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A dielectric model for frozen mineral soils at a frequency of 435 MHz

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ABSTRACT

A single frequency refractive mixing dielectric model at 435 MHz for frozen mineral soils is proposed. The model was created based on the laboratory dielectric measurements of three soil samples in the ranges of soil moisture from $0.01 cm^3\ cm^{-3}$ to $0.42 cm^3\ cm^{-3}$, temperature from– 30°C to– 1°C, clay content (by weight) from 9.1% to 41.3%. Coefficient of determination R^2 and root mean square error (RMSE) predicted by the model and measured values for real () and imaginary () part of the complex relative permittivity (CRP) are = 0.988 (= 0.323) and = 0.987 (= 0.100). Compared to well-known spectroscopic models, this model is simpler in practical engineering use. The input parameters of the model are the volumetric soil moisture, temperature and the content of the clay fraction. The output parameters are the real and imaginary parts of the CRP. The created model may be used to develop new remote sensing retrieval algorithms of temperature, the content of unfrozen water and ice in the root zone of frozen soils for northern regions.$\varepsilon' \varepsilon'' R^2_{\varepsilon'}$ $\text{RMSE}_{\varepsilon'}$ $R^2_{\varepsilon''}$ $\text{RMSE}_{\varepsilon''}$

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1. Introduction

The dielectric model of frozen soils plays akey role in creating physical algorithms for remote sensing of soil moisture, temperature, ice content and determination of the thawed and frozen states of soil in the northern regions (Mironov, Muzalevskiy, and Ruzicka 2016; Roy etal. 2017; Zheng etal. 2018; Yi etal. 2019). At present, the dielectric models of soils in L, C, X-bands are widely used in satellite remote sensing algorithms (Wang and Schmugge 1980; Hallikainen etal. 1985; Peplinski, Ulaby, and Dobson 1995; Mironov, Kosolapova, and Fomin 2009; Zhang etal. 2010; Park etal. 2017). However, with the launch on the orbit of the BIOMASS European Space Agency satellite equipped with aP-band Synthetic Aperture Radar (SAR) (Carreiras etal. 2017), the requirement for dielectric models of P-band will increasessignificantly. Today, several spectroscopic temperature-dependable dielectric models of frozen mineral soils have been developed (Zhang etal. 2010; Mironov etal. 2020). However, as shown in the study (Mironov etal. 2017) the model (Zhang etal. 2010) has an unacceptably high statistical error in predicting complex relative permittivity (CRP) values with respect to experimental data. (The normalized root-

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Table 1. The texture parameters and mineral composition of measured soils.

		Soil texture (%)			Mineral Composition (%)		
No.	Soil type	Sand	Silt	Clay	Quartz	Feldspar	Plagioclase
1	Sandy loam	41.4	49.5	9.1	40	30	30
2	Silt loam	40.4	39.0	20.6	70	15	5–10
3	Silty clay	1.6	57.1	41.3	60	20–25	5

mean-square error (nRMSE) is 26.9% and 85.0% for the real and imaginary parts of the CRP, respectively.) Moreover, as shown in Fomin and Muzalevskiy (2021), the single-frequency model has increased accuracy and simpler equations for practical calculations concerning more complicated spectroscopic dielectric models (Mironov etal. 2020; Zhang etal. 2010). In this letter, asingle-frequency dielectric model at 435 MHz for frozen mineral soils is proposed based on the methodology described in the articles (Mironov etal. 2015; Fomin and Muzalevskiy 2021).

2. Experimental data and the method of CRP measuring of soil samples

The single-frequency refractive-mixing dielectric model (SFRDM) for frozen mineral soils proposed in this paper was developed based on three mineral soils samples taken from the mineral horizon of topsoil at the Yamal Peninsula, Russia. Clay content in soil samples ranged from 9.1% to 41.3% (by weight). Texture parameters and mineral composition of the soil samples are given in Table 1.

The dielectric measurements of the soils samples were carried out in the frequency range from 0.05 GHz to 15 GHz, soil moisture from about zero to field capacity, temperature from– 30°C to 25°C. The dielectric data only at afrequency of 435 MHz and in the temperature range from– 30°C to– 1°C were used for creating and validating the dielectric model. The varying portions of distilled water were added to the soil samples by calibrated pipette to obtain moisturized soil samples. The prepared samples were mixed well and stored in asealed container at least for oneday. The soil sample was then placed into acoaxial cell with across-section and length of 7/3mm and 17mm, respectively. The measuring cell was connected to the vector network analysers to measure the elements of scattering matrix *S*depends on frequency. The isothermal measurements were ensured with the SU-241 Espec chamber of heat and cold with an accuracy of 0.5°C. The algorithm developed in Mironov etal. (2013) was applied to retrieve CRP spectra of soil samples using the measured values of complex transmission coefficients (S_{12} or S_{21}). This algorithm provides the real and imaginary parts of soil CRP with less than 10% and 20% errors, respectively.

3. SFRDM concept

Following the approach of Mironov etal. (2015) and Fomin and Muzalevskiy (2021), refractive index (RI), n = Re, and normalized attenuation coefficient (NAC), κ = Im, where is the CRP, $\varepsilon' = n\left(\sqrt{\varepsilon^*}\right)\left(\sqrt{\varepsilon^*}\right)\varepsilon^* = +\mathrm{j}^{2-}\kappa^2$ and $\varepsilon'' = 2n\kappa$ is the real and imaginary part of CRP, can be presented at afixed frequency as alinear-piecewise function of volumetric soil moisture, W:

$$
\begin{aligned}
n(W,C,T) &= \begin{cases} n_d + (n_b(T) - 1)W, & W \le W_t(C,T), \\ n(W_t,C,T) + (n_i(T) - 1)(W - W_t(C,T)), & W > W_t(C,T), \end{cases} \\
\kappa(W,C,T) &= \begin{cases} \kappa_d + \kappa_b(T)W, & W \le W_t(C,T), \\ \kappa(W_t,C,T) + \kappa_i(T)(W - W_t(C,T)), & W > W_t(C,T), \end{cases}
\end{aligned}
\tag{1}
$$

here the subscripts of d, b, idenote dry soil, bound water and ice, respectively, $W_t(C,T)$ is the maximum fraction of bound (unfrozen) water for the given type of soil, $C$is the soil clay content (by weight), $T$is the soil temperature in Celsius degree. In Figure1 complex refractive index (CRI), $n^* = n + j\kappa =$, is presented depending on volumetric soil moisture for the studied soil samples. The linear growth of CRI in the range of $W < W_t(C,T)$ reflects the presence of only bound (unfrozen) water in the soil samples, and CRI changes linearly with the rate of $n_b(T)$ and $\kappa_b(T)$. In the range of $W > W_t(C, T)$, soil samples contain both bound (unfrozen) water and ice, and CRI is linear growth with arate of $n_i(T)$ and $k_i(T)$. Breakpoint, where the linear growth of CRI changes from the rate of $n_b(T)$ and $k_b(T)$ to the rate of $n_i(T)$

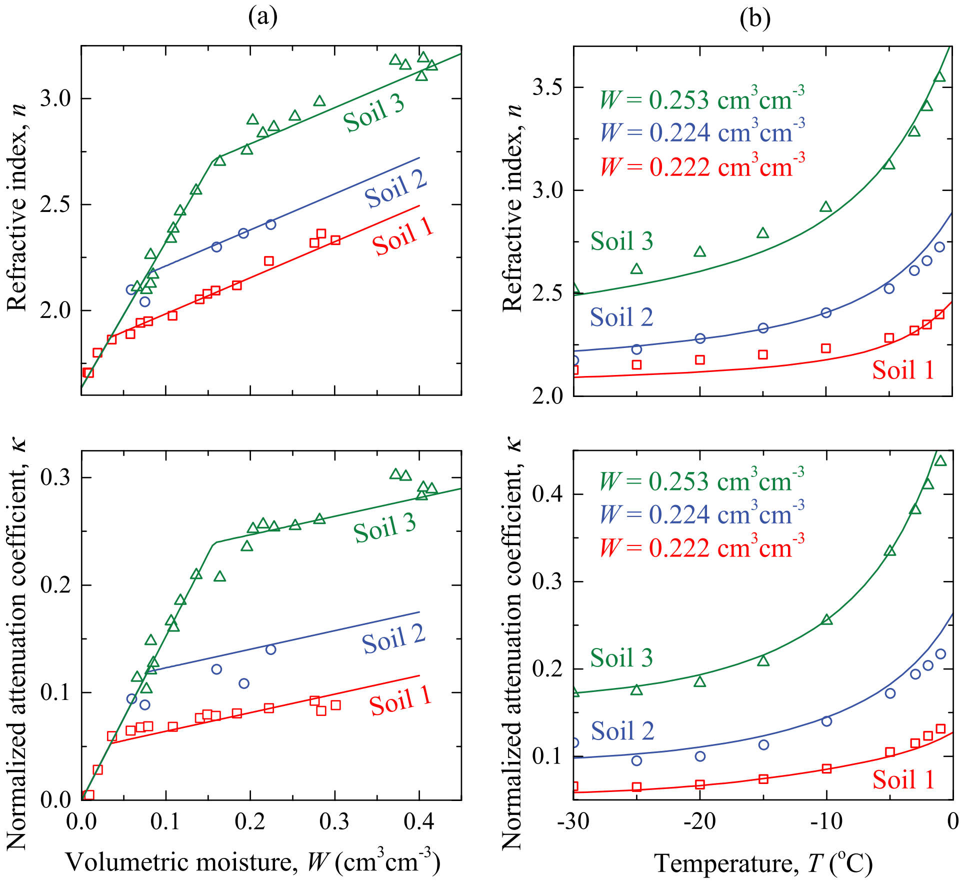

Figure1. Dependence of the measured and calculated RI and NAC for the soil types listed in Table 1 on (a) the volumetric moisture content at $T = -10$°C and (b) the temperature for three slightly different soil moisture values (0.222cm^3 0.253cm^3). Experimental values of RI and NAC are marked as empty squares, circles and triangles for three types of soils. Values of RI and NAC calculated using equations are drawn lines.

and $\kappa_i(T)$, corresponds to $W_t(C, T)$. According to methodology (Mironov etal. 2020), we will assume that CRI of bound (unfrozen) water and ice does not depend on soil type. As aresult, parameters of the model (1) can be found simultaneously for all soils based on regression analysis of measured CRI at different temperature in the range from– 30°C to– 1° C. In the end, $W_t(C, T)$ was determined depending on clay content and temperature for different soils. Similar to the approach described in Fomin and Muzalevskiy (2021), found parameters of the model (1) are summarized in the following Equations: $\sqrt{\varepsilon^*}$

$$\begin{aligned}
&W_t = 3.15 \times 10^{-3} C(1 + 0.917 exp(T/6.64)),\\
&n_d = 1.62, k_d = 0.0,\\
&n_b = 4.340(1 + 1.171 exp(T/27.669)),\\
&k_b = 1.118(1 + 0.835 exp(T/12.179))\\
&n_i = 2.688(1 + 0.213 exp(T/2.759)),\\
&k_i = 8.71 \times 10^{-2} - 2.244 \times 10^{-2} T - 1.93 \times 10^{-3} T^2 - 6.087 \times 10^{-5} T^3 - 6.717 \times 10^{-7} T^4,
\end{aligned} \tag{2}$$

Equations (1)-(2) constitute the proposed SFRDM for frozen mineral soils.

4. Validation of SFRDM

RI and NAC of soils (see Table 1), measured and calculated using Equations (1)-(2) depending on volumetric moisture and temperature, are depicted in Figure1. The correlation between measured and predicted CRP values is shown in Figure2. Coefficient of determination, R^2 (root mean square error (RMSE)), between predicted and measured values for the real and imaginary parts of CRP are = 0.986 (= 0.323) and = 0.987 (= 0.1). Normalized and to average values of and in the range of their variation appeared to be equal to 5% and 11%, respectively. The created single-frequency dielectric model predicts () about 30% (200%) more accurately (in absolute values of CRP) than the previously developed spectroscopic dielectric model (Mironov etal. 2020). Indeed, the root mean square error (coefficient of determination) between calculated using the model (Mironov etal. 2020) and measured and values for soils (see $R^2_{\varepsilon'}$RMSE$_{\varepsilon'}$$R^2_{\varepsilon''}$RMSE$_{\varepsilon''}$RMSE$_{\varepsilon'}$RMSE$_{\varepsilon''}$$\varepsilon'\varepsilon''$ $\varepsilon'\varepsilon''\varepsilon'\varepsilon''$Table 1) appeared to be equal to = 0.448, = 7% (= 0.976) and = 0.224, = 24% (= 0.936). In addition (see RMSE$_{\varepsilon'}$nRMSE$_{\varepsilon'}$$R^2_{\varepsilon'}$RMSE$_{\varepsilon''}$nRMSE$_{\varepsilon''}$$R^2_{\varepsilon''}$Figure2), the created model allows predicting and practically without bias, unlike the model (Mironov etal. 2020).$\varepsilon'\varepsilon''$

5. Conclusion

A single-frequency refractive-mixing dielectric model for frozen mineral soils at afrequency of 435 MHz is proposed in this letter. The created model calculates the complex permittivity of mineral frozen soils with clay content ranging from 9.1% to 41.3%. The accuracy of the proposed model is comparable with the error of instrumental measurements of the complex permittivity. The proposed dielectric model was created on limited soil sample sets, but its texture varied in abroad range. Compared to the spectroscopic model (Mironov etal. 2020), the proposed model presents simple engineering equations which are easy to use. The model was created for practical use in algorithms of soil moisture, temperature, ice content, unfrozen water content retrieval in frozen soils based on remote sensing data in P-band.

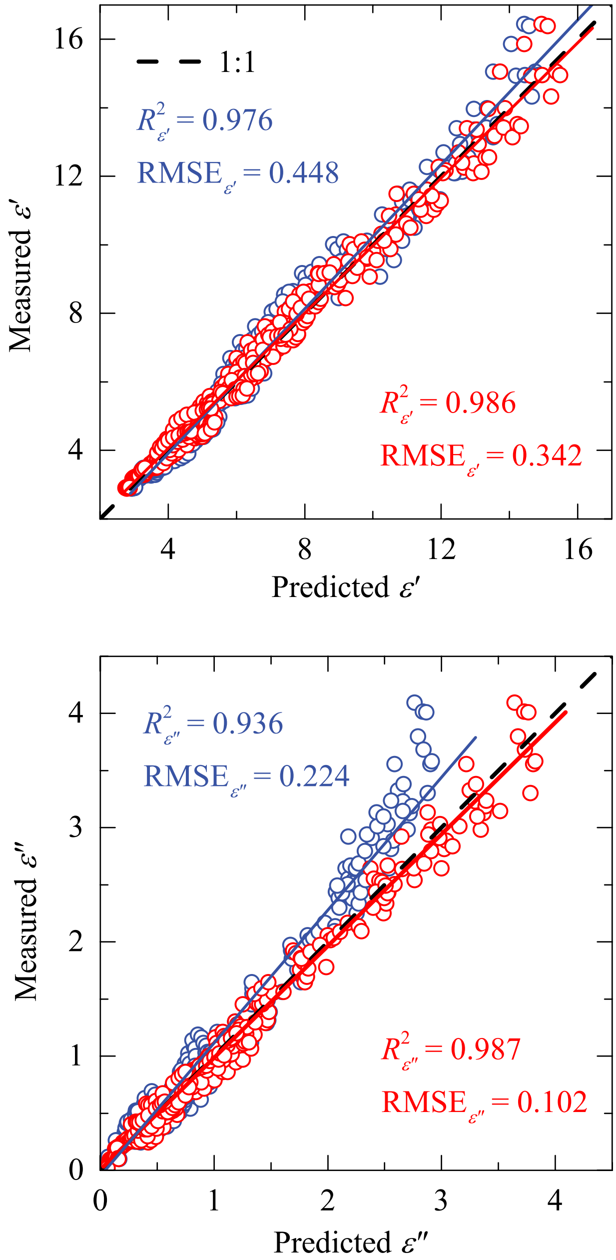

Figure2. Measured versus predicted values of CRPs for all soil samples, using developed single-frequency model (open red circles) and spectroscopic (Mironov etal. 2020) model (open blue circles).

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