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Dielectric Model of Moist Soils with Varying Clay Content in the 0.04 to 26.5 GHz Frequency Range

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***Abstract*— In this paper, a soil texture dependent multi-relaxation generalized refractive mixing dielectric model (MR GRMDM) for moist soils was developed. The model provides for complex permittivity of moist soils in both the gigahertz and megahertz frequency ranges, namely, from 40 MHz to 26.5 GHz.**

***Index Terms*— Moist soil, dielectric model, dielectric spectra, dielectric relaxations, bound soil water, free soil water.**

I. INTRODUCTION

Dielectric models of the soil are an essential part in the algorithms used for data processing with regard to the problems of radar and radiothermal remote sensing of the earth surface. Recently, the multi-relaxation generalized refractive mixing dielectric model (MR GRMDM) of moist soils was developed [1]. By its methodology, this model is similar to the single-relaxation generalized refractive mixing dielectric model (SR GRMDM) earlier introduced in [2]. The major advantage of the MR GRMDM over the SR GRMDM is that it takes into account not only orientational (dipole), as the model in [2] does, but also the Maxwell-Wagner interfacial (ionic) polarization, which is especially pronounced in the megahertz frequency range. As a result, it makes possible predictions of complex dielectric constant for moist soils in both the megahertz and gigahertz ranges, thus significantly expanding the range of application of the SR GRMDM.

In this study, similar to [3], the MR GRMDM will be used as a building block to develop the spectroscopic dielectric model for a continuum of moist soils with different textures, covering the 40 MHz to 26.5 GHz frequency range.

II. CONCEPT OF THE MR DRMDM

Similar to [1], the complex refractive index of moist soil is expressed in the form of the refractive mixing dielectric model [2]:

$$\begin{aligned} n_s^* = n_d^* + (n_b^* - 1)[W + (W_t - W)u(W - W_t)] \\ + \left(n_u^* - 1\right)(W - W_t)u(W - W_t) \end{aligned} \tag{1}$$

where W is the volumetric moisture, $n_p^* = n_p + i\kappa_p = \sqrt{\varepsilon_p}$ is the complex refractive index (ε_p is the complex relative dielectric constant) relating to the moist soil (p=s), dry soil (p=d), bound soil water (p=b), and unbound (free) soil water (p=u), respectively. Wt designates a maximum volumetric fraction of water that can be retained in a bound state by a specific type of soil. $u(x)$ denotes the Heaviside step function: $u(x)=1$ if $x>0$, and $u(x)=0$ if $x\le 0$. When W is less than Wt all water in the soil exists only in a bound state. The amount of soil water in excess of Wt, that is $W - Wt$, is considered as free soil water. As in [1], the real, n_p, and imaginary, κ_p, parts of the complex refraction index are referred to as the refractive index and normalized attenuation coefficient. The latter is a proportion of the standard attenuation coefficient to the free space propagation constant [2]. Based on observations of the compactness of dry soil matter changing with moisture [1], we imply in equation (1) a dependence of the dry soil density on soil moisture, $n_d = n_d(W)$.

We define the complex dielectric constant of soil water by the two-relaxation Debye equation:

$$\varepsilon_p = \varepsilon'_p + i\varepsilon''_p = \varepsilon_{\infty pH} + \frac{\varepsilon_{0pL} - \varepsilon_{0pH}}{1 - i2\pi f\tau_{pL}} + \frac{\varepsilon_{0pH} - \varepsilon_{\infty pH}}{1 - i2\pi f\tau_{pH}} + i\frac{\sigma_p}{2\pi\varepsilon_r f} \tag{2}$$

Here, ε_{0pq} and $\varepsilon_{\infty pq}$, are the dielectric constants in the low and high frequency limit, respectively, in the cases of the ionic (q=L) and dipole (q=H) relaxations, respectively, and $\varepsilon_{\infty pL}=\varepsilon_{0pH}$. While τ_{pL} or τ_{pH}, denote the relaxation times, also in the cases of the ionic (q=L) and dipole (q=H) relaxations. All these parameters must be referred to the bound (p=b) or free (p=u) water in the soil; $\varepsilon_r=8{,}854\cdot 10^{-12}$ F/m – dielectric permittivity of free space. A single-relaxation Debye formula follow from (2) when $\varepsilon_{0uL}=\varepsilon_{0uH}$.

As seen from equations (1) and (2), in the context of the multi-frequency relaxation GRMDM, the dielectric spectrum of a certain type of moist soil can be calculated through the following set of parameters related to the dry soil and soil water: 1) refractive index, n_d, and normalized attenuation coefficient, κ_d, for dry soil; 2) maximum bound water fraction, Wt; 3) dielectric constants in the low, ε_{0pq}, ε_{0pq}, and high, $\varepsilon_{\infty pq}$, frequency limit for the bound (p=b) and free (p=u) water in the soil, concerning both the ionic (q=L) and dipole (q=H) relaxations; 4) relaxation times for ionic, τ_{pL}, and dipole, τ_{pH}, relaxations of the bound (p=b) and free (p=u) water in the soil; 5) ohmic conductivities, for bound, σ_b, and free, σ_u, water in the soil. In the next section, these parameters will be derived by using the equations (1),(2) and measured dielectric data.

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III. FUNCTIONAL DEPENDENCE OF THE MR DRMDM FROM CLAY CONTENT

Following the methodology in [1], we derived the spectroscopic parameters in the formulas (1), (2) for a number of soils having different textures. The bound soil water was supposed to have both the dipole and ionic relaxations. While the free soil water possessed only dipole relaxation. The soil types studied, sources of dielectric data measured at 20°C in the frequency range 0.04 to 26.5 GHz, granulometric clay contents in the soils, and maximum volumetric fractions of bound water are given in Table I, as well as the spectroscopic and conductivity parameters.

TABLE I

PARAMETERS OF SOILS

№	1		2		3		4		5		6	
Type of soil	Clayey silt, brown, [4]		Clayey sand, dark brown, [4]		Silty clay loam, [5]		Clay, gray, [4]		Clayey chernozem, [6]		Clay light gray, [4]	
Clay contents	0.07		0.130		0.297		0.340		0.520		0.760	
Wt (cm/cm)	0.050		0.066		0.123		0.133		0.209		0.280	
	W	n_d	W	n_d	W	n_d	W	n_d	W	n_d	W	n_d
$n_d(W)$	0.06	1.45	0.040	1.50	0.032	1.75	0.070	1.48	0.030	1.60	0.13	1.35
	0.068	1.60	0.179	1.45	0.174	1.65	0.462	1.30	0.098	1.55	0.75	1.35
	0.175	1.40	0.258	1.30	0.344	1.90	0.520	1.68	0.177	1.55	0.94	1.35
	0.179	1.45	0.287	1.35	0.462	1.45	0.571	1.60	0.264	1.55	0.946	1.35
	0.277	1.60	0.316	1.30			0.610	1.50	0.372	1.65		
	0.305	1.25	0.407	1.45			0.620	1.50	0.454	1.60		
	0.428	1.70	0.407	1.60					0.472	1.77		
	0.500	1.55	0.441	1.55					0.514	1.66		
			0.441	1.54								
κd	0.037		0.034		0.027		0.025		0.020		0.015	
ε_{0bL}	690		650		518		518		300		120	
$e_{\infty bH}$	75		66		50		44		40		30	
$\tau_{bL}(ns)$	2.5		2.7		2.3		2.5		2.5		2.5	
$\sigma_b(S/m)$	0.001		0.0001		0.001		0.001		0		0.001	
$\sigma_u(S/m)$	0.165		0.12		0.4		0.25		0.5		0.6	

$\varepsilon_{\infty bH} = \varepsilon_{\infty uH} = 4.9$; $\varepsilon_{0uH} = 100$; τ_{bH}(ps) = 12.5; τ_{uH}(ps) = 10.6

To determine complex refractive index of a dry soil, we used refractive mixing dielectric model for a dry soil, W=0:

$$n_{\mathrm{d}}^{*} = 1 + \frac{n_m^{*} - 1}{\rho_m}\rho_{\mathrm{d}} \tag{3}$$

where n_{m}^{*} and ρ_m are the complex refractive index and specific density, respectively, for a soil mineral contents. ρ_d it is bulk density, which may be determined by many factors related to various natural and artificial processes, and we will be considered it as an independent parameter. As seen from formula (3), the parameter $(n_m^{*} - 1)/\rho_m$ can be determined from such measurements in which the data on both the dry soil bulk density and complex refractive index are available. Unfortunately for the soils shown in Table 1, the data for bulk density of dry soil appeared to be not available. Therefore, we used another set of soils, which is given in Table II.

TABLE II

COMPLEX REFRACTIVE INDEX OF A DRY SOILS

№	1	2	3	4	5
Type of soil	Sand, [7]	Humus, [8]	Sandy loam, [9]	Clayey chernozem, [6]	Bentonite, [10]
Clay contents	0.01	0.17	0.198	0.52	0.57
W_t (cm/cm)	0.027	0.082	0.091	0.200	0.217
$(n_m\text{-}1)/\rho_m$	0.433	0.419	0.420	0.387	0.406
κ_m/ρ_m	0.009	0.007	0.013	0.011	0.017

The next step is to determine the parameters of MR DRMDM as a function of clay content. For this purpose, we obtained regression formulas by fitting clay-dependent parameters of MR DRMDM given in Tables 1 and 2. These regression formulas are shown in Table III.

Also these parameters and regression curves are shown in Fig. 1. by numbered symbols and dash lines, respectively.

TABLE III

REGRESSION FORMULAS

$n_d = (0.432\text{-}0.065 \cdot C)\rho_d$	$\varepsilon_{0bL} = 761\text{-}840 \cdot C$
$\kappa_d = (0.008+0.011 \cdot C)\rho_d$	$\varepsilon_{0bH} = 27.18+61 \cdot \exp(\text{-}C / 0.287)$
$W_t(cm^3/cm^3) = 0.024+0.339 \cdot C$	$\sigma_u(S/m) = 0.097+0.69 \cdot C$

$\varepsilon_{0uH} = 100$; $\varepsilon_{\infty bH} = \varepsilon_{\infty uH} = 4.9$; τ_{bL}(ns) = 2.5; τ_{bH}(ps) = 12.5; σ_b(S/m) = 0.001

To estimate the deviations of the complex dielectric constant values predicted by using the proposed texture dependent MR GRMDM from the measured ones, we correlated them with each other as shown in Fig. 2. The respective Pearson coefficients and standard deviations were estimated as follows: $R_{\varepsilon'} = 0.997$; $R_{\varepsilon''} = 0.986$; $\sigma_{\varepsilon'} = 0.946$; $\sigma_{\varepsilon''} = 1.074$. While the respective regression lines are given by the formulas $\varepsilon'_m = 0.41+1.01\varepsilon'_p$ and $\varepsilon''_m = 0.252+0.928\varepsilon''_p$. These error estimations confirm rather a good ability of the texture dependent MR GRMDM to predict complex permittivity of moist soils over the the broad ranges of soil textures and frequencies, at the room temperature of 20°C.

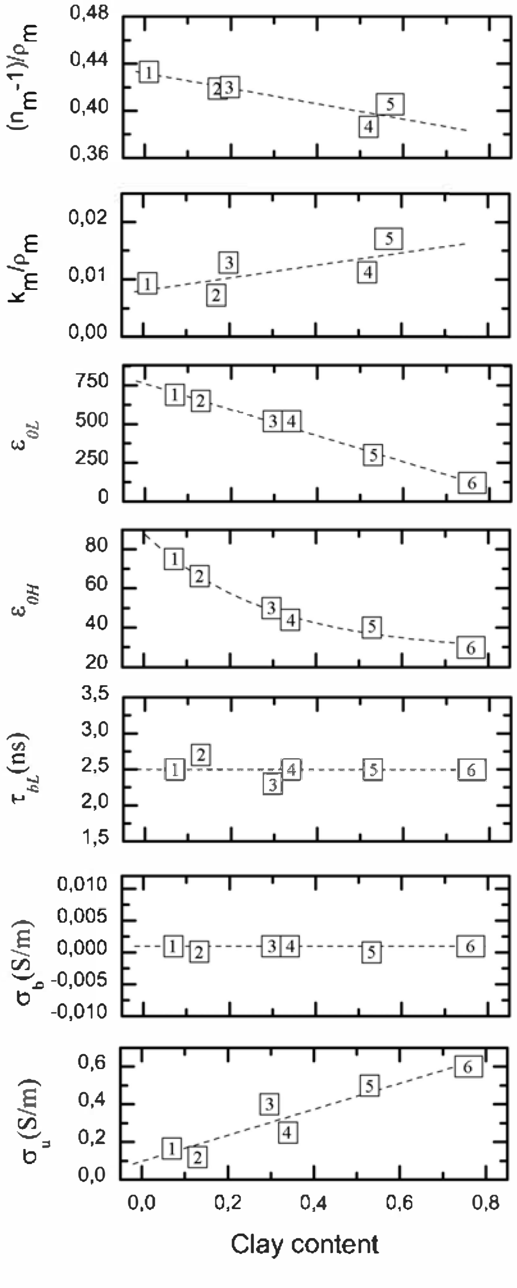

Fig. 1. Parameters of MR DRMDM as a function of clay content.

IV. CONCLUSION

As a result of the analysis carried out in this research, the texture dependent MR GRMDM was developed to provide predictions of the complex dielectric constant for moist soil as a function of soil moisture, granulometric clay contents, and frequency at the temperature of 20°C over the wide range of frequencies from 40 MHz to 26.5 GHz. This model provides a basis for developing the algorithms to retrieve soil moisture sensed by the radars, radiometers, time domain reflectometers, and capacitance sensors working in the gigahertz and megahertz frequency ranges. Not saying anything about dielectric predictions relating to the P band radars, this model also improves the L band dielectric predictions of [3] in the case of rich clay soils.

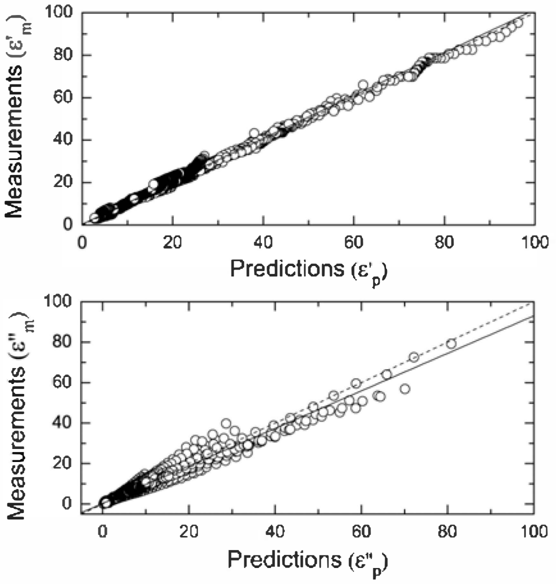

Fig. 2. Correlation between the predicted and measured values of the real, ε', and imaginary, ε''parts of the moist soil complex dielectric constant.

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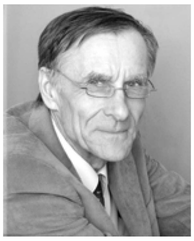

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