# Temperature- and Texture-Dependent Dielectric Model for Moist Soils at 1.4 GHz

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***Abstract*—In this letter, a monofrequent dielectric model for moist soils taking into account dependences on the temperature and texture is proposed, in the case of an electromagnetic frequency equal to 1.4 GHz. The proposed model is deduced from a more general model proposed by Mironov and Fomin (2009) that provides estimations of the complex relative permittivity (CRP) of moist soils as a function of frequency, temperature, moisture, and texture of soils. The latter employs the physical laws of Debye and Clausius–Mossotti and the law of ion conductance to calculate the CRP of water solutions in the soil. The parameters of the respective physical laws were determined by using the CRPs of moist soils measured by Curtis *et al.* (1995) for a wide ensemble of soil textures (clay content from 0% to 76%), moistures (from drying at 105 °C to nearly saturation), temperatures (10 °C–40 °C), and frequencies (0.3–26.5 GHz). This model has standard deviations of calculated CRPs from the measured values equal to 1.9 and 1.3 for the real and imaginary parts of CRP, respectively. In the model proposed in this letter, the respective standard deviations were decreased to the values of 0.87 and 0.26. In addition, the equations to calculate the complex dielectric permittivity as a function of moisture, temperature, and texture were represented in a simple form of the refractive mixing dielectric model, which is commonly used in the algorithms of radiometric and radar remote sensing to retrieve moisture in the soil.**

***Index Terms*—Dielectric constant, dielectric losses, dielectric measurements, mathematical model, passive microwave remote sensing, soil moisture, soil texture.**

## I. Introduction

FOR retrieving correct soil moisture with the use of the brightness temperature measured by the Soil Moisture and Ocean Salinity (SMOS) at a frequency of 1.4 GHz, we need such a dielectric model of moist soils which takes into account the dependence of the complex relative permittivity (CRP) of soil not only on moisture but also on temperature and texture. Currently, the algorithm for retrieving soil moisture from the SMOS measurements uses the dielectric model by Dobson *et al.* [1], which does not account for the temperature dependence. Meanwhile, as follows from the dielectric measurements in [2]–[4], the variations of the real part of the CRP can reach 10%–15%, with temperature changing in the range from 5 °C to 40 °C. Except for that in [5], there are no published dielectric models accounting for temperature dependence at the frequency of 1.4 GHz.

The dielectric model in [5] provides for predictions of the CRP as a function of four variables, namely, wave frequency, moisture, and temperature of the soil and the percentage of clay in the soil texture. A physical origin of this model is based on the following. By using the generalized refractive mixing dielectric model (GRMDM) [6] and dielectric data measured at different temperatures for an individual type of soil, the following parameters and their temperature dependences were determined: 1) CRP of dry soil; 2) maximum fraction of bound water that can be adsorbed by soil (see [6]); 3) the parameters of dielectric relaxation spectrum by Debye, namely, the values of relative permittivity in the low and high frequency limits, and time of relaxation; and 4) ohmic conductivity. At that, all the values were derived separately for bound and free water in soil. Furthermore, in [5], by using the procedure outlined in [4] and [7], the formulas of physical laws of Clausius–Mossotti, Debye, and ion conductance were used for regression analyses of the aforementioned parameters as a function of temperature. As a result, for each individual soil, a set of thermodynamic parameters was derived, namely: 1) the volumetric expansion coefficient; 2) energy of activation; and 3) entropy of activation. This procedure was applied with respect to the ensemble of soils having different clay percentages in their texture. In [5], for this purpose, the CRP spectra measured in [2] were employed. Their ensemble covers the temperatures of 10 °C, 20 °C, 30 °C, and 40 °C, contents of clay in soil texture from 0% to 76%, and frequencies from 0.03 to 26.5 GHz.

Finally, the totality of parameters in the model in [5] consisted of the following: 1) CRP of dry soil; 2) maximum fraction of bound water; 3) low and high frequency limits of relative permittivity; 4) ohmic conductivities at the temperature of 20 °C; 5) volumetric expansion coefficients; 6) energies of activation; 7) entropies of activation; and 8) temperature coefficients of ion conductance, as derived separately for the bound and free water in the soil. In [5], all the aforementioned parameters were expressed with the use of polynomial functions as functions of clay content in soil texture. This methodology involves only an implicit consideration of soil mineralogy by a

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single parameter, namely, the content of clay fraction in the soil texture, but within the mineralogical diversity of soils included in the dielectric database in [2].

The model developed in such a way was validated in [5] by correlating the calculated CRPs with those measured in the whole range of moistures, clay contents, frequencies, and temperatures involved in the measurements in [2]. As shown in [5] and [6], in the case of the model in [5], the standard deviation of the calculated and measured CRPs from each other was substantially smaller than that of the model in [1].

According to Wigneron *et al.* [9], the dielectric model in [5], due to smaller error in CRP predictions, demonstrated a substantially smaller error when modeling the brightness temperature [9], as compared with the dielectric model in [1]. It is worth noting that the model in [5] has been thoroughly tested [9] and implemented in the data processing algorithm of the SMOS mission run by the European Space Agency [16]. However, as seen from its aforementioned description, the model in [5] has a complex structure, which, to a certain extent, hampers its practical usage.

In this letter, the dielectric model in [5] is converted into a simple form of the refractive mixing dielectric model of moist soils, which provides for the CRP dependence on moisture, temperature, and clay content in soil texture at the single frequency of 1.4 GHz. As a result, it has become convenient for practical use, simultaneously retaining the ability of the model in [5] to account for temperature dependence, which is a substantial advantage over the widely used models in [1] and [10]. Moreover, in terms of error of the CRP predictions, it was shown that the proposed model has the same accuracy as the model in [5].

## II. Monofrequent Temperature- and Texture-Dependent Soil Dielectric Model

In accordance with the GRMDM proposed in [6], the real part of CRP $\varepsilon_s'$ and the imaginary part of CRP $\varepsilon_s''$ as functions of volumetric moisture $W$ can be represented in the form of

$$\varepsilon_s' = n_s^2 - \kappa_s^2 \qquad \varepsilon_s'' = 2 n_s \kappa_s \tag{1}$$

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

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

where $n_s$, $n_d$, $n_b$, and $n_u$, and $\kappa_s$, $\kappa_d$, $\kappa_b$, and $\kappa_u$ are the values of refractive index and normalized attenuation coefficient for moist soil, dry soil, bound soil water, and free soil water, respectively. The normalized attenuation coefficient is understood here as a proportion of the standard attenuation coefficient to the free space propagation constant. $W_t$ is a value of the maximum bound water fraction in a given type of soil. Using the model proposed in [5], we calculated the GRMDM parameters $n_b$, $\kappa_b$, $n_u$, and $\kappa_u$ at the frequency of 1.4 GHz as functions of gravimetric clay contents $C$ equal to 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 70% and temperatures $T$ equal to 10 °C, 20 °C, 30 °C, and 40 °C. Then, the calculated data were fitted as a function of clay content, with the temperatures being a parameter. For this purpose, second-order polynomials $f^{(i)} = A_i(T_j) + B1_i(T_j)C + B2_i(T_j)C^2$ were used. Here, $f^{(i)}$ denotes any of the GRMDM parameters ($f^{(i)} = n_b, n_u, \kappa_b, \kappa_u$), and the subscript $i$ of the polynomial coefficients takes the respective GRMDM parameter designation, i.e., $i = n_b, n_u, \kappa_b, \kappa_u$. $T_j$ is the soil temperature. The obtained values of polynomial coefficients $A_i(T_j), B1_i(T_j), B2_i(T_j)$ for all the GRMDM parameters were fitted as a function of temperature by using first- or second-order polynomials. Parameters of $W_t$, $n_d$, and $\kappa_d$ were assumed to be independent of the temperature, and their dependences on clay content were taken from [5]. As a result, we came up with the following formulas for the GRMDM parameters in (1)–(3) as functions of clay content and temperature:

$$W_t = 0.0286 + 0.00307C \tag{4}$$

$$n_d = 1.634 - 0.00539C + 2.75\cdot10^{-5}C^2 \tag{5}$$

$$k_d = 0.0395 - 4.038\cdot10^{-4}C \tag{6}$$

$$n_b = (8.86 + 0.00321T) + (-0.0644 + 7.96\cdot10^{-4}T)C + (2.97\cdot10^{-4} - 9.6\cdot10^{-6}T)C^2 \tag{7}$$

$$\kappa_b = (0.738 - 0.00903T + 8.57\cdot10^{-5}T^2) + (-0.00215 + 1.47\cdot10^{-4}T)C + (7.36\cdot10^{-5} - 1.03\cdot10^{-6}T + 1.05\cdot10^{-8}T^2)C^2 \tag{8}$$

$$n_u = (10.3 - 0.0173T) + (6.5\cdot10^{-4} + 8.82\cdot10^{-5}T)C + (-6.34\cdot10^{-6} - 6.32\cdot10^{-7}T)C^2 \tag{9}$$

$$\kappa_u = (0.7 - 0.017T + 1.78\cdot10^{-4}T^2) + (0.0161 + 7.25\cdot10^{-4}T)C + (-1.46\cdot10^{-4} - 6.03\cdot10^{-6}T - 7.87\cdot10^{-9}T^2)C^2. \tag{10}$$

The ensemble of (1)–(10) represents the developed dielectric model, with the input parameters being expressed in the following units: clay content $C$ in percent, temperature $T$ in degrees Celsius, and moisture $W$ in cubic centimeters per cubic centimeter.

## III. Validation of the Monofrequent Model Predictions Over Dielectric Data

Using dielectric data available in the literature [2], [10] and the results of our own measurements of the CRPs at 1.4 GHz, we estimated relative to the measured data the error of calculations of the CRPs by using the monofrequent model. In addition, we tested the deviations between the CRPs calculated with the proposed model on the one hand and the ones obtained by using the model in [5] on the other hand. At that, we chose the soils with the following: 1) low clay content; 2) middle clay content; and 3) maximum clay content. In order to supplement the data missing in the literature, we carried out our own measurements of the CRPs with the soils collected near Bordeaux and Toulouse, France. In terms of texture, the soils measured by the authors were the following: 1) sand (0% clay, 100% sand, and a bulk density of 1.65 g/cm$^3$); 2) loamy soil (17% clay, 36% sand, and a bulk density of 1.4 g/cm$^3$; and 3) clay loamy soil (34% clay, 29% sand, and a bulk density of 1.3 g/cm$^3$). Our dielectric measurements were performed using a waveguide technique at the frequency of 1.4 GHz and the temperatures of 22 °C $\pm$ 1 °C. The soil samples were placed

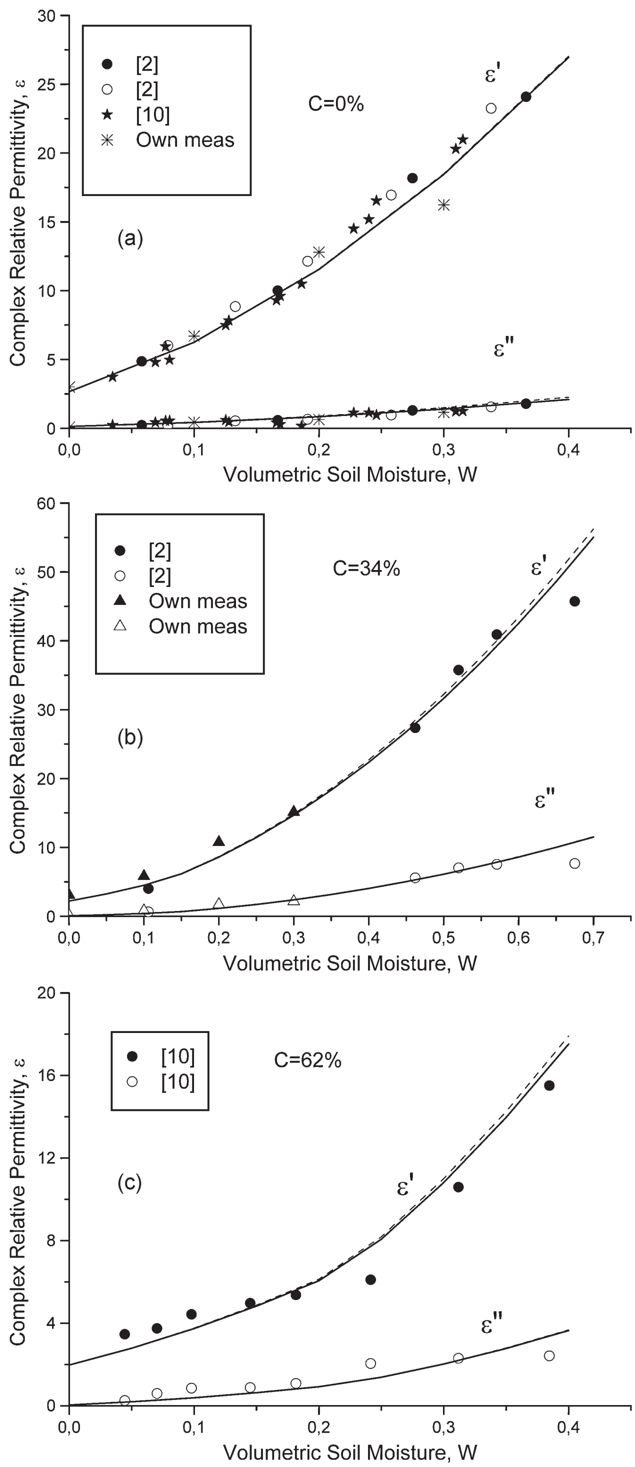


Fig. 1. Measured and calculated CRPs $\varepsilon = \varepsilon' + i\varepsilon''$ for the soils with different clay contents at room temperature (20 °C): (a) $C = 0\%$, (b) $C = 34\%$, and (c) $C = 62\%$. Measured data are taken from [2] and [10] and obtained by the authors (own measurement). Dielectric calculations with the model in [5] and monofrequent model are represented with solid and dashed lines, respectively.

in a segment of the waveguide, which served as a measuring container. The CRPs of the samples were determined using the Nicolson, Ross, and Weir method [11], [12] adapted to a rectangular waveguide.

Fig. 1 shows the measured and calculated values of the real and imaginary parts of CRP as functions of volumetric moisture at room temperature (20 °C−24 °C) for the soils with varying clay content. The following soil types are analyzed: 1) light gray sand $(C = 0\%)$ and white sand $(C = 0\%)$ (data from [2]), Yuma sand $(C = 0\%)$ (data from [10]), and sand $(C = 0\%)$ (data from our own measurements); 2) gray clay $(C = 34\%)$ (data from [2]) and clay loamy soil $(C = 34\%)$ (data from our own measurements); and 3) Miller clay $(C = 62\%)$ (data from [10]). As seen from Fig. 1, the experimental data of different authors correlate well with each other and with the dielectric calculations obtained by using the model in [5] and the proposed monofrequent model. In Fig. 1, the dielectric calculations obtained by using the model in [5] and the monofrequent model are also very close to each other; thus, in some cases, they are graphically indistinguishable from each other.

Next, we compared with each other the dependences of CRPs on temperature at fixed moistures that were calculated by using the proposed monofrequent model and the model in [5] on the one hand and the ones that were either measured by the authors or taken from [2] on the other hand. In Fig. 2 are shown at fixed moistures the CRPs as a function of temperature (5 °C−40 °C) for different soil types: 1) white sand $(C = 0\%)$ (data from [2]); 2) loamy soil $(C = 17\%)$ (data from our own measurements); 3) sandy clay loam $(C = 25\%)$ (data from our own measurements); and 4) gray clay $(C = 34\%)$ (data from [2]). As seen from Fig. 2, the experimental data well correlated with the calculations performed by using the model in [5] or the monofrequent model. In addition, the estimates obtained by using different models deviate from each other by a maximum of 3%, which occurs only in the case of greater moistures, i.e., $W \geq 0.5$.

## IV. Error Estimation

To estimate an error of the proposed model, we correlated the dielectric data taken from [2] and [10], as well as the data measured by the authors, with the results of calculations made by using the model in [5] and the proposed model. In this correlation analysis are used only the dielectric data shown in Figs. 1 and 2. In Fig. 3 are shown the calculated CRPs of the analyzed soils as a function of the respective measured CRPs. The values of correlation coefficients for the real part $R_{\varepsilon'}$ and the imaginary part $R_{\varepsilon''}$ of CRP, alongside with their standard deviations $SD_{\varepsilon'}$ and $SD_{\varepsilon''}$, as well as the equations of linear regression, are given in the following:

1) the model in [5]: $R_{\varepsilon'} = 0.996$, $R_{\varepsilon''} = 0.993$, $SD_{\varepsilon'} = 0.83$, $SD_{\varepsilon''} = 0.25$, $\varepsilon'_{\text{cal}} = -0.12 + 0.98\varepsilon'_{\text{meas}}$, and $\varepsilon''_{\text{cal}} = 0.04 + 0.99\varepsilon''_{\text{meas}}$;
2) the proposed monofrequent model: $R_{\varepsilon'} = 0.996$, $R_{\varepsilon''} = 0.992$, $SD_{\varepsilon'} = 0.87$, $SD_{\varepsilon''} = 0.26$, $\varepsilon'_{\text{cal}} = -0.24 + 1.00\varepsilon'_{\text{meas}}$, and $\varepsilon''_{\text{cal}} = 0.07 + 0.99\varepsilon''_{\text{meas}}$.

As seen from this analysis, the errors of CRP, in terms of standard deviation, obtained by using the model in [5] and the monofrequent model are very close to each other. It is also worth noting that the error of the calculated CRPs, relative to the measured ones, is of the same order as the error of the dielectric measurements.

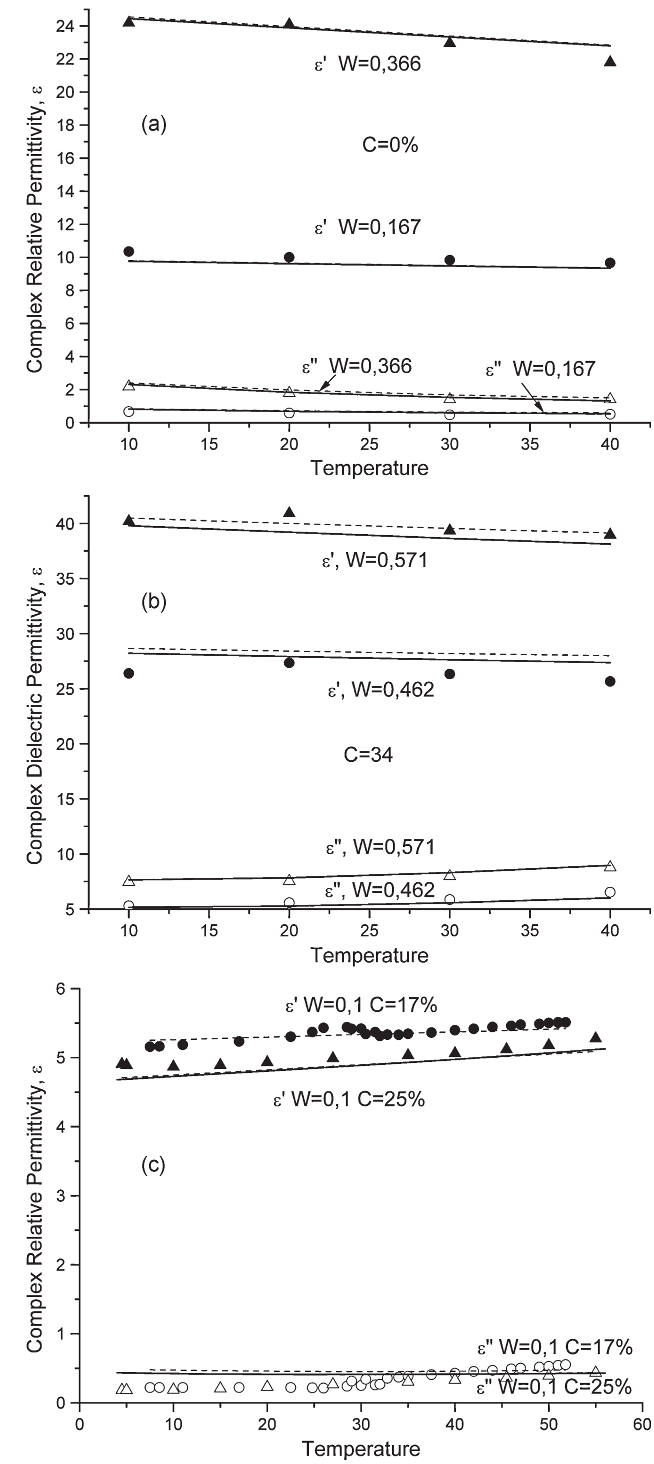


Fig. 2. Measured and calculated CRPs as functions of temperature for soils with different clay contents $C$ and soil moistures $W$: (a) $C = 0\%$, (b) $C = 34\%$, and (c) $C = 17\%$ and 25%. Measured data are taken from [2] and obtained by the authors. Dielectric calculations with the model in [5] and monofrequent model are represented with solid and dashed lines, respectively.

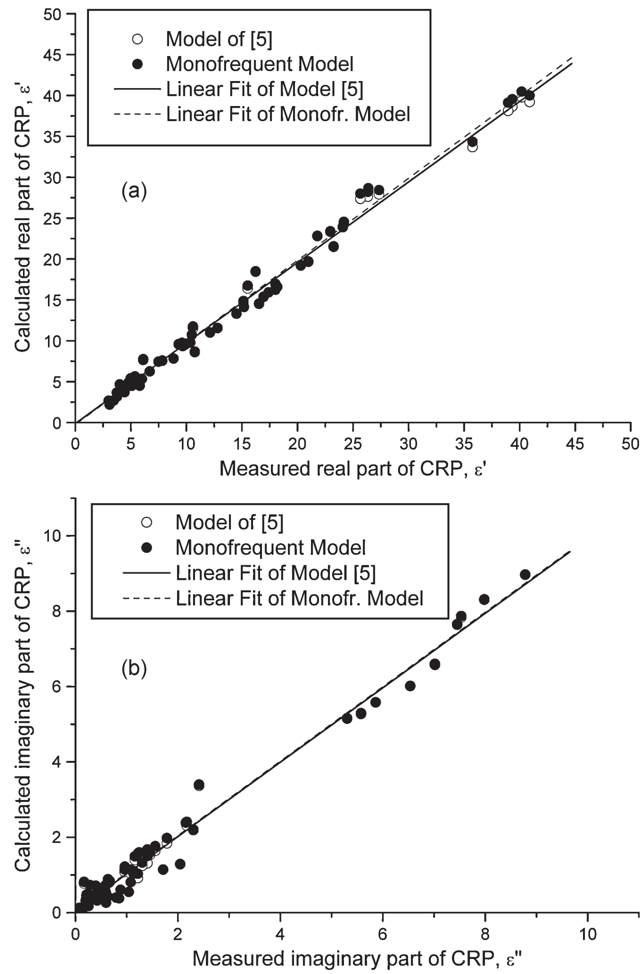


Fig. 3. Correlation of the measured (a) real part $\varepsilon'$ and (b) imaginary part $\varepsilon''$ of CRP with the calculated ones obtained by using the model in [5] and monofrequent model, respectively.

## V. Conclusion

A simple temperature- and texture-dependent moist soil dielectric model at the SMOS frequency of 1.4 GHz has been proposed based on the model developed in [5]. The proposed model provides for predictions of the real and imaginary parts of CRP of moist soils with errors of 0.87 and 0.26, respectively, in terms of their standard deviations with respect to the measured values. As was shown in [13], in the case of using the model in [5], the dielectric model error causes uncertainties in the quantitative determination of soil moisture from the SMOS data which lie in the range of $\pm 0.06\ \mathrm{cm}^3/\mathrm{cm}^3$, in terms of 95% confidence interval. As was shown in Section IV, the errors of the monofrequent model and the model in [5] are equal to each other. Hence, the estimate of uncertainties obtained in [13] for sounding moisture is valid for the proposed model.

Concerning the influence of the soil mineralogy, it should be stated that the dielectric database in [2] consists of the soils containing the following minerals: quartz (from 0% to 100%), smectite clays (from 0% to 80%), K-feldspar (from 0% to 23%), and dolomite (from 0% to 21%), as well as the traces of such mineral components as calcite, Na-plagioclase, mica, and cristobalite. Therefore, it is unreasonable to apply the proposed model to calculate the CRPs of the soils containing mineral components other than those comprising the database in [2], particularly the kaolinites, sulfate hydrates, and zeolites. In addition, it should be noted that the proposed model has not been validated regarding organic-rich and saline soils.

The range of bulk density of soils, for which the proposed monofrequent model can be applied, must correspond to the density of the soils in [2]. Unfortunately, the values of bulk densities are not explicitly given in [2]. Nevertheless, they were estimated to fall in the range from 0.9 to 1.65 g/cm$^3$, using the relationships between the refractive index of dry soil and its bulk density, by the formulas from [14]. For this purpose were employed the data given in [8] and [15] for refractive indexes of soils and minerals comprising soils. Finally, it should be noted that a simple and clear structure of the formulas in the proposed model is its major advantage over the model in [5]. At that, the errors of both models are equal to each other.

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