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EPSIMU, A TOOL FOR DIELECTRIC PROPERTIES MEASUREMENT OF POROUS MEDIA: APPLICATION IN WET GRANULAR MATERIALS CHARACTERIZATION

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Abstract—The principal aim of this article is the presentation of *EpsiMu*, a tool for dielectric properties measurement. This general tool can be used to characterize all types of materials, but in this article we apply it to porous or granular materials. The tool consists of a coaxial cell and dedicated software that allow us to reconstruct the permittivity in almost real-time by a de-embedding process. Dielectric permittivity of soils sample was measured using this microwave tool. So, we can then determine the relationship between the dielectric properties and volumetric water content θ of Fontainebleau sand (center of France) and Dune of Pilat sand (Arcachon Bay area, France). The clay effect on Fontainebleau sand is also studied. We discuss the usefulness of several models that link the permittivity to volumetric water content of soil. It is shown that the soil permittivity model is not directly applicable to Fontainebleau sand and Dune of Pilat sand. We find a good match between our results representing the relative permittivity ε_r versus the volumetric water content θ and the Complex Refractive Index model (CRIM) between 600 MHz and 1 GHz. Alternative regression formulae are proposed. The implication of the determination of volumetric water content, θ, is discussed. A linear relation between the dielectric loss tangent and volumetric water content θ of soils is established.

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1. INTRODUCTION

For many years, the estimation of water content of soil by microwave remote sensing has been widely reported in the literature [1–3]. Ground Penetrating Radar (GPR) [4, 5] and Time Domain Reflectometry (TDR) [6] are the two techniques that have been widely used for water content measurement and contaminant detection. Successful interpretation of GPR and TDR techniques requires understanding of the relationships among dielectric permittivity, water content and soil type textures. There are many empirical models that link dielectric behaviour to water content of soil ([7–8]) in the frequency range of 100 MHz to GHz accepted for over the past three decades. But in a particular type of soil it has been reported that Topp model [6] and Dobson model [7] do not fit experimental results very well ([9–11]), thereby limiting the accuracy with which soil moisture can be estimated. The dielectric properties strongly depend on the soil texture. It is crucial to define the degree of correlation and sensitivity of the literature models [12] for soil moisture estimation data against laboratory data. So the main scope of this paper is to give a support for a successful interpretation of GPR and TDR data. It is also a proof of concept that the optimised microwave tool *EpsiMu* [13] can be used for wet and dry granular material characterization.

In this paper, after some explanations about the *EpsiMu* technique, we determine the dielectric properties of Fontainebleau and Dune of Pilat sand from France. We also report the effect of fraction clay content in Fontainebleau sand at 600 MHz and 1 GHz. The clay component is homogeneously mixed with Fontainebleau sand. We determine the applicability of empirical model that link the relative permittivity to the volumetric water content θ for the specific type of soil that we consider. Indeed, the non applicability of the commonly used empirical models is shown. So the purpose of our study is to accurately determine the dielectric properties and clay effect as a function of volumetric water content θ in the microwave domain of sandy soil. We also establish that the The Complex Refractive Index Model (CRIM) will well fit our experimental results. An extrapolation procedure, based on the linearity with the dielectric loss tangent of function of volumetric water content θ has been established. The clay effect on the conductivity of the soil is shown. The clay content is responsible for the dispersive behaviour of the soil. A similar result has been reported for Sherwood sandstone from NE England [11]. The bulk density ρ is also an important parameter that should be considered when measuring the water content. In fact, during the measurement process of the water content it is hardly affected by the variation of the bulk density caused by the sample compaction and the bulk variation that induce error in the determination of water content deduced from the dielectric properties measured. However, a detailed study on the influence of the bulk density on soil moisture estimation in a hydrological sense is beyond the scope of this paper. The issue will only be addressed here.

The rest of this paper is structured as follow:

1. We describe the methodology, the microwave tool *EpsiMu* [13] and sample preparation protocol for the dielectrics properties characterizations.
2. We compare the experimental results with results obtained with empirical models with their conditions of application at 600 MHz and 1 GHz in the aim to measure the contents of water for the specific type of ground considered in this article.
3. We establish the relationship between the loss dielectric tangent and volumetric water content θ. The conductivity is also determined.

2. METHODOLOGY AND EXPERIMENTAL PROTOCOL

Soil samples were taken from Fontainebleau (center of France) and from Dune of Pilat (Arcachon Bay area, France). The sizes of grains are between 200 µm and 500 µm for sample from Dune of Pilat and between 100 µm and 300 µm for samples from Fontainebleau field. We also considered a mixture sample from Fontainebleau with a proportion of clay (10% and 20% by weight). All of our samples are dried by desiccation in order to destroy large aggregates. To obtain a sample with desired water content, we mix a known mass of distilled and deionized water. The water content is then monitored by weighing and drying our sample in a moisture analyzer. The porosity ϕ can be determined by considering the physical parameters listed in Table 1.

Table 1. Compositions and physical parameters for soils samples.

Samples	Sand Content by Weight, %	Clay Content by Weight, %	Grains Size µm	Bulk density ρ (g cm^{-3})	Field
ECH1	100	0	300–500	1.78	Pilat
ECH2	100	0	100–300	1.78–1.75	Fontainebleau
ECH3	90	10	100–300	1.78–1.75	Fontainebleau
ECH4	80	20	100–300	1.78–1.75	Fontainebleau

The gravimetric water content w, the volumetric water content θ, the bulk density ρ and the porosity ϕ can be linked by the relations below:

$$\begin{cases} \theta = w \cdot \rho \\ \phi = 1 - \rho/\rho_s \end{cases} \tag{1}$$

where ρ_s is the grain density. For pure sand, $\rho_s = 2.66\,\mathrm{g}\cdot\mathrm{cm}^{-3}$. The grain density is constant. In fact when we add water to the bulk, the water displaces air only and changes the soil density. The volume fraction of grains is constant at given water content. We assume specific density of $1\,\mathrm{g}\cdot\mathrm{cm}^{-3}$ for water.

We only consider the dielectric behaviour of our sample by determining the effective relative permittivity ($\varepsilon_{\mathit{reff}}$), the dielectric loss tangent ($\tan\delta_e$) and the effective conductivity (ρ). The effective relative permittivity of a given sample is defined as

$$\varepsilon_{\mathit{reff}} = \varepsilon'_{\mathit{reff}} - j \cdot \varepsilon''_{\mathit{reff}} \tag{2}$$

where j is $\sqrt{-1}$. The real part of the dielectric constant ($\varepsilon'_{\mathit{reff}}$) is mainly associated with the polarizability of the medium. The imaginary part $\varepsilon''_{\mathit{reff}}$ of the permittivity, called the dielectric loss, can be divided into two terms:

$$\varepsilon''_{\mathit{reff}} = \sigma/\omega \cdot \varepsilon_0 + \varepsilon''_{rd} \tag{3}$$

In many cases, the value of σ is very low, but when an electromagnetic field is applied, the material consumes a considerable energy and exhibits some high values of σ in particular frequency ranges. ε''_{rd} represents relaxation, and it is the dissipation energy during polarization and depolarization. In microwave domain σ is dominant. So, we assume that $\sigma = \omega \cdot \varepsilon_0 \cdot \varepsilon''_{\mathit{reff}}$. ε_0 is the permittivity of the vacuum and ω the angular frequency. The dielectric loss tangent is defined by the relation below

$$\tan\delta = \varepsilon''_{\mathit{reff}}/\varepsilon'_{\mathit{reff}} \tag{4}$$

The dielectric properties of soils depend on the volumetric water content, θ. Many empirical relationships have been linked the dielectric properties to the water content of soil. As a matter of fact, the relationships can be divided into two groups, empirical and semi-empirical methods. For direct comparison, we consider the well-known empirical relationship by Topp et al. [6]. It directly relates the real component part of the relative permittivity $\varepsilon'_{\mathit{reff}}$ to the volumetric moisture content θ (Equation (5)). Equation (5) is widely used in soil hydrology for moisture content estimation using TDR. It is validated for the measurement of soils samples with porosities over 40%:

$$\varepsilon'_{\mathit{reff}} = 3.03 + 9.3\theta + 146\theta^2 + 76.7\theta^3 \tag{5}$$

The CRIM, "mixing rules", derived from "Lichteneker-Rother model" [15] incorporates the porosity and the dielectric constant of the mineral solids. For three-phase system, the general formula of the effective permittivity can be defined as:

$$\varepsilon_{reff}^{\alpha} = (1-\phi)\varepsilon_s^{\alpha} + \theta\varepsilon_w^{\alpha} + (\phi-\theta)\varepsilon_a^{\alpha} \tag{6}$$

where ε_s, ε_w and ε_a are, respectively, the relative permittivity of the mineral solid, water and air. α is a fitting parameter. The theoretical variation range of α is between -1 and 1 [16, 17]. But, common in the literature, $\alpha = 0.5$, Equation (6) is reduced to the CRIM as

$$\varepsilon_{reff}^{0.5} = (1-\phi)\varepsilon_s^{0.5} + \theta\varepsilon_w^{0.5} + (\theta-\phi)\varepsilon_a^{0.5} \tag{7}$$

Setting $\alpha = 0.5$ has been validated by many studies [11, 18, 19] and produces good fit in many cases.

The performed empirical model, previously established by Dobson [7, 20] and based on physical aspect of soil, is also considered for direct comparison. A discussion on the theoretical justification and validation of the model is beyond the scope of this paper. The applicability of the model is discussed for the specific type of soil that we considered.

The dielectrics properties of the soil samples were determined by *EpsiMu* toolkit [13]. *EpsiMu* is a microwave tool that combine de-embedding [21] and a Reflexion/Transmission algorithm commonly call NRW procedure ([22, 23]) for fast determination of the materials electromagnetic properties. The toolkit is composed of a coaxial cell (Figure 1) based on two-port transmission line technique and of a dedicated software to monitor a calibrated Vector Network Analyzer (VNA). The coaxial cell is specifically designed for granular material characterization. The diameter of the outer and inner conductors are respectively 3 cm and 1.3 cm. The cell is divided into three parts, a coaxial part and two conical parts (Figure 1). The conical parts allow us to keep an impedance characteristic Z_c equal to 50 Ω, so our cell can be linked with standard connector without energy loss and mismatch

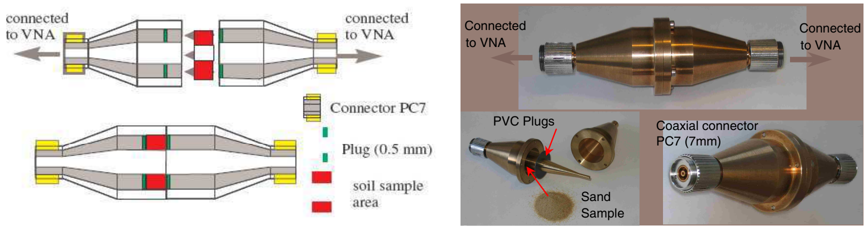


Figure 1. Illustration and photographs of the coaxial cell for the measurement.

connectors. We use two identical dielectric plugs, one on each side of the compacted soil sample in order to keep it in the coaxial part of the cell. The dielectric properties of the plugs are fully taken into account by the procedure for the determination of the dielectrics properties of the samples. In this case, PVC plugs are chosen. This material (PVC) is a low loss dielectric material and causes minimal reflection of the waves. For further details, the whole procedure of *EpsiMu* toolkit is described elsewhere [13].

For any measurement system, the accuracy is an important issue. Indeed, inaccurate result has limited use. The procedure that we follow for the measurement uncertainty estimation of the dielectric properties can be found in [24, 25]. The error that we commit on the transmission (S_{21}) and Reflexion (S_{11}) coefficients depends on the specific VNA which we use for the measurement. In the worst case, typical errors that we commit on S_{21} and S_{11} are of order 10^{-3} in the magnitude and phase. And the global error in the effective relative permittivity is less than 1% for the real part and less than 1.5% for the imaginary part. It should be noted that the cable effects are completely removed after the calibration process so the error sources are due to the repeatability of the measurement for a given sample. We do not consider drift error. In fact, the measurement time is very short, and we assume that the set up is stable during the whole procedure. The error bar is plotted further, when representing both the dielectric loss tangent and the conductivity as a function of the volumetric moisture content.

3. MEASUREMENT RESULTS AND COMPARISONS WITH EMPIRICAL MODELS

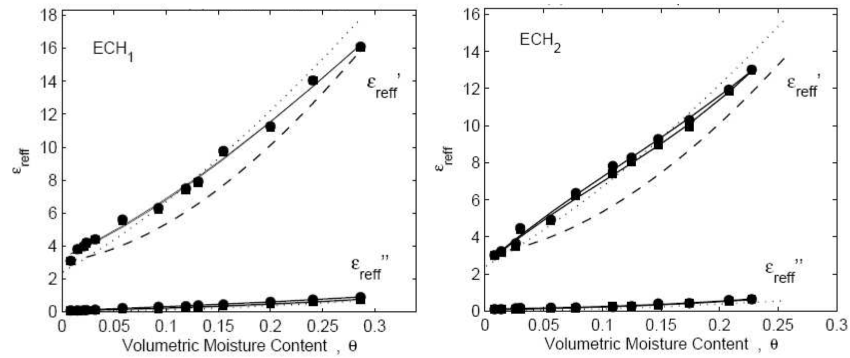
The measured relative permittivity for the four samples (Table 1) are presented in Figures 2 and 3. These figures show the dielectrics properties of the wet soils samples at 600 MHz and 1 GHz as the function of the volumetric moisture content θ. The higher dielectric constant of water increases both the real and imaginary parts of the effective relative permittivity of the soil as the water content increases (Figures 2, 3 and 4). To permit comparisons with the empirical models ([6, 7]; CRIM [18]) a cubic fit of the measured data is shown for both the real and imaginary parts of the relative permittivity. The cubic regressions relations in each case and the quality of the fit (r^2) at 1 GHz are:

$$\begin{aligned}\text{ECH1}\qquad &\varepsilon'_{reff} = 3.28 + 27.23\theta + 85.69\theta^2 - 82.17\theta^3 \quad r^2 = 0.99\\ &\varepsilon''_{reff} = 0.07 + 1.06\theta + 4.66\theta^2 + 0.05\theta^3 \quad r^2 = 0.99 \qquad (8)\end{aligned}$$

$$\begin{aligned}\text{ECH2}\quad & \varepsilon'_{reff} = 2.47 + 54.58\theta - 142.12\theta^2 + 460.09\theta^3 \quad r^2 = 0.99\\ & \varepsilon''_{reff} = 0.06 + 1.35\theta + 0.53\theta^2 + 18.58\theta^3 \quad r^2 = 0.99 \qquad (9)\\ \text{ECH3}\quad & \varepsilon'_{reff} = 3.37 + 22.92\theta + 101.97\theta^2 - 70.26\theta^3 \quad r^2 = 0.99\\ & \varepsilon''_{reff} = 0.03 + 4.18\theta - 11.33\theta^2 + 65.35\theta^3 \quad r^2 = 0.99 \qquad (10)\end{aligned}$$

$$\begin{aligned}\text{ECH4}\quad & \varepsilon'_{reff} = 3.83 - 5.42\theta + 412.02\theta^2 - 1044.7\theta^3 \quad r^2 = 0.99\\ & \varepsilon''_{reff} = 0.14 + 4.63\theta - 28.04\theta^2 + 151.67\theta^3 \quad r^2 = 0.99 \qquad (11)\end{aligned}$$

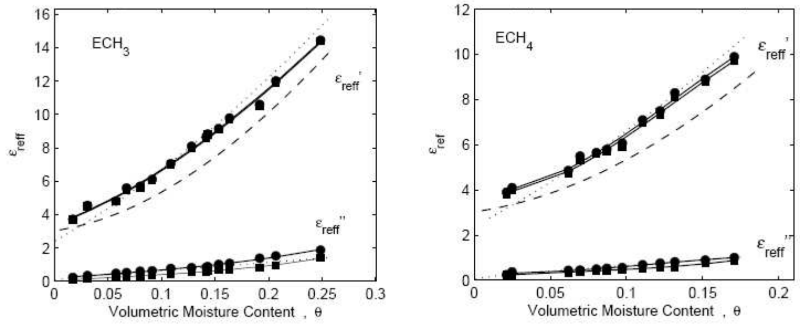
The Topp equation does not take account of the soil composition and texture. According to the model (Equation (5)), the variations of the relative effective permittivity are only due to the moisture content regardless of the soil texture, porosity or the frequency. In Figures 2 and 3, the evolution of the relative permittivity with the moisture content measured at 600 MHz and 1 GHz for the four soil samples deviates well above that predicted by the Topp equation curve. As shown in Figures 2 and 3, when the volumetric moisture content $\theta < 0.25$ the accuracy of the model decreases and is not reliable to the cubic regression fit. In fact, the porosities range of Fontainebleau and Dune of Pilat sand samples are between 33–37% which is less than the porosities of the soils for the model validation. Similar conclusion has been made for rocks with porosities between 22–32% [10] and for Sherwood Sandstone ($\phi = 0.35$) [11]. The Topp model overestimates the moisture content of the type of soil which we consider in this paper.



(a) Dune of Pilat Sand (b) Fontainebleau pure sand

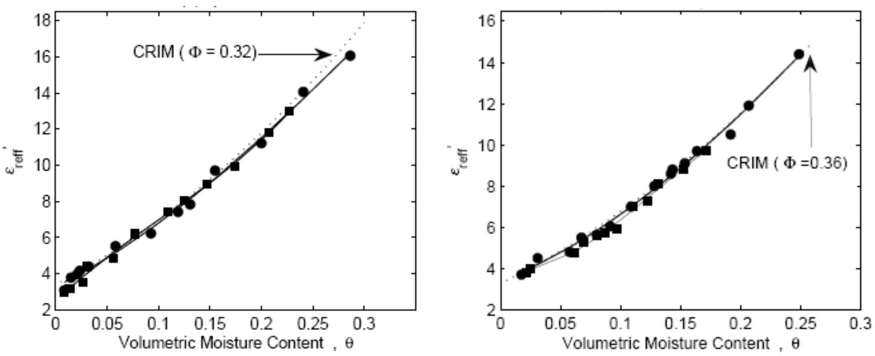
Figure 2. Measured relative permittivity vs. volumetric moisture content. Square marker corresponds to result at 1 GHz and rounded marker corresponds to result at 600 MHz. (a) ECH1. (b) ECH2. Cubic regressions fit (solid line). Topp model [6] (dash line). Dobson model [7] (dotted line).

As shown in Figures 2 and 3, the performed Dobson empirical model [7] does not fit experimental result very well. In this case, a sandy soil is considered (sand content by weight over 50%, and clay content by weight is equal to 15%) for the curve from Dobson model. For this specific sandy soil considered for the model the dielectric is almost the same as those of Peplinski model (Figures 3 and 4), in



(a) Fontainebleau sand +10% clay (b) Fontainebleau sand +20% clay

Figure 3. Measured relative permittivity vs. volumetric moisture content. Square marker corresponds to result at 1 GHz and rounded marker corresponds to result at 600 MHz. (a) ECH3. (b) ECH4. Cubic regressions fit (solid line). Topp model [6] (dashed line). Dobson model [7] (dotted line).



(a) pure sand (b) sand - clay mixture

Figure 4. Measured relative permittivity vs. volumetric moisture content at 1 GHz. (a) ECH1 (rounded marker), ECH2 (Square marker). (b) ECH3 (rounded marker), ECH4 (Square marker). Cubic regressions fit (solid line). CRIM (dotted line).

particular the imaginary part component of relative permittivity. As shown by the figures, for the sandy soil (no clay content) the moisture content of the soils predicted by Peplinski model is underestimated, and the levels of error, $\Delta\theta$, increase with increasing moisture content.

Figures 2 and 3 show clearly that the measured data diverge from the Topp model [6]. The Dobson model [7] shows the same phenomenon in particular for sandy soil (sand content by weight over 50%).

Figure 4 shows that the CRIM describes very well the effective relative permittivity of Dune of Pilat sand, Fontainebleau sand and homogeneous mixture of Fontainebleau sand and clay (10%–20%) over the frequency range 600 MHz to 1 GHz by taking account there porosity and the permittivity of the minerals solids as well. In fact, the regression curves and CRIM curves for the four soil types that we consider are almost identical. These results suggest that the prediction of the volumetric moisture from TDR method or GPR of soil type like Dune of Pilat and Fontainebleau should use model such as CRIM that explicitly takes account the porosity.

4. DETERMINATION OF THE DIELECTRIC LOSS TANGENT AND CONDUCTIVITY FROM PERMITTIVITY VALUES

Equation (1) as well as the CRIM Equation (11) shows explicitly that the effective relative permittivity, $\varepsilon_{\mathit{reff}}$, porosity, ϕ, bulk density, ρ, and volumetric moisture content are linked. The measured complex value of the relative permittivity will be influenced by the moisture content and also by the variation of the bulk density $\Delta\rho$ caused by the compaction of the soil sample during the measurement process. As shown in Table 1, the bulk density as function of moisture of each sample is relatively stable and constant, and $\Delta\rho$ is very small. There are many studies that describe the dependence of the dielectrics properties on the water content and the bulk density [14, 26, 27]. In fact, the moisture measured using dielectric methods and microwave tool is indirect, so to achieve great accuracy, the bulk density effect has to be considered.

Figure 5 is a complex plane plot of the imaginary part of the effective relative permittivity normalized by the bulk density ($\varepsilon''_{\mathit{reff}}/\rho$) as functioned in the four soil types that we consider. As shown in Table 1, the bulk density is practically stable for a given sample. Figure 5 shows a linear relationship between $\varepsilon''_{\mathit{reff}}/\rho$ and $\varepsilon'_{\mathit{reff}}/\rho$ for four soil samples at 600 MHz and 1 GHz. For each soil sample the linearity can

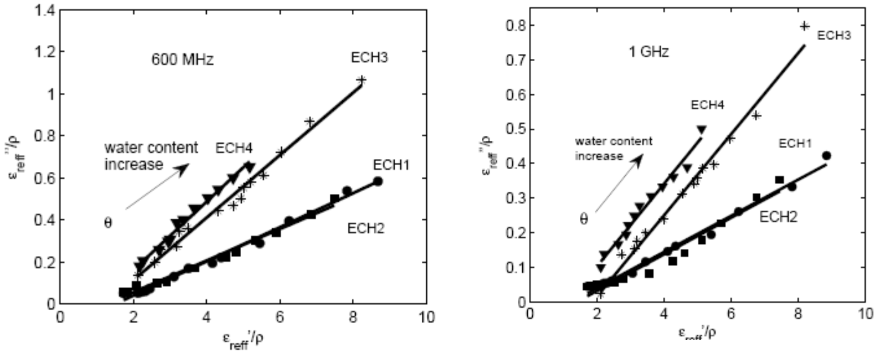


Figure 5. Complex plane plot, imaginary part of the effective relative permittivity normalized by the bulk density ($\varepsilon''_{reff}/\rho$) vs. real part of the effective relative permittivity normalized by the bulk density (ε'_{reff}/ρ). ECH1 (rounded marker). ECH2 (square marker). ECH3 (star marker). ECH4 (triangular marker).

Table 2. Coefficients a, b and regression quality (ρ^2) of Equation (12).

Samples	600 MHz			1 GHz		
	a	b	r^2	a	b	r^2
ECH1	0.081	−0.122	0.99	0.052	1.25	0.99
ECH2	0.075	−0.094	0.98	0.053	1.28	0.98
ECH3	0.148	−0.183	0.99	0.114	1.75	0.99
ECH4	0.162	−0.164	0.97	0.116	1.22	0.98

be expressed as follow

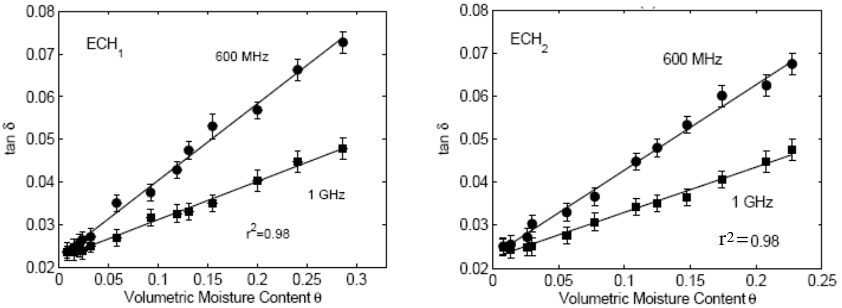
$$\varepsilon''_{reff}/\rho = a \cdot (\varepsilon''_{reff}/\rho - b) \tag{12}$$

where a and b are the linear regression coefficients for a given frequency. These coefficients and the quality of the regressions are reported in Table 2. Equation (12) takes account the variation of the bulk density ($\Delta\rho$) during the dielectric properties measurement. Similar behaviour has been reported at microwave frequencies to reduce the influence of the bulk density variations on the measurement results [26].

From Equation (12), we can deduce the expression of the dielectric loss tangent normalized by the bulk density ρ

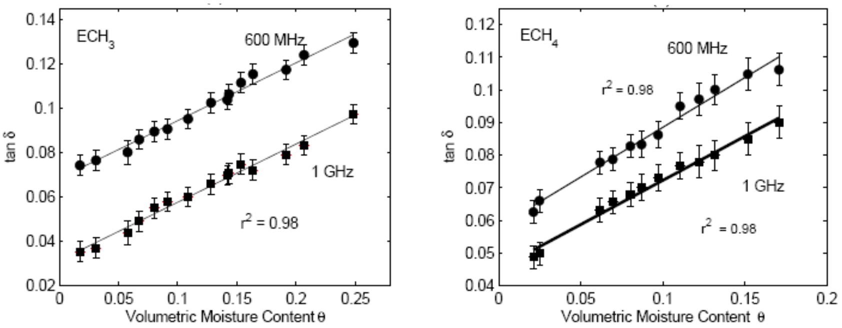
$$\frac{\tan\delta}{\rho} = b \cdot a \frac{1}{a\varepsilon'_{reff} - \varepsilon''_{reff}} \cdot \frac{\varepsilon''_{reff}}{\varepsilon'_{reff}} \tag{13}$$

Figures 6, 7, 8 and 9 clearly show the effect of increasing moisture content, soil texture and measurement frequency as well. The dielectric loss tangent and conductivity both increase with increasing moisture content for a given frequency. The dielectric loss tangent decreases with increasing frequency between 600 MHz and 1 GHz, and the conductivity increases with increasing frequency (Figures 8 and 9). This phenomenon is certainly attributed to the water phase, particularly to the dipolar relaxation of the water molecular [28]. The dielectric loss tangent of the homogeneous sand-clay mixture from Fontainebleau (Figure 7) is relatively high compared to dielectric loss tangent of Dune of Pilat sand and Fontainebleau pure sand (Figure 6) for a given moisture content. For example, for $\theta = 0.15$ the dielectric loss tangent is twice when we add 10% of clay in Fontainebleau sand (Figures 6 and 7). These results are particularly striking. It explicitly shows the clay effect on the soil dielectric dispersive nature. In fact,



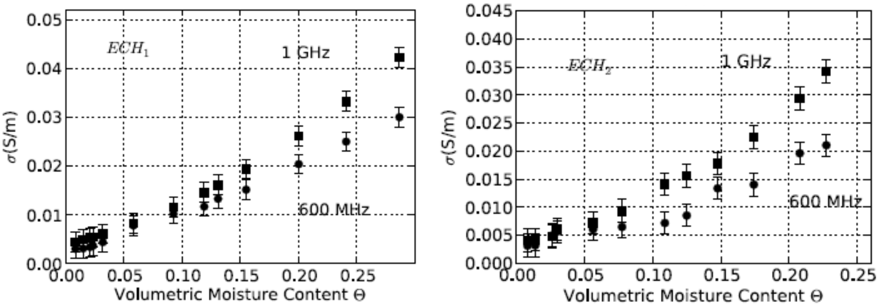
(a) (b)

Figure 6. Dielectric Loss tangent vs. volumetric moisture content. (a) ECH1. (b) ECH2.



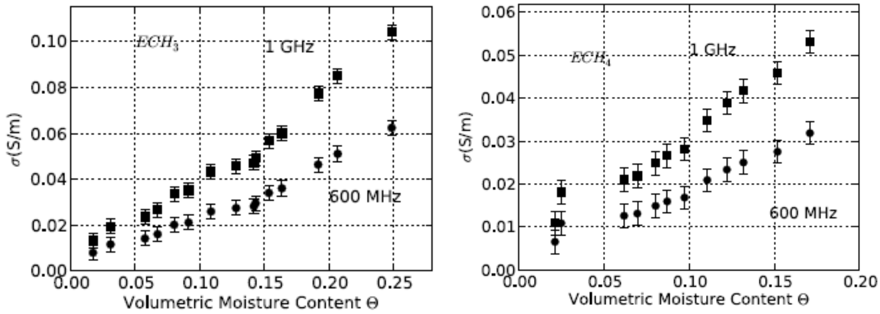
(a) (b)

Figure 7. Dielectric Loss tangent vs. volumetric moisture content. (a) ECH3. (b) ECH4.



(a) (b)

Figure 8. Conductivity vs. volumetric moisture content. Square marker corresponds to result at 1 GHz and rounded marker corresponds to result at 600 MHz. (a) ECH1. (b) ECH2.



(a) (b)

Figure 9. Conductivity vs. volumetric moisture content. Square marker corresponds to result at 1 GHz and rounded marker corresponds to result at 600 MHz. (a) ECH3. (b) ECH4.

the dielectric dispersion of soil not only depends on the frequency but also depends on the clay content in soil. Similar behaviour has been reported by other investigators ([11, 29]).

5. APPLICATION FOR MOISTURE CONTENT ESTIMATION

Figure 4 shows that the CRIM model describes very well the soil dielectrics constant as a function of volumetric moisture content at

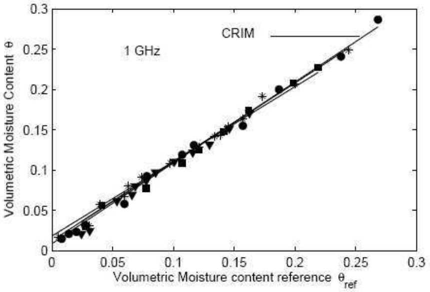


Figure 10. Volumetric moisture content measured vs. volumetric moisture content based on CRIM. Rounded marker: ECH1. Square marker: ECH2. Star marker: ECH3. Triangular marker: ECH4.

Table 3. Slope, a, of the linear plot (Figure 10) and CRIM model parameters (ε_s, ε_a, ε_w and ϕ).

Samples	a	ε_s	ε_a	ε_w	ϕ	r^2
ECH1	1.00	5.0	1.0	80.0	0.32	0.99
ECH2	0.98	5.0	1.0	80.0	0.32	0.98
ECH3	0.98	5.0	1.0	80.0	0.36	0.99
ECH4	1.03	5.0	1.0	80.0	0.36	0.99

600 MHz and 1 GHz. From Equation (11), θ_{ref} is defined as:

$$\theta_{ref} = \frac{\varepsilon_{reff}^{0.5} - (1-\phi)\cdot\varepsilon_s^{0.5} - \phi\cdot\varepsilon_a}{\varepsilon_w^{0.5} - \varepsilon_a^{0.5}} \tag{14}$$

where ε_{reff} is given by measurement of the dielectric properties of the soil samples, and the porosity ϕ is deduced from Equation (1).

Figure 10 represents the measured volumetric moisture content as a function of volumetric moisture content reference θ_{ref}. It shows linear relationships between the volumetric moisture content θ and the volumetric moisture content reference θ_{ref} from CRIM (Equation (14)). The slope (a) of the linear plot and the parameters (ε_s, ε_a, ε_w and ϕ) of the CRIM model are reported in Table 3. The linear plot associated to each soil sample has a good correlation ($r^2 \approx 0.99$). The moisture content estimation based on CRIM model and the measured values of moisture content are similar, and the error that we commit is under 2% for the four soil types considered.

It is clear, from results obtained in Figures 3 and 4, that the error which we commit in the moisture content estimation based on Topp model [6] is too high (up to 10%) in this kind of soil. As shown the

Topp curves strongly deviate from the regression lines which fit to the data from the four sandy soil types that we have considered. The results (Figure 5) suggest that CRIM model should be considered for water content prediction by TDR and GPR applications.

6. CONCLUSION AND PERSPECTIVES

This paper has discussed microwave tool for sandy soil moisture estimation and the applicability of empirical models reported from the literature.

Using *EpsiMu* [13], a microwave tool, the dielectric properties of sandy soils and sand-clay mixtures have been characterized over a range of moisture contents. The de-embedding process associated to the tool allowed fast measurement of the dielectric properties. Over 600 MHz to 1 GHz the results clearly indicate that the real part of the effective relative permittivity is fairly stable, and the imaginary part decreases when the frequency increases as reported by other investigators ([2, 11]). Strong dielectric dispersion (the dielectric loss increases as the frequency decreases) has also been shown due to the presence of the clay (10% and 20%) in the sample from Fontainebleau sand. A linear relationship between the dielectric loss tangent and the moisture content has been established for soil samples from Fontainebleau and Dune of Pilat sand. This behaviour is striking and can be very helpful for moisture estimation of soil and dielectric loss as well. The dielectric loss tangent and conductivity both increase when moisture content increases for each soil sample considered. The result obtained at 600 MHz and 1 GHz of the conductivity shows a similar behaviour to that reported by [30] for soil referred as "Georgia red clay", and the conductivity increases with increasing frequency.

It has been shown that the results obtained with the Fontainebleau sand as well as with the Dune of Pilat sand are not in perfect agreement with the results obtained with the Topp model [6]. Over the most of the moisture range, the Topp model overestimates the moisture content. Moisture estimation using Topp model leads to level of error of order $\Delta\theta = 0.04$. Therefore, Topp model is inaccurate for moisture estimation of this type of soil at 600 MHz and 1 GHz. The Dobson model [7] based on soil textures is not directly applicable to Fontainebleau sand and Dune of Pilat (sand content over 80%) with clay fraction. The result is in agreement with the one obtained with the model in particular when we consider 50% sand content and 15% of clay, but for $\theta > 0.15$, Dobson model [7] underestimates the moisture content and the error that we commit ($\Delta\theta$) increases with increasing θ. The Complex Refractive Index Model (CRIM) provides a good match for the real part of the effective relative as function of the volumetric moisture content behaviour. This result clearly suggests that TDR and GPR methods should take into account the porosity (ϕ) of the soil in particular when $\phi < 0.4$ in order to achieve higher accuracy of soil moisture measurement. Finally, modelling studies of soil hydrologic processes must be intensified. For example, the bulk density influence on soil moisture estimation needs to be carefully examined. This is a major challenge in the future.

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