# Electrical Permittivity Measurement Method

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***(Never give up, because you don't know if the next try will be the one that will work. You never know how strong you are until being strong is your only option.)***

To ***GOD***, primary source of knowledge for allowing me to do this work clearly.

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And to all those who accompanied me in difficult and momentous moments, thank you for helping me lift up even though I was broken into a thousand pieces.

***"The future will show the results and judge each one according to their achievements. I'm not really worried that they want to steal my ideas, I'm worried that they don't have them - Nikola Tesla"***

# Declaration of original work

I declare that:

I read Agreement 035 of 2003 of the Academic Council of the ***Universidad Nacional de Colombia***. <<Regulation on intellectual property>> and the National Regulations related to the respect of copyright. This dissertation represents my original work, except where I acknowledge the ideas, words, or materials of other authors.

When ideas or words from other authors have been presented in this dissertation, it carried out their respective recognition by correctly applying the citation schemes and bibliographic references in the required style.

I have obtained permission from the author or publisher to include any copyrighted material (eg, tables, figures, survey instruments, or large portions of text).

Finally, I have submitted this dissertation to the academic integrity tool, defined by the university.

EDWIN FERNANDO PINEDA VARGAS

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feeding my mind and spirit, with constant challenges, difficult trials in all aspects and for giving me the opportunity to grow day by day, making all my dreams and desires come true. , delivering my maximum potential, building a country from the classrooms ***!!!Making our planet and country a better place to live!!!***

# Resumen


***Método de Medición de Permitividad Eléctrica***

En esta investigación, se presenta un método para medir la permitividad eléctrica, utilizando técnicas de reflectometría con la ayuda de un analizador de redes vectoriales ***(VNA)*** y una ***antena tipo Vivaldi*** desarrollada durante la investigación.

Este método está destinado a ayudar al proceso de identificación de materiales de forma inalámbrica y no invasiva.

El método se enfoca en la banda de frecuencia ***UHF*** porque el equipo de medición, tanto en el ***Laboratorio de Compatibilidad Electromagnética*** de la ***Universidad Nacional de Colombia*** como en el ***Laboratorio de Ingeniería Electrónica*** de la ***Pontificia Universidad Javeriana*** mostró que en esta banda de frecuencia, la medición de la permitividad eléctrica del agua se comporta de manera estable.



**Palabras clave: Permitividad eléctrica, agua, reflectometría, épsilon relativo, antena tipo Vivaldi**

# Summary


***Electrical Permittivity Measurement Method***

In this research, a method is presented to measure electrical permittivity, using reflectometry techniques with the help of a vector network analyzer ***(VNA)*** and a ***Vivaldi type antenna*** developed during the investigation.

This method is intended to assist the material identification process wirelessly and non-invasively.

The method focuses on the ***UHF*** frequency band because the measurement equipment, both in the ***Electromagnetic Compatibility Laboratory*** of the ***Universidad Nacional de Colombia*** as in the ***Electronic Engineering Laboratory*** of the ***Pontificia Universidad Javeriana*** showed that in this frequency band, the measurement of electrical permittivity of water behaves stably.



**Keywords: Electrical permittivity, water, reflectometry, relative epsilon, Vivaldi antenna**

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# Resumen

En esta investigación se presenta un método para medir la permitividad eléctrica, utilizando técnicas de reflectometría con la ayuda de un analizador vectorial de redes ***(VNA)*** y una ***antena tipo Vivaldi*** desarrollada durante la investigación.

Este método está destinado a ayudar en el proceso de identificación de materiales de forma inalámbrica y no invasiva.

El método se enfoca en la banda de frecuencia ***UHF*** debido a que los equipos de medición, tanto en el ***Laboratorio de Compatibilidad Electromagnética*** de la ***Universidad Nacional de Colombia*** como en el ***Laboratorio de Ingeniería Electrónica*** de la ***Pontificia Universidad Javeriana*** demostraron que en esta banda de frecuencia, la medida de la permitividad eléctrica del agua se comporta de manera estable.

**Palabras clave: permitividad eléctrica, agua, reflectometría, épsilon relativo, antena Vivaldi**

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# Introduction

The water, source of life is found in a large part of our planet and has currently aroused the interest of the scientific and monetary community, due to its incursion as an active asset on the *New York* ***(Wall Street)*** [Escamilla, 2020].

In this master's thesis, a low-cost, non-invasive method for detecting fresh water is shown, which could be implemented for the identification of fresh water in some areas of difficult access and thus improve the quality of life of people who they cannot access this precious liquid. *Mendoza Escamilla* in her article, highlights that in the world, one in three people does not have access to the precious liquid according to a report presented by ***UNICEF***. [Escamilla, 2020] [Gutierrez et al., 2018]

Water has an electrical permittivity value close to 80, which is stable at 20C according to recommendation ***UIT-REC-P-527-3-199203***. This permittivity value is very high compared to materials such as metals, ceramics, among others.[UIT, 2017] [Schön, 2015]

This is because global freshwater conditions do not vary much, as freshwater is found in similar conditions in various parts of the world. [Askeland et al., 2017]

The electrical permittivity $\varepsilon_r$, is one of the fundamental properties of matter that contributes to the characterization and identification of materials. This can be found using theoretical models that involve reflectometry techniques and radiofrequency equipment. Normally, the measurement of this parameter is carried out by taking samples of the material under study. That is, implementing invasive methods to determine the electrical permittivity of the material.[Askeland et al., 2017] [Joll, 2009] [Gutierrez et al., 2018]

When finding the electrical permittivity of various materials, the main problem with measurement methods is the increase in measurement error, due to not identifying the variables or situations that make it difficult to establish a correct measurement. [Askeland et al., 2017] [Joll, 2009] [Gutierrez et al., 2018]

For this reason, this thesis is aimed at estimating the electrical permittivity of ***water***, with radio signals and non-invasive measurement methods identifying the variables or situations that make it difficult to establish a correct measurement of this element.

This master's thesis proposes a new ***non-invasive and wireless method for measuring the electrical permittivity of the water***, since it will use electromagnetic waves and reflectometric techniques to achieve it in the ***UHF*** frequencies band. This thesis will have the support of the ***Electromagnetic Compatibility Research Group of the Universidad Nacional de Colombia (EMC-UN)***

# 1 ELECTRICAL PERMITTIVITY

The measurement of the electrical permittivity of materials is of important in fields such as studies of historical-artistic heritage, where the presence of humidity and cracks in monuments that have been affected by modern architectural constructions is appreciated close. In the field of civil engineering to determine the content of water present in materials used for filling soils or the amount of asphalt on roads. In other fields such as agriculture it is used to determine the content of water present in the soil or any other substrate, in order to establish the processes of moistening, desiccation of soils or the presence of surface stones. [Hipp, 1974] [Magán et al., 2001]

The electrical permittivity of a material is the ability to this polarize in the presence of an electric field that passes through it and thus partially annuls the internal electric field. In this case, magnetic permeability is defined as the ability of a material to allow magnetic fields to pass through it, is given by the relationship between the intensity of the magnetic field and the magnetic induction inside said material. [Joll, 2009]

Electrical permittivity can also be defined as the ability of a material to store and release energy in the form of an electric field, which is why its definition is normally related to the concept of capacitance.[Cassidy and Jol, 2009] [Joll, 2009]

Due to the large number of elements that are found in nature and that can be identified through the measurement of electrical permittivity, in this master's thesis, fresh water was chosen as the element to be measured since it is common in several places on the planet, its permittivity is very high ***(Close to 80)*** and the variation in its permittivity value due to its chemical composition in various places on the planet, is minimal according to the recommendations ***ITU R-REC-P527-4-201706*** and ***R-REC-P527-3-199203***. [UIT, 1992] [UIT, 2017] [Schön, 2015]

This could also be evidenced in the article ***Modeling and measurement of complex permittivity of soils in UHF***, where it is appreciated that the value of permittivity of soils in the models proposed there, depends directly on the water content that presents the ground. Where the variations of salts and minerals of the soil, do not contribute greatly to the determination of the value of electrical permittivity of the same. [Pantoja et al., 2019]


Figure 1.1: DAK 3.5 probe manufactured by the Swiss company SPEAG.

Once it has been clarified that the material to be worked on is ***water***, we proceed to use a device that allows the electrical permittivity of water to be measured. The device to be used is the probe ***DAK 3.5*** shown in the figure 1.1, manufactured by the Swiss company ***SPEAG***. Which can be connected to a vector network analyzer ***(VNA)*** and thus obtain the parameter $S_{11}$ from the water to $20°C$ in the city of Bogotá, Colombia.

This measurement equipment was located at the ***Pontificia Universidad Javeriana in the city of Bogotá, Colombia***, who facilitated the loan of this equipment for the development of this thesis.
This probe has the following characteristics:

- Open coaxial type.
- Bandwith: 200MHz a 20GHz
- Probe connector type: 3.5mm male
- Outer conductor inside diameter: 3.5mm
- Inner conductor diameter: 0.93mm
- Flange diameter: 18mm
- Dielectric bead material: Eccostock 0005
- Flange: Stainless steel


Figure 1.2: VNA Anritsu Master MS2028C. [Anritsu, 2020]

- Immersible length: 50mm
- Robustness: High resistance to corrosive materials
- Operating temperature range: $0°C - 60°C$
- High measurement repeatability (typ. within 1%)
- Accuracy: Uncertainty tables based on material properties and frequency are available upon request

The probe manufacturer establishes within its measurement protocol, to take the temperature at which the material to be measured is, since this factor is fundamental in the software to determine the electrical permittivity of the material under test.

This probe was connected to a vector network analyzer (VNA) ***Anritsu Master MS2028C***, which works in a bandwidth between ***5KHz to 20GHz***, as can be seen in the figure 1.2. This ***VNA*** is connected to a computer, which will receive the measurements from the analyzer ***(Parameter S11)*** and with the help of ***it's own software Speag (DAK Software)***, the electrical permittivity of the material under test is determined. The measurement system can be seen in the figure 1.3.

Due to the working bandwidths of the ***Vector Network Analyzer (VNA) and Speag's DAK 3.5 probe***, the measurement was carried out in the frequency range between ***200MHz to 15GHz***.


Figure 1.3: Joint measurement system (VNA - Probe)

To perform the system calibration process, the ***DAK Verification Kit*** is used, where the calibration of the joint equipment ***(Probe - Analyzer)*** is performed using the method traditional ***(Open circuit [Open] - Short circuit [Short] - Reference load [Load])***.

There, the ***open*** is taken by leaving the coaxial probe suspended in the air, the ***short*** is taken by placing a copper metal plate that joins the outer and inner conductors of the probe and the ***load***, is established by taking a reference liquid delivered by the company. The calibration elements can be seen in the figures 1.4, 1.5, 1.6.

The ***DAK 3.5*** probe of ***Speag*** was immersed in water at an approximate distance of ***5cm*** as shown in the figure 1.7, to obtain the parameter S11 of the water at $20°C$ in the city of ***Bogotá, Colombia***.

To ***measure the electrical permittivity of water***, take the assembly of the figure 1.7 and make ***10 measurements throughout the day***, where the The water temperature was over $20°C$, since the average temperature at the place of measurement (Bogotá, Colombia) is $20°C$.

Measurements were made taking into account the measurement protocol established by the manufacturer.


Figure 1.4: Set measurement system calibration (VNA - Probe) open circuit (Open)

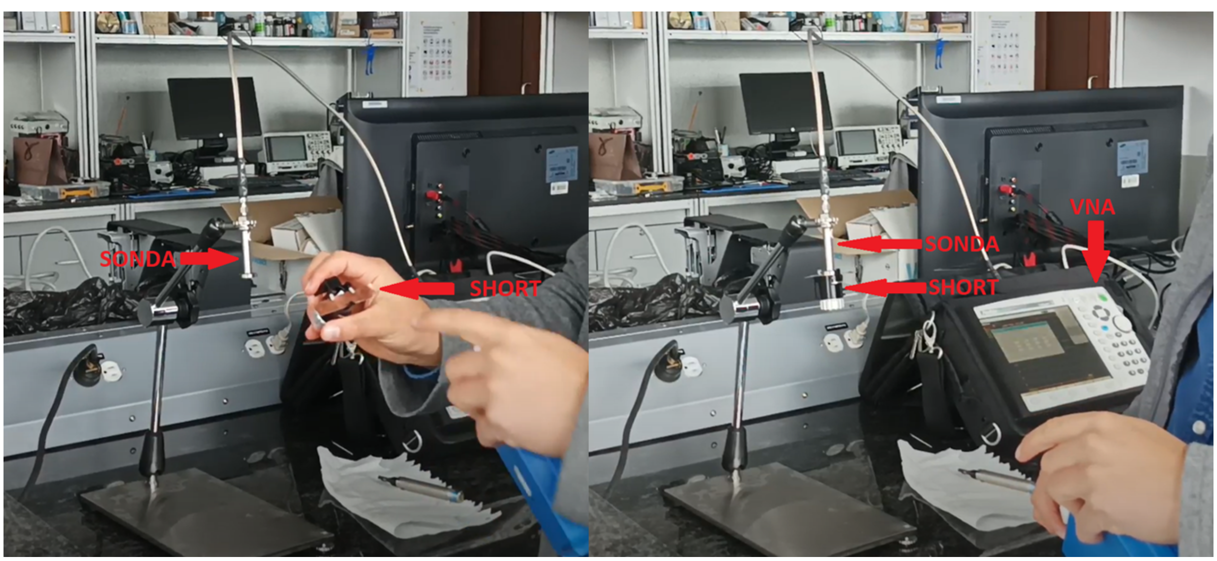


Figure 1.5: Set measurement system calibration (VNA - Probe) short circuit (Short)


Figure 1.6: Calibration of the set measurement system (VNA - Probe) reference load (Load)

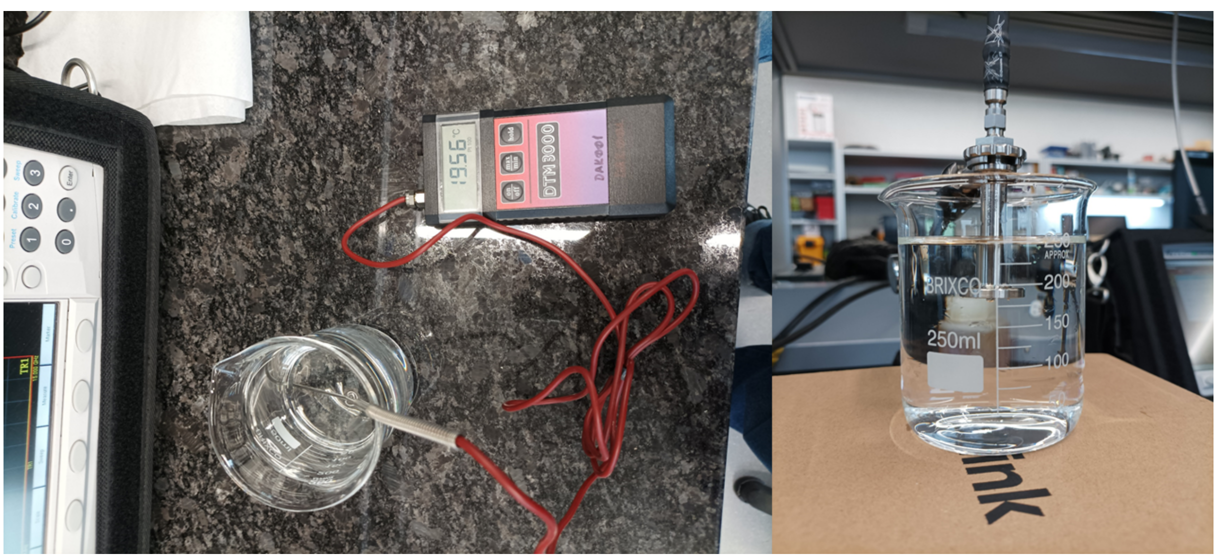


Figure 1.7: Water measurement with probe ***DAK 3.5*** manufactured by ***Speag***. The water is near to $20°C$

The electrical permittivity measurements of the water, taken with the joint equipment ***(Speag DAK 3.5 probe and Anritsu Master MS2028C vector network analyzer (VNA))***, can be seen in the figure 1.8 .

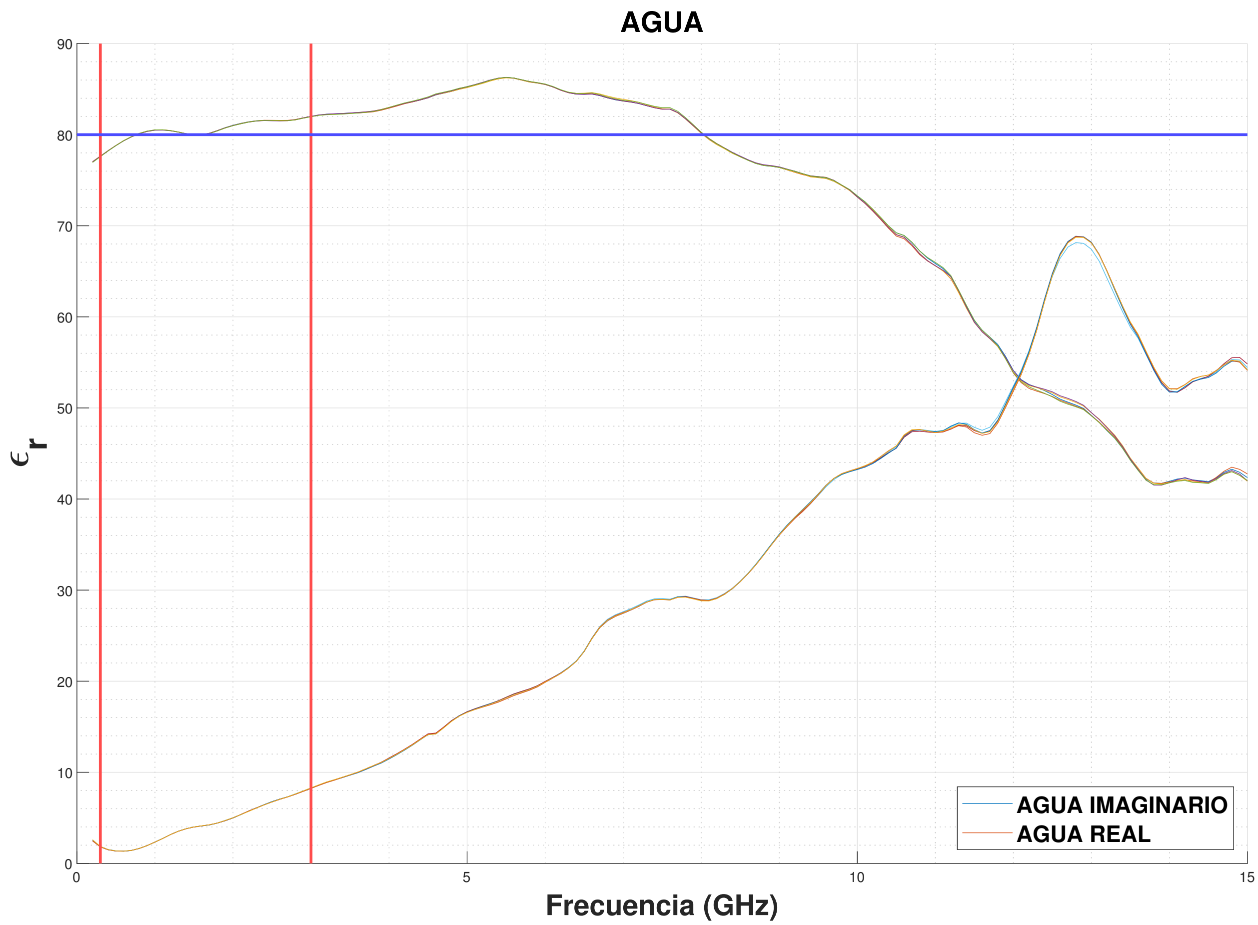


Figure 1.8: Measurement of electrical permittivity of water with ***Speag DAK 3.5 probe (manufactured by Speag) and Anritsu Master MS2028C vector network analyzer (VNA)***

This joint equipment ***(Speag DAK 3.5 probe and Anritsu Master MS2028C vector network analyzer (VNA))***, offers high precision when measuring the electrical permittivity of the materials under test and complies with high international quality standards to perform the measurement. This can be seen in the figure 1.8, where the standard deviation of the data at the time of measurement is very low.

However, it can be seen that in the case of measuring the electrical permittivity of water, there is a small bandwidth between ***300MHz*** and ***3GHz*** where the measurement is stable. For this reason, it was decided to take the measurement in the range of ***UHF***, since this measuring equipment, which could be accessed to measure the electrical permittivity of water in the frequency domain, indicates in its measurements, that the range in which stable water measurement can be achieved is in the band ***UHF (300MHz - 3GHz)***

For the range of frequencies to work, which is in the ***UHF*** band ***(300MHZ - 3GHz)***, these recommendations stablishes that the electrical permittivity of the water is ***80*** as can be seen in the lines ***C*** and ***F*** of the figure 1.9 and in the red line of the figure 1.10, taken from the recommendations ***ITU R-REC-P527-4-201706*** and ***R-REC-P527-3-199203***. [UIT, 1992] [UIT, 2017]

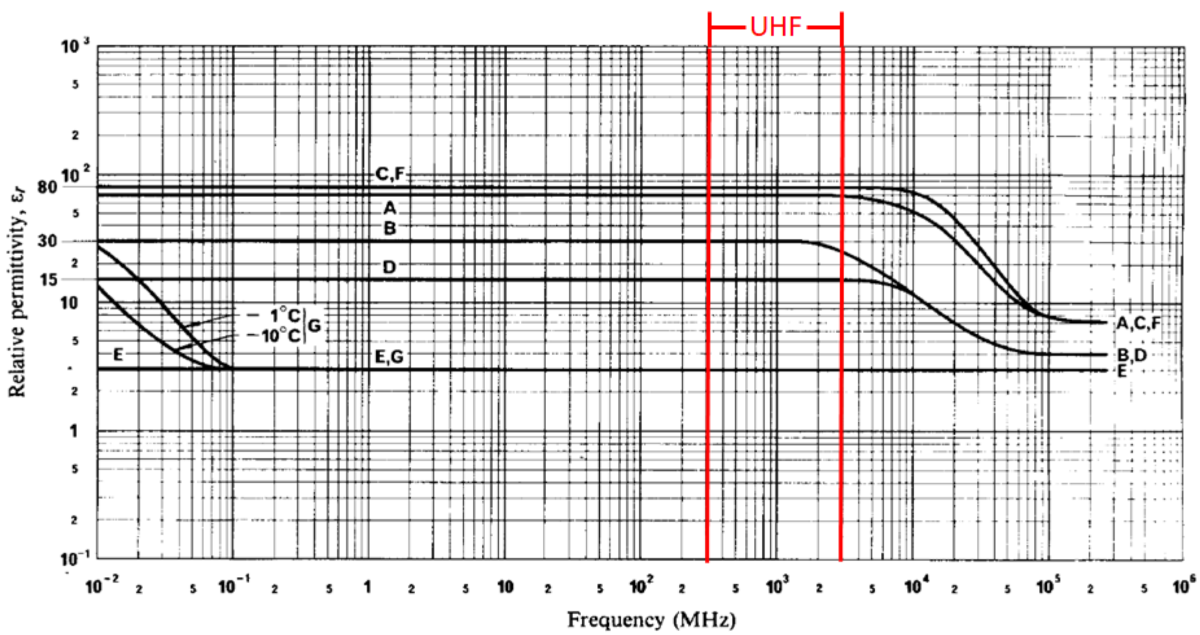


Figure 1.9: Relative permittivity $\epsilon_r$ as a function of frequency. ***REC-P-527-3-199203***. [UIT, 1992]

The figure 1.10 shows seawater, which is referenced in the recommendations ***ITU R-REC-P527-4-201706*** and ***R-REC-P527-3-199203***, varies its electrical permittivity value to ***70*** due to the presence of ***35 grams of salt per kilogram of water*** that is ***35 grams of salt*** for each ***liter of water***. Which affirms the fact that when materials with high water content are analyzed, the permittivity value of the analyzed matter tends to this value of water permittivity, which is ***80*** according to the recommendations ***ITU R-REC-P527-4-201706*** and ***R-REC-P527-3-199203***. [UIT, 1992] [UIT, 2017]

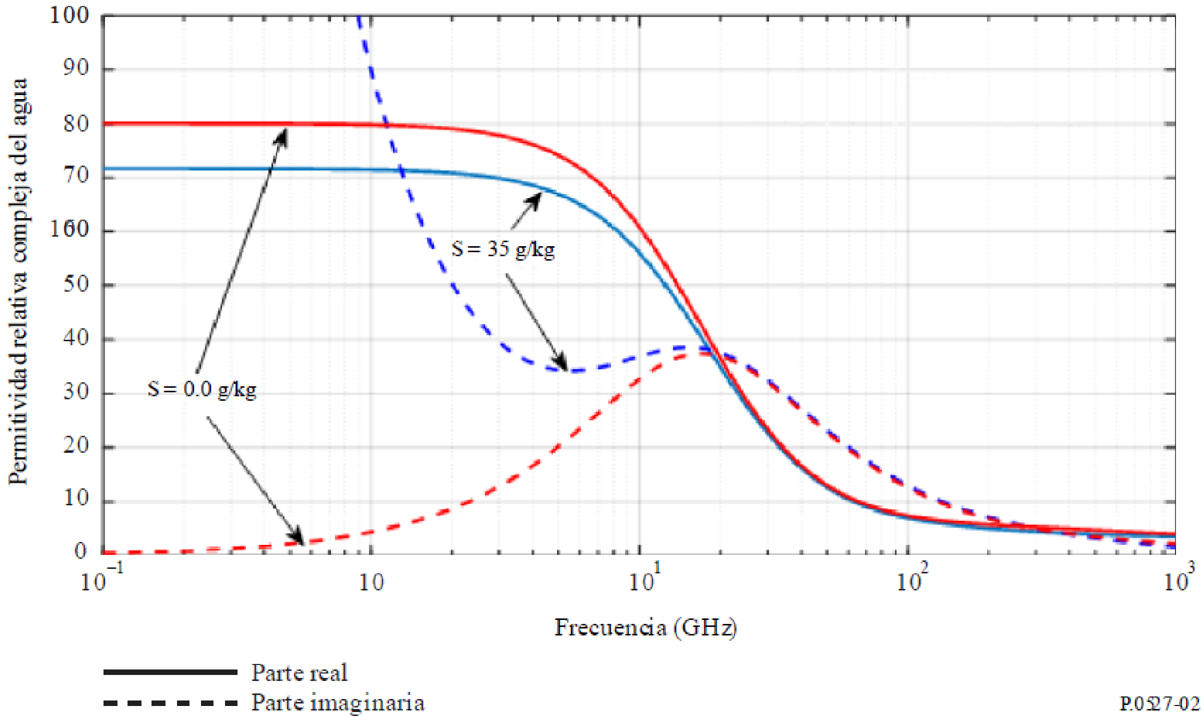


Figure 1.10: Complex relative permittivity of pure water and seawater as a function of frequency (T=20°C). ***REC-P-527-4-201706***. [UIT, 2017]

## 1.1 Electrical permittivity measurement methods

To measure the medium's electrical permittivity, we have techniques such as:

- Time domain reflectometry *(TDR)*.
- Contrast of capacitances.
- Transmission or reflection of transmission lines.
- Open coaxial test probe.
- Resonances.

When measuring the electrical permittivity of an object under test, you can count on ***invasive*** and ***non-invasive*** methods. An ***invasive method*** establishes the extraction of a sample of the material under study, to be analyzed in a laboratory and thus determine its electrical permittivity.

In this method, some conditions of the material under analysis are altered, such as compaction, gravimetric quantity, density, tension, among others, causing in some cases the alteration of the samples when introducing impurities to it, product of the handling of the material under test.

On the other hand, the ***non-invasive method*** establishes the measurement of the electrical permittivity of the material under test, without modifying the conditions in which it is immersed in its environment. [Anritsu, 2021]

### 1.1.1 Time Domain Reflectometry (TDR)

The ***time domain reflectometry (TDR)*** consists of the emission of a step pulse at the end of a transmission line, which will be transmitted to the material under test, that will be analize with the reflections of the electromagnetic wave incident in the material under test. This reflected pulse is detected with a vector network analyzer *VNA* or *oscilloscope* at the same point where the pulse is applied with a receive antenna.

The reflections detected will be the product of the change in amplitude of the characteristic impedance of the transmission line, when there are elements connected or in contact along the transmission line. These changes represent a capacitive, inductive or resistive behavior, depending on the type of material that is in contact. These reflections are obtained by means of the dispersion parameters of the incident electromagnetic waves ***(Scattering Matrix)***, where the reflection coefficient of the material is found. [Anritsu, 2021]

Some drawbacks when using this method lie in obtaining information only from the superficial part of the medium and in some cases, a small error in the measurement could be generate a significant error in the determined permittivity. Which implies executing the method with rigor in its precision. [Anritsu, 2021] [Cassidy and Jol, 2009] [Joll, 2009]

### 1.1.2 Capacitance contrast

It is a widely used technique, since it allows, by means of a parallel plate condenser, to establish the permittivity of the material, comparing it with that of air. The measurement is obtained by measuring changes in the voltage and current values of the capacitances, when in air or with the material under test, subjected to a known voltage and current. [Anritsu, 2021] [Cassidy and Jol, 2009] [Joll, 2009]

This technique is recommended since the permittivity of the material under test can be compared with the electrical permittivity of air. [Anritsu, 2021] [Schön, 2015] [Joll, 2009]

### 1.1.3 Transmission and reflection of transmission lines

The use of transmission lines for the identification of materials is very useful and allows to establish the matrix of parameters S of the object under test, locating it in a network of at least two ports. [Anritsu, 2021] [Schön, 2015] [Joll, 2009]

The method has two ways to find the base material's own parameter matrix S. The first consists of introducing a transmission line into the material under test at a certain depth, while the second consists of extracting a sample of the material under test, and introducing it at a certain point along the transmission line. [Anritsu, 2021]

In both cases with the help of a VNA, the matrix of parameters S of the material of the material under test is found, and then its electrical permittivity is found with the help of a mathematical model [Anritsu, 2021] [Pozar, 2011] [Anritsu, 2021] [Schön, 2015] [Joll, 2009]

### 1.1.4 Open coaxial test probe

This device consists of a transmission line open at one end, which is placed under pressure on the element under test. The open end is composed of two walls that will represent a two-port network, in such a way that the ***matrix of parameters S*** typical of the material can be found, in the open termination. [Hoshina et al., 2001]

This method is considered non-invasive and non-destructive, since it does not alter the conditions in which the material is found by extracting a sample from it, nor does it require that it be destroyed in order to analyze it. This method requires the reflection coefficient in order to find the permittivity of the material. [Hoshina et al., 2001]

### 1.1.5 Resonances

There are two groups of experimental methods for characterizing electromagnetic waves in materials, the ***resonant*** and the ***non-resonant***. The ***resonant*** seeks to identify the frequency and gain of the resonant electromagnetic waves present in the material under study, while the ***non-resonant*** seeks to identify the form of wave propagation . For this case, the characterization method ***resonant*** will be used. [Pérez Gracia, 2001].

# 2 NON INVASIVE ELECTRICAL PERMITIVITTY MEASUREMENT

Normally to characterize materials, it is necessary to use some intrinsic physical property of matter, which is decisive to be able to differentiate them from others.

One of these characteristics of matter that allows this to be achieved is the electrical permittivity, which, as evidenced in chapter 1, in the identification and detection of elements, is one of the most relevant parameters to measure of the material under study, since this characteristic is unique to each element in nature. [Schön, 2015] [Joll, 2009]

One way to measure the electrical permittivity of matter is by incident electromagnetic waves radiated to the object under test. The method consists of radiating an electromagnetic wave to the object under test, where part of that wave upon contact with the object under study will be reflected and part of it will be transmitted through the object. This phenomenon is known as the ***standing wave ratio (SWR)***. The equation 2.1 describes this phenomenon mathematically. [Pozar, 2011] [Schön, 2015] [Joll, 2009]

$$SWR = \frac{|V(z)|_{\max}}{|V(z)|_{\min}} \tag{2.1}$$

Subsequently, as a result of this SWR, the electrical permittivity of the material under study can be obtained as long as there is a two-port network, which will allow to obtain the reflection coefficient of the matter and later use it to find the electrical permittivity of the material under study. [Baker-Jarvis et al., 1990] [Pozar, 2011]

The method consists to establishing the scattering matrix of the material ***Matrix of parameters S***, with the help of a vector network analyzer ***(VNA)***. Subsequently, the values obtained with the vector network analyzer are taken, replacing the parameter of interest in any of the equations 2.2 or 2.3 as appropriate and by means of a substitution process with the remaining equations, the value of the gamma ($\Gamma$) reflection coefficient of the material under test. Keep in mind that in this case, the parameter $S_{11}$ is equal to the parameter $S_{22}$ and in turn, the parameter $S_{12}$ is equal to the parameter $S_{21}$ in this two-port network, as the system is considered free from both internal and external disturbances. [Pozar, 2011]

$$|S_{11}| = \left| \frac{\Gamma\left(1 - z^2\right)}{1 - z^2\Gamma^2} \right| \tag{2.2}$$

$$|S_{21}| = \left| \frac{z\left(1 - \Gamma^2\right)}{1 - z^2\Gamma^2} \right| \tag{2.3}$$

The reflection coefficient in a material is defined as the relationship between the incident wave with which the material is excited, measured in volts $V_{0i}$, and the reflected wave from the same measurement in volts $V_{0r}$, as seen in the equation 2.4. [Pozar, 2011]

$$\Gamma_L = \frac{V_{0r}}{V_{0i}} \tag{2.4}$$

It should be noted that the reflection coefficient can also be found using the standing wave relationship as shown in the equation 2.5. [Pozar, 2011] [Balanis, 2015]

$$\Gamma_L = \frac{S - 1}{S + 1} \tag{2.5}$$

In turn, this reflection coefficient is related to the characteristic impedances of the load and the transmission line as shown in the equation 2.6, where $Z_0$ will be the impedance of the transmission line and $Z_L$ will be the impedance of the load connected to that transmission line. [Pozar, 2011]

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{2.6}$$

The characteristic impedance in the cross section of a transmission line ($Z_0$), is defined as the relationship between the voltage in the load and the current that crosses it as shown in the equation 2.7. The impedance in the load will be taken as $Z_L$. [Pozar, 2011]

$$Z_0 = \frac{V^+}{I^+} = \frac{V^-}{I^-} = \frac{C_1}{C_2} \tag{2.7}$$

Then, the electrical permittivity of the material under observation can be found as shown in the equation 2.8. Where, with the reflection coefficients of the material, it is possible to find the value of its electrical permittivity. [Singh et al., 2017] [Pozar, 2011] [Balanis, 2015]

$$\varepsilon_r = \left( \frac{1 + |\Gamma|}{1 - |\Gamma|} \right)^2 \tag{2.8}$$

## 2.1 Proposed method

The measurement place where this research is carried out is the city of ***Bogotá, Colombia***. There, the average ambient temperature is ***20° C*** and the average atmospheric pressure is ***752.1 hPa***. These parameters according to the recommendations of the ***ITU R-REC-P527-4-201706*** and ***R-REC-P527-3-199203*** are the ones that must be taken into account when calculating the electrical permittivity of water under ambient conditions, were the permittivity of water is ***80***. [UIT, 1992] [UIT, 2017]

But since it is a non-invasive method, it is proposed that the measurement method be wireless. Reason why it is necessary to develop both the analytical method to find the electrical permittivity of water, as well as the way in which the method will be validated through wireless measurement.

Regarding the mathematical method, it must be taken into account that the electromagnetic waves that illuminate the material under study will present a variation in amplitude in the wave incident to the material, thus providing information on the part of that incident wave that is capable of being absorbed by the material under test. This identification is achieved by observing the electromagnetic waves that have the lowest level of gain in a diagram showing the parameter $S_{11}$ ***(Reflection parameter of the electromagnetic wave incident to the material under test)***.

In this diagram, resonant frequencies $S_{11}$ ***(lowest)*** will be found, at the moment of making a frequency sweep in the band of ***UHF (300MHz - 3GHz***, depending of the components of the object of study.

This master's thesis was developed using the ***TDR*** measurement technique in the *microwave* frequency range. The *microwaves* are electromagnetic waves that are between $300MHz$ and $30GHz$ which have an oscillation between $3nS$ and $33pS$, with wavelengths of $30cm$ to $1mm$. The microwaves are classified into ***UHF (Ultra High Frequency)*** $(0.3 - 3GHz)$, *SHF (Super High Frequency)* $(3 - 30GHz)$, and *EHF (Extremely high frequency)* $(30 - 300GHz)$. To develop this project, we opted to work in the ***UHF*** frequency band because at this frequency it is possible to find the electrical permittivity with a stable measurment of water and the ***Electromagnetic Compatibility Laboratory's*** equipment operate on the same bandwidth. [UIT, 1992] [UIT, 2017]

The method proposed below requires the implementation of a vector network analyzer ***(VNA)*** to capture the parameters ***S*** of the measurement system, and an antenna adapted to ***VNA***, which allows the incident wave to be sent to the object under study and captures the reflected wave coming from it.

As it is a wireless system, only the dispersion parameter corresponding to the reflected wave, parameter $S_{11}$, will be used. The other parameters will not be taken into account since the proposed method will have a single port to send and receive the electromagnetic wave.

To start, the transmission coefficient $S_{21}$ must be defined according to the separation distance at which the system measurement antenna is located, this can be achieved as shown in the equation 2.9.

This equation establishes a relationship between the separation distance of an object with respect to an impedance value. In this equation, the separation distance of the object will be denoted by the letter L. While $\gamma$ refers to the propagation constant of the medium in which the antenna is immersed, for this case, it will correspond to air ($\gamma = 1$), since the water measurement will be done with air as the contact element between the measurement antenna and the object under test ***(water)***. [Baker-Jarvis et al., 1990] [Balanis, 2015] [Pozar, 2011]

$$Z = e^{(-\gamma L)} \tag{2.9}$$

The propagation constant of a material in vacuum can be found as shown in the equation 2.10.

$$\gamma = j\sqrt{\frac{\omega^2 \mu_r \varepsilon_r}{C_{VAC}^2} - \left(\frac{2\pi}{\lambda_c}\right)^2} \tag{2.10}$$

Where $\omega$ is the angular velocity of the incident electromagnetic wave, $\mu_r$ is the magnetic permeability of the medium in which the incident wave is found (Air, $\mu_r = 1$), $\epsilon_r$ is the electrical permittivity of the medium in which the incident wave is found (Air, $\epsilon_r = 1$), $\lambda_c$ is the cut-off wavelength and $C_{VAC}$ will be the speed of light in vacuum. [Baker-Jarvis et al., 1990]

As mentioned by ***Jarvis***, the material's reflection coefficient can be obtained by taking into account a parameter called ***R1***, as it appears in the equation 2.11. Which according to ***Jarvis***, is equal to $Z$ as a appears in the equation 2.12 and in the equation 2.9.
[Baker-Jarvis et al., 1990]

$$S_{11} = R_1^2 \left[\frac{\Gamma\left(1 - z^2\right)}{1 - \Gamma^2 z^2}\right] \tag{2.11}$$

$$R_1 = e^{(-\gamma_0 L_1)} \tag{2.12}$$

Where $\gamma_0$ will be the air propagation constant and $L_1$ will be the separation distance between the antenna and the object under test.[Baker-Jarvis et al., 1990]

In such a way that when solving from the equation 2.11 we obtain $\Gamma$ as it appears in the equation 2.13.

$$\Gamma = \frac{1}{S_{11}z^2} \tag{2.13}$$

At the moment of replacing in this equation $\boldsymbol{z}$ by the value that appears in the equation 2.9, we will obtain the equation 2.14.

$$\Gamma = \frac{1}{S_{11}z^2} = \frac{1}{S_{11}(e^{(-\gamma L)})^2} \tag{2.14}$$

In this equation it can be seen that the reflection coefficient is in terms of the parameter $S_{11}$, the separation distance between the antenna and the object under test $L_1$ and the propagation constant of the medium in the one in which the incident wave is immersed (Air, $\mu_r = 1$).

The reflection coefficient according to Snell's Law can also be defined as shown in the equation 2.15. Where the reflection coefficient will be determined by the refractive indices of each material with which the electromagnetic wave interacts $n_1$ and $n_2$. [Pérez Gracia, 2001]

$$\Gamma = \frac{n_2 - n_1}{n_2 + n_1} \tag{2.15}$$

Where $n_1$ will be the index of refraction of the incident medium and $n_2$ will be the index of refraction of the reflected medium. The refractive index can be obtained from the magnetic permeability and electrical permittivity of the object under test, which are intrinsic properties of matter, as shown in the equation 2.16, which can also be relate to the speed of light in a vacuum and the speed of light in the medium in which the electromagnetic wave travels.

$$\eta = \frac{c_{vacio}}{c_{medio}} = \sqrt{\frac{\mu_r}{\varepsilon_r}} \tag{2.16}$$

Taking into account the equation 2.16, replacing the value of $\eta_1$ and $\eta_2$ in the equation 2.15 according to whether it is the incident wave or the reflected wave, the expression of the equation 2.17 is obtained.

$$\Gamma = \frac{\sqrt{\frac{\mu_{reff(medium\ _reflected)}}{\varepsilon_{reff(medium\ _reflected)}}} - \sqrt{\frac{\mu_{reff(medium\ _incident)}}{\varepsilon_{reff(medium\ _incident)}}}}{\sqrt{\frac{\mu_{reff(medium\ _reflected)}}{\varepsilon_{reff(medium\ _reflected)}}} + \sqrt{\frac{\mu_{reff(medium\ _incident)}}{\varepsilon_{reff(medium\ _incident)}}}} \tag{2.17}$$

In the case of our model, we are working with two materials. Water for the case of the reflected wave and air for the case of the incident wave. So now our equation 2.17 becomes the equation 2.18

$$\Gamma = \frac{\sqrt{\frac{\mu_{r(water)}}{\varepsilon_{r(water)}}} - \sqrt{\frac{\mu_{r(air)}}{\varepsilon_{r(air)}}}}{\sqrt{\frac{\mu_{r(water)}}{\varepsilon_{r(water)}}} + \sqrt{\frac{\mu_{r(air)}}{\varepsilon_{r(air)}}}} \tag{2.18}$$

For the materials involved in this study, water and air, the considerations that appear in table 2.1 must be taken into account.

| ***Physical property*** | ***Value*** |
|---|---|
| $\mu_{r(air)} = \mu_{r(water)} = \varepsilon_{r(air)}$ | 1 |
| $\mu_{reff(medium\ _{i}ncident)} = \mu_{r(medium\ _{i}ncident)}$ | $\mu_{r(air)}$ |
| $\mu_{reff(medium\ _{r}eflected)} = \mu_{r(medium\ _{r}eflected)}$ | $\mu_{r(water)}$ |
| $\varepsilon_{reff(medium\ _{i}ncident)} = \varepsilon_{r(medium\ _{i}ncident)}$ | $\varepsilon_{r(air)}$ |
| $\varepsilon_{reff(medium\ _{r}eflected)} = \varepsilon_{r(medium\ _{r}eflected)}$ | $\varepsilon_{r(water)}$ |

Table 2.1: Considerations for calculating the electrical permittivity of water. [Joll, 2009]

Therefore, taking into account the values of the table 2.1 and replacing them in the equation 2.18, the expression of the equation 2.19 is obtained.

$$\Gamma = \frac{\sqrt{\frac{1}{\varepsilon_{r(water)}}} - 1}{\sqrt{\frac{1}{\varepsilon_{r(water)}}} + 1} \tag{2.19}$$

At the moment of equating the equation 2.14 with the equation 2.19 as shown in the equation 2.20, the value of the relative electrical permittivity of the material under study can be found, which will be from where the reflected wave starts ($\varepsilon_r$), in this case ***water***, as shown in the equation 2.21.

$$\Gamma = \frac{1}{S_{11}e^{(-2L)}} = \frac{\sqrt{\frac{1}{\varepsilon_r}} - 1}{\sqrt{\frac{1}{\varepsilon_r}} + 1} \tag{2.20}$$

$$\varepsilon_r = \left[\frac{\frac{e^{j2L}}{S_{11}} - 1}{-\frac{e^{j2L}}{S_{11}} - 1}\right]^2 \tag{2.21}$$

The equation 2.21 will then be the equation with which the electrical permittivity of water can be calculated wirelessly, using an antenna that allows, with the help of a VNA, to obtain the parameter $S_{11}$ of the water in the frequency range ***UHF*** from ***(300MHZ - 3GHz)***. This electrical permittivity value will be ***80*** according to the ***ITU*** considerations. [UIT, 1992] [UIT, 2017]

# 3 VALIDATION

To carry out the validation process of the method proposed in chapter 2, two procedures were carried out.

1. Simulation with CST
2. Experimental measurement using a VNA

In both cases, a Vivaldi-type antenna developed during the thesis was used to capture the reflected electromagnetic wave, coming from the water block that was simulated, as well as the water block that was measured experimentally.

## 3.1 Vivaldi type antenna

To carry out the validation of the method proposed in chapter 2 theoretically and experimentally, it was necessary to develop a wide bandwidth antenna, which would operate in the UHF band (300MHz-3GHz), adapted below -10dB and coupled to 50Ω, so that it could be implemented with a VNA at 50Ω and thus obtain the $S_{11}$ parameter, which allowed obtaining the electrical permittivity value of the water.

The antenna starts from a pre-established design that was provided by the ***Electromagnetic Compatibility Research Group of the Universidad Nacional de Colombia (EMC-UN)***. This antenna was replicated preserving its original dimensions and construction materials, in a computational model developed in CST, which allowed to verify its operation in the frequency band of interest ***UHF***.

The antenna was used in a project where a ground penetrating radar was used and allowed the identification of objects through the use of radar techniques. But for the elaboration of this thesis it presented many problems to be implemented. Among which is appreciated its high cost of manufacturing and import since it comes from abroad, excessive manufacturing times, design and exclusive materials that are not found in Bogotá, Colombia, as well as an acceptable adaptation for the measurement bandwidth. For these reasons, its original design was modified.

Notable design modifications include:

- Variation in the electromagnetic coupling fan, changing its shape by one to a quarter of a circumference, which was also moved to the place where the electromagnetic coupling begins with the ground plane of the antenna, which improved its electromagnetic coupling in the bands of interest (UHF).

- The number of frequency combs located on the sides of the antenna was modified from 20 slots to 16, which allowed a better adaptation to the frequencies of interest in the UHF band (300MHZ - 3GHz).

- The antenna was developed in a material known as FR4, which is easily accessible in Bogotá, Colombia and not in the original material whose substrate to date is unknown both its origin and its electrical properties.

- Due to the required operating bandwidth in the UHF frequency band (300MHz-3GHz), the antenna underwent a modification in its dimensions, which also allowed to improve the adaptation of the antenna to meet the criterion of $-10dB$, which establishes that for any antenna that guarantees that the incident electromagnetic wave generated by the antenna has enough energy to penetrate a material, the antenna must have a resonance frequency whose magnitude is below $-10dB$. This criterion can be verified when simulating the antenna in CST without objects in front of it, and in the case of experimental verification, pointing the antenna in a space free of electromagnetic interference or objects that cause reflections of the waves. electromagnetic signals emanating from the antenna. Allowing to pass a smaller antenna. [Balanis, 2015] [Schön, 2015] [Joll, 2009] [Pozar, 2011]

- The width of the transmission line was changed in shape but not in dimensions. This modification improved the performance of the antenna against the electromagnetic coupling of the fan and the generation of the incident wave of the antenna to perform the measurements of the electrical permittivity of the water.

These modifications and the final design can be seen in figure 3.1.

The behavior of this antenna in the ***UHF(300MHZ - 3GHz)*** frequency range can be seen in the figure 3.2, where the parameter $S_{11}$ of the same oriented in free space *(Pointing to the sky)*.

In the figure 3.2 it can be seen that the antenna meets the adaptation criterion for frequencies above $1.2GHz$ up to $3GHz$, but also for the frequency band between $800MHz$ and $850MHz$.[Balanis, 2015] [Pozar, 2011]

In figure 3.3, the far field pattern of the antenna can be seen at a frequency of 300MHZ, in the figure 3.4 1.3GHz and in the figure 3.5 it can be seen for a frequency of 3GHz, from where

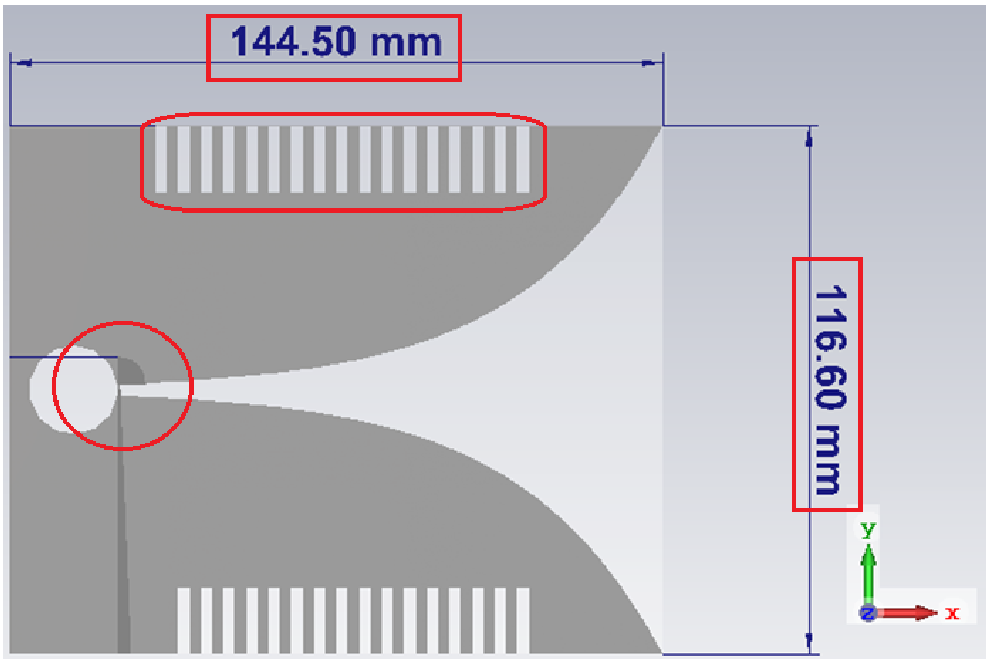


Figure 3.1: Variations presented in the final design. Final antenna design developed during the thesis

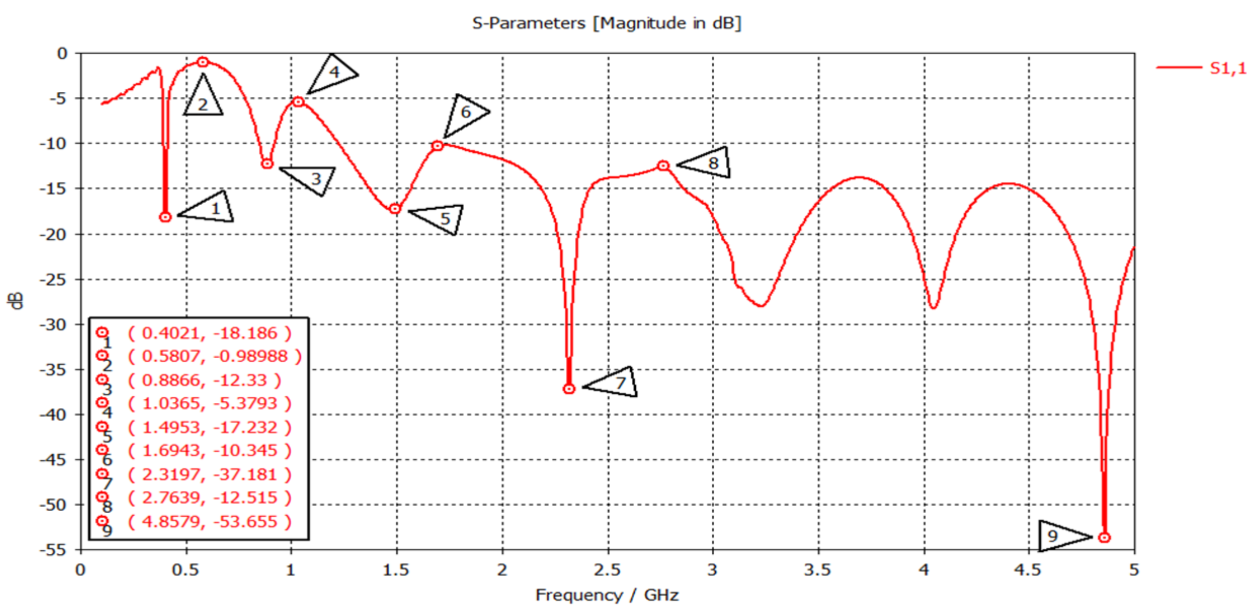


Figure 3.2: Parameter $S_{11}$ Vivaldi antenna developed in FR4 and pointed to free space (Aimed at the sky)

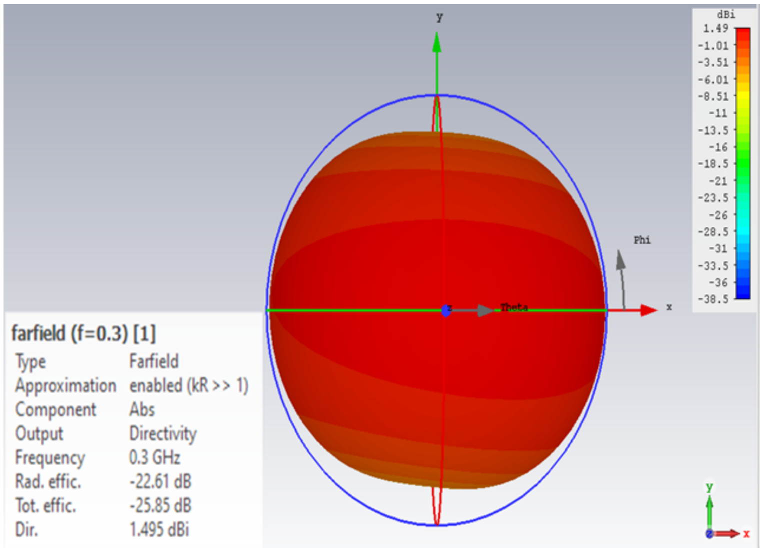


Figure 3.3: Far field Vivaldi antenna developed for the thesis at 300MHz

it can be observed that the electromagnetic waves emanated of the antenna are directed mostly towards the front of it, avoiding lobes towards the back of it, which shows a better management of the energy delivered to electromagnetic waves in the operating bandwidth of the antenna Vivaldi developed for this thesis.

In figure 3.6, we can see the Vivaldi antenna built to carry out the experimentation.

The Vivaldi antenna developed in this thesis was measured in free space. Those measurements are shown in figure 3.7. It should be noted that the vertical red bars indicate the bandwidth of interest (UHF) throughout the document.

To obtain the frequency response of the antenna, it was measured four times at different times of the day, where the measurements were made in the morning, noon, afternoon and night. The result of the standard deviation of the collected data can be seen in the figure 3.8. There it can be seen that the antenna has a very low standard deviation, which indicates that the measurement has good precision.

## 3.2 Theoretical validation of the model

For the theoretical validation of the model, several simulations were carried out in the CST simulation software.

There, several models were evaluated where the Vivaldi type antenna shown in figure fig6

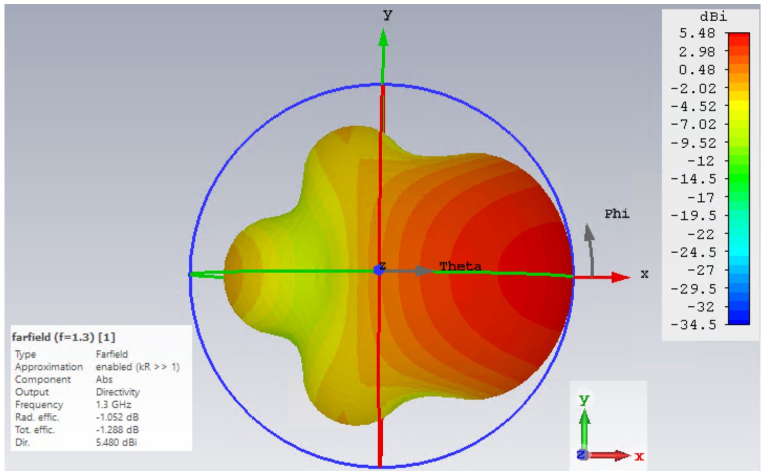


Figure 3.4: Far field Vivaldi antenna developed for the thesis at 1.3GHz

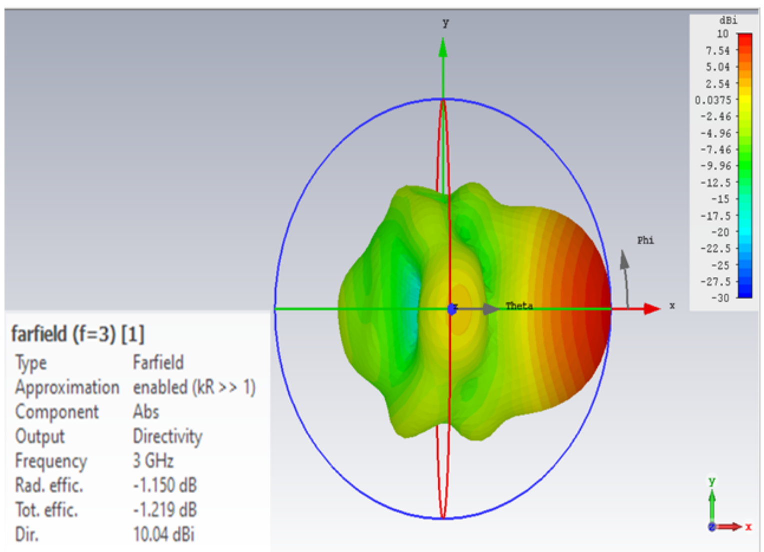


Figure 3.5: Far field Vivaldi antenna developed for the thesis at 3GHz

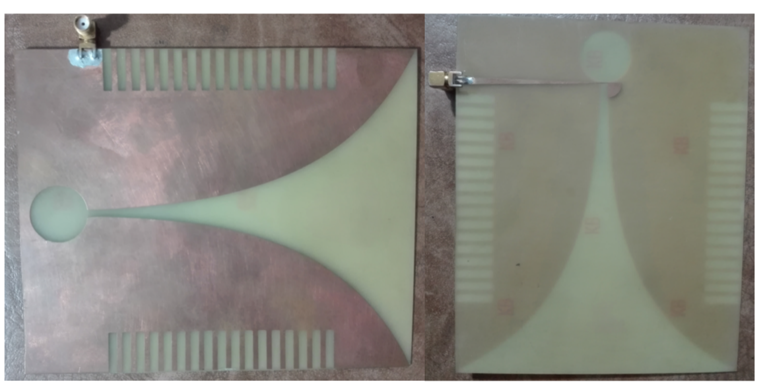

Figure 3.6: Vivaldi type antenna built for the experiment

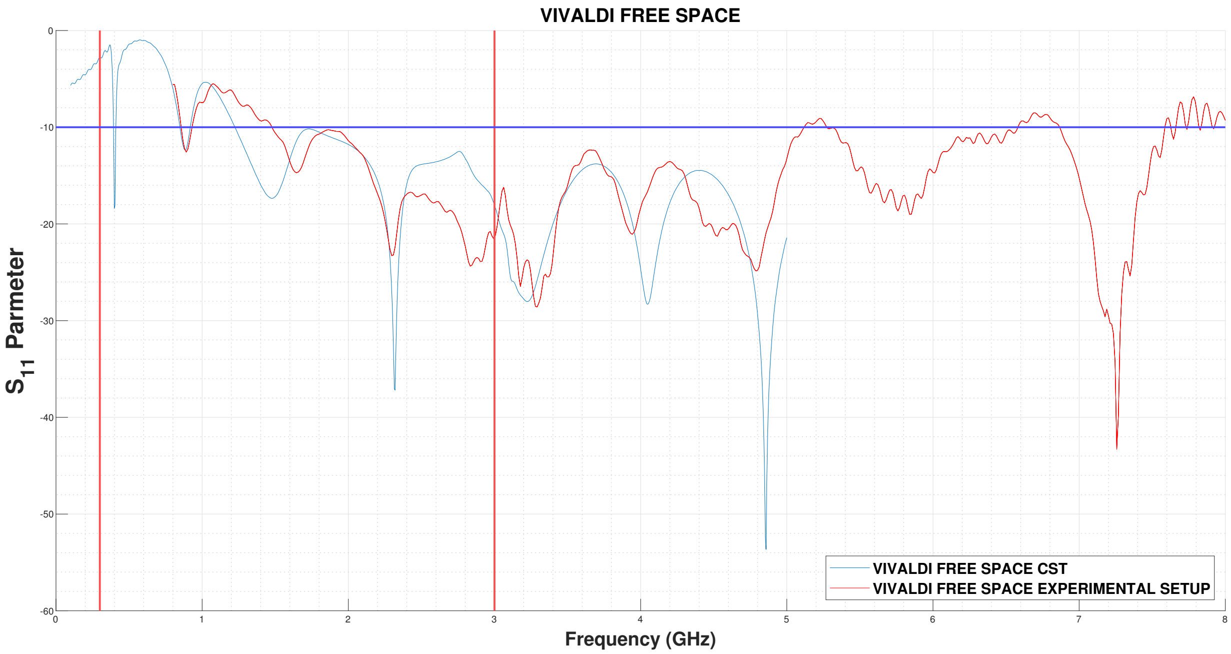


Figure 3.7: Theoretical and experimental values of the Vivaldi-type antenna built for the experiment

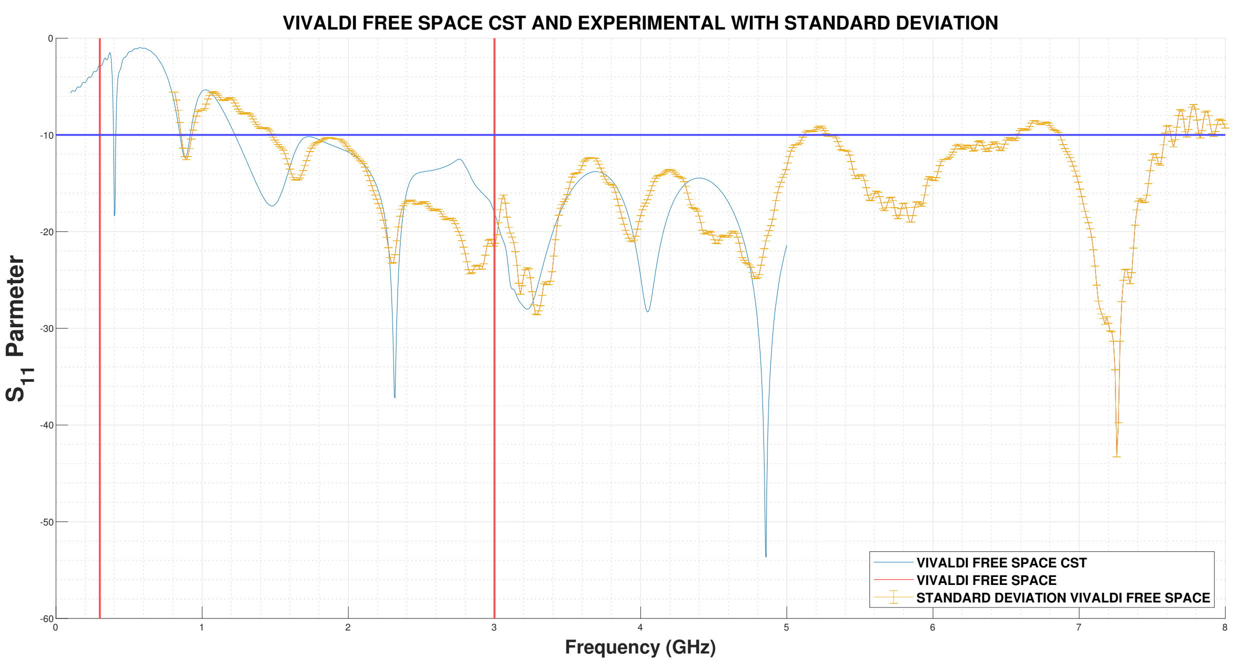


Figure 3.8: Theoretical and experimental values of the Vivaldi-type antenna built for the experiment

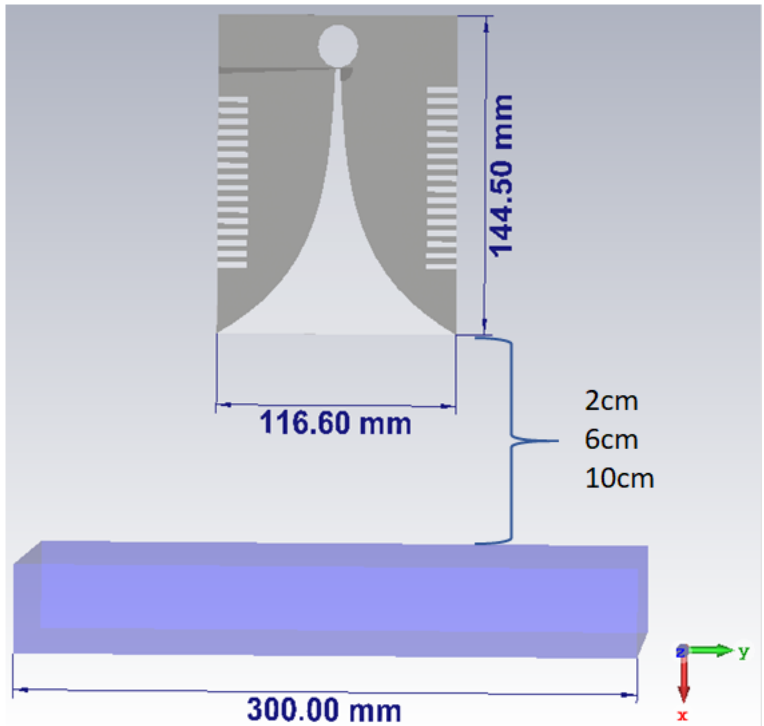


Figure 3.9: CST set up with Vivaldi antenna developed and water block

was located, at different distances of separation with respect to a block of water in liquid state that is below the antenna as seen in the figure 3.9

The simulated separation distances in CST between the antenna and the water block were 2cm, 6cm and 10cm.

Using the equation 2.21, developed in the second chapter of this book to obtain the electrical permittivity of water wirelessly and non-invasively, from the separation distance of the antenna and extracting the S11 parameter from the simulation in CST, the results of electrical permtivity of the water shown in figure 3.10 are obtained for a frequency sweep in the ***UHF (300MHz-3GHz)*** band.
As can be seen in the figure 3.10 the measure of electrical permittivity of water ***(80)***, is obtained when the antenna is 6cm away from the water block in the following frequency ranges:

- 855 MHz a 865 MHz
- 1,26 GHz y 1,5GHz
- 1.91 GHz

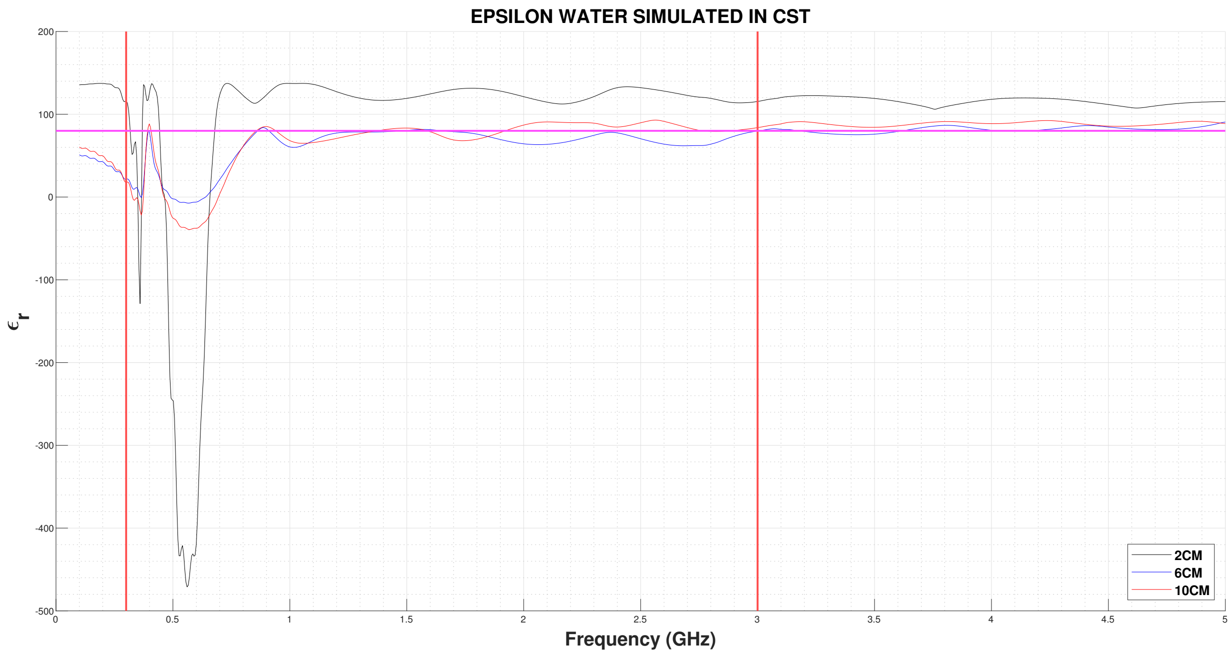


Figure 3.10: Epsilon water find with equation 2.21 and S11 parameter extaract simulated at CST 0 - 5GHz

While the water permittivity value close to ***80*** for a separation distance of 10cm between the antenna and the water block, is obtained at 1.92 GHz, 2.76 and 2.88 GHz.

It is also evident that in all cases the separation distance of 2cm is not reliable since the permittivity value found is well above the value of ***80***.

This is due to the multiple reflections caused by the electromagnetic wave fronts that bounce between the antenna and the water block as a result of the proximity between the antenna and the water block.

## 3.3 Experimental validation of the model

As explained previously in chapters 1 and 2, we will work with water in the city of ***Bogotá, Colombia***, with an ambient temperature of $20°C$, atmospheric pressure of 752.1 hPa and a relative humidity of 70%. The experimentation is carried out in an open field to guarantee that the electromagnetic wave incident on the water is not reflected by some element that is nearby that could affect the measurement in the ***UHF frequency range (300MHz - 3GHz).***. The measurement technique to be implemented will be time domain reflectometry ***(TDR)*** using a vector spectrum analyzer ***VNA***, which in this case will be a ***MiniTiny VNA*** provided by the ***Electromagnetic Compatibility Research Group of the Uni-***

***versidad Nacional de Colombia (EMC-UN)***, which can be seen in the Figure 3.13. And the antenna to be used in this experiment is shown in the Figure 3.6

The water has been taken from the tap, it has been placed in a container to carry out the measurement, it is in a liquid state and at room temperature at the time of measurement ($20°C$). The measurement setup can be seen in Figure 3.11.

In the configuration of figure 3.11, the antenna of figure 3.6 was placed on a series of supports that are transparent to electromagnetic waves at the frequency of interest ***(UHF (300MHz - 3GHz)***.

The support in the figure 3.11 is made of dry wood, cotton and PVC pipes. In this support the antenna developed in the thesis for the measurement is held, which is connected to a ***Mini Tiny VNA*** that can be seen in the figure 3.13, which in turn is connected to a computer to capture the data of the parameter ***S11*** coming from the antenna. The connection between the ***MiniTiny VNA*** and the antenna is done using very low loss coaxial cables. On this occasion, the cables used were the 1 meter long ***PE350*** manufactured by the company ***Pasternack***, which can be seen in the figure 3.12.

These cables have the following characteristics and specifications:

- Connector Series 1 SMA
- Connector Gender 1 Male
- Connector Polarity 1 Standard
- Connector Angle 1 Straight
- Connector Mount Method 1 None
- Connector Impedance 1 50
- Connector Series 2 SMA
- Connector Gender 2 Male
- Connector Polarity 2 Standard
- Connector Angle 2 Straight
- Connector Mount Method 2 None
- Connector Impedance 2 50

Figure 3.11: Electrical permittivity measurement set up of water in ***Bogotá, Colombia***


Figure 3.12: SMA Male to SMA Male Cable $PE350$ coaxial Pasternack. [Pasternack, 2020]

- RF Cable Part Number PE-P141
- RF Cable Type PE-P141
- RF Cable Impedance 50Ω

The ***Mini Tiny VNA*** is a pocket vector network analyzer, which is connected to a computer via USB port to acquire the dispersion parameters of an electromangetic wave (Matrix Scatering), which, by means of a application in ***JAVA***, shows the user the values obtained in the hardware, using the computer screen used in the measurement process.

This device has its own calibration kit, which was used at the end of the low-loss cable connected to it, in such a way that the calibration plan does not include the measurement antenna shown in figure ref fig11 but if the low loss connection cable shown in the figure 3.12. The calibration was done taking the entire bandwidth of the device ***(1MHz - 3GHz)*** with a thousand samples and a single full span sweep.

This device has the following specifications and features:

- Frequency range from 1MHz to 3GHz
- Frequency step of 10Hz
- Range of Z from 1 to 1000 ohm
- RF Generator power output of -6dBm @ 500 MHz
- Dynamic range of up to 70 dB @ 500 MHz
- Supply is Powered from USB
- SMA connectors for better isolation

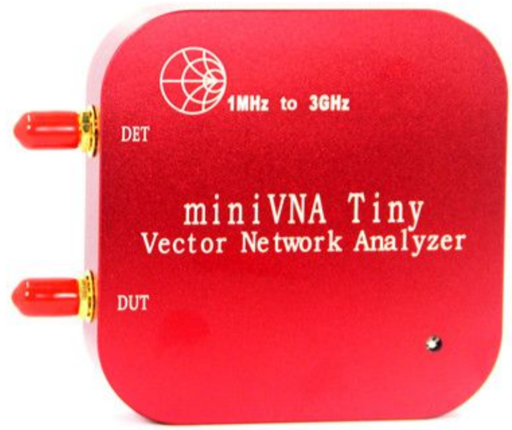


Figure 3.13: Miny Tiny VNA. [Solutions, 2020]

- Calibration using open-short-load for accurate results
- Two ports VNA with S11 and S21; displayed and save results
- Full Phase measurement
- Export data in several formats JPEG, EXCEL, ZPLOT, S2P, PDF
- Boot loader for future firmware upgrades
- User friendly interface for PC Windows Linux and Mac
- Integrated Smith chart in software
- SMA calibration kit with short, open and load (50Ω)

With the set-up of Figure 3.11 and with the help of a VNA ***Mini Tiny VNA*** shown in Figure 3.13, a total of 100 measurements were taken in three instants different from the day between 7 am and 4 pm, at the same time of year ***(November 1 to November 11, 2020)***, where the ambient temperature was over 20 $^{circC}$, the atmospheric pressure at 752.1hPa and the relative humidity of the air above 70%.

These one hundred measurements are carried out in order to guarantee the reproducibility and repeatability of the experiment under the conditions in which it was carried out.

The variations in climatic conditions at the time of making the measurements were minimal, therefore the measurements were very little affected by this factor and consequently, the value of electrical permittivity of the water was not affected by this cause either. This can be seen in the dispersion of the data shown in Figures 3.15, 3.16 and 3.17.

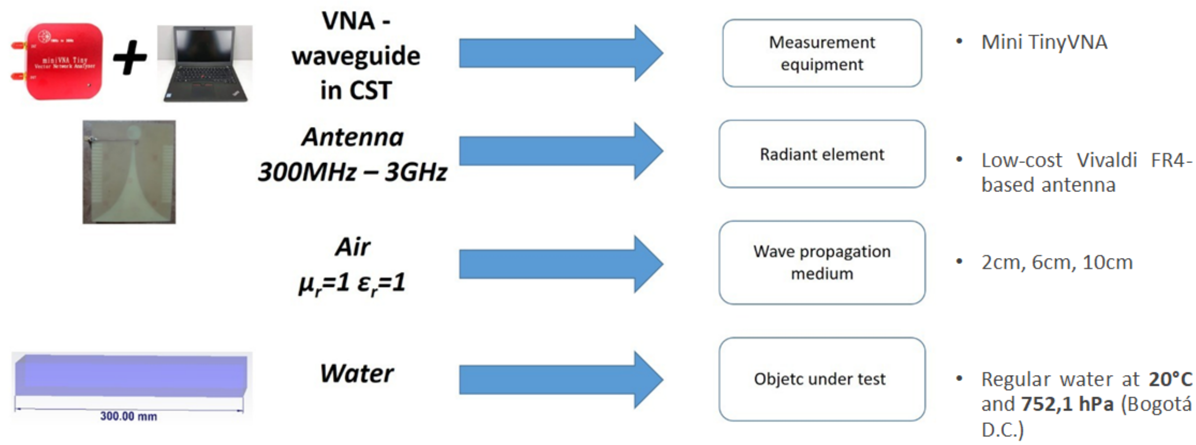


Figure 3.14: Measurement Set Up

The measurement scheme can be seen in figure 3.14, where there is the MiniVNA Tiny with a pc as the data acquisition system, with which the parameter $S_{11}$ of the incident signal is captured, which in turn In turn, it is connected to the antenna developed during this thesis to propagate the electromagnetic wave that is sent to the water.

In this diagram it can be seen that as a general consideration, the electrical permittivity of the air as well as the magnetic permeability of the air are equal to 1 and the object of tests or study, which in this case is water, will be located three distances apart, 2cm, 6cm and 10cm.

It must be remembered that the study takes place in the city of Bogotá, Colombia with an ambient temperature of $20°C$ and an average atmospheric pressure of 752.1 hPa.

All the data and Figures of this thesis were processed using ***MATLAB***, thanks to the student license that we have at the ***Universidad Nacional de Colombia*** as members of the academic community.

As can be seen in Figure 3.15 and 3.17, the measurements do not have a high dispersion, since the standard deviation of the data taken is low, which is evidenced in the bar diagram shown in the Figure 3.15 and it is corroborated when calculating their standard deviation shown in Figure 3.17, where one of the frequency values with the lowest standard deviation in its measurements is 1.3GHz.

Therefore, with the Figures 3.15, 3.16 and 3.17, it can be seen that the frequency at which the system manages to obtain the best measurement for the electrical permittivity of water

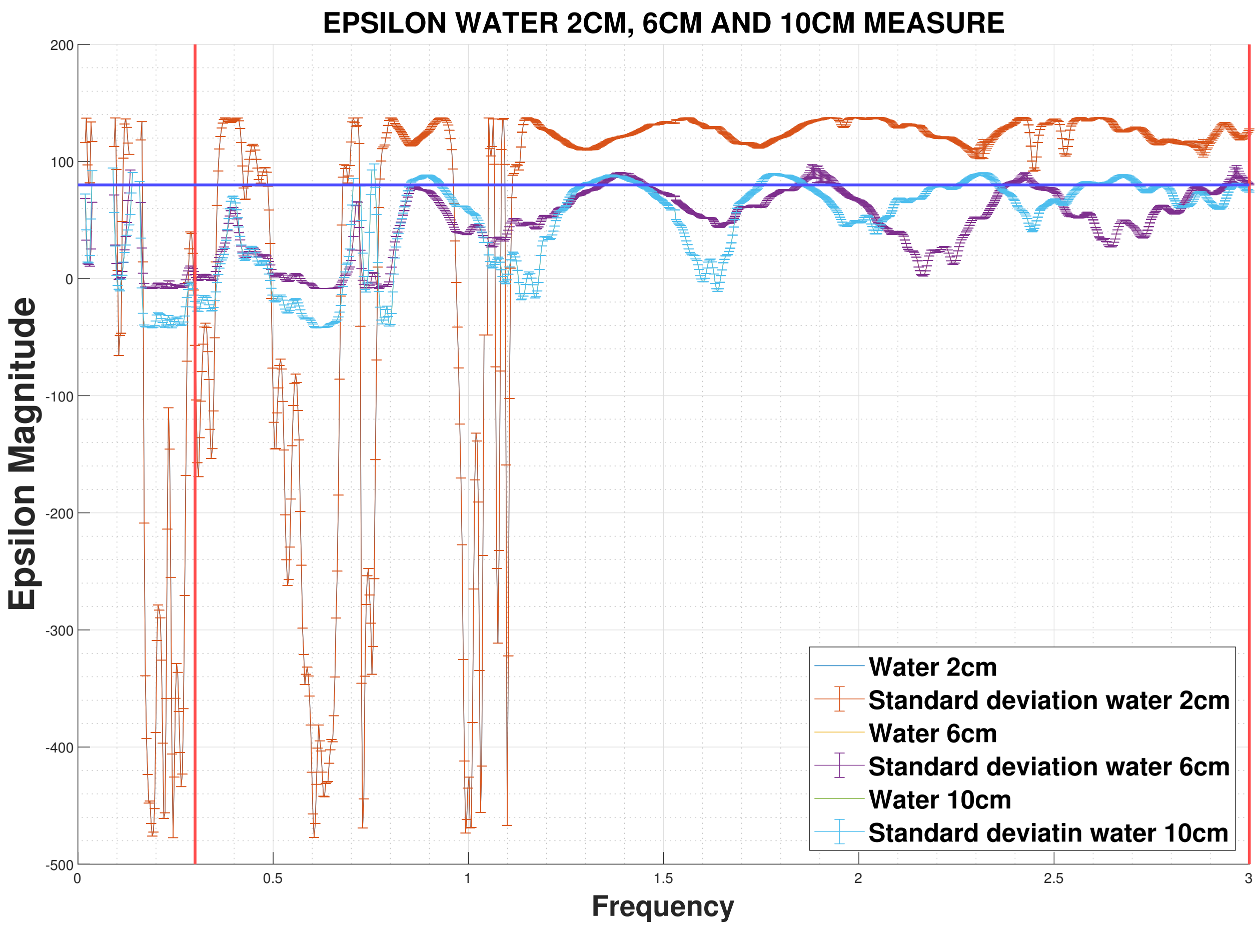


Figure 3.15: Standar Deviation of Epsilon water find with equation 2.21 and $S_{11}$ parameter measurmenet with setup sowed in the Figure 3.10 and 0 - 5GHz

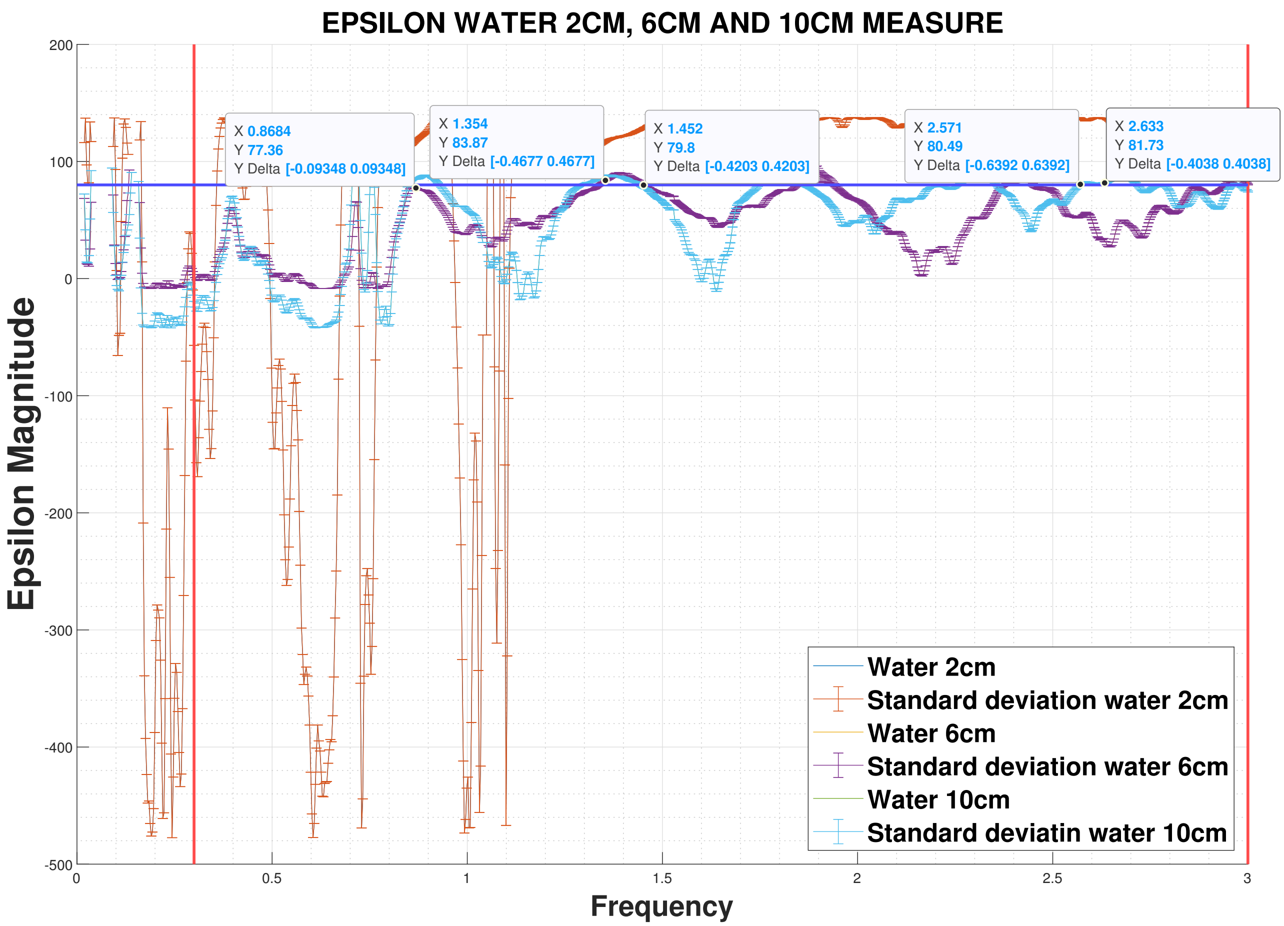


Figure 3.16: Standar Deviation of Epsilon water find with equation 2.21 and $S_{11}$ parameter measurmenet with setup sowed in the Figure 3.10 and 0 - 5GHz

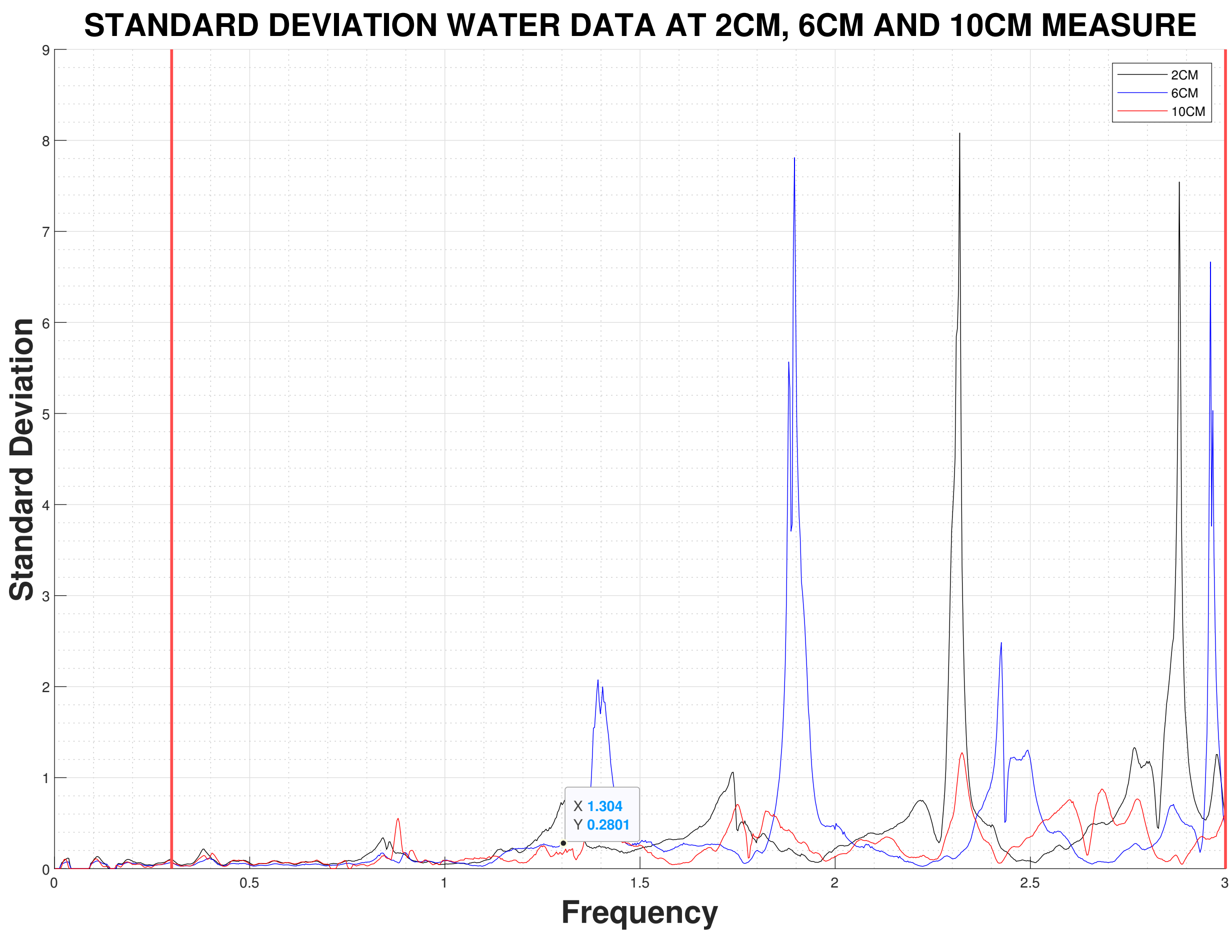


Figure 3.17: Standar Deviation $S_{11}$ water parameter measurment with set-up showed in the Figure 3.10 and 0 - 5GHz

is ***1,3GHz***.

## 3.4 Author's contributions

The main contributions of this thesis are:

- Development of a method for non-invasive measurement of Dielectric Permittivity with low-cost equipment (Potentially Patentable).
- Development and construction of a low-cost Vivaldi-type antenna, designed and manufactured on the FR4 substrate. (Potentially patentable).
- Mathematical modeling for the evaluation of dielectric permittivity based on the non-invasive $S_{11}$ parameter (potentially patentable).

- Using the method described in this thesis, it can be seen that the efficient band to measure the electrical permittivity of water is 1.3GHz – 1.35GHz with a separation distance between the antenna and the object under test of 6cm to 10cm.
- During the development of this master's thesis, we contributed to the design and evaluation of permittivity and conductivity of materials for SAR evaluation in the human body.
- The study of electrical permittivity of water, has allowed during the development of this master's thesis, to contribute to the design and construction of phantoms for SAR evaluation.

### 3.4.1 Author's written papers

During the development of this master's thesis, the writing of the following scientific articles was contributed:

1. Fabricación de sustitutos de tejido humano para análisis de SAR en radiocomunicaciones. EMC, Technology and Health, IEEE Third Workshop of Electromagnetic Compatibility, International Workshop EMCC, Nov 11,2021.

   In this conference, developed models of liquid materials that emulate human tissue were shown for the analysis of electromagnetic waves in the radiofrequency range, taking into account the IEC/IEEE 62209-1528-2020 standard.

2. John J. Pantoja, Sergio Gutierrez, Edwin Pineda, David Martinez, Christoph Baer and Felix Vega, Modeling and measurement of complex permittivity of soils in UHF. IEEE Geoscience and Remote Sensing Letters, 2019.

   From the study of the electrical permittivity, Colombian soils are analyzed and a modeling is elaborated from measurements of their complex permittivity.

3. S.I. Rodríguez, A. Gallego, E. Pineda, J.C. Vargas, M.R. Pérez, F. Román and J.L. Araque, Low-cost Setup for Electromagnetic SAR Evaluation in a Human Phantom. IEEE-EUCAP, 2022.

   In this article, based on the analysis of the electrical permittivity of materials and with the help of the IEC/IEEE 62209-1528-2020 standard, liquids that emulate human tissue are developed for the analysis and incidence of radiofrequency electromagnetic waves in the human body.

4. Andrés Gallego, Edwin Pineda, Sergio Gutierrez, Francisco Román. Complex Natural Resonances extraction methods for Ground Penetrating Radar operations. Digital

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In this article he contributed with the analysis of electrical permittivity of some materials and its impact on the improvement of signal processing in GPR ground penetrating radar operations.

5. Oscar Montero, John J. Pantoja, Marlon Patiño, Edwin Pineda, David Martinez, Gilma Angel, Johana Cruz, Martha Suarez, Felix Vega, Attenuation of Radiofrequency Waves due to Vegetation in Colombia. En 2018 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC). IEEE, 2018.

   This article contributed to the study of the attenuation of electromagnetic waves in vegetation, taking into account the behavior of the electrical permittivity of vegetation in Colombia.

6. Francisco Román. Jorge Rodríguez, Edwin Pineda, Daniel Rodríguez, Carlos Rivera, Alejandro Cristancho, María Barajas, Andrés Rojas, Protección Personal Contra Rayos Empleando Textiles Conductores. En: Costa Rica Congreso de Alta Tensión y Aislamiento Eléctrico ALTAE 2021

   From the study of the electrical permittivity of human tissue, we contributed to the development of phantoms that allowed the development of laboratory tests that recreated real conditions of use in lightning shelters using conductive textiles.

## 3.5 Future Jobs

Taking into account the current state of research and analyzing its potential evolution in the process of identifying materials using radio frequency, the following future works are proposed:

- The process of identifying materials with radiofrequency should be deepened even more using the method described in this thesis.
- More research should be done on the close relationship between the distance at which the detection antenna is from the object for the process of identifying materials from electrical permittivity.
- It is necessary to go deeper into the consistency of the mathematical model described in this thesis for the determination of other materials from their electrical permittivity.
- Determination of various tissues for disease diagnosis.

- Develop a suitable calibration procedure for the system in general, which allows reducing the error seen in the measurements obtained in this thesis.
- It should start to build databases of materials identified with this method, which allow increasing applications in other fields of science where it is necessary to detect materials in a non-invasive way
- It must be checked whether the method described in this thesis works adequately for the detection of water in other states of matter at different temperatures.
- More research needs to be done on the relationship between temperature and electrical permittivity of matter.

# 4 Conclusions

- In the measurement system proposed in this thesis, the optimal frequency range to find the permittivity of water is ***1.3GHz to 1.35GHz at a distance of 6cm to 10cm***
- The measurement method is applicable to measure water at $20°C$, with an average atmospheric pressure of 752.1 hPa and a relative humidity close to 70% in the city of ***Bogotá, Colombia***
- In the reference system, although the equipment is highly accurate, the electrical permittivity measurement of water is stable in the range of ***UHF (300MHz - 3GHz)***
- A low-cost, non-invasive method was presented to determine the electrical permittivity of water in liquid state, where the antenna to be implemented can be easily constructed.
- It was shown that the method described in this thesis gives the value of permittivity of water in various ranges of frequencies, contrary to the effectiveness of high-cost equipment, great precision and accuracy, where this value is not constant for all frequency ranges and their ranges are narrow.
- Based on the measurements made with the high-cost system and the measurements made with the system proposed in this thesis, it is shown that both measurements are stable in the range of ***UHF (300MHz - 3GHz)*** for water measurement. However, this method is non-invasive, and low-cost materials.
- It was shown that it is possible to determine the electrical permittivity of water, by means of the TDR detection technique, using only the reflection parameter $S_{11}$.

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