2015 International Siberian Conference on Control and Communications (SIBCON)

Dielectric model of a mineral arctic soil thawed and frozen at 0.05-15 GHz

Valery L. Mironov
Laboratory of Radiophysics of the Earth Remote Sensing
L. V. Kirensky Institute of Physics SB RAS
Krasnoyarsk, Russia
rsdvm@ksc.krasn.ru

Ilia P. Molostov, Vsevolod V. Scherbinin
Laboratory of Physical Problems of Monitoring Agricultural Systems
Altai State University
Barnaul, Russia
ilia_9090@mail.ru

***Abstract*—The dielectric model for an arctic soil both thawed and frozen has been developed. The model is based on the soil dielectric measurements carried out in the ranges of gravimetric moisture from 0.01 to 0.43 g/g, dry soil density from 1.25 to 1.83 g/cm^3, and temperature from 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 for the bound, transient bound, and unbound soil water components were derived, being further complimented with the thermodynamics parameters to ensure a complete set of parameters of the temperature dependent multi-relaxation spectroscopic dielectric model for moist soils proposed. To calculate complex dielectric constant of soil, the following input variables have to be assigned: 1) density of dry soil, 2) gravimetric moisture, 3) wave frequency, and 4) temperature. The error of the dielectric model was evaluated in terms of RMSE, yielding the values RMSE of 0.53 and 0.43 for the soil dielectric constant and loss factor, respectively. These values appeared to be in the order of the dielectric measurement error itself. The dielectric model suggested can be applied in the active and passive remote sensing techniques in microwave to develop algorithms for retrieving soil moisture and freeze/thaw state of the topsoil in the Arctic regions.**

Keywords—dielectric model; temperature dependence; dielectric relaxation; soil; Arctic regions; remote sensing

I. INTRODUCTION

The most promising results in remote sensing techniques of soil moisture, freeze/thaw state, and temperature over land surfaces have been obtained with the use of microwave radiometry and radar techniques. The contemporary space missions using these techniques, e.g., AQUA, GCOM-W, SMOS, SMAP, RADARSAT, ALOS PALSAR, employ radiometers and radars functioning in a frequency range from 1.2 GHz to 89 GHz. To obtain with these techniques such geophysical characteristics of the land surface as soil moisture, temperature, and freeze/thaw state, the dielectric models of topsoil are used as a crucial element in the respective retrieval algorithms. Recently, the research in microwave radiometry and radar remote sensing has been focused on the Arctic area territories [1]-[5]. The dielectric model for the only organic rich arctic soil collected in the area of North Slope, Alaska, has been proposed in [6]. This model provides complex dielectric constant (CDC) predictions as a function of frequency, temperature, and moisture for only one type of organic rich soil samples, both thawed and frozen, as a function of frequency, temperature, and moisture ranging from 1 to 16 GHz, from 25 to –30°C, and from 0.05 to 1.1 g/g, respectively. Once there are no more published dielectric models for other types of Arctic soil samples, the problem of the CDC dependence on a type of Arctic soil is still challenging in remote sensing.

In this paper, an alternative Arctic soil sample collected on the Yamal peninsular was measured, and a temperature dependent multi-relaxation spectroscopic dielectric model (TD MRSDM) was developed. As compared to [6], the frequency range was substantially extended to low frequency range, with additional dielectric relaxation of soil water being detected in the frequency range 0.05-1.0 GHz. As a result, a new approach to processing the measured dielectric data was applied, and the theoretical dielectric model of moist soil used in [6] was essentially modified to meet a multi relaxation character of the measured dielectric data for soil samples, as was previously considered in [7] in the case of a mineral thawed soils. In contrast to the dielectric model of [6], the temperature range for frozen soil samples was also substantially extended from –30°C to –7°C to –30°C to –1°C, allowing to take into account most intensive phase transitions of soil water in the range from –1°C to –7°C, observed in a cooling run.

II. THE SOIL SAMPLES AND MEASURING PROCEDURES

The soil samples analyzed in this paper come from fieldwork conducted at the site situated in the area of Yamal peninsular at N 70º 25′ 52″, E 68º 25′ 19″. This sample consist of quartz ~60%, plagioclase ~15%; potassium feldspar ~10%, chlorite ~5-10% and amphibole, siderite, mica, smectite in trace amount (< 1 percent). There was used the procedure of soil samples processing as given in [8]. The gravimetric moisture of soil samples, m_g, was determined as proportion or soil water mass, M_w, to that of a dried soil sample, M_d, that is, $m_g = M_w/M_d$. For the samples measured, the gravimetric moisture varied from 0.01 to 0.43 g/g. The dry soil density, ρ_d, was determined as $\rho_d=M_d/V$, where V is the volume of the

978-1-4799-7103-9/15/$31.00 ©2015 IEEE

measuring coaxial container, and it varied from 1.25 to 1.83 g/cm^3. The errors of measurement for m_g and ρ_d were estimated to be less than 6 %. Similar to [6], [8], a E5071C Agilent 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], with an error varying from 3 to 30% dependent on frequency. The isothermal measurements were ensured with the use of an KTX-40 chamber of heat and cold providing temperature stability inside chamber within 1°C. Unlike the measurements in [6], to avoid depression of the soil sample freezing temperature, some nuclei of ice crystallization in a soil sample were especially induced to ensure frozen soil samples at the temperature of –1 °C.

III. The Temperature Dependent Multi-Relaxation Spectroscopic Dielectric Model

A. Concept of the model

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

$$\left(n_s^*-1\right)/\rho_d=\left(\sqrt{\varepsilon_s^*}-1\right)/\rho_d=\left(n_s-1\right)/\rho_d+i\kappa_s/\rho_d\,, \quad (1)$$

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]:

$$\frac{n_s^*-1}{\rho_d(m_g)}=\begin{cases}\left(n_m^*-1\right)/\rho_m+m_g(n_b^*-1)/\rho_b, & m_g<m_{g1};\\ \left(n_m^*-1\right)/\rho_m+m_{g1}(n_b^*-1)/\rho_b & \\ +(m_g-m_{g1})(n_t^*-1)/\rho_t, & m_{g1}\le m_g\le m_{g2};\\ \left(n_m^*-1\right)/\rho_m+m_{g1}(n_b^*-1)/\rho_b & \\ +(m_{g2}-m_{g1})(n_t^*-1)/\rho_t & \\ +(m_g-m_{g2})\left(n_{u,i}^*-1\right)/\rho_{u,i}, & m_g>m_{g2}.\end{cases} \quad (2)$$

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. m_{g1} separates the range of bound water from that of transient water, and m_{g2} separates the range of transient bound water from that of unbound water which exists in a form of unbound-liquid water and moistened ice in the cases of thawed and frozen soil, respectively. The first, second and third equations in formulas (2) have to be applied in the ranges of bound water, $m_g < m_{g1}$, transient water, $m_{g1} \le m_g \le m_{g2}$, and unbound water, $m_g > m_{g2}$, respectively. The subscripts s, d, m, b, t, u, and i, relating to n, κ, and density ρ refer to the moist soil, dry soil, solid component 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, ρ_i =0.917 g/cm^3 in a frozen soil. This presumption concerns the densities of soil water components only in the frame of the soil dielectric model proposed, and the validation of this presumption will be made when validating the dielectric model as a whole.

According to (1), the RI, n_p, and NAC, κ_p, with subscript p indicating bound ($p = b$), transient bound ($p = t$), unbound-liquid ($p = u$), and moistened ice ($p = i$) soil water components, can be expressed through the dielectric constant (DC), ε_p', and loss factor (LF), ε_p'', as follows:

$$n_p\sqrt{2}=\sqrt{\sqrt{(\varepsilon_p')^2+(\varepsilon_p'')^2}+\varepsilon_p'}\,, \quad (3)$$

$$\kappa_p\sqrt{2}=\sqrt{\sqrt{(\varepsilon_p')^2+(\varepsilon_p'')^2}-\varepsilon_p'}\,. \quad (4)$$

Similar to [7], let us express the DC and LF of the components of soil water in (3) and (4) using the equations for the Debye multiple relaxations [10] of non-conductive liquids, which account only for the bias electric currents:

$$\varepsilon_p'+i\varepsilon_p''=\left(n_p^*\right)^2=\frac{\varepsilon_{0pL}-\varepsilon_{0pM}}{1-i2\pi f\tau_{pL}}+\frac{\varepsilon_{0pM}-\varepsilon_{0pH}}{1-i2\pi f\tau_{pM}}+\frac{\varepsilon_{0pH}-\varepsilon_{\infty pH}}{1-i2\pi f\tau_{pH}}+\varepsilon_{\infty pH}\,. \quad (5)$$

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. All these parameters should be related to the bound ($p = b$), transient bound ($p = t$), unbound-liquid ($p = u$), and moistened ice ($p = i$) components of soil water. In the case of bound water, a three relaxations equation (5) is used. While in the case of moistened ice, transient bound and unbound water a single relaxation equation is used, which follows from (5) when $\varepsilon_{0uL} = \varepsilon_{0uM} = \varepsilon_{0uH}$.

The LFs, ε'_p, determined by equation (5) does not include the term accounting for ohmic conductivity of soil water components. Nevertheless, keeping in mind that only the 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, ε''_{sb}, and the conductivity currents, ε''_{sc}, running through the moist sample. The terms accounting for bias and ohmic conductivity currents can be expressed as $\varepsilon''_{sb} = 2n_s\kappa_s$ and $\varepsilon''_{sc} = \sigma_s/2\pi f\varepsilon_r$, respectively. Here n_s and κ_s are calculated from (2)-(5). σ_s is the specific conductivity of the moist soil, and ε_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:

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

From equations (2)-(7), it can be seen that the DC and LF spectra at a given soil temperature, as a function of input variables, that is, 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 should vary with the temperature. In the next section, we will outline the methodology for retrieving all the parameters of the multi-relaxation spectroscopic dielectric model.

B. Retrieving the parameters of the model

To retrieve the parameters of the multi-relaxation dielectric model of moist soil, laboratory measurements of the CDC spectra were used. The measured reduced RI and NAC are shown in Fig. 1 alongside with the results of fitting the equation (2) to the data measured. As seen from Fig. 1, the model (2) is quite satisfactory. Indeed, the RI and NAC measurements are piecewise linear in certain moisture ranges, indicating contributions of particular forms of water. As a result of fitting, the values of $(n_m-1)/\rho_m$ and κ_m/ρ_m can be obtained as the value of $(n_s-1)/\rho_d$ and κ_s/ρ_d at m_g = 0. The maximal fractions m_{g1} and m_{g2} are determined as a point of transition from one linear segment of the fit to another. These values were retrieved using simultaneous fitting of (2) to the measured reduced RI and NAC data. As seen from Fig. 1, the maximal fractions m_{g1} and m_{g2} depend on the temperature, particularly in the case of frozen soil samples. These dependences were derived and fitted with the following formulas:

$$\begin{aligned} m_{g1} &= 0.115 + 0.000022T, && 0^{o}C \le T \le 25^{o}C; \\ m_{g2} &= m_{g1}, && 0^{o}C \le T \le 25^{o}C; \\ m_{g1} &= 0.096 + 0.0197exp(T/18.39), && -30^{o}C \le T \le -1^{o}C; \\ m_{g2} &= 0.219 + 0.0105exp(T/7.991), && -30^{o}C \le T \le -1^{o}C. \end{aligned} \qquad (8)$$

In the case of thawed soil, the transient bound water appeared to be not distinguished from the unbound water, so $m_{g1} = m_{g2}$. Values of reduced RI, $(n_m-1)/\rho_m$, and NAC, κ_m/ρ_m, were found not to vary with temperature:

$$(n_m - 1)/\rho_m = 0.441; \qquad \kappa_m/\rho_m = 0. \qquad (9)$$

Now that the complex refractive index dependence on moisture has been established, and the division between frozen and thawed states clarified, we shall turn our attention to the methodology of retrieving the spectral parameters present in formula (5). 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 these spectra relating to the soil samples both thawed and frozen are shown in Fig. 2. As can be deduced from the equations in (8), the samples shown in Fig. 2 contain only bound water (plot 3), bound water and transient bound water (plots 4), bound water and unbound-liquid water (plots 1 and 2) and all three components of soil water (plots 5). At that, the frozen soil samples contain unbound soil water in the form of moistened ice.

In the first phase of fitting, the DC spectra of the samples with the values of soil moisture limited in the range $0 < m_g < m_{g1}$, so that only the bound water component is contained in the samples, are fitted, simultaneously for all the measured moistures available in this range. Values of the soil DC corresponding to the theoretical model, which is fitted to the measured spectra, are calculated by applying formulas (2), (3), (4), (5), (6), (8), and (9).

The theoretical spectra containing i) only high frequency relaxation, ii) high frequency and middle frequency relaxations, and iii) high frequency, middle frequency and low frequency relaxations are successively fitted to measured data, yielding respectively the following sets of spectroscopic parameters: i) ε_{0bH}, τ_{bH}, $\varepsilon_{\infty bH}$; ii) ε_{0bH}, τ_{bH}, $\varepsilon_{\infty bH}$, ε_{0bM}, τ_{bM}; and iii) ε_{0bH}, τ_{bH}, $\varepsilon_{\infty bH}$, ε_{0bM}, τ_{bM}, ε_{0bL}, τ_{bL}.

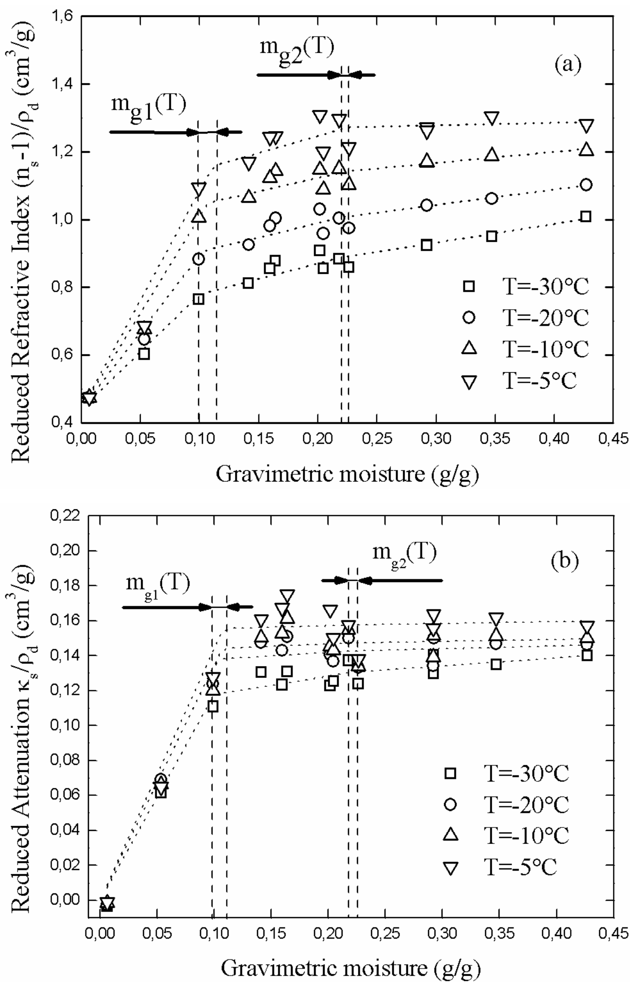

Fig. 1. Behavior of the reduced characteristics for (a) the reduced RI, $(n_s-1)/\rho_d$, and (b) NAC, κ_s/ρ_d, vs. gravimetric moisture at the fixed frequency, 1.4 GHz, with the temperatures varying from −5ºC to −30ºC. The doted lines indicate fits of equation (2) to the data measured.

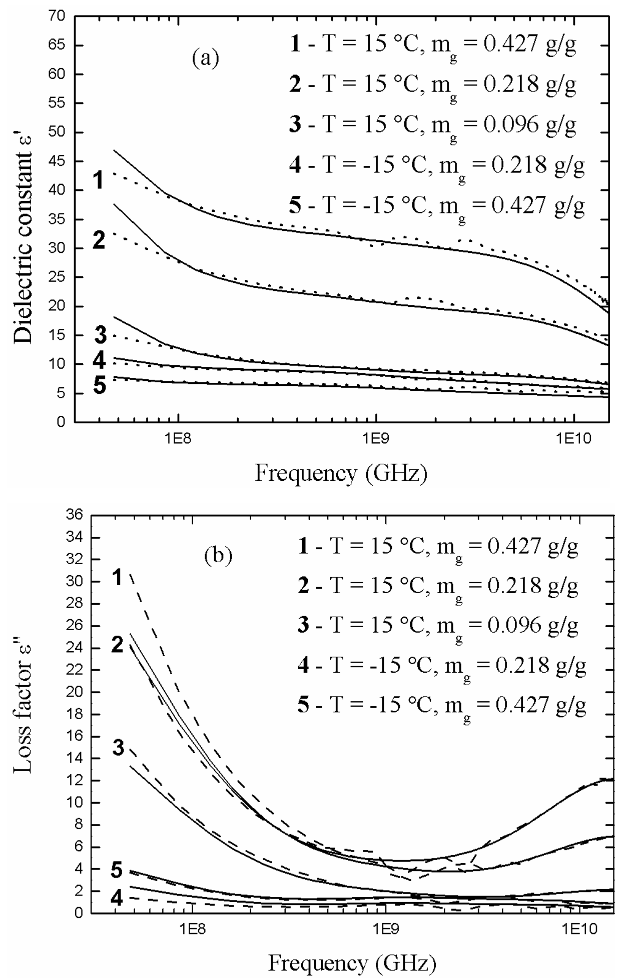

Fig. 2. Spectra of (a) dielectric constant, ε′, and (b) loss factor, ε″, measured (solid lines) and fitted (dashed lines) with the use of the two sets of formulas i) (2), (3), (4), (5), (6), (8), (9) and ii) (2), (3), (4), (5), (7), (8), (9), respectively.

After all the spectroscopic parameters for bound soil water, namely, ε_{0bH}, $\varepsilon_{\infty bH}$, τ_{bH}, $\varepsilon_{\infty bH}$, ε_{0bM}, τ_{bM}, ε_{0bL}, τ_{bL} were derived, using only DC spectra measured for moist soil samples, we can proceed with further fitting to obtain values of specific conductivity of the bound soil water from the LF spectra measured for the gravimetric soil moistures limited in the range $0 < m_g < m_{g1}$. To calculate the values of theoretical model for LF, we will apply a set of equations (2), (3), (4), (5), (7), (8) and (9), employing the values of spectroscopic parameters, namely, ε_{0bH}, $\varepsilon_{\infty bH}$, τ_{bH}, $\varepsilon_{\infty bH}$, ε_{0bM}, τ_{bM}, ε_{0bL}, τ_{bL} as those were previously derived. As a result of this fitting, the value of specific conductivity for the bound soil water, σ_b, was obtained as a function of temperature.

In the second phase of fitting, the spectra measured for the samples containing both the bound water and transient bound water components were used, and the same approach of fitting applied, with the values of parameters ε_{0bH}, τ_{bH}, $\varepsilon_{\infty bH}$, ε_{0bM}, τ_{bM}, ε_{0bL}, τ_{bL} and σ_b being known as a result of the first phase of fitting. In the third phase of fitting, there were used the spectra measured for the samples containing all the three components of soil water. At that, the values of parameters ε_{0bH}, τ_{bH}, $\varepsilon_{\infty bH}$, ε_{0bM}, τ_{bM}, ε_{0bL}, τ_{bL}, σ_b, ε_{0tH}, τ_{tH}, $\varepsilon_{\infty tH}$, ε_{0tL}, τ_{tL} and σ_t are considered to be known as a result of the first and second phases of fitting. 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 a single relaxation case was outlined.

We suggest that the temperature dependences for the low and high frequency limits follow the equation, which was obtained in [6] with the use of Clausius-Mossotti law [11]:

$$\varepsilon_{qpQ}(T) = \frac{1 + 2\exp\left[F_{qpQ}(T_{qs\varepsilon pQ}) - \beta_{qvpQ}(T - T_{qs\varepsilon pQ})\right]}{1 - \exp\left[F_{qpQ}(T_{qs\varepsilon pQ}) - \beta_{qvpQ}(T - T_{qs\varepsilon pQ})\right]},$$

$$F_{qpQ}(T) = \ln\left[\frac{\varepsilon_{qpQ}(T) - 1}{\varepsilon_{qpQ}(T) + 2}\right], \qquad (10)$$

where ε_{qpQ} and β_{qvpQ} stand for the low ($q = 0$) and high ($q = \infty$) frequency limit dielectric constants and volumetric expansion coefficients, relating to the bound water ($p = b$), transient bound water ($p = t$), unbound-liquid water ($p = u$), and moistened ice ($p = i$) components of soil water. While the subscript Q stands for the low ($Q = L$), middle ($Q = M$), and high ($Q = H$) frequency relaxations of the soil water components. $T_{qs\varepsilon pQ}$ designates the starting temperature for which any value can be taken from the temperature intervals measured. The values of β_{qvpQ} and $\varepsilon_{qpQ}(T_{qs\varepsilon pQ})$ can be determined using fitting for the functions (10) to the obtained temperature dependences of low and high frequency limits dielectric constants. This fitting is performed separately for the thawed and frozen soil samples. The values of β_{qvpQ}, $T_{qs\varepsilon pQ}$, and $\varepsilon_{qpQ}(T_{qs\varepsilon pQ})$ derived from fitting are given in Table I.

The next parameter needing a temperature dependence is the relaxation time. The measured relaxation time can be described by the Debye relation [11]:

$$\ln\left(\frac{kT_K}{h}\tau_{pQ}\right) = \frac{\Delta H_{pQ}}{R}\frac{1}{T_K} - \frac{\Delta S_{pQ}}{R}, \qquad (11)$$

where h is the Plank constant (6.624×10^{-34} Js), k is the Boltzmann constant (1.38×10^{-23} JK^{-1}), ΔH_{pQ} is the activation energy of the relaxation process, R is the universal gas constant (8.314×10^{3} JK^{-1} kmol^{-1}), and ΔS_{pQ} is the entropy of activation. T_K is the temperature in Kelvin. The values of $\Delta H_{pQ}/R$ and $\Delta S_{pQ}/R$ thus determined are given in Table I and can be used to calculate relaxation time using formula (11).

Finally, we suggest that the conductivity, σ_p, has a linear dependence on the temperature, which is characteristic to ionic solutions:

$$\sigma_p(T) = \sigma_p(T_{s\sigma p}) + \beta_{\sigma p}(T - T_{s\sigma p}) \qquad (12)$$

Here, $\beta_{\sigma p}$ is the derivative of conductivity with respect to temperature, that is, the conductivity temperature coefficient, and $\sigma_p(T_{s\sigma p})$ is the value of conductivity at an arbitrary starting temperature, $T_{s\sigma p}$, being taken from the measured range. The parameters $\beta_{\sigma p}$, $\sigma_p(T_{s\sigma p})$ and $T_{s\sigma p}$ are given in Table I.

As a result of consideration conducted in this section, the TD MRSDM can be defined as an assembly of the following steps comprising its algorithm procedure.

1. The temperature, T, has to be assigned in the cases of thawed or frozen soil.

2. The values of the Debye parameters, namely the low and high frequency limit, relaxation time, and conductivity, for all types of soil water are to be calculated with the use of formulas (10), (11), (12) and data in Table I.

3. Once the values, $\varepsilon_{0pQ}(T)$, $\varepsilon_{\infty pQ}(T)$, $\tau_{pQ}(T)$, and $\sigma_p(T)$, and are known, the values of dielectric constant, $\varepsilon'_p(f, T)$, and loss factor $\varepsilon''_p(f, T)$ for all the components of soil water can be calculated as a function of frequency at a given temperature using the formulas in (5).

4. The translation from the values $\varepsilon'_p(f, T)$ and $\varepsilon''_p(f, T)$ to the RI, n_p, and NAC, κ_p, regarding all the components of soil water, have to be made with the formulas in (3) and (4).

6. The gravimetric soil moisture, m_g, and dry soil bulk density, ρ_d, have to be assigned, and formulas (2), (8), and (9) applied to make calculations for the soil RI, $n_s(\rho_d, m_g, f, T)$, and NAC, $\kappa_s(\rho_d, m_g, f, T)$, accounting for bias currents.

7. Finally, the values $n_s(\rho_d, m_g, f, T)$ and $\kappa_s(\rho_d, m_g, f, T)$ are translated to the soil dielectric constant, $\varepsilon'_s(\rho_d, m_g, f, T)$ and loss factor, $\varepsilon''_s(\rho_d, m_g, f, T)$, with formulas (6) and (7), respectively, using the values of specific conductivities from Table I.

In the following section, the developed TD MRSDM for an Arctic soil will be evaluated in terms of prediction error by correlating the moist soil dielectric data predicted with those measured in the multidimensional domain of temperature,

TABLE I. TD MRSDM PARAMETERS FOR ALL FORMS OF SOIL WATER IN THE TEMPERATURE RANGE $-30°C \le T \le +25°C$.

Soil water component		**Bound Soil Water (*p=b*)**						**Transient Bound Water (*p=t*)**	**Moistened Ice Water (*p=i*)**	**Unbound-Liquid Water (*p=u*)**
Relaxations		***High (Q = H)***		***Middle (Q = M)***		***Low (Q = L)***		***High (Q=H)***	***High (Q=H)***	***High (Q=H)***
Temperature ranges		$T<T_f$	$T>T_f$	$T<T_f$	$T>T_f$	$T<T_f$	$T>T_f$	$T<T_f$	$T<T_f$	$T>T_f$
Parameters	***Units***									
$\varepsilon_{0p}(T_{0s\varepsilon pQ})$	-	59.5	67.9	89.0	95.9	628.9	715.9	4.9	2.1	73.9
$T_{0s\varepsilon pQ}$	ºC	-2	0	-2	0	-2	0	-2	-2	0
β_{0vpQ}	$1/K\times10^{-3}$	-6.10	-0.01	-2.08	-0.05	-0.58	-0.08	-0.36	-5.58	0.16
$\Delta H_{pQ}/R$	K	691.6	1999.7	292.8	834.9	124.3	124.3	331.6	1655.9	1655.9
$\Delta S_{pQ}/R$	-	-2.19	2.76	-5.57	-4.03	-10.23	-10.23	-4.49	1.61	1.61
Temperature ranges		$T<T_f$			$T>T_f$			$T<T_f$	$T<T_f$	$T>T_f$
$\varepsilon_{\infty p}(T_{\infty s\varepsilon pH})$		12.1			4.9			4.9	2.1	4.9
$T_{\infty s\varepsilon pH}$	ºC	-2			0			0	-2	0
$\beta_{\infty vpH}$	$1/K\times10^{-3}$	-6.00			0			0	-5.58	0
$\sigma_p(T_{s\sigma p})$	S/m	0			0			0	0	0.01
$\beta_{\sigma p}$	$(S/m)/K\times10^{-3}$	0			0			0	0	0
$T_{s\sigma p}$	ºC	0			0			0	0	1.6

frequency, and moisture.

C. Evaluation of the model

In order to quantitatively study the correlation between the TD GRMDM predictions and the measured DC and LF, the values measured are plotted as a function of the predicted ones in Fig. 3. The data in this figure includes an ensemble of soil conditions: thawed and frozen, with moisture contents varying from only bound water to bound and liquid in the case of thawed soils and from only bound water to a mixture of bound and transient bound water or bound, transient bound and moistened ice water in the case of frozen soils. As follows from Fig. 3, a good quantitative correlation is observed between the TD GRMDM predictions and the respective values measured over the whole domain of moistures, frequencies, and temperatures performed in this research. To estimate the deviations of the predicted CDC values from the measured ones in the whole domain of dry densities, moistures, temperatures, and frequencies measured, we calculated the coefficient of determination for the DC, $R^2_{\varepsilon'}$, and the LF, $R^2_{\varepsilon''}$. Their values were found to be $R^2_{\varepsilon'} = 0.994$ and $R^2_{\varepsilon''} = 0.996$. While the estimates of the RMSE of the predicted values relative to the measured ones, yielded the following values: $RMSE_{\varepsilon'} = 0.53$ and $RMSE_{\varepsilon''} = 0.43$ in the cases of DC and LF, respectively. Such errors of the CDC predictions are quite acceptable for practical use in the remote sensing algorithms.

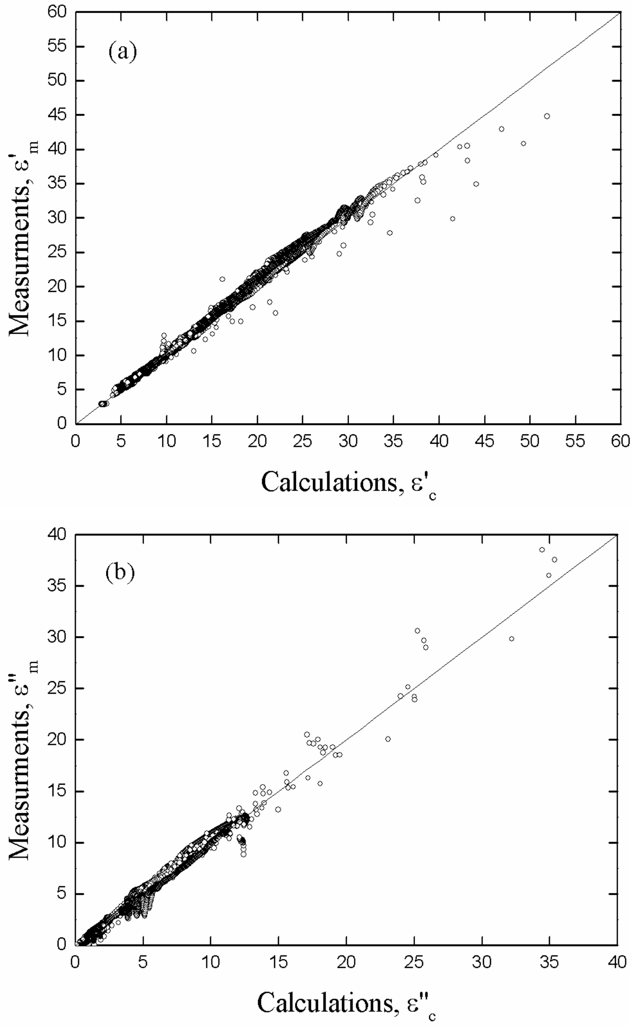

Fig. 3. Correlation of the TD GRMDM predictions for the (a) DC ε'_c and (b) LF ε''_c of moist soil with the measured ones ε'_m and ε'_m. The solid lines represent the bisectors

IV. CONCLUSIONS

The temperature dependent multi-relaxation spectroscopic dielectric model has been developed for an Arctic soil collected from the grassy moss tundra site located on the Yamal peninsular, Russian Federation. Presented as the ensemble of analytical expressions, this model gives the complex dielectric constant of the soil both thawed and frozen, with the dry soil density, gravimetric moisture, temperature, and wave frequency being 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 0.006 to 0.427 g/g, and over temperature from −30ºC to +25ºC, with the dry soil densities varying from 1.251 to 1.826 g/cm3.

In such a wide domain of variations of all the aforementioned input variables, the values of coefficient of determination for the dielectric constant, $R^2_{\varepsilon'}$, and loss factor, $R^2_{\varepsilon''}$ were found to be $R^2_{\varepsilon'} = 0.994$ and $R^2_{\varepsilon''} = 0.996$. While the estimates of the RMSE of the predicted values relative to the measured ones, yielded the following values: $RMSE_{\varepsilon'} = 0.53$ and $RMSE_{\varepsilon''} = 0.43$ in the cases of dielectric constant and loss factor, respectively. These 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.

A major advantage of the dielectric model proposed as compared to the previous single-relaxation model of [6] is that it covers a lot wider frequency band, that is, 0.05 to 15 GHz instead of 1 to 16 GHz, which became possible due to taking into account multiple relaxations of various soil water components. In addition, a realistic soil freezing temperature of -1°C was attained in a freezing run, instead of a depressed soil freezing temperature of -7°C inherent to the model in [6].

This model makes basis for developing data processing algorithms for the modern remote sensing missions such as AQUA, GCOM-W, SMOS, SMAP, RADARSAT, ALOS PALSAR, as well as for the perspective P-band sensors, for which the depth of sensing is expected to increase. In addition, it facilitates application of the GPR and TDR instruments, working in the megahertz band, to interpret the results of in situ measurements of the active permafrost layer, including studies of the freeze/thaw processes.

ACKNOWLEDGMENT

This study was made possible through a grant from the Russian Science Foundation (project 14-17-00656).

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,” Geoscience and Remote Sensing, IEEE Transactions on, vol. 45(7), 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-Band—Theoretical Modeling,” Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of, vol. 6(3), pp. 1781-1785, 2013.

[3] K. Rautiainen et al, “L-band radiometer observations of soil processes in boreal and subarctic environments,” Geoscience and Remote Sensing, IEEE Transactions on, vol. 50(5), pp. 1483-1497, 2012.

[4] M. Watanabe et al, “Analysis of the sources of variation in L-band backscatter from terrains with permafrost,” Geoscience and Remote Sensing, IEEE Transactions on, vol. 50(1), 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,” Geoscience and Remote Sensing, IEEE Transactions on, vol. 50(5), pp. 1468-1482, 2012.

[6] V. L. Mironov, R. D. De Roo, I. V. Savin “Temperature-dependable microwave dielectric model for an Arctic soil” Geoscience and Remote Sensing, IEEE Transactions on, vol. 48(6), pp. 2544-2556, 2010.

[7] V. L. Mironov, P. P. Bobrov, S. V. Fomin & A. Y. Karavaiskii, “Generalized refractive mixing dielectric model of moist soils considering ionic relaxation of soil water” Russian Physics Journal, vol. 56(3), pp. 319-324, 2013.

[8] V. L. Mironov, S. A. Komarov, Y. I. Lukin & D. S. Shatov, “A technique for measuring the frequency spectrum of the complex permittivity of soil” Journal of Communications Technology and Electronics, vol. 55(12), pp. 1368-1373, 2010.

[9] V. L. Mironov, I. P. Molostov, Y. I. Lukin & A. Y. Karavaisky, “Method of retrieving permittivity from S 12 element of the waveguide scattering matrix,” Control and Communications (SIBCON), 2013 International Siberian Conference on. IEEE, 2013.

[10] F. Kremer, A. Schonhals, and W. Luck, Broadband Dielectric Spectroscopy. New York: Springer-Verlag, 2002.

[11] The Electrical Engineering Handbook. 2nd ed. R.C. Dorf, Ed. Boca Raton, FL: CRC Press, 1997.

Valery L. Mironov received the M.S. and Ph.D degrees in radio physics from the Tomsk State University, Tomsk, Russia, in 1961 and 1968, respectively. Also in radio physics, he received a full professor degree from the Russian Academy of Sciences in 1984 and entered the Russian Academy of Sciences as a correspondent member in 1991.

Since 2004, he is a Laboratory Head at the Kirensky Institute of Physics Siberian Branch of the Russian Academy of Sciences (SB RAS), Krasnoyarsk. From 1961 to 2004, he worked as a Senior Researcher, Laboratory Head, Full Professor, and Chair Head at the Tomsk State University, Altai State University, Institute of Atmospheric Optics, and Krasnoyarsk Science Center SB RAS. He also served as a Deputy Director Research for the Institute of Atmospheric Optics from 1982 to 1986 and the President for the Altai State University from 1986 to 1997. As a visiting scientist, he worked at the University of British Columbia, Canada, and Geophysical Institute at the University of Alaska, USA, in 1997/1998 and 2001, respectively, taking position of Affiliate Professor Geophysics.

His current research interests include electromagnetic wave propagation and scattering linked to the radar and radio thermal microwave remote sensing of the land, including the studies of dielectric properties of moist soils. In the period of last 10 years, he published more then 50 papers in the IEEE Journals and Magazines and Conference Publications. In 2012, his temperature and mineralogy dependent dielectric model has been introduced in the SMOS data processing algorithm to retrieve soil moisture from the earth surface radiobrightness observations.

He is a reviewer for the IEEE Transactions on Geoscience and Remote Sensing, IEEE Geoscience and Remotes Sensing Letters, International Journal of Remote Sensing, and Remote Sensing of Environment.

Ilia P. Molostov was born in Barnaul, Russia, in 1990. He received the M.S. degree in physics from the Siberian State Aerospace University, Krasnoyarsk, Russia, in 2014.

He is presently a postgraduate student at the Altay State University, Barnaul, Russia. His research interests include dielectric spectroscopy of moist soils, methods of measuring the permittivity. He is the author or coauthor of 4 scientific publications.

Vsevolod V. Scherbinin was born in Barnaul, Russia, in 1975. He received the M.S. degree in physics from the Altai State University, Barnaul, Russia, in 1998 and Ph.D. degree in Tomsk State University, Tomsk, Russia in 2006.

He is currently a scientific associate with the Altai State University, Barnaul and L. V. Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences (SB RAS), Krasnoyarsk. His research interests include theoretical and experimental methods for radiation and scattering of the electromagnetic waves studying. He is the author or coauthor of 80 scientific publications.