TEMPERATURE DEPENDENT MULTI-RELAXATION SPECTROSCOPIC DIELECTRIC MODEL FOR AN ARCTIC SILT CLAY LOAM SOIL THAWED AND FROZEN AT 0.1-15 GHZ

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ABSTRACT

The dielectric model for an arctic silt clay loam soil collected on the Yamal peninsula both thawed and frozen has been developed. The model is based on the soil dielectric measurements carried out in the ranges of gravimetric moisture 0.01 to 0.33 g/g, dry soil density 1.28 to 1.65 g/cm3, and temperature 25 to -30°C (cooling run), in the frequency range 0.1–15 GHz. To fit the results of measurements of the soil complex dielectric constant as a function of soil moisture and wave frequency, the refractive mixing dielectric model in conjunction with the Debye multi-relaxation equations were applied. As a result, the spectroscopic parameters of dielectric relaxations and electrical specific conductivities for the bound, transient bound, and unbound soil water components were derived, being further complimented with the thermodynamics parameters. Having these parameters, the complex relative permittivity of soil can be predicted as a function of 1) density of dry soil, 2) gravimetric moisture, 3) wave frequency, and 4) temperature[1].

Index Terms— Mineral soil, moisture, temperature, dielectric model, thawed and frozen soil, remote sensing.

1. INTRODUCTION

The contemporary space missions employing radiometers and radars need dielectric models at 1.2 GHz to 89 GHz for topsoil of respective land surfaces as a crucial element in soil moisture and temperature retrieval algorithms. Recently, such research has started focusing on the regions of Arctic and boreal forests [1], [2]. To address this problem, an arctic silt clay loam soil sample collected in the Yamal peninsular was measured, and a temperature dependent multi-relaxation spectroscopic dielectric model (TD MRSDM) was developed, taking into account both the dipole and interfacial relaxations of soil water molecules in the near gigahertz and megahertz frequency range. The methodology of this model is similar to that of [3], in which an organic rich soil collected in an Yamal peninsular area has been studied. This model is designed to predict complex relative permittivity (CRP) in the frequency range 0.1 to 16.0 GHz and temperature ranges 25 to -30 to -1°C (frozen soil) and 0 to 25°C (thawed soil).

2. THE SOIL SAMPLES AND MEASURING PROCEDURES

The soil samples analyzed in this paper come from fieldwork conducted at the site situated at N 70°17′39,6″ E 68°55′45.7″. The sample consists of mineral solids and the traces of decomposed organic matter. The percentages of mineral solids are as follows: quartz ~60 %, plagioclase (albite, oligoclase) ~20-25 %, potash feldspar ~5 %, chlorite ~5 %, low content of dioctahedral mica (illite), smectite, amphibole, siderite. The procedures of soil samples processing and dielectric measurements are given in [3], [5]. The gravimetric moisture of soil samples, m_g, and dry soil density, ρ_d, varied from 0.01 to 0.33 g/g and from 1.28 to 1.65 g/cm^3, respectively. A Agilent E5071C vector network analyzer was used to measure frequency spectra of the elements of scattering matrix for a coaxial measuring container. From this measurement, the soil sample CRP values were derived as in [3]-[5]. The isothermal measurements were ensured with the use of a chamber of heat and cold with accuracy 0.5 °C.

3. CONCEPT OF A MULTI-RELAXATION SPECTROSCOPIC DIELECTRIC MODEL (MRSDM)

As in [3], we will analyze the CRP of moist soil, ε^*_s, in terms of the reduced complex refractive index (CRI):

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$$(n_s^*-1)/\rho_d = (\sqrt{\varepsilon_s^*}-1)/\rho_d = (n_s-1)/\rho_d + i\kappa_s/\rho_d;\tag{1}$$

where $n_s = Re\sqrt{\varepsilon^*_s}$ and $\kappa_s = Im\sqrt{\varepsilon^*_s}$ are the refractive index (RI) and normalized attenuation coefficient (NAC), respectively. The NAC is understood here as a proportion of the standard attenuation coefficient to the free-space propagation constant. For the reduced CRI, we will use the refractive mixing dielectric model, as given in [3]:

$$\frac{n_s^*(m_g)-1}{\rho_d(m_g)} = \begin{cases} \dfrac{n_m^*-1}{\rho_m} + \dfrac{(n_b^*-1)}{\rho_b} m_g, \\ m_g \le m_{g1}; \\ \dfrac{n_s^*(m_{g1})-1}{\rho_d(m_g)} + \dfrac{(n_t^*-1)}{\rho_t}(m_g - m_{g1}), \\ m_{g1n} \le m_g \le m_{g2}; \\ \dfrac{n_s^*(m_{g2})-1}{\rho_d(m_g)} + \dfrac{n_{l,i}^*-1}{\rho_{l,i}}(m_g - m_{g2}), \\ m_g \ge m_{g2}. \end{cases}\tag{2}$$

In (2), m_{g1}, and m_{g2} are the maximal gravimetric fractions of bound water and of total bound water (consisting of bound water and transient bound water), respectively. The subscripts s, d, m, b, t, l, and i, relating to n, κ, and density ρ refer to the moist soil, dry soil, solids of soil, bound water, transient bound water, unbound-liquid water, and moistened ice, respectively. In further, we presume that $\rho_b = \rho_t = \rho_l = 1$ g/cm^3 in a thawed soil, and $\rho_b = \rho_t = 1$ g/cm^3, $\rho_i = 0.917$ g/cm^3 in a frozen soil.

According to (1), the RI, n_p, and NAC, κ_p, can be expressed through the dielectric constant (DC), ε_p', and loss factor (LF), ε_p'', as follows:

$$\begin{aligned} n_p\sqrt{2} &= \sqrt{\sqrt{(\varepsilon_p')^2 + (\varepsilon_p'')^2} + \varepsilon_p'}, \\ \kappa_p\sqrt{2} &= \sqrt{\sqrt{(\varepsilon_p')^2 + (\varepsilon_p'')^2} - \varepsilon_p'}. \end{aligned}\tag{3}$$

Similar to [7], let us express the DC and LF of the components of soil water in (3) using the equations for the Debye multiple relaxations of non-conductive liquids, which account only for the bias electric currents:

$$\begin{aligned} \varepsilon_p' = {} & \frac{\varepsilon_{0pL} - \varepsilon_{0pM}}{1+\left(2\pi f\tau_{pL}\right)^2} + \frac{\varepsilon_{0pM} - \varepsilon_{0pH}}{1+\left(2\pi f\tau_{pM}\right)^2} + \\ & \frac{\varepsilon_{0pH} - \varepsilon_{\infty pH}}{1+\left(2\pi f\tau_{pH}\right)^2} + \varepsilon_{\infty pH}; \end{aligned}\tag{4}$$

$$\begin{aligned} \varepsilon_p'' = {} & \frac{\varepsilon_{0pL} - \varepsilon_{0pM}}{1+\left(2\pi f\tau_{pL}\right)^2} 2\pi f\tau_{pL} + \frac{\varepsilon_{0pM} - \varepsilon_{0pH}}{1+\left(2\pi f\tau_{pM}\right)^2} 2\pi f\tau_{pM} + \\ & \frac{\varepsilon_{0pH} - \varepsilon_{\infty pH}}{1+\left(2\pi f\tau_{pH}\right)^2} 2\pi f\tau_{pH}. \end{aligned}\tag{5}$$

Here f stands for wave frequency. ε_{0pL}, ε_{0pM}, ε_{0pH} are the low frequency limits of the dielectric constants corresponding to respective relaxations. $\varepsilon_{\infty pH}$ is a high frequency limit for the dielectric constant of the dipole relaxation. The subscript H, M, and L refer to the high frequency, middle frequency, and low frequency relaxations, respectively. The high frequency relaxation is a dipole relaxation. While the middle frequency and low frequency relaxations are supposed to be the interfacial (Maxwell–Wagner) ones arising due to periodic recharges of soil water layers under the influence of an alternating electromagnetic field. τ_{pL}, τ_{pM}, and τ_{pH} are the times of respective relaxations. In the case of bound water, a three relaxations equation (5) is used. In the case of transient bound and unbound water, a single relaxation equation is used, which follows from (5) with $\varepsilon_{0uL} = \varepsilon_{0uM} = \varepsilon_{0uH}$.

Keeping in mind that only bias currents account for the DC of moist soil, ε'_s, we can express this value in the form

$$\varepsilon_s' = n_s^2 - \kappa_s^2;\tag{6}$$

where formulas (2)-(5) are used to calculate the RI, n_s, and NAC, κ_s. At the same time, the LF of moist soil, ε''_s, can be represented as the sum of two terms that account for the bias currents, $\varepsilon''_{sb} = 2n_s\kappa_s$, and the conductivity currents, $\varepsilon''_{sc} = \sigma_s/2\pi f\varepsilon_r$. Here n_s and κ_s are calculated from (2)-(5). σ_s is the specific conductivity of the moist soil, and $\varepsilon_r = 8.854$ pF/m is the dielectric constant of the free space. We now represent the specific electrical conductivity of the moist soil, σ_s, as the sum of the specific conductivities, σ_p, of all the components of soil water ($p = b, t, u, i$), being weighed by their relative volumetric fractions, W_p, that is, $\sigma_{\mathrm{sc}} = W_b\sigma_b + W_t\sigma_t + W_{u,i}\sigma_{u,i}$. By definition, the volumetric fraction, W_p ($p = b, t, u, i$), is expressed as $W_p = V_p/V$, where V is the sample volume, and V_p is the volume of water in soil relating to a specific component p. V and V_p can be expressed through the respective masses and densities, that is, $V = M_d/\rho_d$, $V_p = M_p/\rho_p$. Consequently, the volumetric fraction W_p can be expressed in the form $W_p = m_{g,p}(\rho_d/\rho_p)$ where $m_{g,p}$ is the gravimetric moisture relating to a specific soil water component p. As a result, the expression for the LF of moist soil can be written as follows:

$$\varepsilon_s''(m_g) = \begin{cases} 2n_s\kappa_s + \rho_d(m_g)(m_g/\rho_b)\sigma_b / 2\pi f\varepsilon_r, \\ 0 \le m_g \le m_{g1}; \\ \varepsilon_s''(m_{g1}) + [(m_g - m_{g1})/(\rho_t)]\sigma_t]/2\pi f\varepsilon_r, \\ m_{g1} \le m_g \le m_{g2}; \\ \varepsilon_s''(m_{g2}) + [(m_g - m_{g2})/\rho_{u,i}]\sigma_{u,i}]/2\pi f\varepsilon_r, \\ m_g \ge m_{g2}; \end{cases} \quad (7)$$

From equations (1)–(7), it can be seen that the soil DC and LF spectra at a given soil temperature, as a function of dry soil density, ρ_d, gravimetric soil moisture m_g, wave frequency f can be calculated using the following set of parameters: $(n_m - 1)/\rho_m$, κ_m/ρ_m, m_{g1}, m_{g2}, ε_{0pQ}, $\varepsilon_{\infty pH}$, τ_{pQ}, σ_p, relating to i) the bound ($p=b$), transient bound ($p=t$), unbound-liquid ($p=u$), moistened ice ($p=i$) components of soil water and ii) high frequency ($Q=H$), middle frequency ($Q=M$), low frequency ($Q=L$) relaxations of soil water components. Apparently, the listed above parameters vary with the temperature. In the next section, we will outline the methodology for retrieving the parameters of the multi-relaxation spectroscopic dielectric model**.**

4. RETRIEVING THE PARAMETERS OF THE MULTI-RELAXATION SPECTROSCOPIC DIELECTRIC MODEL

To retrieve the parameters of the multi-relaxation dielectric model of moist soil, laboratory measurements of the CRP spectra were used. The measured reduced RI and NAC are shown in Fig. 1 alongside the results of fitting the equations in (2) to the data measured. As seen from Fig. 1, the model (2) is quite satisfactory. As a result of fitting, the values of $(n_m-1)/\rho_m$, κ_m/ρ_m and maximal fractions m_{g1} and m_{g2}, which are hydrological parameters, can be obtained as a function of temperature.

Now that the complex refractive index dependence on moisture has been established we shall turn our attention to retrieving the spectroscopic parameters and specific electrical conductivities present in formulas (4), (5), and (7). For this purpose, the spectra for DC and LF of moist soil samples measured at varying moistures and temperatures will be used. A certain number of patterns of DC and LF spectra relating to the soil samples both thawed and frozen are shown in Fig. 2 together with the fits calculated by using the formulas in (2)-(7) and the parameters $(n_m-1)/\rho_m$, κ_m/ρ_m, m_{g1} and m_{g2} previously retrieved by fitting procedure illustrated in Fig. 1. As a result of fitting shown in Fig. 2, the spectroscopic parameters $\varepsilon_{\infty bH}$, ε_{0bH}, τ_{bH}, ε_{0bM}, τ_{bM}, ε_{0bL}, τ_{bL}, $\varepsilon_{\infty tH}$, ε_{0tH}, τ_{tH}, $\varepsilon_{\infty uH}$, ε_{0uH}, τ_{uH}, $\varepsilon_{\infty iH}$, ε_{0iH}, τ_{iH} and electrical conductivities σ_b, σ_t, σ_u, σ_i were obtained as a function of temperature for both thawed and frozen soil samples. Now, when the temperature dependences for all the spectroscopic parameters and specific conductivities are obtained, we will consider the temperature dependent multi-relaxation spectral dielectric model (TD MRSDM) for moist soil following the methodology of [3].

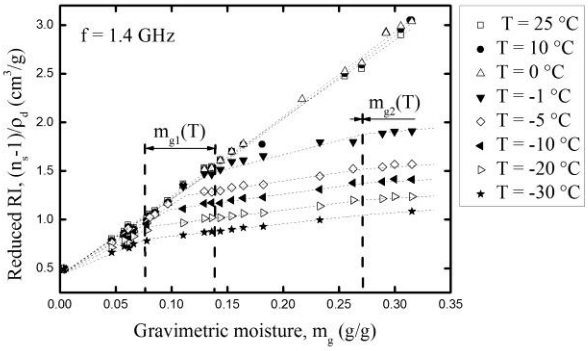

Fig. 1. Behavior of the reduced characteristics for the RI, $(n_s-1)/\rho_d$ vs. gravimetric moisture at the fixed frequency, 1.4 GHz, with the temperatures varying from 25 ºC to −30 ºC. The dashed lines indicate fits of equations in (2) to the data measured.

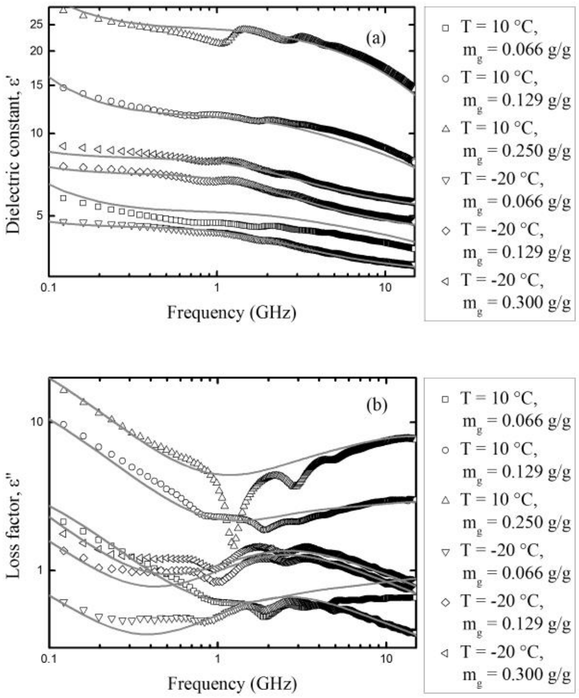

Fig. 2. Spectra of (a) dielectric constant, ε΄, and (b) loss factor, ε″, measured (symbols) and fitted (lines).

5. THE TD MRSDM

In accordance with [3], we will use as theoretical models in regression analysis the Clausius-Massotti formula, Debye equation, and linear law, for temperature dependences of the low frequency limits, relaxation times, and specific conductivities, respectively. By separately fitting these theoretical models to experimental dependences of spectroscopic parameters and conductivities for all the components of soil water and all the relaxations involved in formulas (2)-(7), we can derive the volumetric expansion coefficients, energy and entropy of activation, and temperature conductivity coefficients as the thermodynamics parameters of the TD MRSDM. The considered totality of hydrological, spectroscopic, and thermodynamics parameters in conjunction with the formulas in (1)-(7) represent the TD MRSDM, which allows to make dielectric predictions for a considered soil as a function of soil dry density, soil moisture, wave frequency, and temperature. In the next section we will validate the developed model.

6. VALIDATION OF DIELECTRIC MODEL

To obtain the error of the developed model, we correlated the predicted CRPs with the measured ones. In Fig. 3, the measured DCs (Fig 3 a) and LFs (Fig. 3 b) are shown against the respective predicted values. As seen from Fig. 3, the predicted and measured values are in good agreement in the whole domain of dry densities, moistures, temperatures, and frequencies measured. At that, the Pearson coefficients for DCs and LFs are equal to 0.994 and 0.991, respectively, with their RMSEs being of 0.475 and 0.330. Such an error of predictions is quite acceptable for practical use in the remote sensing algorithms.

7. CONCLUSIONS

The temperature dependent multi-relaxation spectroscopic dielectric model has been developed for a silt clay loam soil collected from the tundra site located in the Yamal peninsular, Russian Federation. This model predicts the spectra of complex relative permittivity of the soil both thawed and frozen, with the dry soil density, gravimetric moisture, temperature, and wave frequency as the only input variables. The validation of this model demonstrates good agreement with the data measured over frequencies from 0.1 to 15 GHz, over gravimetric moistures from 0.01 to 0.33 g/g, and over temperatures from −30 ºC to +25 ºC, with the dry soil densities varying from 1.28 to 1.65 g/cm^3. In such a wide domain of variations of all the aforementioned input variables, the error estimates are in the order of that available for the soil dielectric measurement itself. Therefore, the model is quite acceptable for practical use to develop respective remote sensing algorithms pertinent to the Arctic regions.

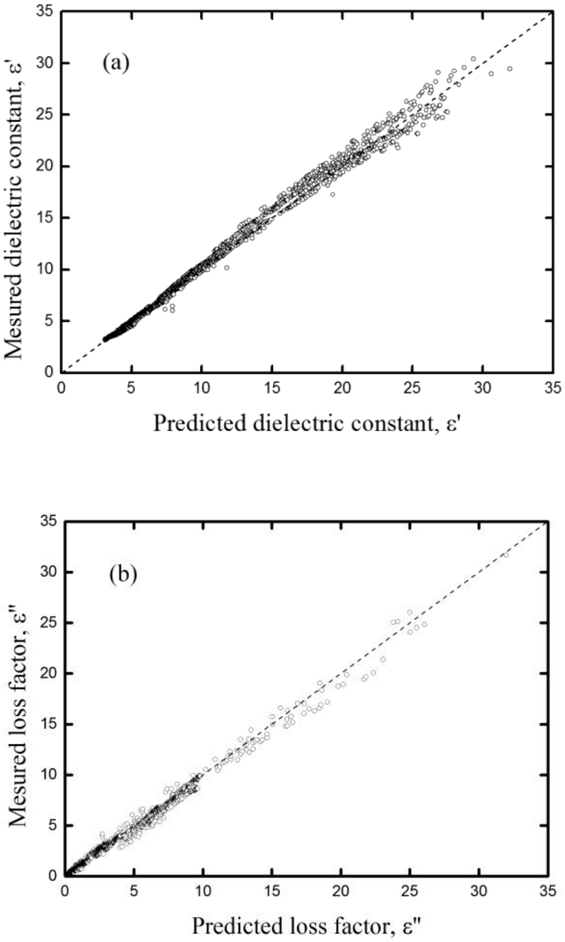

Fig. 3 The predicted dielectric constant of moist soil as a function of the measured ones. a) The real part of CRP, ε', b) the imaginary part of CRP, ε''.

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