Experimental Analysis and Empirical Model of the Complex Permittivity of Five Organic Soils at 1.4 GHz in the Temperature Range From −30 °C to 25 °C

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***Abstract*— The dielectric measurements were made for five organic soils taken from the tundra territories of Alaska, Yamal, and Taimyr, with the content of organic matter varying from 35% to 80%. The measurements were carried out in the temperature range from −30 °C to 25 °C, frequencies from 0.45 to 16 GHz and soil moisture from close to zero to the field moisture capacity. The refractive mixing model was applied to fit the measurements of the soil's complex refractive index (CRI) as a function of soil moisture, with the values of temperature being fixed. As a result, a respective dielectric model was developed. The amounts of bound and transient water in the thawed and frozen soils were introduced as parameters of the developed model and derived as a function of temperature and content of soil organic matter. The other parameters which concern the CRIs of soil solids as well as bound, transient, and liquid soil water or ice components were derived as a function of temperature. The errors of the proposed model estimated in terms of the values of normalized root-mean-sqaure error for the real and imaginary parts of the soil complex relative permittivity appeared to be 6%–7% and 23%, respectively. The proposed dielectric model can be applied in active and passive remote sensing, in particular, for the SMOS, SMAP, and Aquarius missions after testing in ground-based experiments.**

***Index Terms*— Dielectric measurement, microwave measurement, predictive models, soil moisture.**

I. INTRODUCTION

DIELECTRIC models for thawed mineral soils developed by Dobson *et al.* [1] and Mironov *et al.* [2] are well known and now extensively used as basic elements in the soil moisture retrieval algorithm of the SMOS and SMAP missions [3]. In contrast to the mineral soils, the soil moisture retrieval algorithm over organic soils is in the process of developing, regarding the appropriate dielectric model. Dielectric properties of the organic soils are less studied than those of the mineral soils. In this research, we will consider organic soils which according to [4] are determined as the soils containing more than 20% by weight of organic matter. Organic soils occupy the total area of more than 300 million ha worldwide. About 80% of the world's organic soils are situated in the Russian Federation and Canada [4].

For the first time, dielectric model for an organic soil in thawed and frozen state was developed in [5]. This model allows estimating the complex refractive permittivity (CRP) for the only soil with an organic matter content of 90% by weight as a function of soil moisture, bulk density in the ranges of temperature and wave frequency from −30 °C to 25 °C, and 1 to 15 GHz, respectively. This model is based on the measured soil dielectric data, which are fit with the refractive mixing dielectric model formulated for the reduced complex refractive index (CRI) of the soil, and the Debye model for the spectra of the soil water components. Later, this model was extended over the frequency range from 0.05 to 15 GHz by including the lower frequencies subrange from 0.05 to 1 GHz. The latter was done due to using the multirelaxation Debye formulas for the dielectric spectra of the soil water components [6].

In addition, a simple single-frequency (1.4 GHz) dielectric model of one organic soil (with an organic matter content of 80%) was developed in [7], which allows calculating the CRP of this soil in the thawed and frozen state as a function of moisture, dry soil bulk density and temperature. To develop a dielectric model for a group of soils with different contents of organic matter for determination parameters of this model, a method analogous to the one used in [8] was applied. As a result, the one more model parameter, namely the amount of organic matter in the soil was introduced. This is the novelty of this paper in comparison with [7] where the soil with a fixed content of organic matter was considered. Thus, the purpose of this research is to create a dielectric model for a group of organic soils having different contents of organic matter and to estimate the error of this model. The input data of such a model should be readily available parameters characterizing organic soils and affecting the CRP of organic soils. This, apparently, such available a priory soil physical properties as moisture, dry soil density, temperature (as we consider thawed and frozen soils) and organic matter content.

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TABLE I
CHARACTERISTICS OF THE MEASURED SOILS

Soil	Location, Peninsula	Coordinates	Samples Bulk Density, g/cm^3	Bulk Density in situ	Organic Matter Content, %
Soil 1	Yamal (Russia)	N57°06′, E66°12′	0.51-0.69	0.39	35
Soil 2	Yamal (Russia)	N70º25′, E68º25′	0.71-0.87	0.26	50
Soil 3	Yamal (Russia)	N66º48′, E69º42′	0.61-0.77	0.44	61
Soil 4	Alaska (US)	N68º38′, W149º35′	0.56-0.66	0.08	80
Soil 5	Taimyr (Russia)	N69º21′, E88º17′	0.67-0.85	0.15	38.5

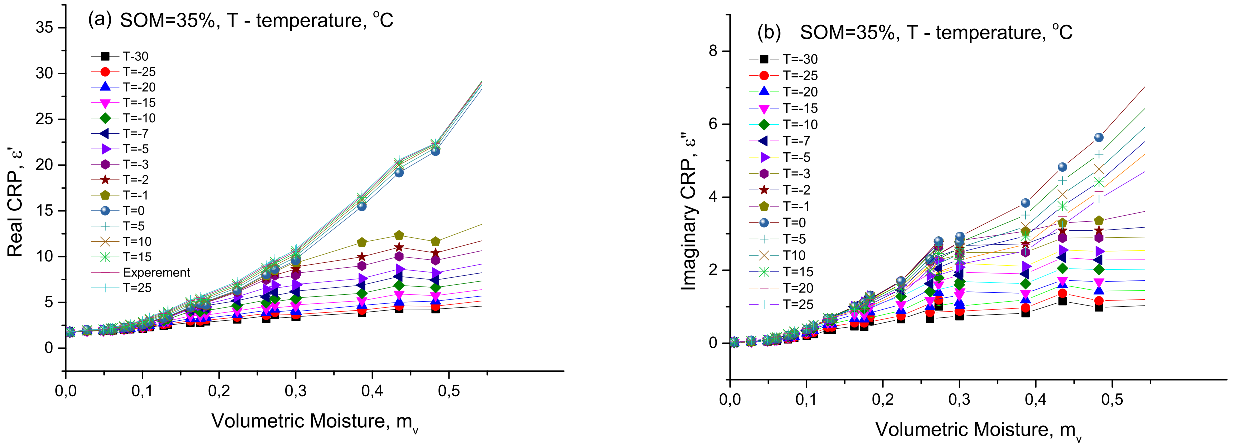

Fig. 1. Dependences of CRP on volumetric moisture at different temperatures (T°C) for the soil from Yamal with the SOM content 35%. (a) Real part of CRP. (b) Imaginary part of CRP.

II. DIELECTRIC MEASUREMENTS OF ORGANIC SOILS

To develop the dielectric model, four basic tundra soils were used, three of which were collected on the Yamal Peninsula (Russia) with the organic contents of 35%, 50%, and 61%, respectively, and one soil containing 80% of organic matter was taken from Alaska. Also, for independent estimation of the model accuracy, a soil with an organic content of 38.5% collected near the city of Norilsk (Taimyr Peninsula) was used. The physical and geographical data on these soil samples are shown in Table I.

In this paper, dielectric measurements of organic soils were carried out using the technique previously apply for mineral soils. This technique is described in detail in [8]. Therefore, only the main elements of this technique will be discussed below in terms of the experimental apparatus, and the corresponding experimental conditions. Before performing the dielectric measurements, the soil samples were ground using a coffee grinder. The ground samples were dried in an oven at 60 °C for 24 h. After that, a predetermined amount of distilled water was added to soil samples. When filling the measurement cell the soil was compacted with a cylinder pestle. To conduct dielectric measurements, the soil matter was placed into a cell formed by a section of coaxial waveguide. The cell was connected to the ZVK Rohde & Schwarz vector network analyzer to measure the frequency spectra of the $S11$, $S22$, $S12$, and $S21$ elements of the scattering matrix S over the frequency range from 0.045 to 16 GHz. The isothermal measurements were ensured with the use of an SU-241 Espec chamber of heat and cold with accuracy 0.5 °C. The dielectric measurements of the soil samples at the same assigned in advance water content and sample density could not be repeated, because control of soil sample moisture, and densities was not possible in process of packing soil in the measuring cell. As a result, the measured dielectric data referred to the soil samples with simultaneously changing values of moisture and density. Sometimes the samples with the close values of water content and density happened, and then their CRP measured values coincided. The algorithm developed in [9] was applied to retrieve the spectra of the CRP of moist soil sample using the measured values of scattering matrix. This algorithm provides the real part of the CRP with the errors less than 10%, and imaginary part of the CRP, with the errors about 20%.

The typical behavior of the CRP of thawed and frozen organic soil with the value of soil organic matter (SOM) of 35%, as a function of volumetric moisture at the fixed temperatures is shown in Fig. 1. The real part of the CRP, ε', in the case of the thawed soil depends on temperature weakly, as follows from Fig. 1. However, more significant dependence for the imaginary part, ε'', of the thawed organic soil CRP on temperature is observed. At that, ε'', decreases with increasing temperature at a frequency of 1.4 GHz. The effect of temperature on the real and imaginary parts of the CRP for the frozen organic soil is much more noticeable as compared to the thawed soil. Both ε', and ε'' decrease with the temperature decreasing from −1 °C to −30 °C. In the thawed organic soil, the real and imaginary parts of the CRP increase when soil moisture increases. As to the frozen soil, ε' and ε'' significantly change only in the range of volumetric moistures from 0.05 to 0.3 cm^3/cm^3. From the above consideration, It can be concluded that the effect of moisture has the strongest impact on the soil CRP in the case of thawed organic soils, and the effect of temperature has the strongest impact on the soil CRP in the case of frozen organic soils.

The effect of the organic matter content on soil CRP was estimated through the relative difference, δ, for two organic soils with minimal and maximal organic matter content. To calculate relative difference, δ, was used formula

$$\delta = \frac{\varepsilon_{\max} - \varepsilon_{\min}}{(\varepsilon_{\max} + \varepsilon_{\min})/2} \times 100\%.$$

The relative difference between the CRPs for thawed soils with volumetric moisture 0.4 cm^3/cm^3 at the temperature of 20 °C was about 6% and 47% for the real and imaginary parts of CRP, respectively. As for frozen soils with volumetric moisture 0.4 cm^3/cm^3 at the temperature of −30 °C, these values yielded 11% and 34%, respectively. Thus, the soils organic matter content weakly affects real part of CRP, but noticeably affects imaginary part of CRP.

III. DIELECTRIC MODEL

The measured soil CRPs, $\varepsilon*$, will be analyzed in terms of the reduced CRI

$$(n^* - 1)/\rho_{\mathrm{d}} = (\sqrt{\varepsilon^*} - 1)/\rho_{\mathrm{d}} = (n - 1)/\rho_{\mathrm{d}} + i\kappa/\rho_{\mathrm{d}} \quad (1)$$

where $n = \mathrm{Re}\sqrt{\varepsilon^*}$ and $\kappa = \mathrm{Im}\sqrt{\varepsilon^*}$ are the real and imaginary parts of CRI, respectively. ρ_d is the dry soil bulk density. Such an approach allows analyzing the dielectric data measured at simultaneously changing values of moisture and density. Moreover, the gravimetric moisture of the soil samples m_g, which is the ratio of the mass of soil water to that of the dry soil sample, can be the only variable when fitting the reduced CRI measured as a function of gravimetric moisture at different values of soil bulk density. Different values of soil bulk density for soil samples with varying moistures arise in the process of packing soil samples into a dielectric measurement cell.

The dependences of the dry soil bulk density on the sample moisture for the measured soils observed in the experiment are shown in Fig. 2.

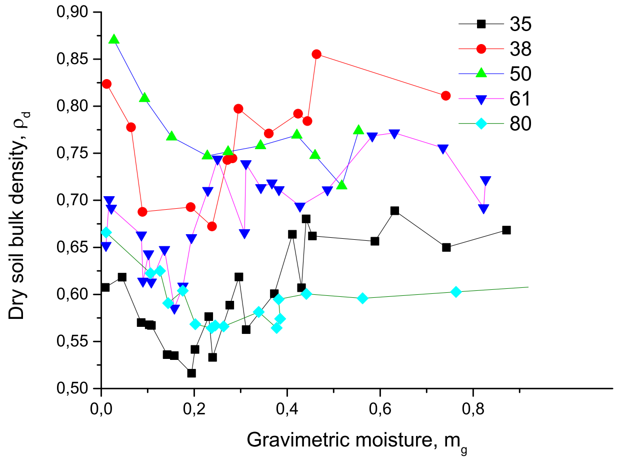

Fig. 2. Dry soil bulk density as a function of gravimetric moisture for the measured soils with different organic matter content.

We suggest that the modified, as it was done in [6], refractive mixing dielectric model (RMDM) can be expressed by the following equations:

$$\frac{n_s - 1}{\rho_d} = \begin{cases} \dfrac{n_o - 1}{\rho_o} + \dfrac{n_b - 1}{\rho_b} \cdot m_g \quad 0 \le m_g \le m_{g1} \\ \dfrac{n_o - 1}{\rho_o} + \dfrac{n_b - 1}{\rho_b} \cdot m_{g1} + \dfrac{n_t - 1}{\rho_t} \cdot (m_g - m_{g1}) \\ \quad m_{g1} \le m_g \le m_{g2} \\ \dfrac{n_o - 1}{\rho_o} + \dfrac{n_b - 1}{\rho_b} \cdot m_{g1} + \dfrac{n_t - 1}{\rho_t} \cdot (m_{g2} - m_{g1}) \\ + \dfrac{n_{l/i} - 1}{\rho_{l/i}} \cdot (m_g - m_{g2}), \quad m_g \ge m_{g2} \end{cases} \quad (2)$$

$$\frac{\kappa_s}{\rho_d} = \begin{cases} \dfrac{\kappa_o}{\rho_o} + \dfrac{\kappa_b}{\rho_b} \cdot m_g, \quad 0 \le m_g \le m_{g1} \\ \dfrac{\kappa_o}{\rho_o} + \dfrac{\kappa_b}{\rho_b} \cdot m_{g1} + \dfrac{\kappa_t}{\rho_t} \cdot (m_g - m_{g1}) \\ \quad m_{g1} \le m_g \le m_{g2} \\ \dfrac{\kappa_o}{\rho_o} + \dfrac{\kappa_b}{\rho_b} \cdot m_{g1} + \dfrac{\kappa_t}{\rho_t} \cdot (m_{g2} - m_{g1}) \\ + \dfrac{\kappa_{l/i}}{\rho_{l/i}} \cdot (m_g - m_{g2}), \quad m_g \ge m_{g2}. \end{cases} \quad (3)$$

The indices s, o, b, t, l, and i denote moist soil, organic solids, bound, transient, liquid water, and ice, respectively. The empirical parameters m_{g1} and m_{g2} are the maximum gravimetric fractions of: 1) bound water and of 2) total bound and transient soil water components. As seen from (2) and (3), the reduced CRI does not depend on soil bulk density. In Fig. 3(a) and (b), the reduced soil CRI as a function of gravimetric moisture are shown together with best fitting functions (2) and (3) at different temperatures.

As follows from Fig. 3(a) and (b), the modified RMDM (2) and (3) is a good approximation for the measured data. Further, parameters m_{g1}, and m_{g2} were estimated as a function of temperature for each soil with different organic matter contents. For this purpose, the measured values of $(n_s - 1)/\rho_d$, and κ_s/ρ_d were fit as a function of gravimetric moisture at

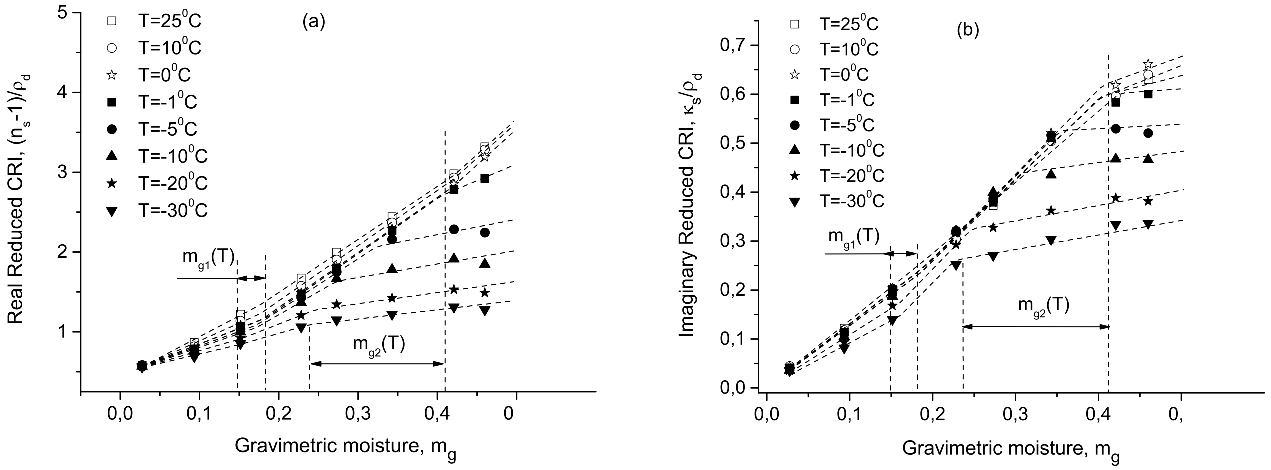

Fig. 3. Typical behavior of the reduced CRI as a function of gravimetric moisture at fixed temperatures together with the best fitting functions. (a) Real part of reduced CRI. (b) Imaginary part of reduced CRI.

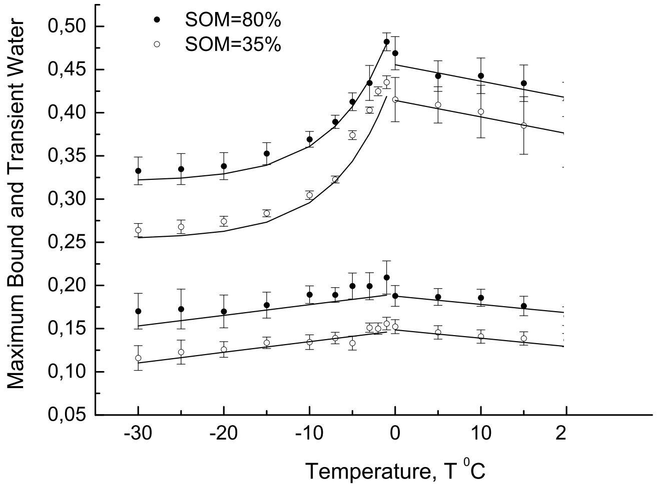

Fig. 4. Maximum amount of bound water m_{g1} and the maximum amount of both the bound and transient water m_{g2} as a function of temperature for the soils with different contents of organic matter (SOM) and their standard errors. Dashed lines correspond to the developed model.

fixed temperatures. The results of this fitting are presented in Fig. 4. As seen from Fig. 4, only insignificant (on the order of a few percent) decreases in m_{g1} are observed with the temperature decreasing from −1 °C to −30 °C. In the case of thawed soils m_{g1} increase with the temperature decreasing, and this increase is even less significant compared to the frozen soils. The more significant effect is observed for the temperature dependences of m_{g2} (see Fig. 4). The value of m_{g2} for frozen soils increases by the factor of about 2, with the temperature increasing from −30 °C to −1 °C. At the same time, in the case of thawed soils the variations of m_{g2} with the temperature are found (see Fig. 4) to be about 10%. As can be deduced from the results presented in Fig. 4, the value of m_{g1} increases by the factors of about 1.5 and 1.3 for the frozen and thawed soils, respectively, with the organic matter increasing from 35% to 80%.

After that, the obtained values of m_{g1} and m_{g2} for thawed soils were fit as a function of temperature by a linear function. For frozen soils, m_{g1} and m_{g2} were fit as a function of temperature with linear and exponential functions, respectively. Thus, obtained dependences of m_{g1} and m_{g2} on temperature and content of organic matter can be approximated by the functions presented in Table II.

The other empirical parameters, namely, $(n_o - 1)/\rho_o$, $(n_b - 1)/\rho_b$, $(n_t - 1)/\rho_t$, $(n_l - 1)/\rho_l$, $(n_i - 1)/\rho_i$, κ_o/ρ_o, κ_b/ρ_b, κ_t/ρ_t, κ_l/ρ_l, κ_i/ρ_i, of the dielectric model were determined by fitting the measured values of $(n_s - 1)/\rho_d$ and κ_s/ρ_d as a function of m_g at the fixed temperatures simultaneously for all basic soils [Fig. 5(a) and (b)]. In this fitting, the only value for each parameter being determined was used in spite of the content of organic matter in the soil. At that, the values of m_{g1} and m_{g2} were assigned as previously determined. This means that the soil type, which is identified by the content of organic matter in soil, has a significant effect only on m_{g1} and m_{g2} and does not affect the other parameters. The parameters of the theoretical dielectric model (2) and (3) that correspond to the smallest standard deviations of the calculated values from the experimental data are derived with the help of the least-squares method applying the software ORIGION 9. In a result of statistical analysis of the proposed dielectric model, the 95% confidence intervals were found for all ten model parameters, which are shown in Figs. 4 and 5(a) and (b). To determine one parameter, an average of 15 measured values of the CRI of the soil sample is used. All the determined parameters as a function of temperature and organic matter content are given in Table II.

The real part, ε'_s, and the imaginary part, ε''_s, of the soil CRP $\varepsilon_s* = \varepsilon'_s + i\varepsilon''_s$ are related to the CRI $n_s* = n'_s + i\kappa''_s$ by the following relationships:

$$\varepsilon'_{\mathrm{s}} = n_{\mathrm{s}}^2 - \kappa_{\mathrm{s}}^2, \varepsilon''_{\mathrm{s}} = 2n_{\mathrm{s}}\kappa_{\mathrm{s}}. \qquad (4)$$

Formulas (2)–(4) with the empirical parameters defined in Table II represent the developed temperature- and organic matter-dependent dielectric model for thawed and frozen organic soils at 1.4 GHz.

As follows from Table II, the developed dielectric model contains 10 empirical parameters that are functions of only

TABLE II

MODEL PARAMETERS AS A FUNCTION OF TEMPERATURE (T °C) AND SOM CONTENT (SOM%) AND THEIR STATISTICAL ERRORS (R^2 IS THE DETERMINATION COEFFICIENT; RMSE IS THE ROOT MEAN SQUARE ERROR)

Frozen soils	***Thawed soils***
$m_{g1} = 0.114 + 9.516\times10^{-4}\times SOM + 1.23\times10^{-3}\times T$	$m_{g1}=0.118+8.695\times10^{-4}\times SOM-9.6\times10^{-4}\times T$
$R^2=0.99$, RMSE$=9.59\times10^{-5}$	$R^2=0.99$, RMSE$=9.02\times10^{-5}$
$m_{g2}=0.205+1.43\times10^{-3}\times SOM+0.187\times\exp(T/6.6)$	$m_{g2}=0.382+9.208\times10^{-4}\times SOM-1.91\times10^{-3}\times T$
$R^2=0.96$, RMSE$=0.013$	$R^2=0.99$, RMSE$=7.70\times10^{-5}$
$(n_o-1)/\rho_o = 0.507+1.24\times10^{-3}\times T$	$(n_o-1)/\rho_o = 0.504+8.75\times10^{-7}\times T$
$R^2=0.71$, RMSE$=0.006$	$R^2=0.79$, RMSE$=9.46\times10^{-4}$
$(n_b-1)/\rho_b = 2.941+0.0188\times T$	$(n_b-1)/\rho_b = 3.010+0.0328\times T$
$R^2=0.90$, RMSE$=0.051$	$R^2=0.99$, RMSE$=0.016$
$(n_t-1)/\rho_t = 8.371+0.304\times T+3.81\times10^{-3}\times T^2$	$(n_t-1)/\rho_t = 7.572-8.33\times10^{-4}\times T$
$R^2=0.99$, RMSE$=0.054$	$R^2=0.85$, RMSE$=0.046$
$(n_i-1)/\rho_i = 1.567+0.01263\times T$	$(n_l-1)/\rho_l = 8.906-0.0207\times T$
$R^2=0.81$, RMSE$=0.049$	$R^2=0.99$, RMSE$=0.009$
$\kappa_o/\rho_o = 7.65\times10^{-3}-1.81\times10^{-4}\times T$	$\kappa_o/\rho_o = 0$
$R^2=0.55$, RMSE$=0.002$	----------------------------------
$\kappa_b/\rho_b = 0.89+0.0185\times T$	$\kappa_b/\rho_b = 1.057+2.39\times10^{-3}\times T$
$R^2=0.96$, RMSE$=0.024$	$R^2=0.66$, RMSE$=0.023$
$\kappa_t/\rho_t = 2.263+5.65\times10^{-3}\times T-8.32\times10^{-4}\times T^2$	$\kappa_t/\rho_t = 1.831-0.0252\times T$
$R^2=0.99$, RMSE$=0.008$	$R^2=0.99$, RMSE$=0.020$
$\kappa_i/\rho_i = 0.169-4.93\times10^{-3}\times T$	$\kappa_l/\rho_l = 0.832-2.21\times10^{-2}\times T+4.37\times10^{-4}\times T^2$
$R^2=0.65$, RMSE$=0.029$	$R^2=0.99$, RMSE$=0.005$

two variables characterizing the soils, namely, temperature and organic matter content. As a result, a complete set of the input data of the developed dielectric model consist of the dry soil bulk density, moisture, temperature, and the content of organic matter in the soil.

IV. VERIFICATION OF THE MODEL

The model was verified by comparing the calculated CRP with the measured ones for the four basic soils (based on which the model was developed) and for one independent soil. (The data of which were not used to develop the model.) As an example, both the calculated and measured values of CRP as a function of temperature at three fixed moistures for two basic soils with the smallest (35%) and the largest (80%) content of organic matter and one independent soil with organic matter content of 38.5% are shown in Figs. 6(a) and (b) and 7(a) and (b), respectively. According to the Fig. 6(a) and (b) and 7(a) and (b), the calculated and measured values of soil CRP are well consistent with each other.

The most large deviation of the calculated CRPs from the measured ones are observed for the basic soil with the larger content of organic matter and the independent soil at the highest values of moisture. The input soil data at which the values of CRP shown in Figs. 6 and 7 were calculated are given in Table III.

Moreover, we compared the CRP values calculated with the help of the developed model with experimental data obtained independently by another scientific group, who used dielectric measurement procedure for undisturbed soil samples [10]. The results of this comparison presented in Fig. 8 show that the calculated values of the CRP lie within the range of the measured values. Unfortunately, verification of the developed model on the bases of a few measured data available in [11]–[15] appeared not possible because the data on organic matter content, and soil bulk density were absent.

Thus, the developed dielectric model takes into account the structure changes through the dry soil bulk density, which is an independent input parameter of the model, integrally accounting for the soil structure. To use the dielectric model

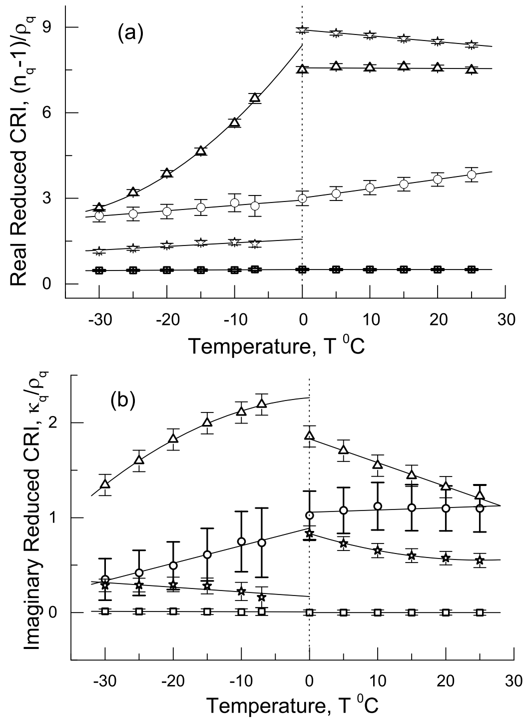

Fig. 5. Temperature dependences of the model parameters. (a) $(n_q - 1)/\rho_q$. (b) κ_q/ρ_q. For organic solids, $q = o$, (squares); bound water, $q = b$, (circles); transient water, $q = t$, (triangles); liquid water/ice, $q = l/i$, (asterisks).

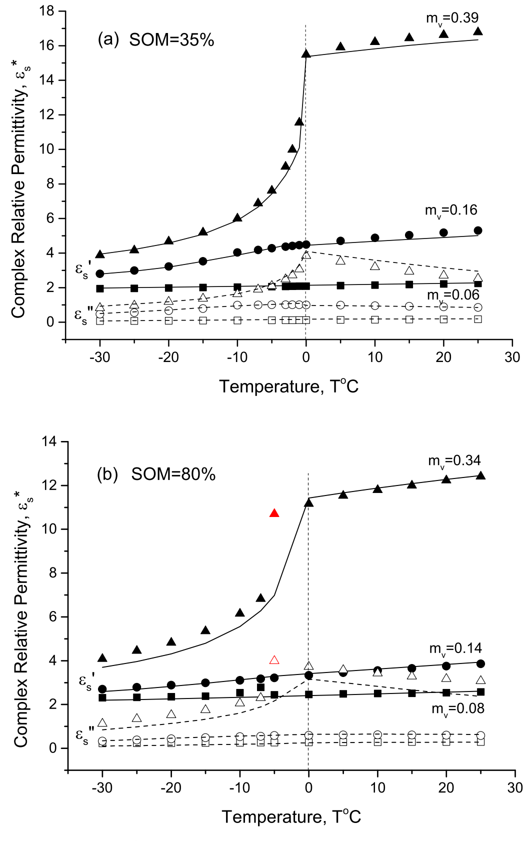

Fig. 6. Comparison of the calculated (lines) and measured (symbols) values of the soil CRP as a function of temperature at different values of volumetric moisture, m_V, for two basic soils. (a) SOM = 35%. (b) SOM = 80%.

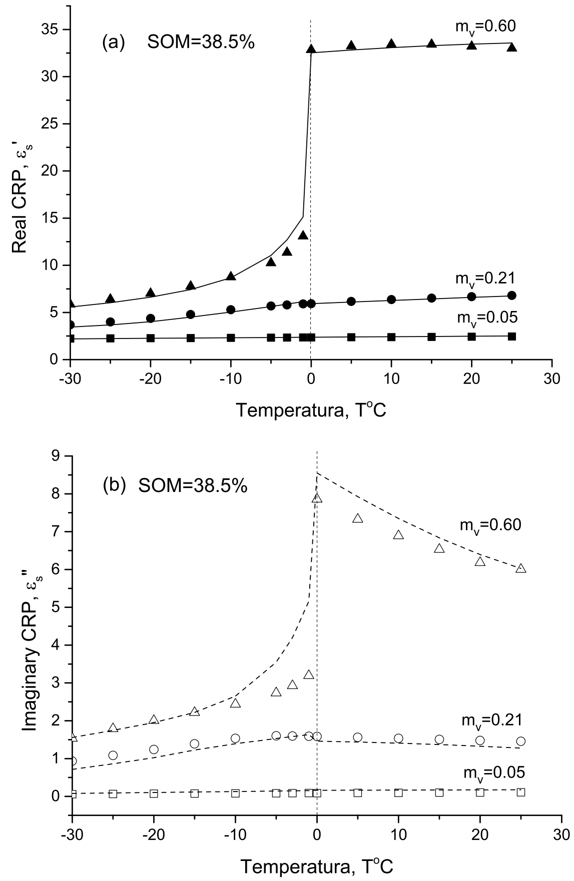

Fig. 7. Comparison of calculated (lines) and measured (symbols) values of the CRP for independent soil at different values of volumetric moisture, m_V. (a) Real part of CRP. (b) Imaginary part of CRP.

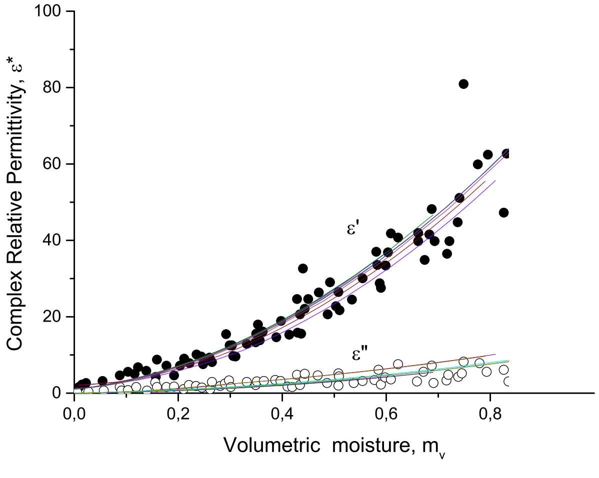

Fig. 8. Comparison of the calculated (lines) and measured (symbols) values of the soils CRP as a function of volumetric moisture, m_V. The measured values of the soils CRP are taken from [10].

developed on the bases of laboratory measurements of soil samples with modified structure in the case of natural soil having a different structure, it is necessary to assign the value of the dry soil bulk density corresponding to natural soil. The calculated real and imaginary parts of CRP values in the cases of the basic soils and the independent one against the measured ones are shown in Fig. 9, giving a visual representation for the deviations of these values from each other.

Quantitative estimations of these deviations were conducted in terms of root-mean-square error (RMSE), normalized RMSE (nRMSE), and determination coefficient (R^2).

TABLE III

INPUT DATA FOR MODEL CALCULATIONS PRESENTED IN FIGS. 6 AND 7

SOM	m_v	ρ_d	m_g	*SOM*	m_v	ρ_d	m_g	*SOM*	m_v	ρ_d	m_g
%	cm^3/cm^3	g/cm^3	g/g	%	cm^3/cm^3	g/cm^3	g/g	%	cm^3/cm^3	g/cm^3	g/g
35	0.06	0.57	0.11	**80**	0.08	0.63	0.13	**38.5**	0.05	0.78	0.06
	0.16	0.58	0.28		0.14	0.57	0.25		0.21	0.74	0.28
	0.39	0.66	0.59		0.34	0.60	0.56		0.60	0.81	0.74

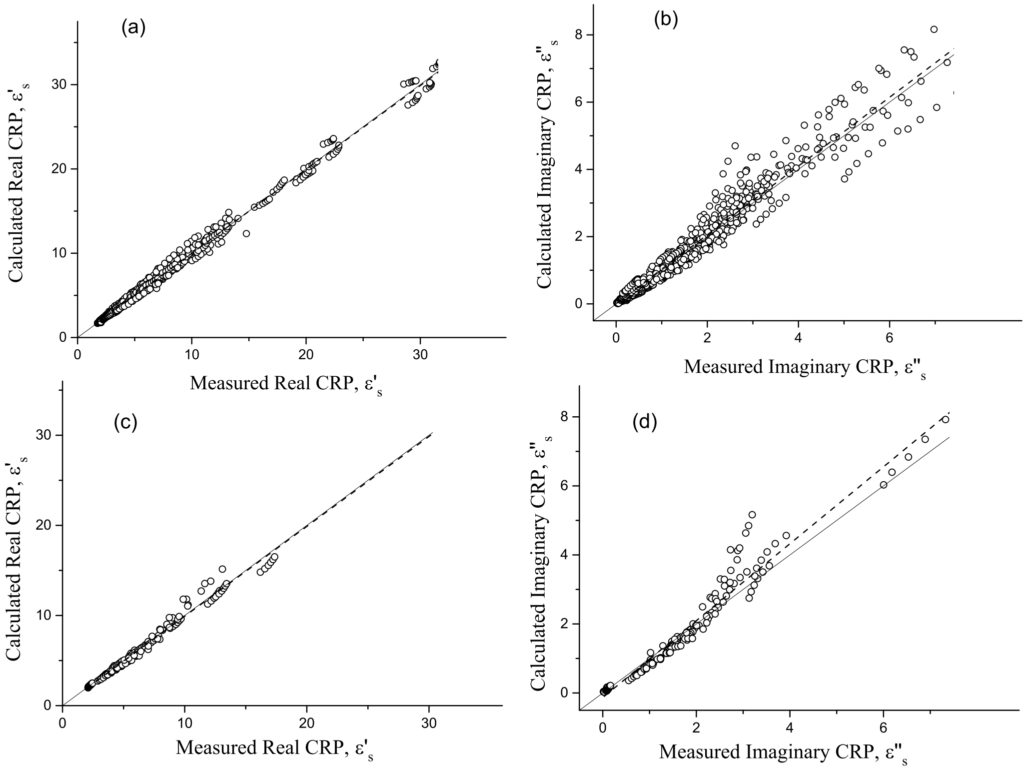

Fig. 9. Calculated CRP's values of moist soils as a function of the measured ones in the temperature ranges of −30 °C $\leq T \leq$ 25 °C. (a) Real part of CRP, ε_s', for basic soils. (b) Imaginary part of CRP, ε_s'', for basic soils. (c) Real part of CRP, ε_s', for independent soil. (d) Imaginary part of CRP, ε_s'', for independent soil. The bisectors and linear fits are represented by solid and dashed lines, respectively.

The respective formulas for these errors can be found in [8]. The results of quantitative estimations for the deviations between the calculated and measured soil CRP values are given in Table IV.

We were able to identify with the help of the software Grafula 3 the values of volumetric moisture and dielectric permittivity for the data of five (36 samples) from 10 soils shown in [10, Fig. 4(b)]. As a result, it appeared to be possible to estimate the error of the developed model relative to the dielectric data of these five soils. These are the soils with the content of organic matter (22.27%, 51.27%, 64.95%, 72.98%, 91.65%) and dry soil bulk density (0.79, 0.28, 0.81, 0.1, 0.12 g/cm3), respectively. Quantitative estimations of these errors were conducted in terms of RMSE, nRMSE, and R^2. The results of these estimations are given in Table IV. As seen from Table IV, the errors of the developed model estimated relative to the dielectric data measured by independent scientific group in the case of undisturbed (*in situ*) soils did not increase noticeably in terms of nRMSE. In the range of this accuracy the developed dielectric model can be applied to the organic soils with the values of dry soil density observed *in situ*.

The values of normalized RMSE for the real (6%–7%) and imaginary (23%) parts of CRP for basic and independent soils are on the order of the dielectric measurement errors themselves.

V. DISCUSSION

There is a relationship between the models of the complex dielectric permittivity of moist mineral and organic soils considered in [1], [2], and [5]–[8] and TDR models for the apparent dielectric constant. These models underlie TDR technologies for moisture measurement of composite materials,

TABLE IV

ACCURACY OF THE MODEL PREDICTIONS

Evaluated value	*RMSE*	*nRMSE, %*	*R^2*
Real CRP (Basic soils)	0.37	6	0.996
Imaginary CRP (Basic soils)	0.29	23	0.958
Real CRP (Independent soil)	0.47	7	0.994
Imaginary CRP (Independent soil)	0.36	23	0.947
Real CRP (soils from [10])	1.98	10.5	0.985
Imaginary CRP (soils from [10])	0.92	31	0.790

including those containing organic substances [16]–[21]. Namely, the value of apparent dielectric constant is approximately equal to the real part of the CRP in the case of low-loss composite media. So, we can compare the real part of thawed organic soil CRP calculated with TDR dielectric model and the developed model for mutual validation.

The initial empirical dependences between apparent dielectric constant and volumetric soil moisture appeared in [22] and [23]. The Topp formula gives the dependence of the apparent dielectric constant (K_{a}) of thawed soils on volumetric soil moisture content (θ_{v}) [22]. In particular, for organic soils this formula has the form

$$K_{\mathrm{a}} = 1.74 - 0.34\theta_{\mathrm{v}} + 135\theta_{\mathrm{v}}^2 + 55.3\theta_{\mathrm{v}}^3. \qquad (5)$$

For low loss, nearly homogenous materials K_{a} is approximately equal to the real part of CRP. This formula is based on TDR measurements in the frequency range from 0.02 to 1 GHz for one organic soil at the temperature of 20.5 °C. One more empirical formula was proposed in [23]. In the Skierucha formula, the real part of CRI (n) of moist soil is represented as a function of soil volumetric moisture (θ_{v}) and soil bulk density (ρ_{d})

$$n = 0.573 + 0.582\rho_{\mathrm{d}} + (7.755 + 0.792\rho_{\mathrm{d}})\theta_{\mathrm{v}}. \qquad (6)$$

Formula (2) is applicable for both the mineral and organic soils. It is based on TDR measurements conducted for 19 mineral soils, nine organic soils, and nine mixtures composed of these mineral and organic soils at the temperature of 20 °C. At that, the upper frequency of the TDR signal was 1 GHz. As pointed out in [23] the bulk density of organic soils varied from 0.12 to 0.65 g/cm^3. These formulas do not take into account the dependence of moist soil permittivity either on the temperature or the content of SOM, and concern only thawed soils.

Further, we will compare the values of the real part of soil CRP estimated using (5) and (6) and the developed dielectric model with the respective measured values. In Fig. 10(a) and (b) is shown the measured data for the two organic soils with organic matter content of 35% and 80% at the temperature of 20 °C alongside the respective values calculated with the use of the developed dielectric model (2)–(4) and the Topp (5) and Skierucha (6) models. In calculations with the Skierucha formula (6), we used the soil bulk densities obtained in our measurements at different moistures. The real part of CRP, ε', shown in Fig. 10 was estimated as $\varepsilon' = K_{\mathrm{a}}$ and $\varepsilon' = n^2$ in the cases of Topp (5) and Skierucha (6) models, respectively. As follows from Fig. 10, the values calculated with the Topp and Skierucha models are in good agreement with both the measured data and the results of respective estimations obtained with the developed model.

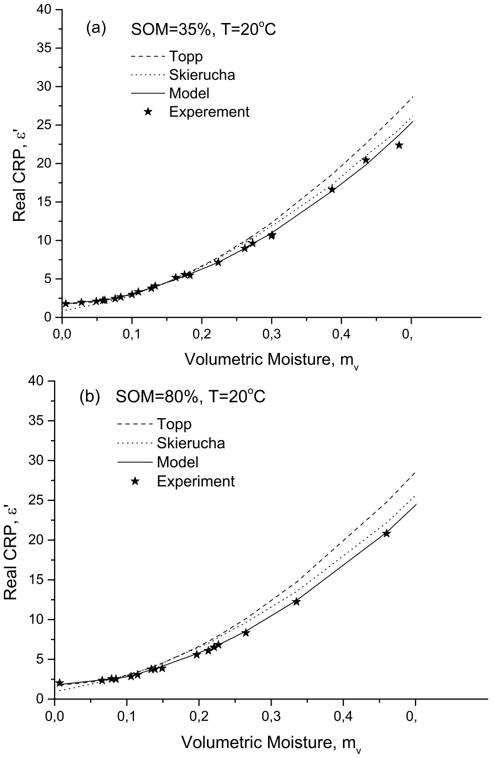

Fig. 10. Comparison the real part of CRP calculated with the Topp, Skierucha models, and the developed model with the respective measured ones for the two soils; (a) low organic matter content 35% and (b) high organic matter content 80%.

The deviations of the real part of CRP calculated with the Topp, Skierucha, and developed models from the respective measured values were estimated in terms of nRMSE. These estimations yielded the values 22%–46%, 5.7%–12%, and 1.8%–1.2% for the soils in low and high organic matters for the Topp, Skierucha, and developed models, respectively.

The obtained above estimations for the values of nRMSE proves that taking into account the soil bulk density significantly decreases the error of Skierucha model compared to the Topp model. In our model, the bulk density of soil is also an important parameter. Therefore, we draw the attention of possible users of the developed dielectric model to the fact that the empirical formula linking the soil bulk density (ρ_{d}) to the content of soil organic carbon (SOC) was obtained in [24]. This formula was obtained for Canada's arctic and subarctic soils

$$\begin{aligned}\rho_{\mathrm{d}} &= 0.071 + 1.32\exp(-0.071\mathrm{SOC}\%)\\ n &= 1376, \quad R^2 = 0.984.\end{aligned} \tag{7}$$

SOC is expressed through SOM by the following formula [25]:

$$\mathrm{SOC} = 0.58\mathrm{SOM}. \tag{8}$$

As follows from the above discussion, the error of the dielectric model developed by us is smaller by the factors of 12–38, 3–10 compared to the models by Topp, and Skierucha, respectively. In addition, it is worth noting that the preceded models developed by Topp, and Skierucha are applicable only to the thawed soils and do not account for the temperature dependence and organic matter content.

VI. CONCLUSION

For the first time, the dielectric model of thawed and frozen organic soils at the frequency of 1.4 GHz which accounts for temperature and organic matter content was developed. The model predicts the CRP of organic soil as a function of organic matter content (from 35% to 80%), bulk density, moisture (from air dry to the field capacity value), and temperature (from −30 °C to 25 °C). At that, the values of organic matter content and soil bulk density are entire characteristics of the organic soil type and have to be assigned in advance. The most innovative feature of the developed model is its ability to provide for CRP in the case of frozen soils, including substantial dependence of frozen soil CRPs on temperature. The errors of the developed model evaluated relative to the data of laboratory measurements in terms of normalized RMSE for the real (6%–7%) and imaginary (23%) parts of CRP for organic soils are on the order of the dielectric measurement errors themselves. As the proposed model was calibrated on laboratory measuring data which usually has the dry soil bulk density values larger than those of the soils *in situ*, the model should be calibrated *in situ* conditions. This model opens new opportunities in microwave radiometry and radar remote sensing. In particular, the model can be used in the recently developed remote sensing algorithm for deriving the temperature profiles in the frozen soil from the radio brightness observations conducted on the bases of the SMOS instrument [26].

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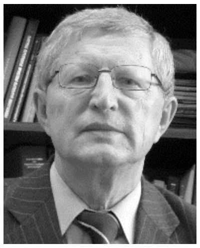

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