# NON-LINEARITY OF SOIL DIELECTRIC CONSTANT AS A FUNCTION OF RADAR FREQUENCY AND SOIL MOISTURE CONTENT

*Maritza Torres- Graduate Student, Dr. Hamed Parsiani- Advisor*
*Electrical & Computer Engineering Department - UPRM*
*parsiani@ece.uprm.edu*

## ABSTRACT

Soil is a mixture of four components: air, free water, bound water and soil particles. The microwave dielectric constant of soil is strongly dependent on the soil moisture content. The dielectric constant is a measure of the response of a material to an applied electric field, such as an electromagnetic wave. It has a real and an imaginary component. Soil particles' dielectric constant depends on the physical properties of the soil, and not on frequency. Water's dielectric constant depends on frequency, temperature and salinity and therefore so does the soil mixture's dielectric constant. There are different dielectric mixing models that are used to determine the dielectric constant or the moisture content. In this work, the concept of complex dielectric constant and its nonlinearity due to changes in frequency, and actual soil moisture values are revisited. The complex dielectric constant non-linearity as a function of frequency for an example of clay soil is verified with a previously published work in the range of our Ground Penetrating Radar (GPR) bandwidth frequencies whose center frequency is at 1.5 GHz. The soil's dielectric constant dependence on the soil moisture content will also be shown.

## 1. INTRODUCTION

Soil moisture content measurements are very important for various environmental studies. The methods that have been used overtime are point measurements; these are invasive and have a low spatial resolution. Remote sensing is the alternative that has been used now for a while, since it is noninvasive and has a much better spatial resolution. In our study a Ground Penetrating Radar (GPR) was, specifically, the GSSI SIR-20 with a bow-tie antenna centered at 1.5 GHz.

The dielectric constant of water and soil particles are very different, this difference is used to estimate the water content from the dielectric constant. Dielectric constants have a real ($e^{'}$) and imaginary ($e^{''}$) part expressed by: $e = e' - je''$. The real part determines the propagation characteristics of the electromagnetic wave in the material, or velocity; and the imaginary part determines the energy losses or absorptions of the electromagnetic wave. Water's dielectric constant at 1.5 GHz is approximately, 80-j6, and completely dry soil particles have a dielectric constant independent of frequency, and real part between 2-4 and imaginary part of less than 0.05 [1]. The range of values for dry soil particles is determined by the soil bulk density, a physical property of the soil. In Figure 1, we are able to see how the soil dielectric constant varies with frequency and with moisture content. The temperature is 24°C and the soil is Goodrich clay.

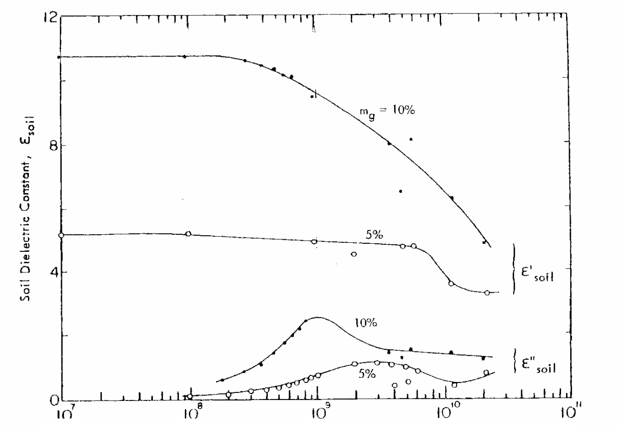

Figure. 1: Dielectric Constant vs. Frequency
(Hoekstra and Delaney, 1974, [1])

Water is the key factor when determining the dielectric constant of soil mixture. Its dielectric constant is very high and differs a lot from that of soil particle alone, for this reason it is useful for determining the moisture content of soil. This has been studied by various people and there are various dielectric mixing models, these models need as an input many characteristics of the soil.

## 2. DIELECTRIC MIXING MODELS

There are many models that have been developed by different people. Models include: physical soil models, two-component formulas and semi-empirical models among others. Some are more elaborate and some approximate more. The model used is the four-component dielectric mixing model, created by [2], and then modified by [3].

## 2.1. Four-component dielectric mixing model

It consists of an empirical relationship with separate polynomial expressions for both the real and imaginary parts of the dielectric constant between observation frequencies of 1.4 and 18 GHz. These polynomial expressions relate the real and imaginary parts of the complex dielectric constant, to the volumetric soil moisture content and the percentages of sand and clay, with coefficients that depend on the observation frequency. The four components are the soil particles, air, free water and bound water. Bound water is the water that is absorbed by the particles and its dielectric constant is lower than that of free water, because its molecules can't move so freely. This is why they are treated differently.

The model of Peplinski et al. (1995)[3] is currently the most commonly used soil-water-air dielectric mixing model, being a compromise between the complexity of the theoretical model and the simplicity of the empirical models. Furthermore, this mixing model has the widest validity range in terms of observation frequency and accounts for the most important factors, including observation frequency, soil texture and soil temperature. This model [3] is presented below in terms of the volumetric soil moisture fraction $\theta$, soil bulk density $\rho_b$ (g cm$^{-3}$), soil specific density $\rho_s$ (≈ 2.66 g cm$^{-3}$), and an empirically determined constant $\upsilon$ = 0.65.

$$\varepsilon'_r = \left[1 + \frac{\rho_b}{\rho_s}\left(\varepsilon_s^{\upsilon} - 1\right) + \theta^{\beta'}\varepsilon'^{\upsilon}_{fw} - \theta\right]^{\frac{1}{\upsilon}} \quad \text{-- (2.1a)}$$

$$\varepsilon''_r = \left[\theta^{\beta''}\varepsilon''^{\upsilon}_{fw}\right]^{\frac{1}{\upsilon}} \quad \text{-- (2.1b)}$$

The values ß’ and ß” were found empirically and each is a function of the percentage of sand and clay in the soil.

$$\beta' = 1.2748 - 0.519S - 0.152C \quad \text{-- (2.2a)}$$
$$\beta'' = 1.33797 - 0.603S - 0.166C \quad \text{-- (2.2b)}$$

The quantities $\varepsilon'_{fw}$ and $\varepsilon''_{fw}$ are the real and imaginary parts of the dielectric constant of free water, given by

$$\varepsilon'_{fw} = \varepsilon_{w\infty} + \frac{\varepsilon_{wo} - \varepsilon_{w\infty}}{1 + (2\pi f\tau_w)^2} \quad \text{-- (2.3a)}$$

$$\varepsilon''_{fw} = \frac{2\pi f\tau_w(\varepsilon_{wo} - \varepsilon_{w\infty})}{1 + (2\pi f\tau_w)^2} + \frac{\sigma_{eff}}{2\pi\varepsilon_o f}\frac{(\rho_s - \rho_b)}{\rho_s\theta} \quad \text{-- (2.3b)}$$

where $\varepsilon_{w\infty}$ = 4.9, is the high frequency limit of $\varepsilon'_{fw}$, it is independent of temperature and salinity, $\varepsilon_o$ is the dielectric constant of free space (8.854 × 10$^{-12}$ F.m$^{-1}$), and $f$ is the observation frequency in Hertz.

The dielectric constant of the soil particles is given by,

$$\varepsilon_s = (1.01 + 0.44\rho_s)^2 - 0.062 \quad (2.4)$$

As seen it does not depend on frequency only on the soil bulk density.

For frequencies between 0.3 and 1.3 GHz the real part of the relative dielectric constant is given by the linear adjustment in (2.5), while for frequencies between 1.4 and 18 GHz it is given directly by (2.1a).

$$\varepsilon'_r = 1.15\varepsilon'_{r(2.1a)} - 0.68 \quad (2.5)$$

were $\varepsilon'_{r(2.1a)}$ is the real component of the relative dielectric constant from (2.1a).

In evaluating the imaginary part of the relative dielectric constant, the effective conductivity $\sigma_{eff}$ is given in (2.6a) is used for frequencies between 0.3 and 1.3 GHz, while that given in (2.6b) is used for frequencies between 1.4 and 18 GHz.

$$\sigma_{eff} = 0.0467 + 0.22049\rho_b - 0.4111S + 0.6614C \quad \text{-- (2.6a)}$$
$$\sigma_{eff} = -1.645 + 1.939\rho_b - 2.25622S + 1.594C \quad \text{-- (2.6b)}$$

The relaxation time for water, $\tau_w$, and the static dielectric constant of water, $\varepsilon_{wo}$, are given as a function of soil temperature $T$ (°C) by[1]

$$2\pi\tau_w(T) = 1.1109\times10^{-10} - 3.824\times10^{-12}T + 6.938\times10^{-14}T^2 - 5.096\times10^{-16}T^3 \quad \text{-- (2.7)}$$

$$\varepsilon_{wo}(T) = 88.045 - 0.4147T + 6.2958\times10^{-4}T^2 + 1.075\times10^{-5}T^3 \quad \text{-- (2.8).}$$

## 3. SOIL ANALYSIS

The soils used were: sand- construction sand, loam - San Antón Loam from Juana Diaz, PR and clay- Daguey Clay from the Finca Alzamora on the UPR Campus in Mayagüex, PR. The soils were analyzed for their chemical and physical properties by SoilCon Laboratory, Ltd. Of British Columbia, Canada. All of the results of the analysis are given in a table in [4]. For this model the values needed are shown in the following table:

| Soil Type | Bulk Density (g cm$^{-3}$) | Particle Density (g cm$^{-3}$) | % of Sand | % of Clay |
|---|---|---|---|---|
| Sand | 2.67317 | 2.67317 | 96 | 1.62 |
| Loam | 2.53314 | 1.35097 | 35.99 | 23.87 |
| Clay | 2.53736 | 1.09238 | 3.61 | 67.27 |

Table 1. Soil Analysis

## 4. PROCEDURE AND RESULTS

Using equations 2.1-2.8 and the values obtained from the analysis of the soil shown in Table 1, a program was created using Matlab©. The program has the capability of plotting the dielectric constant of the specific loam, sand and clay that we have versus frequency or moisture content, as variables. One variable is fixed so that the dielectric constant is given in terms of the other variable.

First the moisture content was kept fixed and the frequency was set from 10MHz to 100GHz. The program prompts the user to enter the moisture content and the result is a graph of dielectric constant vs. frequency for all three soils at that specific moisture content as shown in Figure 2:

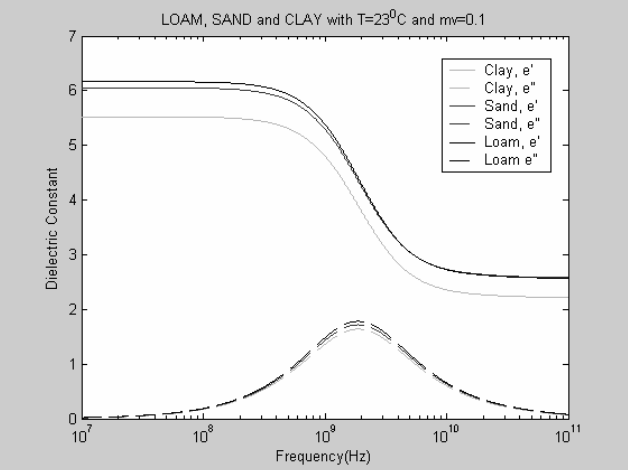

Figure 2. Dielectric Constant vs. Frequency for Sand, Loam and Clay with moisture content of 10%

In order to see how the moisture content relates to the dielectric constant, the frequency was fixed and the moisture content was set to go from 0% to 40%. The program prompts to enter the desired frequency. The value of 1.5GHz was entered, and the result is a graph of dielectric constant vs. moisture content for all three soils, at that specific frequency as shown in Figure3.

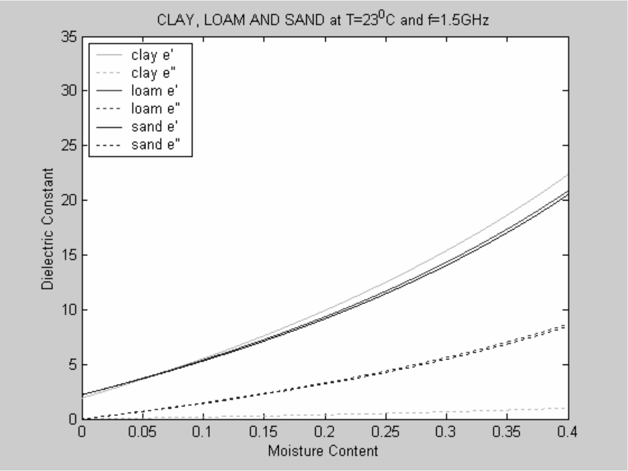

Figure 3. Dielectric Constant vs. Moisture Content for Sand Loam and Clay with frequency of 1.5GHz

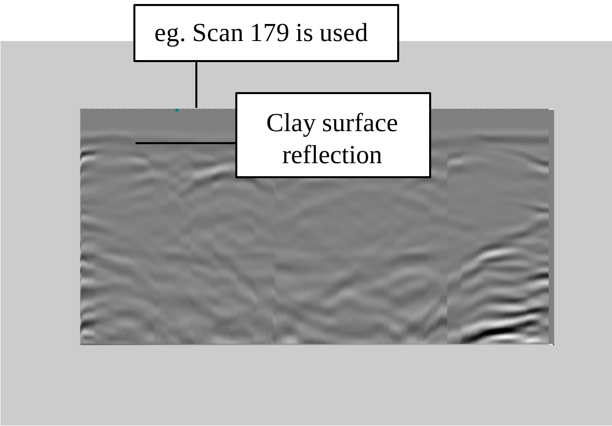

Figure 4. GPR Image

Following the theory of propagation of electromagnetic waves at the interface of two materials with different dielectric and electric properties a reflection will occur. The strength of the reflection depends on the difference of the material properties, and can be calculated by the well-know reflection coefficient R from Fresnel,

$$|R|e^{jq} = \frac{\sqrt{e_{r_1}} - \sqrt{e_{r_2}}}{\sqrt{e_{r_1}} + \sqrt{e_{r_2}}}. \tag{4.1}$$

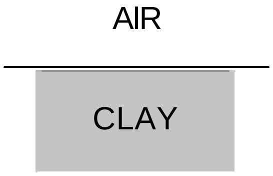

Figure 5. Boundary between air and clay

In our case the two layers are air and ground, where $e_r$ of air is one, and the reflection coefficient is given by,

$$\left|R\right|e^{jq} = \frac{1-\sqrt{e_{r_2}}}{1+\sqrt{e_{r_2}}} . \qquad (4.2)$$

This coefficient has a magnitude and a phase, this is due to the fact that $e_r$ is a complex number. From equation 4.2, we can obtain the value for $e_{r2,}$ the dielectric constant for clay:

$$e_{r_2} = \left(\frac{1-R}{1+R}\right)^2 \qquad (4.3)$$

From equation 4.3 we obtain the real and imaginary part for the dielectric constant of clay, using,

$$e'_{r2} = \left|e_{r2}\right|\cos q \qquad (4.4)$$ and

$$e''_{r2} = \left|e_{r2}\right|\sin q \qquad (4.5).$$

The GPR was applied to the surface of clay soil, image shown in Figure 4, with a boundary as illustrated in Figure 5. The reflection signal magnitude and phase was obtained using Fourier transform. Evaluating equations 4.3, 4.4 and 4.5 we obtained a plot shown in Figure 6. This figure shows that GPR measurements of dielectric constants were similar to the calculated values, Fig. 2, using the mixing model [3].

## 5. CONCLUSION

The spatial measuring device, GPR, and other point measuring devices (such as Time Domain Reflectrometer) operate at different frequencies. The dielectric constant (a complex number with amplitude and phase angle) which is ultimately a measure of moisture is a nonlinear function of frequency. On the other hand, the dielectric constant non-linearity increases as the actual soil moisture increases. The moisture models must incorporate these nonlinearities in order for a dielectric constant to be correctly converted to a moisture value. At a fixed frequency for different dielectric constants, there are different moisture values, and it is not a linear relationship. There were many problems in the validation using point measuring devices, since their frequencies of operation were different. In order to validate, a model must be chosen, and the soil analyzed. The results from the model are then used for validation. From GPR results it was shown that the measured values were very similar to the results obtained from the model [3].

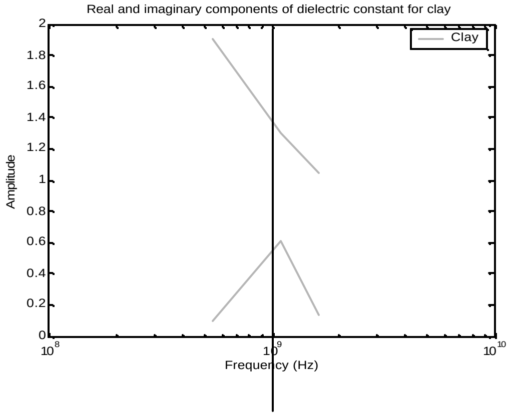

Figure 6. Dielectric constant obtained from the GPR

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