Modeling and Measurement of Complex Permittivity of Soils in UHF

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***Abstract*—The complex permittivity of different types of soils in the ultra-high frequencies (UHF) is studied in this paper. A new model, whose inputs are the low-frequency conductivity and the volumetric water content, is proposed to estimate the complex permittivity of soils in UHF. The model is compared with complex-permittivity values of each soil in the UHF range, which are determined from two-port S-parameters measurements of a coaxial probe designed for material characterization. Results show that the model is in a good agreement with the measurements despite some differences in soils with high resistivity. The soil samples used in this study include locations where humanitarian demining operations are being conducted.**

***Index Terms*—Soil Permittivity, permittivity, resistivity, field measurements, soil models.**

I. Introduction

The electromagnetic (EM) properties of soil are determinant in the performance of ground penetrating radars (GPR) and other devices based on the perturbation of EM fields for the identification or detection of buried objects. The knowledge of the soil permittivity, for example, determines the resolution of GPR images and facilitates the discrimination of buried objects [1]. EM soil properties varies with the type of soil and with the specific terrain conditions, such as the moisture, compactness, and vegetation. In addition, soils are dispersive materials therefore these properties vary with the frequency.

Different models have been proposed to describe the dispersive behavior of soils. However, some of these models result impractical due to the requirement of knowledge of several soil characteristics [2]. Simplified semiempirical models, used for the analysis of EM pulses on buried wires [3] and used for lightning-protection systems assessment [4] [5] [6] [7], have been also considered. However, these models are limited to frequencies in the range of hundreds of MHz. In [8], an extension of the useful bandwidth of the Messier soil model is proposed. There are also soil models based in the equations proposed by Debye [2] and Topp [9] that are restricted to the microwave frequency range.

On the other side, practical experimental procedures to determine the permittivity of dielectric materials are restricted in frequency and still show some issues with the variation of compactness and moistures of samples [2], [10], [11]. Ultra low frequency characteristics of soils can be obtained using an earth tester. An impulsive test can be performed to determine the permittivity and dielectric losses in the low and medium frequency range [12]. An open-ended coaxial probe can be used to estimate the complex permittivity of soils between 10 and 1000 MHz [13]. In the range of microwaves, a field deployable system based in the transmission/reflection response of a coaxial sample has been recently proposed [14]. Although the combination of these techniques can cover the complete frequency range required for the setup and post-processing of GPR measurements, a more practical procedure would be desirable in some applications, such as humanitarian demining operations.

This paper presents a simplified model to estimate the soil permittivity. Additionally, values calculated with the proposed model for different types of soils are compared against complex permittivity measurements in the UHF range. This paper is organized as follows. In Section II, the simplified soil model for ultra-wide band analysis is explained. In Section III, the experimental setup used to verify the model is presented. Soils with humanitarian demining operations in Colombia were specially selected, characterized, and used for the verification. In Section IV, experimental results and a comparison with the proposed model are presented. Finally, we conclude in Section V.

II. Soil Permittivity Models

In this section, some engineering models to estimate the soil permittivity are described and a new model intended for the UHF range is proposed.

A. Messier Model

Messier model [7] estimates the frequency dependence of the permittivity and the conductivity of soils between $100\,\mathrm{Hz}$ and $1\,\mathrm{MHz}$ using

$$\varepsilon(f) = \varepsilon_\infty \left(1 + \sqrt{\frac{\sigma_0}{\pi f \varepsilon_\infty}}\right), \tag{1}$$

$$\sigma(f) = \sigma_0 \left(1 + \sqrt{\frac{4\pi f \varepsilon_\infty}{\sigma_0}}\right), \tag{2}$$

where σ_0 is the DC or low-frequency conductivity, $\varepsilon_\infty = 8\varepsilon_0$, and ε_0 is the free-space permittivity. Therefore, the high frequency complex permittivity is calculated from a low frequency conductivity measurement.

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TABLE I: Coordinates, soil taxonomy, low-frequency resistivity, and soil type of the measurement locations

Location	Latitude	Longitude	Taxonomy	Resistivity (Ωm)	θ_v	Soil type	Organic content %
Bogotá	$4°38'47.73''$	$-74°4'50.05''$	Urban zone	38.5	38%	Black soil	14.0
Cáqueza	$4°24'29.76''$	$-73°56'25.53''$	Typic Dystrudepts	30.9	39%	Black soil	16.7
La Mesa	$4°40'1.69''$	$-74°25'33.62''$	Typic Ustorthents	99.4	46%	Sand clay	2.5
Mosquera	$4°41'0.22''$	$-74°13'6.86''$	Aeric Endoaquepts	10.4	41%	Rural soil, clay	7.6
San Juan de Arama	$3°21'54.68''$	$-73°52'34.23''$	Fluventic	2300	47%	Clay	10.5
Mesetas	$3°21'34.37''$	$-74°10'18.32''$	Typic	1840	56%	Clay	14.0

B. Topp's equation

Topp's equation is the well known relationship presented in (3). It relates the relative permittivity value between 0.1 and 1 GHz and the volumetric water content of soil θ_v [9], [10].

$$\theta_v = -5.3\times10^{-2}+2.92\times10^{-2}\varepsilon_r-5.5\times10^{-4}\varepsilon_r^2+4.3\times10^{-6}\varepsilon_r^3 \quad (3)$$

C. Roth's equations

Roth et al. proposed in [15] relations between dielectric permittiviy and moisture for mineral (4) and organic (5) soils for TDR applications.

$$\varepsilon_r = 2.87 - 11.1\theta_V + 276\theta_V^2 - 272\theta_V^3 \quad (4)$$

$$\varepsilon_r = 0.97 - 10.9\theta_V + 87.4\theta_V^2 - 28.0\theta_V^3 \quad (5)$$

D. Proposed Model

From Messier and Debye models, Pantoja et al. in [8] proposed a model governed by (6) and (7). This model was shown to be consistent with independent experimental results in the UHF and microwave frequency ranges.

$$\varepsilon_r(f) = \frac{1}{\varepsilon_0}\left(\varepsilon_{w\infty} + \frac{\varepsilon_s - \varepsilon_{w\infty}}{1+(2\pi f\tau_w)^2}\right), \quad (6)$$

$$\varepsilon_r''(f) = \frac{1}{\varepsilon_0}\left(\frac{2\pi f\tau_w\varepsilon_{w\infty}}{1+(2\pi f\tau_w)^2} + \varepsilon_s - \varepsilon_{w\infty} + \frac{\sigma_0}{2\pi f}\right), \quad (7)$$

where $\varepsilon_{w\infty} = 4.9\varepsilon_0$ and $\tau_w = 0.231$ ps are, respectively, the high frequency limit and the relaxation time for the free water dielectric constant [2], and ε_s is the real-part of the soil permittivity calculated using (1). It is valuable to notice that the input variables in (6) and (7) are the frequency and σ_0; the rest of parameters are constant.

Since the permittivity's real part in the GHz frequency range depends on the soil moisture, as shown in (3), in this paper, a modification in the model presented in [8] is proposed. This change is included to increase the agreement with experimental results in the microwave frequency range with only an additional input: the volumetric water content of soil. In the proposed model in this paper, the complex permittivity is also calculated using (6) and (7) but the high frequency limit, $\varepsilon_{w\infty}$, and the variable ε_s are calculated as follows:

$$\varepsilon_s(f) = \varepsilon_M\varepsilon_0\left(1+\sqrt{\frac{\sigma_0}{\pi f\varepsilon_M\varepsilon_0}}\right), \quad \text{and} \quad (8)$$

$$\varepsilon_{w\infty} = \varepsilon_M\varepsilon_0, \quad (9)$$

where ε_M is the limit of the real part of the relative permittivity in the microwave frequency range calculated with (4) or (5), depending on the soil type.

III. Measurement setup

To verify the proposed model, an experimental campaign was developed. Different kinds of soils and locations were considered as detailed below. In each soil, the complex permittivity in the UHF range, the low frequency conductivity, and the volumetric water content were measured.

A. Soil Samples.

Soil samples taken from 6 Colombian locations were considered in the study. The selection of these locations aimed to include soils of different type as described in Table I. The classification of each soil was taken from the information reported by the Geographical Institute Agustín Codazzi (IGAC) [16] and arranged according to the taxonomy of the United States Department of Agriculture (USDA) [17]. Soil organic content in Table I is based in data reported in [18].

B. Low-frequency conductivity and moisture.

The low-frequency conductivity was measured using the earth tester Metrel MI2088 in the 4-wires configuration. To obtain the average conductivity in each location, six measurements were carried out. In each measurement, the earth-tester electrodes were placed in a straight line, as shown in Fig. 1. Then, the electrodes were moved to measure the soil conductivity in the orthogonal direction, obtaining measurements in cross. Finally, the electrodes were turned 45° and −45° to obtain measurements in an X shape. Table I presents the low-frequency soil resistivity calculated as the inverse of the measured average conductivity. The type of soil according to the obtained resistivity [19] is also shown in the table.

In each measured location, the volumetric water content of the soil was also obtained. Samples of 500 g extracted from the terrain at approximately 15 cm deep were collected and its volumetric water content was measured using the gravimetric method with oven drying [20].

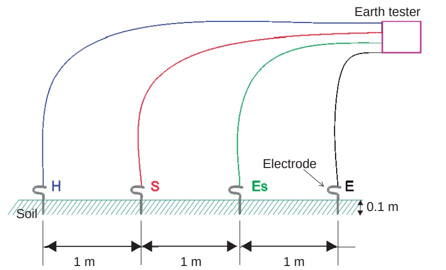


Fig. 1: Earth-tester connection circuit.

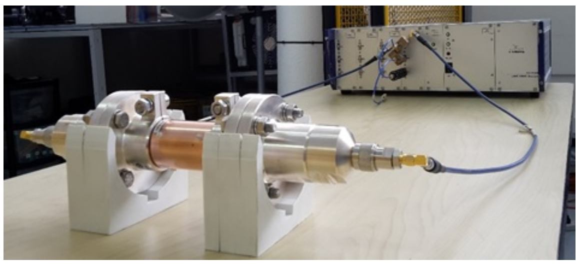


Fig. 2: Coaxial probe used to measure the wide-band complex permittivity of soil samples.

C. Wideband complex permittivity

The complex permittivity of the soil samples in the UHF range was estimated from the measured scattering parameters of a coaxial specimen holder, containing the material under test as shown in Fig. 2. The scattering parameters are calculated from time domain measurements performed using a ultra-wideband M-sequence device using the procedure presented in [14].

The effect of the mechanical transitions due the adapters used to connect the standard (SMA) RF connector and the coaxial specimen holder were eliminated from the measurements by a TRL-calibration procedure using an eight-error term model [21]. This calibration required a set of two-port measurements of three calibration elements (i.e. through, short, and transmission line) fabricated with the same dimensions of the coaxial specimen holder [14].

The procedure for each measured location was as follows. First, three coaxial probes were filled with the soil sample. In order to avoid air-gaps during the filling process, the soil sample was compressed into the coaxial probe using a hand press tool. Then, the TRL calibration standards were measured. Finally, the S-parameters of the material under test were measured and the complex permittivity of each sample was calculated using the procedure described in [14].

IV. Results

Experimental results of the characterization of six soil samples in the frequency range of 300 MHz up to 5.5 GHz are presented in this section. The complex permittivity measured using the coaxial probe and calculated using the proposed model are presented in Figs. 3a-3f. The soil's moisture and low-frequency resistivity used in the proposed model are shown in Table I. Soils with organic content higher than 10 % where considered organic soils.

Figures 3a-3f show that the measured permittivity is relatively constant for frequencies between 1 GHz and 5.5 GHz. Despite of the diversity of soil, in this frequency range, the real-part of the relative permittivity ranges from 19 to 40, while the imaginary part is below 15 in all cases. Below 1 GHz the complex permittivity increases considerably as the frequency decreases, as described by Messier's model. Above 2 GHz, the permittivity's imaginary part slightly increases with the frequency due to the resonance of free water contained in the soils. This effect is not modeled by the Messier model but is included in the model proposed here, as shown in Fig. 4, where measurements performed in Bogotá are compared with estimations of different models.

The obtained results also show that the proposed model is in agreement with the experimental results. To quantify the difference between model and experimental results, the deviation of the relative permittivity and the tangent losses were calculated respectively as follows

$$D_{\varepsilon_r} = |\varepsilon_m - \varepsilon_e|/\varepsilon_e, \tag{10}$$

$$D_{\varepsilon_r''} = |\varepsilon_m'' - \varepsilon_e''|/\varepsilon_e'', . \tag{11}$$

where the subindex m and e refer, respectively, to model and experimental results.

As shown in Fig. 5, the deviation between the permittivity estimated by the proposed model and experimentally obtained with the coaxial probe, D_{ε_r}, is lower than 16 % for the considered soils. The highest difference is presented for the case of Mosquera (Fig. 3d), which corresponds to a soil with a low value of resistivity and with high water content. Extreme values of resistivity reduces the signal-to-noise ratio in the complex perittivity measurement; while high water content difficult the introduction of the soil sample in the coaxial probe, which could cause leak of water. On the other hand, the deviation of the permittivity's imaginary part is below 60 % between 1 and 5 GHz. The higher deviation in the imaginary part is obtained for the Caqueza soil. This soil, particularly, was being used for agriculture, which could have modified its properties.

Similar errors are reported in the literature [22], even for recently proposed models with more input parameters [23]. In [23], for example, an absolute error of 60 % in ε_r'' is reported for the soil semiempirical mineralogy-related to-water dielectric model (SSMDM) for θ_V=0.4 It is remarkable that the simple proposed model, which only requires the soil's low frequency resistivity, moisture, and the type of soil, estimates with reasonable accuracy the real, as well as, the imaginary part of the soil permittivity. Therefore, the soil's EM behavior in the UHF range could be calculated using standard and practical field measurements.

V. Conclusion

In this paper, the complex permittivity of soils in the UHF is analyzed using an analytical model and field measurements. The proposed model, which is based in the well known

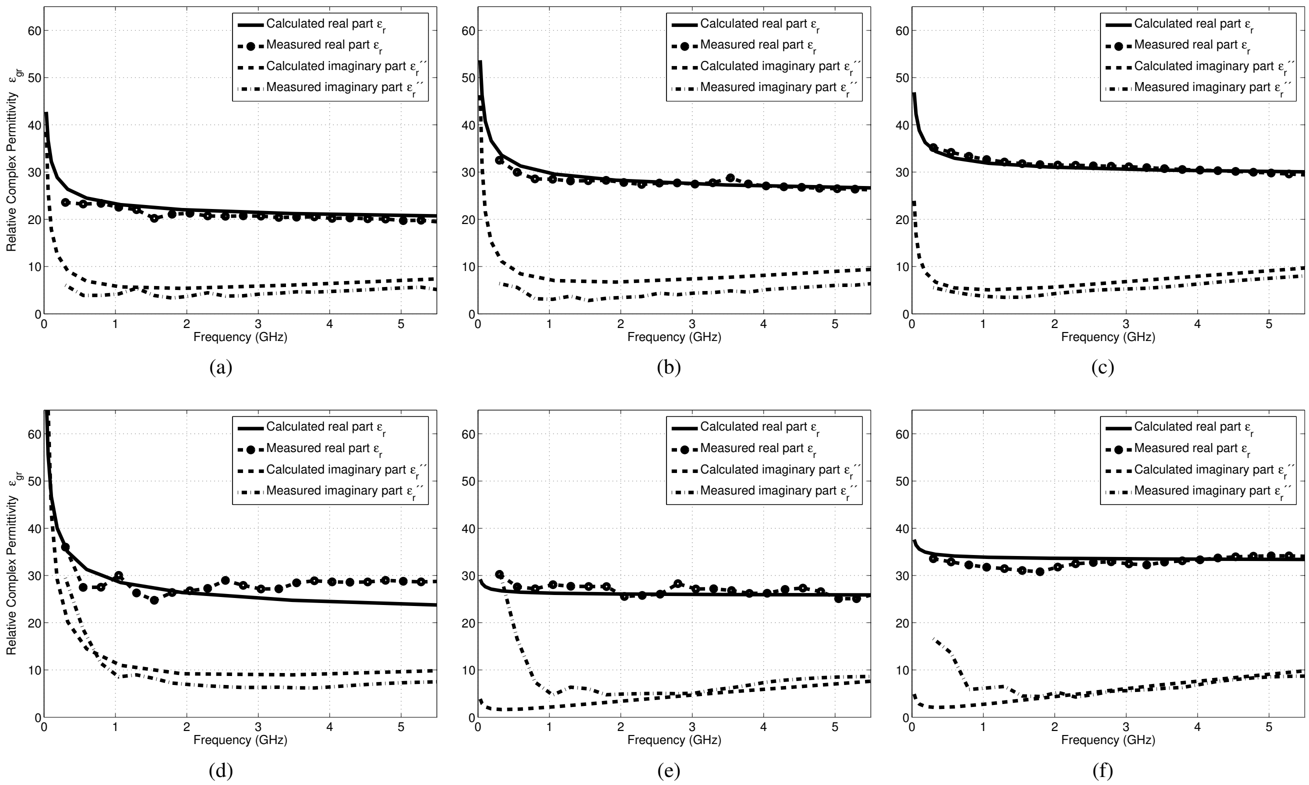


Fig. 3: Measured and calculated complex permittivity of the soils. Locations: (a) Bogotá, (b) Cáqueza, (c) La Mesa, (d) Mosquera, (e) San Juan de Arama, (f) Mesetas.

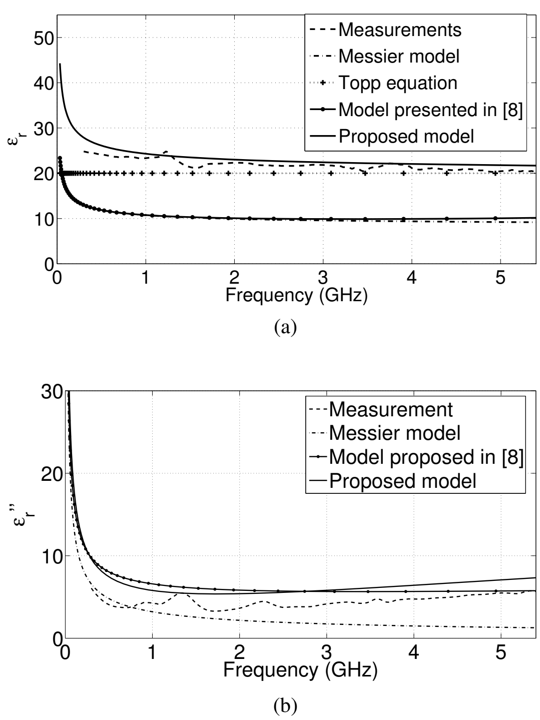
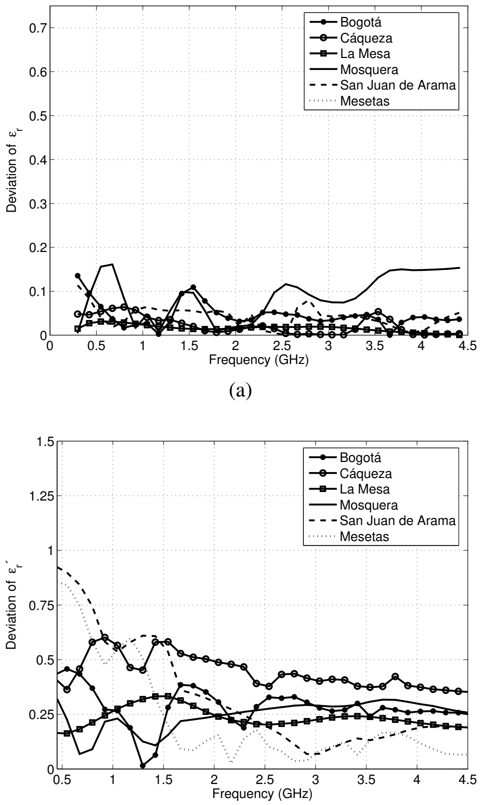


Fig. 4: Measured and estimated (a) real and (b) imaginary part of the relative permittivity of soil sample taken in Bogotá, Cundinamarca. Estimations are calculated with the models presented in Section II.

Messier and Debye models and Roth's equations, provides a simple way to estimate the soil permittivity in the UHF from measurements of low-frequency conductivity and volumetric water content. Despite of the few input parameters required for the model, a good agreement was obtained between the estimated and the measured complex permittivity of six natural soils of different taxonomy, resistivity, and moisture conditions. It shows that the proposed model describes the macroscopic behavior of natural soils in the considered frequency range.

Results show that the inclusion of the volumetric water content as input in the soil model considerably improves the agreement with experimental results. In this study, we focused the analysis in the response of the model for frequencies higher than $1\,\mathrm{GHz}$. However, there are some differences between the proposed model and the measurement results for frequencies below $1\,\mathrm{GHz}$, particularly for high resistivity soils (i.e. $>1000\,\Omega\mathrm{m}$). Therefore, further permittivity measurements for soils with high resistivity are required.

Although a variety of soils complex-permittivity models have been developed, the model proposed here has desirable characteristics for engineering applications. In humanitarian demining, for example, an initial estimation of the soil parameters can be used to adjust the GPR setup to improve the identification of buried objects. In this case, the estimation can be obtained from moisture and conductivity measurements performed in the field instead of performing direct permittivity measurements that commonly require laboratory facilities and



(a)

(b)

Fig. 5: Deviation between the proposed model and permittivity measurements of (a) real and (b) imaginary part for the six characterized soils.

can become impractical for this kind of applications.

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