DIELECTRIC MODEL FOR THAWED AND FROZEN ORGANIC SOILS AT 1.4 GHz

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ABSTRACT

Dielectric measurements of organic soils for five samples with different contents of organic matter are carried out in the temperature range from -30 °C to 25 °C in a wide frequency range from 0.45 to 16 GHz. On their basis, a simple single-frequency dielectric model of thawed and frozen organic soils has been created to calculate the complex relative permittivity of thawed and frozen organic soils, depending on the moisture, temperature and organic matter content at 1.4 GHz[1].

Index Terms— Organic soils, moisture, temperature, dielectric model, thawed and frozen soils, remote sensing, 1.4 GHz

1. INTRODUCTION

Remote sensing of the Earth's surface from space is now becoming an effective tool for monitoring soil moisture and temperature. The soils dielectric models are a key element of algorithms for retrieving moisture and soil temperature from remote sensing data. Earlier we created a dielectric model for thawed mineral soils [1], which is currently included in the soil moisture retrieving algorithms of SMOS (ESA) [2] and SMAP (NASA) along with the Dobson dielectric model [3]. Later we created a single-frequency dielectric model of frozen mineral soils [4]. These two models together allow one to calculate the complex relative permittivity of thawed and frozen mineral soils depending on moisture, temperature and soil type at a frequency of 1.4 GHz. The type of mineral soils is characterized by their granulometric composition, where the content of a clay fraction in the soil renders the main effect on the dielectric properties of moist soils. Soils containing more than 20-30% organic matter by weight are classified as organic. Organic soils are not so extensive as are mineral soils, yet their total area is quite large, more than 300 million ha world wide. About 80% of the world's organic deposits are found in the Russia and Canada [5]. Earlier we developed spectroscopic and single-frequency models of individual organic soils. In this paper, we represent the general single-frequency dielectric model of thawed and frozen organic soils. The main parameter characterizing organic soils will be the content of organic matter by weight percentage.

2. DIELECTRIC MODEL

Four basic organic soils were used to develop the dielectric model, three of which were collected on the Yamal Peninsula (Russia) with organic content of 35%, 50%, and 61%, respectively, and one soil containing 80% organic matter was taken from Alaska. Also, for an independent assessment of the accuracy of the model, a soil with an organic content of 38.5%, taken from Taimyr Peninsula (Russia), was used. The main difference between the dielectric behavior of organic soils and mineral ones is as follows. The variability of organic soils, depending on the structure (the content of organic matter) is much weaker than the variability of mineral soils, depending on the texture (clay content). The effect of moisture has the strongest impact on the soil complex relative permittivity (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.

An example of measured reduced complex refractive index (CRI) for the soil with organic matter 50% as a function of moisture at some temperatures is presented at Fig. 1. The experimental data will be analyzed in the form of a reduced CRI of the soil. The measured CRP of moist soil, $\varepsilon_s^* = \varepsilon_s'+i\varepsilon_s''$, can be fitted with polynomial of the second or third degree, while the measured CRI can be fitted with piecewise linear function. The main difference between the measured data of organic soils and the ones of mineral soils is the fact that in organic soil we can identify three components of water in the soil, namely, bound water, transient, and free water (ice in frozen state). While in mineral soils, we can distinguish with confidence only two types of soil moisture, namely, bound and free water (ice). In Fig. 1, the value m_{g1} separates the range of bound water from that of the transient water, and the value m_{g2} separates the range of transient water from that of free water (ice).

The soil CRI, $n_s^* = n_s+i\kappa_s$, is related with the complex relative permittivity (CRP) of the soil, $\varepsilon_s^* = \varepsilon_s'+i\varepsilon_s''$, by the following relationships:

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$$\varepsilon_s' = n_s^2 - \kappa_s^2 , \quad \varepsilon_s'' = 2n_s\kappa_s . \tag{1}$$

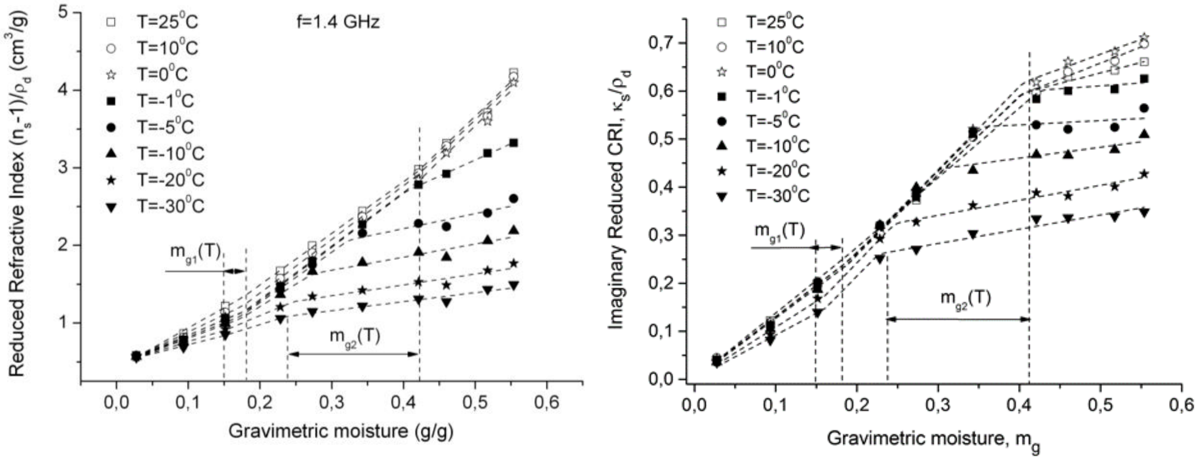

Fig. 1. The measured reduced CRI vs. gravimetric moisture at the temperatures varying from 25ºC to −30ºC at 1.4 GHz. a) the real part of reduced CRI, b) imaginary part of reduced CRI. The dashed lines indicate fitting function (2) to the measured data.

The refractive model for the reduced CRI of soil is written as piecewise linear function:

$$\frac{n_s-1}{\rho_d}=\begin{cases}\dfrac{n_m-1}{\rho_m}+\dfrac{n_b-1}{\rho_b}\cdot m_g, \quad 0\le m_g\le m_{g1};\\ \dfrac{n_m-1}{\rho_m}+\dfrac{n_b-1}{\rho_b}\cdot m_{g1}+\dfrac{n_t-1}{\rho_t}\cdot\left(m_g-m_{g1}\right), \quad m_{g1}\le m_g\le m_{g2};\\ \dfrac{n_m-1}{\rho_m}+\dfrac{n_b-1}{\rho_b}\cdot m_{g1}+\dfrac{n_t-1}{\rho_t}\cdot\left(m_{g2}-m_{g1}\right)+\\ +\dfrac{n_{f/i}-1}{\rho_{f/i}}\cdot\left(m_g-m_{g2}\right), \quad m_g\ge m_{g2}\end{cases} \tag{2}$$

$$\frac{\kappa_s}{\rho_d}=\begin{cases}\dfrac{\kappa_m}{\rho_m}+\dfrac{\kappa_b}{\rho_b}\cdot m_g, \quad 0\le m_g\le m_{g1};\\ \dfrac{\kappa_m}{\rho_m}+\dfrac{\kappa_b}{\rho_b}\cdot m_{g1}+\dfrac{\kappa_t}{\rho_t}\cdot\left(m_g-m_{g1}\right), \quad m_{g1}\le m_g\le m_{g2};\\ \dfrac{\kappa_m}{\rho_m}+\dfrac{\kappa_b}{\rho_b}\cdot m_{g1}+\dfrac{\kappa_t}{\rho_t}\cdot\left(m_{g2}-m_{g1}\right)+\\ +\dfrac{\kappa_{f/i}}{\rho_{f/i}}\cdot\left(m_g-m_{g2}\right), \quad m_g\ge m_{g2}\end{cases} \tag{3}$$

Where m_g is the gravimetric soil moisture, ρ_d is the density of dry soil. The indices *s*, *d*, *m*, *b*, *t*, *f*, and *i* denote moist soil, dry soil, organo-mineral component of soil, bound, transient, free water, and ice, respectively. m_{g1} and m_{g2} are the values of the maximum of bound water and the total maximum of bound and transient water.

In the process of fitting measured reduced CRI, we used two hypothesis: 1) the maximum of bound water, m_{g1}, and the total maximum of bound and transient water, m_{g2}, are suggested to be dependent on both texture (organic matter content) and temperature of soil. While the other parameters in formulas (2) and (3) are considered to be dependent only on soil temperature. The data on measured CRI for the fore soils (with organic matter content of 35, 50, 61, and 80%) as a function of soil moisture at a fixed temperature were fitted simultaneously by the piecewise linear functions (2) and (3), using the software ORIGIN 9.0. The parameters $(n_m-1)/\rho_m$, $(n_b-1)/\rho_b$, $(n_t-1)/\rho_t$, $(n_{f/i}-1)/\rho_{f/i}$, κ_m/ρ_m, κ_b/ρ_b, $(\kappa_t-1)/\rho_t$, and $\kappa_{f/i}/\rho_{f/i}$ were share for fitting functions, but m_{g1}, and m_{g2} were individual for every type of soil.

The results of fitting measured reduced CRI for the four soils at the region of temperatures from -30°C to 25 °C with the help of functions (2) and (3) for parameters m_{g1}, and m_{g2} are shown at Fig. 2.

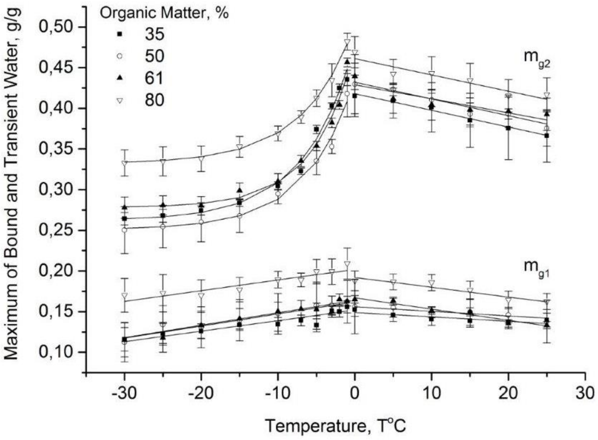

Fig. 2. The maximum of bound water, m_{g1}, and the total maximum of bound and transient water, m_{g2}, are as the functions of temperature for the soils with different content of organic matter together with the standard errors. Solid lines correspond to the being developed model.

The obtained values for m_{g1}, m_{g2} were approximated as a function of temperature by linear and exponential functions (lines in Fig. 2). Temperature dependences for other parameters of the model were obtained in a similar way. The model parameters determined by fitting of the measured reduced CRI for four organic soils with an organic matter content from 35% to 80% for thawed ($0 \geq T \leq 25$°C) and frozen states ($-30 \geq T \leq -1$°C) , are presented in Table 1.

Table 1. The parameters of the model as a function of temperature (T°C) and content of organic matter (O%) in the soil.

Frozen Soils

m_{g1}=0.114+9.516·10^{-4}O+ 1.23·10^{-3}T

m_{g2}=0.205+1.43·10^{-3}O+ 0.187exp(T/6.6)

$(n_m-1)/\rho_m$ = 0.507+1.24·10^{-3}T

$(n_b-1)/\rho_b$ = 2.941+0.0188T

$(n_t-1)/\rho_t$ = 8.371+0.304T+ 3.81·10$^{-3}T^2$

$(n_i-1)/\rho_i$ = 1.567+0.01263T

κ_m/ρ_m = 7.65·10^{-3}-1.81·10^{-4}T

κ_b/ρ_b = 0.89+0.0185T

κ_t/ρ_t = 2.263+5.65·10^{-3}T - 8.32·10$^{-4}T^2$

κ_i/ρ_i = 0.169-4.93·10^{-3}T

Thawed Soils

m_{g1}=0.118+8.695·10^{-4}O-9.6·10^{-4}T

m_{g2}=0.382+9.208·10^{-4}O-1.91·10^{-3}T

$(n_m-1)/\rho_m$=0.504+8.75·10^{-7}T

$(n_b-1)/\rho_b$ = 3.010+0.0328T

$(n_t-1)/\rho_t$ = 7.572-8.33·10^{-4}T

$(n_f-1)/\rho_f$= 8.906-0.0207T

κ_m/ρ_m = 0

κ_b/ρ_b = 1.057+2.39·10^{-3}T

κ_t/ρ_t = 1.831-0.0252T

κ_f/ρ_f=0.832-2.21·10^{-2}T +4.37·10$^{-4}T^2$

The formulas (1)–(3) together with the parameters defined in Table 1 represent the developed dielectric model, with the input parameters being expressed in the following units: organic matter content O in percent, temperature T in degrees Celsius, gravimetric moisture m_g in g/g, and dry soil density in g/cm^3.

3. VALIDATION OF THE MODEL

The results of comparison of measured and calculated values of complex dielectric permittivity for independent soil as a function of temperature at three fixed volumetric moistures, W, are presented in Fig. 3. The permittivity of the soil is usually represented as a function of the volumetric moisture content. Soil volumetric moisture, W, with gravimetric moisture, m_g, is related by the following dependence: $W = m_g \cdot \rho_d$.

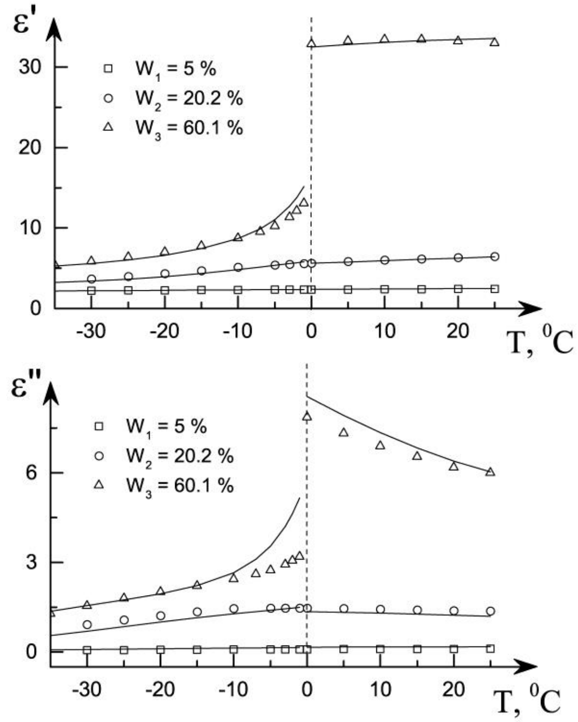

Fig. 3. Comparison of the calculated and measured CRPs of independent organic soil as a function of temperature: a) the real part of CRPs, ε_s', b) the imaginary part of CRPs, ε_s''.

Table 2. Input Data for calculations presented in Fig.3

Organic matter, %	ρ_d, g/cm^3	m_g, g/g	W, %
38.5	0.78	0.06	5
	0.74	0.28	20.2
	0.81	0.74	60.1

As can be seen from Fig. 3, the model describes the experimental data rather well even for independent soil, i.e. for soil, the measured values ε'_s and ε''_s of which were not used to construct the model. The errors in the calculated values of soil CRPs relative to the measured values for the basic soils, which were used for the model development, are shown in Fig. 4. Quantitative estimation of the model accuracy is performed through the coefficient of determination, R^2, and the root mean square error, RMSE, which for basic soils are equal to: $R^2_{\varepsilon'}$=0.996, $R^2_{\varepsilon'}{}'$=0.955, RMSE$_{\varepsilon'}$=0.37, RMSE$_{\varepsilon''}$=0.29, and for independent soil are equal to $R^2_{\varepsilon'}$=0.994, $R^2_{\varepsilon''}$=0.931, RMSE$_{\varepsilon'}$= 0.47, RMSE$_{\varepsilon''}$=0.36.

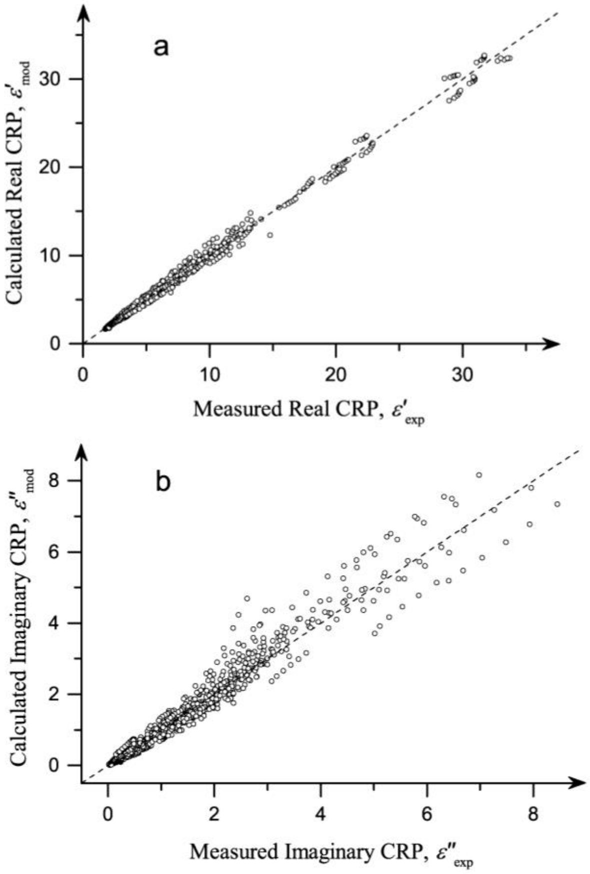

Fig. 4. The calculated CRPs of organic soils as a function of the measured ones a) the real part of CRPs, ε_s', b) the imaginary part of CRPs, ε_s'', in the temperature ranges of $-30°C \le T \le +25°C$. Bisectors represented by the dash lines.

4. CONCLUSIONS

The general single-frequency dielectric model of thawed and frozen organic soils has been created for the first time, which allows calculating the CRP of organic soils (with different organic matter content) as a function of moisture in the temperature range from -30°C to +25°C at a frequency of 1.4 GHz. In order to calculate the CRP of an arbitrary organic soil at a certain moisture and temperature, it is necessary to know density of dry soil and the content of organic matter in percent by weight. In practice, this information can be find in database, for example [6]. This model can be used to determine the amount of unfrozen water in frozen organic soils, to retrieve moisture and temperature of organic soils from remote sensing data by radiometric and radar methods.

5. REFERENCES

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