in using two sets of antennas due to the significant mutual coupling between them, which degrades the image quality.

3.3 PCB design

In an attempt to use more than four CABAVA with a 4-port VNA, a SP4T switch [38] is required to commute between the antennas, as illustrated in Fig. 3.43.

![Figure 3.43: Antenna commutation.](image)

We need to insert the switch in a PCB circuit, in order to properly connect the switch pins to SMA connectors and DC poles. The design of the PCB was based on this datasheet [38] and build in CST Studio Suite, to operate in the frequency band 0.1 GHz - 6 GHz. The circuit has two copper layers and the substrate used is FR-4, and it is illustrated in figure 3.44.

![Figure 3.44: SP4T switch.](image)

A VNA is connected to port 1 of the PCB as the source signal. Ports 3, 5, 7 and 9 are the outputs to connect the antennas. The signal inputted to port 1 is conducted to one of the four output ports.
accordingly to the antenna we want to select. Only one path is opened at a time and its selection is performed by inputting a sequence of two binary digits, represented by A and B, as we can see in Fig. 3.44.

At this point, to analyze the performance of the switch, we only need to account for the results of the scattering parameters, as they were simulated and presented in Fig. 3.45. We want to have maximum transmission along the co-planar lines and minimum reflection ($|S_{11}| \leq -15$ dB and $|S_{21}| \approx 0$ dB), which is corroborated in Fig. 3.45. Since the switch revealed positive results, we conclude it is functional and it was fabricated.

Figure 3.45: Simulated S-parameters from the switch. (a) Reflection coefficients $S_{11}, S_{33}, S_{55}, S_{77}, S_{99}$. (b) Transmission coefficients $S_{21}, S_{43}, S_{65}, S_{87}, S_{10,9}$.
Chapter 4

Experimental Results

This chapter addresses the experimental results of permittivity measurements and microwave breast imaging, as it is divided in two sections. The first section presents the open-ended coaxial probe method experimental results for de-embedding the relative permittivity of liquid, solid and semi-solid samples.

The second section regards the experimental results of microwave breast imaging. It is divided in three sub-sections. The first sub-section describes the measurement setup used for microwave breast imaging, including the breast phantom and the distribution of the antennas around the breast. The second sub-section presents an user-friendly graphical user interface that helps technicians and doctors performing the examination. The third sub-section presents the results of microwave breast imaging with two different antennas and the results of the new designed switching network.

4.1 Permittivity Measurements Experimental Results

In this section, the experimental results of dielectric properties are presented. The purpose of these measurements is to study the sensitivity of this method to the probe contact with materials of different hardness and heterogeneity, different water content, and sample size.

Three terminations were used for probe calibration: open circuit, short circuit and distilled water as shown in figure 4.1. We selected distilled water (instead of Teflon as in the numerical analysis of Section 3.1.2) because this method is not suitable for solid samples, and also distilled water is a well documented reference liquid.

Fig. 4.2 shows the expected and experimental reflection coefficient in free-space, using a probe based on the EZFlex 86 coaxial cable. The expected $S_{11}$ differs approximately -0.25 dB but shows a ripple all over the frequency range 0.5 GHz - 6 GHz. Similar agreement was obtained for the short circuit measurement and for the distilled water measurement.
Figure 4.1: Three standard terminations for probe calibration. (a) Open circuit. (b) Short circuit. (c) Distilled water.

Figure 4.2: Simulated and measured $S_{11}$ from EZFlex 86 in free-space.

We measured the permittivity for liquid, solid and semi-solid samples. We used a VNA E5071C for 1-port measurements in order to obtain the reflection coefficient. For liquid samples, we chose ethanol and glycerin, which were available in the lab, and mixtures which simulate tumor and fat properties [39] to be used in the breast phantoms. Measurement frequency range goes from 0.5 GHz up to 6 GHz. Fig. 4.3 shows the measured permittivity of ethanol and glycerin, de-embedded through Eqs. 2.4 and 2.5. Given that both liquids are at a temperature of 25°C, the results agree with [40] for ethanol. Glycerin shows high relative permittivity given the expected results in [41].

Our research team already previously measured permittivity results for tumor and fat liquid mixtures. Thus, Fig. 4.4 shows the comparison between those results and the ones measured during this work.

Fat has a lot of distortion in the measured permittivity, and at 1 GHz it is about 20% above the expected permittivity, while tumor has a deviation of less than 1%. This difference becomes smaller as frequency increases, therefore the results are considered acceptable. The method used in [42] also has a substantial uncertainty, thus we cannot conclude which one is more correct. Moreover, when changing between liquids, we cleaned the probe with ethanol. We found out later that the alcohol impregnated the
teflon of the probe, which contributed to increase the error of the measurements.

Figure 4.3: Measured permittivity of liquid samples along the frequency range. (a) Ethanol. (b) Glycerin.

As to show the limitations of this method in the estimation of the properties of solid slabs, we have also measured polyethyelene and Polylactide acid (PLA). Polyethyelene is known for having a permittivity of \( \epsilon_c = 2.3 - j0.0007 \), whereas PLA is around \( \epsilon_c = 2.75 - j0.3 \) [43]. The permittivity results with the coaxial probe are shown in Fig. 4.5. Leaning the probe to a solid sample creates an air gap between the probe tip and the sample, regardless of being carefully positioned, without bending the probe. The air gap may be the reason of the presence of a ripple all over the frequency range.
Figure 4.4: Permittivity of liquid samples along the frequency range. Blue curve represents previous data from our research team and red curve the measured permittivity during this work. (a) Tumor mixture. (b) Fat mixture.

Lastly, we tested the probe in animal tissues: beef and pork belly. Beef is mostly muscle and pork belly is fat. Thus, muscle permittivity ($\epsilon_r \approx 50$) is higher than fat permittivity ($\epsilon_r \approx 5$), due to higher content of water [44]. In order to avoid air gaps between the probe and the sample, we applied as much pressure on the tissue as possible without bending the probe.

Figure 4.6 (a) shows the initial beef sample with 80x42x24 mm$^3$. Its size was later on reduced successively to reach the minimum size that still allows a reliable determination of the sample permittivity. First, we measured the permittivity in different points of the sample, marked in Fig. 4.6 (b).
Figure 4.5: Measured permittivity of solid samples along the frequency range. (a) PLA. (b) Polyethylene.

Figure 4.6: Initial beef sample. Points 1, 2 and 4 represent areas with high content of fat; points 3 and 5 represent areas with low content of fat. (a) Beef Sample. (b) Sample points measured.

The permittivity results are presented in Fig. 4.7. Points 3 and 5 fall in an area with low content of fat and the respective results are consistently higher than points 1, 2 and 4, given that points 1 and 2 are located on top of fat spots. Point 4 is definitely the area with higher content of fat, and the reason for the
lower values of permittivity.

Similarly to what was done numerically, we analyzed the sensitivity of the probe technique regarding the sample dimension. To this end, we started with the original (large) sample - Fig. 4.6 (a) - and have successively cut the sample in half, until the smallest acceptable sample we could be measured, which has had dimensions 4x4x2 mm$^3$. Fig. 4.8 shows permittivity values for the number of samples, from higher volume to lower sample volume, at 1 GHz. The point of sample to be measured was always the same, and preferably an area with low content of fat. In the first half of measurements, the results show higher variation than the second half. This may be due to incorrect pressure over the sample. First we reduced the sample by almost half the larger dimension, and then the reductions become smaller. Thus, we may infer that the sample volume no longer influenced the last seven measurements. Sample volumes number 6, 7 and 18 did not show useful results probably due to incorrect pressure of the probe. This pressure also shows some limitations, not just probe bending, but also water accumulation around the probe tip, which may produce false results. Overall, the heterogeneity nature of beef sample, over the sample volume, is a clear limitation to this method.

Fat is the other sample chosen to measure its permittivity and has 75x30x27 mm$^3$ as initial dimensions. Fat has lower value of permittivity than beef and once again, we pressed the probe against the
sample, with a penetration depth, as shown in Fig. 4.9. Sample dimensions are successively reduced, just as the beef sample.

![Image of a probe submersed in fat sample.](image)

Figure 4.9: Probe submersed in fat sample.

The fat sample was reduced twelve times, until the sample failed to allow reliable measurement of the permittivity, which has dimensions $6 \times 4 \times 5$ mm$^3$. We measured the same point in the sample, during the twelve measurements. Fig. 4.10 shows permittivity results of the fat sample.

Results show a variation in permittivity values, along the frequency range. Sample volumes 6 and 12 may have had errors during the measurement due to incorrect pressure over the sample.

![Permittivity results for the number of fat samples.](image)

Figure 4.10: Permittivity results for the number of fat samples, from higher to lower volume, at 1 GHz, considering always the same sampling point.

The results are acceptable and we can conclude that the coaxial cable method to determine complex permittivity of tissue samples is really sensitive to the pressure applied to the sample. Tissue heterogeneity also influences the results but it is a limitation inherent to the sample. However, the method is not sensitive to sample size variations, since the results are reasonably consistent along the variation of the volume sample, excluding the ones due to inconsistent pressure. Besides, it is important to clean the probe with alcohol free products or even non-liquid products, because it may impregnate the probe by capillarity and degrade the results.
4.2 Experimental Results of Microwave Breast Imaging

4.2.1 Measurement setup

The real application will consist in a bed, where the patient lies on prone posture, with a circular opening where the breast is pending. The best approach in the lab was based on a plexyglass platform in order to be transparent, allowing to see the setup. The breast is represented by an MRI-derived phantom [45] that was 3D-printed using PLA. The breast container was filled with a homogeneous mixture which mimics the dielectric properties of fatty tissues. This mixture was already characterized in the previous section 4.1. The probe antennas are distributed around the phantom. As in a real exam, the antennas are allowed to move vertically, in order to ensure adequate resolution along the vertical axis. The measurement setup is shown in Fig. 4.11.

![Measurement setup](image_url)

Figure 4.11: Measurement setup with reference system. (a) Measurement setup. (b) Coordinate system regarding the top view of the breast phantom. The origin is located at the center of the phantom, in the top most part, at the plexiglas level.
The rail attached to the bottom part of the glass top supports a platform containing a Raspberry Pi Zero W, a webcam, a motor and a power bank. This hardware equipment was selected mainly due to their small size and portability, in order to apply the least possible weight in the rail. The Raspberry Pi is powered by the power bank, and controls the webcam and the motor. The webcam is turned on and the motor moves the platform along the rail in order to take snapshots of the breast phantom, in intervals of 15° (this parameter may be changed in the interface), in an almost 360° profile. The set of snapshots is processed to obtain a full profile of the phantom, based on the colour contrast between the phantom and the background. The profile is crucial for signal processing due to the different refractive indexes of the two media, which is shown in Eq. 2.8.

In the setup, the vertical movement is provided by for infinite screws that move the antennas up and down. The screws are handled by a stepper motor at the bottom of the setup (not shown in Fig. 4.11).

A 4-port VNA E5071C series is used as signal source and receiver to perform the measurements and is calibrated with an ECaL module. After the calibration, the antennas are connected to the VNA with coaxial cables.

The examination time depends on the number of antennas used in the setup, at a cost of setup complexity. Also, it is possible to measure several height levels by moving the antennas vertically, in order to obtain more resolution along the z-axis.

As in the numerical results, we assume the “ideal calibration” procedure, as to eliminate the skin backscattering. We emphasize that this is not a realistic technique. However, the goal of the thesis is not to develop an artifact removal technique, but rather to assess the imaging performance of the developed setup in ideal conditions.

We performed the experimental measurements with a single antenna and a 4-element antenna. Thus, the breast phantom requires a single rotation to obtain the scattering information regarding an 8-element antenna. In a real case scenario, the patient will be steady (the breast does not rotate) and the 8-element antenna will perform the exam. The reason why it is the breast phantom to rotate and not the antenna is to minimize the errors associated with cable twist, and keep the setup steady. Moreover, the goal is not to rotate the antennas, but to place a complete 8-element antenna configuration in order to accelerate the measurement procedure. We are only considering 4 antennas because we lack the equipment to fabricate a larger circuit.

4.2.2 Graphical User Interface

In this section, we develop a graphical interface which is intended to be used by technicians and doctors. This interface allows a simple interaction of the user with the instruments and devices, requiring from them little knowledge on how to control them. It automates the measurement measurement process, thus facilitating the usage of this technology. The purpose of the application is to emulate the instrument environment that can be used for a complete clinical exam.

The graphical interface was implemented in Matlab. The interaction with the VNA is made by a control computer which is connected to the VNA by Universal Serial Bus (USB). The computer also
controls the Raspberry Pi, which in turn controls the camera and the motors.

The graphical interface is divided in three parts. The first part regards to the Setup menu as shown in Fig. 4.12. The Setup menu is composed by several sub-menus that allow the equipment technicians to prepare the setup for the exam, which includes configuring the VNA, the Raspberry Pi and the wiring network. Given the results in Chapter 3, we may not be interested in using the entire S-matrix. As a result, it is also possible to choose the S-parameters to be used in the image reconstruction, in the Wiring menu, as well as distribute the antennas through the switching network.

![Figure 4.12: Equipment Setup menu.](image)

The second menu, Calibration, is also intended to be used by technicians. It concerns the calibration of the antenna rewiring network through the switch. This functionality was not implemented, thus it does not have sub-menus associated.

The third menu is intended for the medical staff performing the examination. It is divided in three sub-menus: Target Shape, Scanning and Imaging, as shown in Fig. 4.13.

The Target Shape sub-menu allows breast shape acquisition, which is obtained using the webcam, controlled by the Raspberry Pi. The webcam takes a snapshot every step. After acquiring the set of snapshots, an image processing algorithm is used to reconstruct the breast profile based on the colour contrast between the breast and the background [46]. The breast shape is crucial in the imaging reconstruction, since it can accurately calculate the interface point that separates wave propagation through air and tissues, thus accounting for different propagation velocities.

The Scanning sub-menu allows to manage the actual microwave measurements, where the S-matrix is measured. This data is then inputted to the Imaging menu, where the reflectivity map is computed.

In the Imaging sub-menu, the medical doctor may observe the three main planes: XY, YZ and XZ planes, in search of a possible tumor inside the patient’s breast, as illustrated by Fig. 4.14. In order to help in the perception of the breast size and tumor location, it is also presented the breast contour in the reconstructed images. Fig. 4.14 shows an example of an image reconstructed from a lab measurement, with a single CABAVA on breast phantom. The white line represents the breast contour and target center location is at \((x, y, z) = (10, 20, -26)\) mm. The calculations take about 9 minutes, in a computer with an
Intel Core i7 processor, occupying 1 GB of RAM; note that the examination duration may be shortened by adjusting the desired resolution of the final image (at the cost of less detail), which can be also done in the interface.

Figure 4.13: Exam menu.

The graphical interface also provides more features, such as loading previous exams, for instance from the same patient. This way, the medical staff can compare the evolution of the patient over time. A step-by-step guide was developed in order to help the user to work with the application.

Figure 4.14: Example of a reconstructed image resulting from a lab measurement, using the graphical interface. 2D slice of XY plane at \( z = -25.5 \) mm.

### 4.2.3 Microwave breast imaging

In this section, the experimental results of microwave imaging using the measurement setup described in section 4.2.1 are presented. The imaging results are compared using a single antenna and with a 4-element CABAVA.
4.2.3.1 CABAVA in free space

Initially, the CABAVA antenna was fabricated and it is shown in figure 4.15.

![1-element CABAVA](image)

Figure 4.15: 1-element CABAVA.

The $S_{11}$ was measured with the CABAVA in free space, along the frequency range of 1 GHz - 10 GHz. The simulated $S_{11}$ from figure 3.17 is shown below in figure 4.16 for easier comparison with the $S_{11}$ measured in lab. The results show good agreement all over the frequency range. The small discrepancies are attributed to manufacturing imprecision and numerical inaccuracies.

![Comparison between simulated and measured $S_{11}$ of CABAVA](image)

Figure 4.16: Comparison between simulated and measured $S_{11}$ of CABAVA.

4.2.3.2 CABAVA with breast phantom

We image the breast using a single antenna element for three different positions of the tumor. It took a total of eight measurements around the breast for each of the three scenarios, at a single height of $z = -18$ mm. The measurement frequency range is 2 GHz - 7 GHz. The results are shown in Figs. 4.17, 4.18 and 4.19. 1 mm resolution was used to reconstruct the images, and the power of the electric field absolute value is represented.

Although there are some artifacts which are due to small misalignment between the antenna and the breast, the tumor is successfully detected and it is easily identified for the three positions. Low resolution
was already expected in XZ and YZ planes, due to the fact that the measurements were performed for a single z coordinate. Although the set-up is prepared to measure at more z-planes, this was not done in this case because this is not the intended final configuration (which will be discussed ahead).

Figure 4.17: 2D images of slices through the inclusion in first position at \((x, y, z) = (10, 15, -25)\) mm. The white lines define the breast phantom contour. (a) XY plane at \(z = -25\) mm. (b) YZ plane at \(x = 10\) mm.

Figure 4.18: 2D images of slices through the inclusion in second position at \((x, y, z) = (10, -5, -25)\) mm. The white lines define the breast phantom contour. (a) XY plane at \(z = -25\) mm. (b) YZ plane at \(x = -10\) mm.
4.2.3.3 4-element CABAVA in free space

The 4-element CABAVA was fabricated and it is shown in figure 4.20. The reflection and transmission coefficients were measured and the results are shown in Figs. 4.21 and 4.22, respectively.

Fig. 4.22 shows an antenna coupling below -15 dB between 2.5 GHz and 8 GHz, while the reflection coefficients in Fig. 4.21 show acceptable isolation accounting the proximity between the antennas. The results show a similar behaviour as the numerical results of section 3.2.2.1.

Figure 4.20: 4-element CABAVA.
4.2.3.4 Microwave breast imaging using 4-element CABAVA

The second experiment with the breast phantom involves the 4-port antenna CABAVA to extract the tumor response. It uses the same breast phantom to mimic the unhealthy and the healthy breast. The measurement procedure is much faster than using the 1-port CABAVA. The measurement frequency range is 2 GHz - 7 GHz. After applying the imaging algorithm to the acquired data, we obtained the results shown in Figs. 4.23, 4.24 and 4.25 for one level of antennas at z = -42 mm.

The results for the 4-element CABAVA show improvements compared to the 1-element CABAVA, because bistatic information is added besides the monostatic information already obtained with CABAVA. These results corroborate the conclusions drawn in Chapter 3 based on numerical results. Moreover, comparing with the spectrum of intensity values of CABAVA experimental results of Figs. 4.17, 4.18 and 4.19, we observe that the 4-element CABAVA leads to an increase of intensity peak from 1 to 35, which is due to the addition of bistatic information accounted in the imaging algorithm.
Figure 4.23: 2D reconstructed images of slices through the tumor in first position at (x,y,z) = (10, 15, -35) mm. (a) XY plane at z = -35 mm. (b) YZ plane at x = 10 mm.

Figure 4.24: 2D reconstructed images of slices through the tumor in second position at (x,y,z) = (-10, -5, -35) mm. (a) XY plane at z = -35 mm. (b) YZ plane at x = -10 mm.
Additionally, we took more measurement points, by moving the 4-port CAVABA vertically. The measured z-coordinates were: $z = -32$ mm, $h = -42$ mm and $z = -51$ mm. First, the results for $z = -32$ mm and $z = -42$ mm were combined in order to simulate the simultaneous use of two sets of antennas, and the results with monostatic plus bistatic information between adjacent antennas are shown in Figs. 4.26, 4.27 and 4.28. Second, we merged the same information for the last two z coordinates, $z = -42$ mm and $z = -51$ mm, and the results are shown in Figs 4.29, 4.30 and 4.31. Third, we merged the information from the three coordinates to simulate three antenna sets and the results are shown in Figs. 4.32, 4.33 and 4.34.

Figure 4.25: 2D reconstructed images of slices through the tumor in third position at $(x,y,z) = (15, -20, -35)$ mm. (a) XY plane at $z = -35$ mm. (b) YZ plane at $x = 15$ mm.

Figure 4.26: 2D reconstructed images of slices through the tumor in first position at $(x,y,z) = (10, 15, -35)$ mm. Merged results of antenna coordinates at $z = -32$ mm and $z = -42$ mm. (a) XY plane at $z = -35$ mm. (b) YZ plane at $x = 10$ mm.
Figure 4.27: 2D reconstructed images of slices through the tumor in second position at \((x,y,z) = (-10, -5, -35)\) mm. Merged results of antenna coordinates at \(z = -32\) mm and \(z = -42\) mm. (a) XY plane at \(z = -35\) mm. (b) YZ plane at \(x = -10\) mm.

Figure 4.28: 2D reconstructed images of slices through the tumor in third position at \((x,y,z) = (15, -20, -35)\) mm. Merged results of antenna coordinates at \(z = -32\) mm and \(z = -42\) mm. (a) XY plane at \(z = -35\) mm. (b) YZ plane at \(x = 15\) mm.
Figure 4.29: 2D reconstructed images of slices through the tumor in first position at $(x, y, z) = (10, 15, -35) \text{ mm}$. Merged results of antenna coordinates at $z = -42 \text{ mm}$ and $z = -51 \text{ mm}$. (a) XY plane at $z = -35 \text{ mm}$. (b) YZ plane at $x = 10 \text{ mm}$.

Figure 4.30: 2D reconstructed images of slices through the tumor in second position at $(x, y, z) = (-10, -5, -35) \text{ mm}$. Merged results of antenna coordinates at $z = -42 \text{ mm}$ and $z = -51 \text{ mm}$. (a) XY plane at $z = -35 \text{ mm}$. (b) YZ plane at $x = -10 \text{ mm}$.

Figure 4.31: 2D reconstructed images of slices through the tumor in third position at $(x, y, z) = (15, -20, -35) \text{ mm}$. Merged results of antenna coordinates at $z = -42 \text{ mm}$ and $z = -51 \text{ mm}$. (a) XY plane at $z = -35 \text{ mm}$. (b) YZ plane at $x = 15 \text{ mm}$.
Figure 4.32: 2D reconstructed images of slices through the tumor in first position at (x,y,z) = (10, 15, -35) mm. Merged results of antenna coordinates at z = -32 mm, z = -42 mm and z = -51 mm. (a) XY plane at z = -35 mm. (b) YZ plane at x = 10 mm.

Figure 4.33: 2D reconstructed images of slices through the tumor in second position at (x,y,z) = (-10, -5, -35) mm. Merged results of antenna coordinates at z = -32 mm, z = -42 mm and z = -51 mm. (a) XY plane at z = -35 mm. (b) YZ plane at x = -10 mm.

Figure 4.34: 2D reconstructed images of slices through the tumor in third position at (x,y,z) = (15, -20, -35) mm. Merged results of antenna coordinates at z = -32 mm, z = -42 mm and z = -51 mm. (a) XY plane at z = -35 mm. (b) YZ plane at x = 15 mm.
Overall, we conclude that there is a clear improvement on the results from the 1-element CABAVA to the 4-element CABAVA. The increased number of antennas and the correct information chosen for data processing, give us a correct and clear detection of the target. Regarding the 4-element CABAVA results, it is possible to observe an expected improvement in resolution along the z-axis, with the addition of measured data for more than one z-plane. Also, the range of intensity values increased from 35 to 140, when we scan multiple z-planes. Although it was not a significant improvement, this approach presents better results than using two sets simultaneously, represented in section 3.2.5.2, which show a decreasing in the spectrum of intensity values. This is due to mutual coupling between the two sets, which does not constitute a problem when using one set scanning multiple z-planes. However, there is no advantage in scanning more than two coordinates along the z-axis, since the results from Figs. 4.32, 4.33 and 4.34 show similar results to the ones from Fig. 4.26 to Fig. 4.31.

4.3 Switch

The PCB for SP4T switch designed in section 3.3 was fabricated and it is shown in figure 4.35.

![Figure 4.35: Fabricated PCB with the SP4T switch.](image)

We used a 4-port VNA to measure the scattering parameters of the switch, in a frequency range of 0.5 - 6 GHz. We initially connected RFC, RF1, RF2 and RF3 to the VNA ports 1, 2, 3 and 4, respectively. The four cables (blue, yellow, red and black) shown in Fig. 4.35 are connected to a Raspberry Pi. The red cable feeds the switch with 5 V and the black cable is connected to the ground. Each RF path is selected via two bits applied to the A and B control inputs, through the blue and yellow cables, respectively. The digital control inputs are listed in table 4.1.

First, we selected the RF1 path corresponding to port 2. Fig. 4.36 shows the measured reflection coefficients of the four ports. We want maximum transmission between RFC and RF1 (i.e. ports 1 and 2, respectively), and $S_{11}$ and $S_{22}$ curves should present a low magnitude level ($\leq -15$ dB). We observe in Fig. 4.37 that $S_{12}$ presents an isolation of 15 dB between port 1 and 2, when it should behave as $S_{11}$ and $S_{22}$ in Fig. 4.36. The remaining $S_{ij}$ show an isolation below -30 dB, which is acceptable.
Table 4.1: Digital control inputs for RF path selection.

<table>
<thead>
<tr>
<th>RF path</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RF2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>RF3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>RF4</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4.36: Reflection coefficients when RF1 is selected.

Figure 4.37: Transmission coefficients when RF1 is selected.

Next, we selected the RF2 path corresponding to port 3, and the reflection and transmission coefficients are shown in Figs. 4.38 and 4.39, respectively. We observe the same behavior of the S-parameters of Figs. 4.36 and 4.37. $S_{11}$ and $S_{33}$ should present a low magnitude level ($\leq -15$ dB) instead of the approximately zero value currently presenting. $S_{13}$ was expected to raise the curve from -30 dB to almost 0, and still shows an isolation of -15 dB.

The results for the RF3 and RF4 paths are similar to RF1 and RF2, thus they are omitted.
Due to the incorrect behaviour of the S-parameters, the PCB was analyzed, with the help of the technical team. We concluded the terminations of the RF paths presented a very thin gap, in the exact location of the connection with the switch. This could be causing the most of the energy, which flows through the RF paths, to be dispersed in the metallization, instead of being transferred to the switch. This way, the PCB needs to be redesigned with larger gaps in the terminations of the RF gaps, so that it could be tested once more and to provide the ability to use eight antennas simultaneously for the MWI experimental measurements.
Chapter 5

Conclusions and Future Work

5.1 Conclusions

The main goal of this work was to build a setup where we integrated the research team knowledge about microwave imaging, in order to constitute a first approach for pre-clinical tests. Besides, the work developed in the framework of this thesis has additional contributions, such as materials characterization in order to develop more realistic phantoms, and the development of a circular configuration of antennas, in order to accelerate the measurement procedure and to maintain the setup steady.

The challenges faced during the work regard the difficulty in reducing the size of ultrawideband antennas, in order to match the requirements of the circular configuration, without sacrificing the good isolation between adjacent antennas, which represents the main feature to reconstruct images with high resolution and low clutter. Another challenge is to construct a simple, practical, cost-effective and modular setup that allows future evolution and integration of new developed techniques.

The first part of this dissertation addresses the study of the open-ended coaxial cable method. First, a numerical analysis was conducted through careful simulations in order to de-embed the dielectric permittivity of well-known materials and to understand the method sensitivity. We calibrated the probe with three different terminations (OC, SC and third well-known termination) to be loaded with the SUT afterwards. The method produced good results, and we concluded the method is not sensitive to sample size but to the probe size. Among the three simulated probes, we opted for the probe which confines the electromagnetic fields to a more limited space in the probe tip, resulting in better achieved values of relative permittivity of the SUT. The probe was fabricated to be used in the experimental procedure.

We measured liquid, solid and semi-solid samples. The method is suitable for liquid and semi-solid samples but not for solid samples, due to inevitable air gaps formed between the probe tip and the SUT. Overall for liquid and semisolid samples, the results were good, but the main limitation of the open-ended coaxial cable method is the high sensitivity to the pressure applied to the probe over the sample. Incorrect pressure leads to incorrect results, as we observed. This way, it is imperative to know how to control this parameter.

The second part regards microwave breast imaging. First, we designed a new compact antipodal
Vivaldi antenna and then submitted it to a shape evolution process, in order to achieve the best possible compromise between size and bandwidth. Since we wanted to distribute the antennas around the breast, as closely as possible from the breast, the best trade-off was achieved with 8 antennas packed side-by-side in a circular arrangement, with an inner radius of 6 cm, and with an isolation of 15 dB between the antennas. This circular configuration corresponds to a set of eight CABAVAs.

Next, we simulated the set of antennas in two different scenarios: a sphere target suspended in air, and a sphere target immersed in a dielectric medium. The target was successfully detected for both cases. Afterwards, we added a second circular array, at 1 cm off z-distance, to reconstruct the images using more information. The same two scenarios were used and we concluded that the picked-up intensity levels decreased, compared to the results obtained with only one set of antennas, although the target was correctly detected. Moreover, we concluded that expanding the useful information to the entire S-matrix in the imaging algorithm contributes to deteriorate the results instead of improving them. Thus, we achieved the best results using monostatic plus bistatic information between adjacent antennas, for one set. For two sets, we added bistatic information between the two sets, although we observed that there is a substantial mutual coupling between them.

A PCB for SP4T switch encapsulation was designed in order to commute between the antenna pairs. The simulation exhibited good results, contrarily to the experimental results after fabrication. However, the PCB was analyzed and we concluded that the possible cause is thin gaps in the RF paths terminations. The energy flowing from the RF paths may be dispersed in the metallization layer, instead of being transferred to the switch.

Since the numerical analysis produced good results, the measurement setup was prepared in order to extract the tumor response from the breast phantom. The developed GUI executes essential steps which automate the measurement procedure. The CABAVA was fabricated and used in the experimental measurements, as well as a 4-port CABAVA. The 4-port CABAVA takes less time to perform the measurements, and the results show improvements given the 1-port CABAVA. Moreover, we scanned several z-planes with the 4-port CABAVA and when we merged that information, we observed that the results slightly improved compared to one CABAVA. This way, we concluded that the approach with one set produces better results than multiple sets used simultaneously. We did not fabricate an 8-port CABAVA due to current antenna size limitation of the fabrication process available in the lab. The entire "ring" has substantial dimensions.
5.2 Future work

Regarding the working experience with the open-ended coaxial cable method to de-embed the dielectric properties of samples, we need to control the pressure applied by the probe in the sample. For this purpose, we may include a precision scale in the measurement setup, in order monitor the pressure applied to the sample and establish optimum and repeatable measurement conditions.

Although the currently developed graphical interface is prepared only for microwave imaging measurements, it aims to incorporate the permittivity measurements functionality in order to have a completely functional microwave medical imaging application. Future work includes designing and optimizing the application to implement this functionality. Moreover, it includes featuring the skin-removal method already developed by our research team, since it is currently implemented the ideal calibration technique. The measurement time also requires to be improved, since it takes a while to perform the measurements and it does not allow to measure in real time.

Regarding the MWI setup, the PCB for the switching network needs to be re-designed in order to obtain results that makes sense, as the simulated ones in CST. Once the switching circuit produces correct results, it is intended to fabricate an 8-element CABAVA in order to complete the octagonal configuration designed in Chapter 3. This way, we can overcome the 180° rotation of the breast, which is not feasible in a real case scenario, and the measurement time can be reduced.
Bibliography


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Appendix A

Antenna Phase Center

In this Appendix, we present a study of the stability of the BAVA phase center given the target position. Nine positions were chosen in front of BAVA, as illustrated in Fig. A.1. Due to the symmetry of the problem, we consider for study the five positions marked from A to E, in Fig. A.1.

Figure A.1: BAVA with target positions.

BAVA has length 110 mm and the target positions distance 50 mm from BAVA. The target positions are located in YZ plane at \( x = 150 \) mm, and each adjacent target position distances 30 mm, as shown in Fig. A.2. \( d' \) corresponds to the electrical distance between the target and the phase center, assuming the phase center is located in \( x \)-axis.

Figure A.2: Distances between BAVA and target positions, and phase center definition.

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One metallic sphere is placed at a time in each position from A to E, and the reflected signals are subtracted by a calibration measurement in free-space. This way, we obtain only the target response. Fig. A.3 shows the results for the five target positions. The calculated distances were measured along the frequency range 2.5 GHz - 6 GHz.

Each curve peak corresponds to the electrical distance $d'$. Table A.1 shows the electrical distance and the phase center location, given the target position.

<table>
<thead>
<tr>
<th>Target</th>
<th>$d'$ [mm]</th>
<th>Phase center location [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>187</td>
<td>-27</td>
</tr>
<tr>
<td>B</td>
<td>193</td>
<td>-30.65</td>
</tr>
<tr>
<td>C</td>
<td>208</td>
<td>-39.16</td>
</tr>
<tr>
<td>D</td>
<td>188</td>
<td>-25.59</td>
</tr>
<tr>
<td>E</td>
<td>199</td>
<td>-29.74</td>
</tr>
</tbody>
</table>

Table A.1: Electrical distances introduced by BAVA given the target position.

The results show that there is a major phase center instability along the z-axis. Phase responses do not match, given the problem symmetry, and intensity level are different. It is clear that the phase center depends on the angle between the target and x-axis, and the difference becomes larger when the target is out of sight of the antenna aperture.
Appendix B

Numerical results of microwave imaging with BAVA

This Appendix presents the numerical results of microwave imaging with BAVA, which constitute intermediate results, with several configurations, of section 3.2.2.

B.1 Linear configuration with 3 BAVA

Three identical BAVA were initially distributed in a linear configuration, as shown in Fig. B.1. Since it is intended to use multiple identical antennas in order to improve the results of microwave imaging, it is necessary to understand how the S-parameters behave along the frequency range with the presence of other antennas. The results for the S-parameters are shown in Fig. B.2.

![Linear configuration of 3 BAVA](image)

Figure B.1: Linear configuration of 3 BAVA.

The reflection coefficients (Fig. B.2(a)) show a good agreement all over the frequency range, comparing to the reflection coefficient of the antenna alone, without degrading the performance. The trans-
mission coefficients (Fig. B.2(b)) show an isolation of 20 dB for $S_{12}$ and $S_{13}$, while $S_{23}$ presents an isolation of 30 dB, because antennas 2 and 3 are more distant and the energy coupled among both antennas is lower.

Figure B.2: Measured S-parameters for three antennas positioned in a linear configuration. (a) Reflection coefficients. (b) Transmission coefficients.

The results infer that it is possible to use multiple antennas without degrading the performance of each antenna.
B.2 Linear configuration with two sets of 3 BAVA

A second set of BAVA, equivalent to the level studied in B.1, is introduced in the linear configuration, composed by a total number of six antennas. The goal is to understand the performance of the antennas when multiple sets are used. The new configuration is illustrated in Fig. B.3. Both sets are separated by 1 cm.

The scattering parameters were measured and shown in Fig. B.4. The reflection coefficients exhibit a slight degradation in the performance of the antennas, which may be due to mutual energy coupling between the antenna sets. This fact is also reflected in the transmission coefficients in Fig. B.4(b). $S_{15}$ shows an isolation of 10 dB between antennas 1 and 5, which are located in different sets, while $S_{14}$ and $S_{16}$ about 20 dB. $S_{23}$ shows an isolation of 30 dB, while $S_{12}$ and $S_{13}$ 20 dB, such as Fig. B.2(b) with one set.
Figure B.4: Measured S-parameters for two antenna sets positioned in a linear configuration. (a) Reflection coefficients. (b) Transmission coefficients $S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{23}$. 
B.3 Linear configuration with two sets of 3 BAVA, with offset

One advantage in using two levels is adding an offset to one level so that we can improve resolution along y-axis. One set was raised in half the antenna aperture, 34.5 mm, as shown in Fig. B.5.

Comparing to the results of Fig. B.4, the s-parameters show approximately the same behaviour with the offset, as shown in Fig. B.6. The major difference observed is the improvement in isolation between antennas 1 and 4, represented by $S_{14}$, since they became more separated. This way, we conclude it is possible to use two sets with offset of half the antenna aperture without significantly degrading the results.
Figure B.6: Measured S-parameters for two antenna sets positioned in a linear configuration, with offset. (a) Reflection coefficients. (b) Transmission coefficients $S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{23}$. 
B.4 Microwave imaging results for a circular configuration of 8 BAVA - 1 set of antennas

This scenario consists in a circular configuration of 8 BAVA, with a metallic sphere of radius 5 mm, suspended in air, as shown in Fig. B.7. The metallic sphere is placed at \((x_s, y_s, z_s) = (25, -15, 0)\) mm, given the origin \((x_o, y_o, z_o) = (0, 0, 0)\) mm at the center of the circular configuration.

The imaging algorithm is applied to the collected data. The measurement frequency range is 2 GHz - 7 GHz. Two scenarios were measured: first, only monostatic information is used to reconstruct the reflectivity map; and second, all multistatic information was used to obtain the microwave imaging results, presented in Fig. B.8. Once more, YZ and XZ planes are omitted.

The response of the metallic sphere was extracted and it is clearly visible in both images. However, there are some artifacts around the target, mainly when we expand the useful information to the entire S-matrix.
B.5 Microwave imaging results for a circular configuration of 8 BAVA - 2 sets of antennas

We added a second set of BAVA, equivalent to the one used in the previous section, to measure the response of the same metallic sphere, suspended in the air, as shown in Fig. B.9.

Figure B.9: Circular configuration with two sets of 8 BAVA, with a metallic sphere, suspended in the air, at \((x_s, y_s, z_s) = (25, -15, 0)\) mm.

Once again, the imaging algorithm is applied to the data, and the measurement frequency range is 2 GHz - 7 GHz. The results are presented in Fig. B.10 for the two scenarios described in the previous section.

![Image](image.png)

Figure B.10: 2D image of XY plane, at \(z = 0\) mm, through the inclusion at \((x_s, y_s, z_s) = (25, -15, 0)\) mm, with two sets of antennas. (a) Only monostatic information was accounted. (b) All multistatic information was accounted.

As a result of the addition of the second set, the results suffered a deterioration, as we may observe in the range of values between Figs. B.8 and B.10, where intensity maximum value decreases from 1100 to 900. However, the target is clearly and correctly detected.
Appendix C

Microwave Imaging Results - Metallic Cylinder Immersed in Dielectric

This Appendix regards complementary numerical results of sections 3.2.3.2 and 3.2.5.2 of microwave imaging in a circular configuration of eight CABAVAs.

C.1 One set of CABAVA

This section addresses some results involving the dielectric medium and the metallic target, in order to show what happens when we place the target too close to the wall of the dielectric body. We replaced the sphere by a metallic cylinder and submersing it in a dielectric cylinder, with $\varepsilon_r = 4$ and $\tan(\delta) = 0.1$, already used in sections 3.2.3.2 and 3.2.5.2. The metallic cylinder is centered in $(x_c, y_c, z_c) = (25, -15, 0)$ mm, has length of 12 cm and 1 cm diameter. The dielectric cylinder is centered in the origin, has length of 12 cm and 8 cm diameter. The configuration is illustrated in figure C.1.

Figure C.1: Circular configuration of 8 CABAVA, with one metallic cylinder submersed in dielectric, at $(x_c, y_c, z_c) = (25, -15, 0)$ mm.
The reconstructed images are presented in Fig. C.2. Resolution along the z-axis is low, thus the reconstructed images for XZ and YZ planes are omitted.

Figure C.2: 2D images of slices through the inclusion at \((x_c, y_c, z_c) = (25, -15, 0)\) mm, submersed in dielectric medium. XY plane at \(z = 0\) mm. (a) Only monostatic information was accounted. (b) Monostatic and bistatic information (between adjacent antennas) was accounted.

The results show lots of artifacts, which may be due to the fact that the metallic cylinder is very close to the walls of the dielectric cylinder. The solution is to move the metallic cylinder to a more centered location, which was chosen to be \((x_c, y_c, z_c) = (15, -5, 0)\) mm. The configuration is illustrated in figure C.3, and the results are shown in Fig. C.4.

Figure C.3: Circular configuration of 8 CABAVA, with one metallic cylinder submersed in dielectric, at \((x_c, y_c, z_c) = (15, -5, 0)\) mm.
Figure C.4: 2D images of slices through the inclusion at \((x_c, y_c, z_c) = (15, -5, 0)\) mm, submersed in dielectric medium. XY plane at \(z = 0\) mm. (a) Only monostatic information was accounted. (b) Monostatic and bistatic information (between adjacent antennas) was accounted.

The results show a highlight in the correct position of the target, which means it was correctly detected, even with medium transition. When combining monostatic with bistatic information, the intensity maximum values improves from 4000 to 14000.

### C.2 Two sets of CABAVA

A metallic cylinder, with 1 cm diameter and 12 cm length, is submersed in the same dielectric medium of previous section, at \((x_c, y_c, z_c) = (15, -5, 0)\) mm. This time, we added another set of CABAVAs, separated by 1 cm, as shown in Fig. C.5.

Figure C.5: Circular configuration with two sets of eight CABAVA, with one metallic cylinder submersed in dielectric medium, at \((x_c, y_c, z_c) = (15, -5, 0)\) mm.
The results of microwave imaging are presented in Fig. C.6. Resolution along the z-axis is still low with two sets, thus the reconstructed images for XZ and YZ planes are omitted.

Figure C.6: 2D images of slices through the inclusion at \((x_c, y_c, z_c) = (15, -5, 0)\) mm. XY plane at \(z = 0\) mm. (a) Only monostatic information were accounted. (b) Monostatic plus bistatic information between the antennas of different levels, plus adjacent antennas.

The target was correctly detected, although the introduction of a second set of antennas slightly deteriorates the results, as the range of intensity values has lowered from 14000 to 10000.