A TEMPERATURE-DEPENDENT MULTI-RELAXATION SPECTROSCOPIC DIELECTRIC MODEL FOR THAWED AND FROZEN ORGANIC SOIL AT 0.05-15 GHZ

V. L. Mironov, I. V. Savin, and K.V. Muzalevskiy

Kirensky Institute of Physics SB RAS

ABSTRACT

The dielectric model for an arctic organic-rich soil collected on the Yamal peninsula (50% of organic matter) both thawed and frozen has been developed. The model is based on the soil dielectric measurements carried out in the ranges of gravimetric moisture 0.03 to 0.55 g/g, dry soil density 0.72 to 0.87 g/cm^3, and temperature 25 to -30°C (cooling run), in the frequency range 0.05-15 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 dielectric constant 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*—** Organic 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 tundra and boreal forest territories [1]-[5] where the topsoil is widely represented by organic rich soils. Currently, the only dielectric model proposed in [6] for an organic rich arctic soil both thawed and frozen is available. This model is designed to predict complex relative permittivity in the frequency range 1.0 to 16.0 GHz and temperature ranges 25 to -30 to -7°C (frozen soil) and -6 to 25°C (thawed soil). It also should be noted that the modelling approach used in [6] takes into account only dipole relaxations of water molecules. While, as was recently shown in [7], the interfacial Maxwell-Wagner relaxations of water molecules noticeably affect moist soil permittivity at the lower edge of the gigahertz range. Moreover, due to freezing point offset in a closed measuring container used in [6], the temperature range for frozen soil -6 to -1°C appeared to be out of scope.

In this paper, an alternative organic rich soil sample collected on 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. In contrast to the dielectric model of [6], a special mode of freezing was applied to ensure soil samples to get frozen, in the course of cooling run, at the temperature of -1°C, instead of -7°C, as was observed in [6]. Therefore, the temperature range for frozen soil samples -1°C to -6°C was involved, allowing to take into account most intensive phase transitions of unfrozen soil water

2. THE SOIL SAMPLES AND MEASURING PROCEDURES

The soil samples analyzed in this paper come from fieldwork conducted at the site situated at N 70º 25′ 52″, E 68º 25′ 19″, which represents a typical grassy moss tundra. The sample consists of mineral solids and decomposed organic matter, having the following percentages: organic matter ~50%, quartz ~30%, potassium feldspar ~5-10%, plagioclase ~5-10%, and chlorite, mica, smectite in trace amount (< 1 percent). The procedures of soil samples processing and dielectric measurements are given in [6] [8]. The gravimetric moisture of soil samples, m_g, and dry soil density, ρ_d, varied from 0.03 to 0.55 g/g and from 0.72 to 0.87 g/cm^3, respectively. Similar to [6], [8], a ZVK Rohde&Schwarz 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 CDC values were derived as in [8], [9]. The isothermal measurements were ensured with the use of an SU-241 Espec chamber of heat and cold providing temperature stability inside chamber within 0.5C. Unlike the

---

[1] The study was supported by the Russian Science Foundation (project 14-17-00656).

measurements in [6], to avoid depression of the soil sample freezing temperature down to -7°C, some nuclei of ice crystallization in a soil sample were especially induced to ensure frozen soil samples at the temperatures -1 to -7 °C.

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

As in [6], we will analyze the CRP of moist soil, ε^*_s, in terms of the reduced complex refractive index (CRI):

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

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 [6]:

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

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:

$$n_p\sqrt{2} = \sqrt{\sqrt{(\varepsilon'_p)^2 + (\varepsilon''_p)^2} + \varepsilon'_p}\,, \quad \kappa_p\sqrt{2} = \sqrt{\sqrt{(\varepsilon'_p)^2 + (\varepsilon''_p)^2} - \varepsilon'_p}\,. \qquad (3)$$

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:

$$\varepsilon'_p = \frac{\varepsilon_{0pL} - \varepsilon_{0pM}}{1 + (2\pi f \tau_{pL})^2} + \frac{\varepsilon_{0pM} - \varepsilon_{0pH}}{1 + (2\pi f \tau_{pM})^2} + \frac{\varepsilon_{0pH} - \varepsilon_{\infty pH}}{1 + (2\pi f \tau_{pH})^2} + \varepsilon_{\infty pH} \quad , (4)$$

$$\varepsilon''_p = \frac{\varepsilon_{0pL} - \varepsilon_{0pM}}{1 + (2\pi f \tau_{pL})^2} 2\pi f \tau_{pL} + \frac{\varepsilon_{0pM} - \varepsilon_{0pH}}{1 + (2\pi f \tau_{pM})^2} 2\pi f \tau_{pM} + \frac{\varepsilon_{0pH} - \varepsilon_{\infty pH}}{1 + (2\pi f \tau_{pH})^2} 2\pi f \tau_{pH} \qquad (5)$$

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. While in the case of transient bound water a two relaxation equation is applied, which follows from (4), (5) at $\varepsilon_{0tL} = \varepsilon_{0tM}$. Finally, in the case of unbound water, a single relaxation equation is used, which follows from (4), (5) when $\varepsilon_{0uL} = \varepsilon_{0uM} = \varepsilon_{0uH}$.

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

$$\varepsilon'_s = n_s^2 - \kappa_s^2 \qquad (6)$$

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, $\sigma_{sc} = W_b\sigma_b + W_t\sigma_t + W_{u,i}\sigma_{u,i}$. 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:

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

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 with 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.

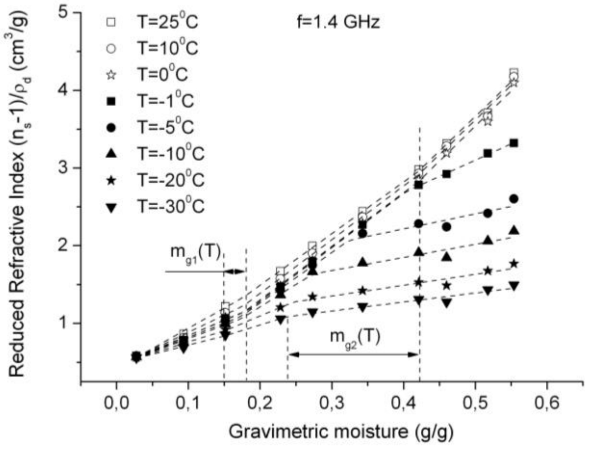

Fig. 1. Behavior of the reduced characteristics for the RI, $(n_s-1)/\rho_d$ vs. gravimetric moisture at the fixed frequency, 1.4 GHz, with the temperatures varying from 25ºC to −30ºC. The dashed lines indicate fits of equations in (2) to the data measured.

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 ε_{0bH}, τ_{bH}, ε_{0bM}, τ_{bM}, ε_{0bL}, τ_{bL}, ε_{0tH}, τ_{tH}, ε_{0tL}, τ_{tL}, and ohmic conductivities σ_b, σ_t, $\sigma_{u,i}$ 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 [6], in which only a single relaxation case was considered.

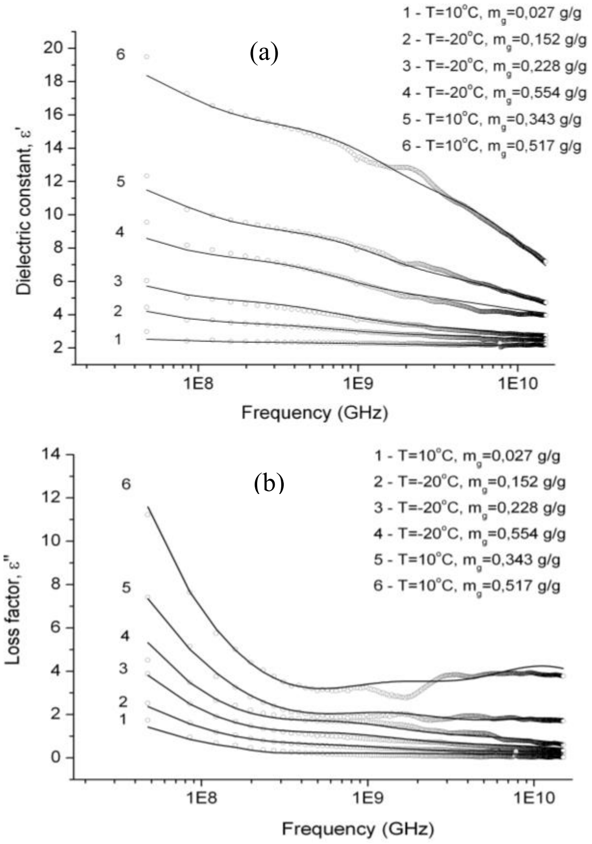

Fig. 2. Spectra of (a) dielectric constant, ε′, and (b) loss factor, ε″, measured (symbols) and fitted (lines).

5. THE TD MRSDM

In accordance with [6], 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 conjunctions with the formulas (1)-(7) represent the TD MRSDM, which allows to make dielectric predictions for a given organic-rich 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. Fig. 3, the predicted DCs (Fig 3 a) and LFs (Fig. 3 b) are shown against the respective measured 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 0.997 and 0.991, respectively, with their RMSEs being of 0.348 and 0.188. Such an error of predictions is quite acceptable for practical use in the remote sensing algorithms.

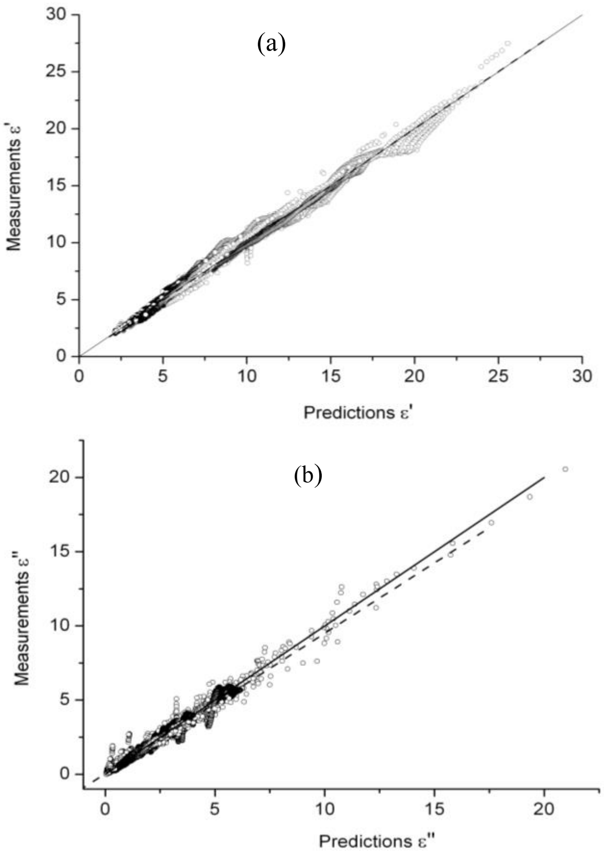

Fig. 3 Correlation of the TD GRMDM predictions for dielectric constant, ε'_{sp} (a), and loss factor, ε''_{sp} (b), of moist soil with the measured ones, ε'_{sm}, ε''_{sm}. Dotted and solid lines represent bisectors and linear fits, respectively.

7. CONCLUSIONS

A spectroscopic dielectric model has been developed for an organic rich soil collected from the grassy moss tundra site located on 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 0.05 to 15 GHz, over gravimetric moistures from 0.03 to 0.55 g/g, and over temperature from −30ºC to +25ºC, with the dry soil densities varying from 0.72 to 0.87 g/cm^3. The error estimates are in the order of that available for the soil dielectric measurement itself. Therefore, the model is acceptable for developing remote sensing algorithms pertinent to the Arctic regions. A more detailed outline of this research is available at http://dx.doi.org/10.1016/j.pce.2015.02.011, J. Phys. Chem. Earth (2015), in press.

REFERENCES

[1] L.A. Jones, J.S. Kimball, K.C. McDonald, S.T.K. Chan, E.G. Njoku, W.C. Oechel, "Satellite microwave remote sensing of boreal and arctic soil temperatures from AMSR-E," *IEEE TGRS*, Vol. 45, pp. 2004-2018, 2007.

[2] V.L. Mironov, K.V. Muzalevskiy, I.V. Savin, "Retrieving temperature gradient in frozen active layer of arctic tundra soils from radiothermal observations in L -Band—theoretical modeling," *IEEE JSTARS*, Vol. 6, pp. 1781-1785, 2013.

[3] K. Rautiainen, J. Lemmetyinen, J. Pulliainen, J. Vehvilainen, M. Drusch, A. Kontu, J. Kainulainen, J. Seppanen, "L-band radiometer observations of soil processes in boreal and subarctic environments," *IEEE TGRS*, Vol. 50, pp. 1483-1497, 2012.

[4] M. Watanabe, G. Kadosaki, Kim Yongwon, M. Ishikawa, K. Kushida, Y. Sawada, T. Tadono, M. Fukuda, M. Sato, "Analysis of the sources of variation in L-band backscatter from terrains with permafrost," *IEEE TGRS*, Vol. 50, pp.44-54, 2012.

[5] S. Bircher, J.E. Balling, N. Skou, Y.H Kerr, "Validation of SMOS brightness temperatures during the HOBE airborne campaign, western Denmark," *IEEE TGRS*, Vol. 50, pp. 1468 – 1482, 2012.

[6] V.L. Mironov, R.D. De Roo, I.V. Savin, "Temperature-dependable microwave dielectric model for an arctic soil," *IEEE TGRS*, Vol. 48, pp. 2544-2556, 2010.

[7] V.L. Mironov, P.P. Bobrov, S.V. Fomin, and A.Yu. Karavaiskii, "Generalized refractive mixing dielectric model of moist soils considering ionic relaxation of soil water," *Russian Physics Journal*, Vol. 56, pp. 319-324, 2013.

[8] V. L. Mironov, S.A. Komarov, Yu.I. Lukin, and D. S. Shatov, "A technique for measuring the frequency spectrum of the complex permittivity of soil," *J. Commun. Technol. Electron*., Vol. 55, pp. 1368–1373, 2010.

[9] V.L. Mironov, I.P. Molostov, Y.I. Lukin, A.Yu. Karavaisky, "Method of retrieving permittivity from S12 element of the waveguide scattering matrix," *IEEE SIBCON*, 2013. doi:http://dx.doi.org/10.1109/SIBCON.2013.6693609.