Dielectric Model for Thawed Organic Soils at Frequency of 435 MHz

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***Abstract*— To date, models describing the complex dielectric constant (CDC) of tundra soils with different contents of organic matter (more than 30%) in the P-band were poorly reported and not developed. In this letter, a refractive dielectric model for moist organic soils at a frequency of 435 MHz was developed. The model was developed on the basis of dielectric measurements of five samples of organic soils with different organic content from 35% to 80% and the soil moisture from air-dry to field capacity at a temperature of 20 °C. The developed model is a function of only two parameters, namely, the organic content by weight and volumetric soil moisture. The new model and future BIOMASS mission will be creating the bases for developing new soil moisture profile retrieving algorithms in the root zone.**

***Index Terms*— BIOMASS ESA, dielectric model, moisture, organic soil, P-band, temperature.**

I. Introduction

THE root zone soil moisture (RZSM) is an essential variable in meteorology, hydrology, and agriculture. A penetration depth sufficient to sense RZSM requires frequencies below about 500 MHz (I- and P-bands) [1], [2]. In addition, the P-band is well suited for studying the mechanisms of scattering from the surface of the earth in the presence of vegetation [3] as well as for studying the active layer of permafrost in the Arctic regions [4].

The launch in the near future (2021) of the satellite BIOMASS ESA, equipped with SAR in the P-band, provides a technological opportunity to develop new algorithms for remote sensing of soil moisture profiles [5]. When developing such algorithms, one cannot do without knowing the dependencies of the complex dielectric constant (CDC) of the soil on parameters, such as temperature, moisture, and soil composition. However, at present, models describing the CDC of soils in the P-band are poorly covered in the literature. Studies of the CDC in the P-band were carried out earlier [6], [7]. At the same time, in [7], the model of the dependence of the CDC on the mineralogical composition of the soil is even presented. However, these studies are limited only to mineral soils, while for the study of agricultural or arctic soils, knowledge of the effect of organic matter on the CDC is necessary.

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TABLE I
MINERALOGICAL COMPOSITION OF THE STUDIED SOIL SAMPLES

№	Organic matter, %	Mineralogical composition, %						
		Quartz	Feldspar	Plagioclase	Calcite	Smectite	Mica	Chlorite
1	~ 50	~ 30	~ 5-10	~ 5-10	< 1			
2	~ 62	~ 25	~ 5-10	~ 5-10	< 1			
3	~ 35	~ 40	~ 15	~ 10	< 1			
4	~ 80	~ 8	-	~ 1	~ 4.5	< 1	~ 1.5	< 1
5	~ 38	~ 45	~ 5-10	~ 5-10	< 1			

A model at frequencies of 0.5–40 GHz is presented in [8], which describes the dependence of the CPD of mineral soils on the content of organic matter from 0% to 17%, while organic matters are considered as soils, where the organic content is 30% or more. In addition, there are a number of spectroscopic dielectric models for individual mineral and organic soils in the frequency range from 10 MHz to 15 GHz [9]–[12]. At the same time, a model describing the CDC of various organic soils, similar to the models from [13]–[17], in the P-band was not presented. Therefore, at present, the development of CDC models of thawed soils with different contents of organic matter in this frequency range is relevant.

In this letter, a refractive dielectric model for thawed organic soils at a frequency of 435 MHz was developed. The model was created on the basis of dielectric measurements of five samples of organic soils with a variation in the organic matter from 35% to 80% and different soil moisture contents from ~0 to 0.6 cm^3/cm^3 at a temperature of 20 °C. In contrast to the above-described models, the model developed is a function of only two parameters, namely, the weight content of organic matter and the volumetric moisture of the soil. The proposed dielectric model was developed on the basis of the method described in [14]. In the course of creating the model, CDC values of bound and unbound waters were found, and their amount and the type of regression dependencies on the content of organic matter were determined. A comparative analysis between the developed single-frequency model and the previously developed spectroscopic models [9], [10] was conducted.

II. Description of the Used Soil Samples

Soil samples were collected from the organic horizon of topsoils from different test sites in the Arctic tundra region.

TABLE II
RANGES OF MOISTURE AND BULK DENSITY OF STUDIED SOILS

Samples	ρ_d, g/cm^3	W, cm^3/cm^3
№1	0.72-0.87	0.024-0.428
№2	0.59-0.77	0.007-0.597
№3	0.52-0.69	0.005-0.583
№4	0.56-0.67	0.007-0.573
№5	0.67-0.86	0.01-0.601

The samples consist of mineral solids and decomposed organic matter and having the following percentage (see Table I). Samples No. 1, No. 2, and No. 3 were collected in herbal moss tundra on the Yamal peninsula, at the coordinates N70°25′, E68°25′; N66°48′, E69°42′; and N57°06′, E66°12′ [10]. Sample No. 4 was collected in shrub tundra on North Slope of Alaska [11] at the coordinate of N68°38′, W149°35′. Finally, sample No. 5 was collected in herbal moss tundra on Taimyr peninsula (N69°21′, E88°17′). Table I shows that in addition to the organic matter, the studied soils contain mainly sandy minerals, such as quartz, feldspar, and plagioclase, while clay minerals, such as smectite, chlorite, and calcite, are contained in small quantities. An exception is sample No. 4 in which the ratio of sand and clay minerals is comparable, but the amount of clay in the sample relative to the amount of organic matter is negligible.

Based on the foregoing, we assume that the ratio of organic matter to sand will have the main effect on the dielectric properties of soils since the amount of organic matter affects the maximum bound water in the soil [13]–[17].

III. PREPARATION OF SOIL SAMPLES AND MEASUREMENTS PROCEDURE

The soil samples were processed using the procedure given in [10]. For each soil, samples were prepared about 10–23 probing samples with different moisture contents. The measurements using coaxial cells were carried out at a temperature of 20 °C. Ranges of soils' moisture content and soils' density of samples that were used in course of measurements are given in Table II.

Similar to [10] and [11], the coaxial measurement container and Rohde & Schwarz ZVK and Keysight PNA-L vector network analyzers were used for frequency measurements of the scattering matrix coefficients. From this measurement, the soil samples' CDC values were derived as in [10] and [11]. Isothermal measurements were ensured using an SU-241 Espec heat and cold chamber, which provided temperature stability in the camera within 0.5 °C.

IV. RETRIEVING THE PARAMETERS OF THE DIELECTRIC MODEL

The concept of a generalized refractive mixing dielectric model (GRMDM) of soils is described in detail in [18]. According to this concept, the CDC of a moisture soil ε_s^* is analyzed, in terms of the complex refractive index (CRI)

$$n_s^* = \sqrt{\varepsilon_s^*} = n_s + i\kappa_s \tag{1}$$

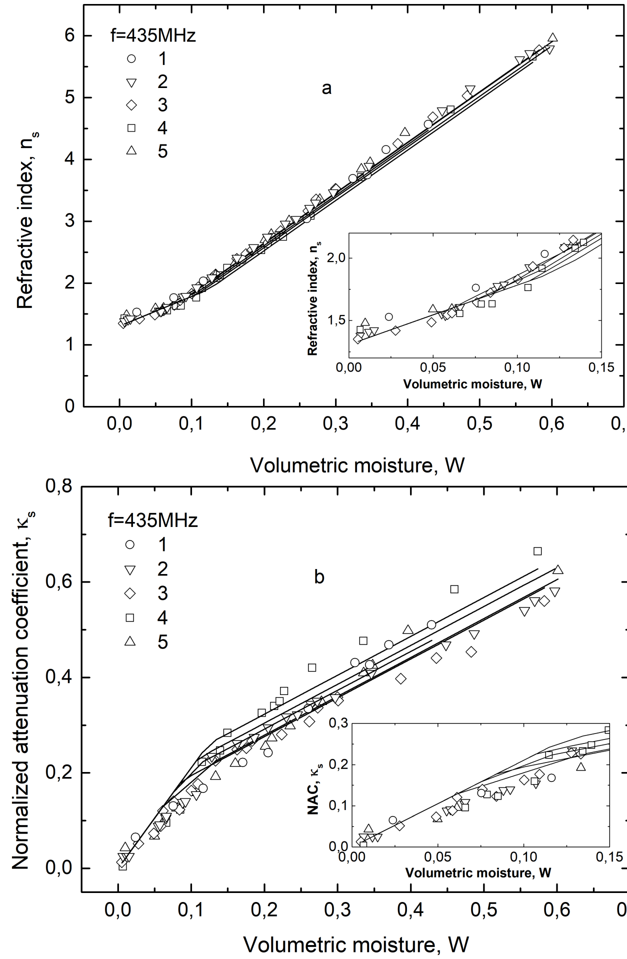

Fig. 1. Dependencies of (a) RI and (b) NAC from moisture measured in the experiment (symbols) and calculated based on model (solid lines)

where $n_s = \mathrm{Re}\sqrt{\varepsilon *_s}$ and $\kappa_s = \mathrm{Im}\sqrt{\varepsilon *_s}$ are the refractive index (RI) and the normalized attenuation coefficient (NAC), respectively. The NAC is considered to be a proportion of the standard attenuation coefficient to the free-space propagation constant. According to the refractive dielectric model of the mixture, described in [18], the RI and NAC can be written as

$$n_s = \begin{cases} n_d + (n_b - 1)W; & W \le W_t \\ n_d + (n_b - 1)W_t + (n_u - 1)_t(W - W_t); & W \ge W_t \end{cases} \tag{2}$$

$$\kappa_s = \begin{cases} \kappa_d + \kappa_b W; & W \le W_t \\ \kappa_d + \kappa_b W_t + \kappa_u(W - W_t); & W \ge W_t \end{cases} \tag{3}$$

where W_t is the maximum content of bound water in the soil; and W is the volumetric soil moisture content; $n_d, n_b, n_u, \kappa_d, \kappa_b, \kappa_u$, RI and NAC for dry soil, bound water, and unbound water, respectively.

To determine the parameters of GRMDM, the dependencies of RI and NAC on the volumetric moisture were used. In Fig. 1, symbols show the experimental dependencies of RI and NAC on moisture for all the soils studied in this letter. It can be seen from Fig. 1 that the dependencies are piecewise linear.

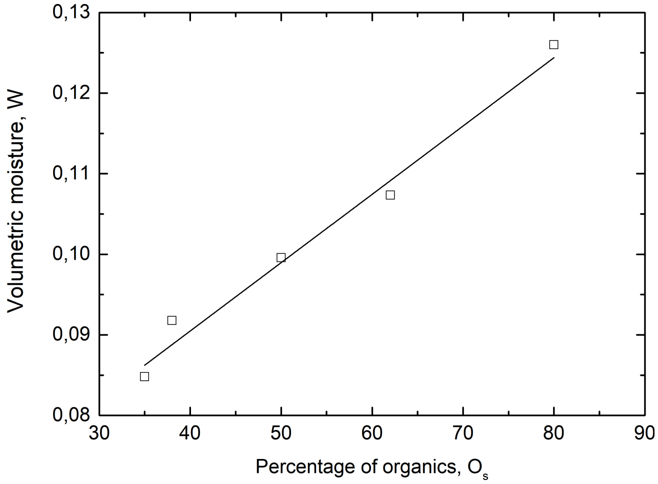

Fig. 2. Dependence of the maximum of bound water W_t on the content of organic matter in the soil O_s (symbols) and linear approximation (solid line). $W_t = 0.059 + 8.146 \cdot 10^{-4} O_s$.

In [19], it was noted that the dielectric properties of individual components of soil water in organic soils weakly depend on the content of organic matter. Therefore, in this letter, it is assumed that $n_b, n_u, \kappa_d, \kappa_b$, and κ_u are independent of organic matter content and moisture. To determine the parameters included in (2) and (3), we used the technique described in detail in [14] for the frequency 1.4 GHz. As the basis of this method, simultaneous multidimensional regression analysis of dependencies of the RI and NAC from moisture was conducted (see Fig. 1). Dependencies of the RI and NAC from moisture calculated based on models (2) and (3) are also shown in Fig. 1.

As a result of the regression analysis, the general parameters of (2) and (3) for the studied soils were found: $n_d = 1.307$, $n_b = 5.767$, $n_u = 9.169$, $\kappa_d = 0$, $\kappa_b = 2.108$, and $\kappa_u = 0.814$, and also the dependence of the parameter W_t on the content of organic matter O_s was found (see Fig. 2)

$$W_t = 0.059 + 8.146 \cdot 10^{-4} O_s. \tag{4}$$

Thus, using (2) and (3) and the parameters obtained earlier, values of RI, NAC, and CDC can be calculated for a specific soil with known moisture and organic matter content.

V. Estimation of Modeling Errors

In Fig. 3, the measured values of RI and NAC show respect to the calculated ones using the GRMDM model. A good correspondence between the measured and modeled values can be seen from Fig. 3. In order to quantitatively estimate the deviations of the predicted RI and NAC values from the measured values, the determination coefficient R^2, the root-mean-square error (RMSE), and normalized RMSE (NRMSE) were calculated.

Values of evaluation parameters of GRMDM for RI and NAC are shown in Table III, as well as the values of estimations R^2, RMSE, and NRMSE calculated for soils from this letter at a frequency of 435 MHz using different dielectric models of organic soils from sources [10], [11].

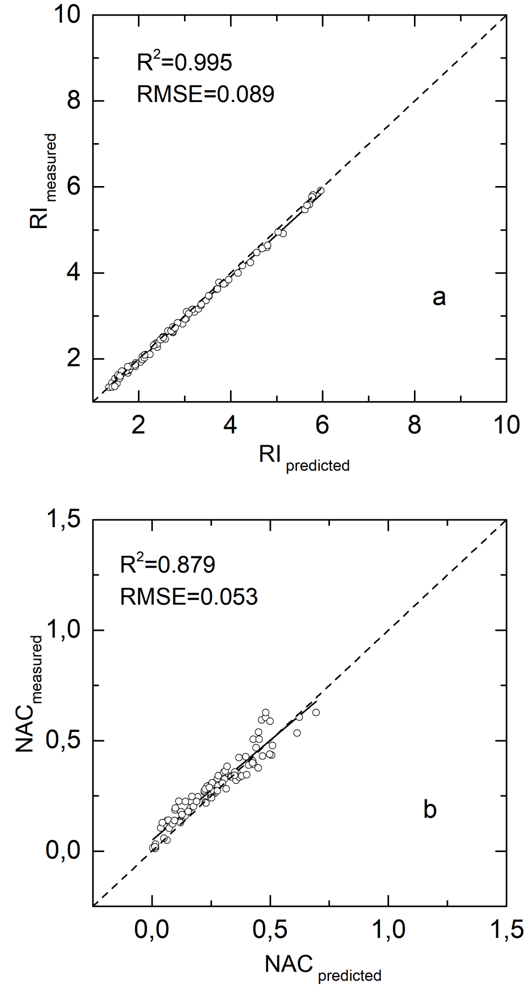

Fig. 3. Measured (a) RI and (b) NAC as a function of the predicted ones. Dotted and solid lines represent bisectors and linear fits, respectively. $R^2_{\mathrm{RI}} = 0.995$, $\mathrm{RMSE}_{\mathrm{RI}} = 0.089$, $R^2_{\mathrm{NAC}} = 0.879$, and $\mathrm{RMSE}_{\mathrm{NAC}} = 0.053$.

TABLE III
Error Estimations for Various Organic Soil Models

	R^2		RMSE		NRMSE, %	
	RI	NAC	RI	NAC	RI	NAC
GRMDM	0.995	0.879	0.089	0.053	3	19
Model [10]	0.994	0.895	0.097	0.051	4	20
Model [11]	0.989	0.852	0.127	0.065	5	26

From Table III, it can be seen that models [10], [11] can be used for calculating the CDC of thawed organic soils in the P-band. However, these models are much more difficult for practical use since they have many additional parameters compared with GRMDM.

VI. Conclusion

In this letter, the CDC model on the frequency of 435 MHz, at the temperature 20 °C, was developed, which takes into account the volumetric soil moisture and organic matter content. The created model allows predicting the values of the CDC, which are in good agreement with the measured values for organic-rich soils (volumetric content of organic matter

$>30\%$). Wherein, determination coefficients are $R^2_{\mathrm{RI}} = 0.995$ and $R^2_{\mathrm{NAC}} = 0.879$ for the RI and NAC, respectively. RMSEs are $\mathrm{RMSE}_{\mathrm{RI}} = 0.089$ and $\mathrm{RMSE}_{\mathrm{NAC}} = 0.053$, respectively. The errors of the developed model are smaller than the errors calculated for spectroscopic models [10], [11] at a frequency of 435 MHz, and the developed model is much simpler for practical use than broadband spectroscopic models. In contrast to the models [9]–[12], the developed model is a function of only two parameters, namely, the weight content of organic matter and the volumetric soil moisture. The new model and future BIOMASS mission will be creating the bases for developing new soil moisture profile retrieving algorithms in the root zone.

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