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SPECTRAL INVESTIGATIONS OF COMPLEX DIELCTRIC PERMITTIVITY OF MOIST SOILS

S. A. Komarov,[1] V. L. Mironov,[2] and Yu. I. Lukin[2]

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An investigation of the frequency spectrum of complex dielectric permittivity (CDP) of soil taken from a test site of the settlement Bor of Krasnoyarsk territory is performed. Parameters of a refraction model of this soil are found. A method to take into account the effects of discontinuities of the measurement system is discussed. Applicability of this method is tested by measuring CDP of air and a mixture of soil and distilled water.

INTRODUCTION

With an advent of apparatus for remote sensing of the Earth's covers in RF range, interpretation of the data obtained becomes a challenging problem. In so doing, it is often necessary to relate the results of radiometric or radar measurements to the physical parameters of the Earth. To achieve this, research work is ongoing to study the dependence of CDP on physical and geophysical parameters such as temperature, moisture content, and mineral composition. The use of laboratory measurements and model description of CDP that is based on the experimentally obtained knowledge of characteristic physical parameters of the model allows one to significantly simplify solution of a number of problems of radiophysical sounding. In [1, 2], applicability of the refraction model for the description of dielectric permittivity and tangent loss in soils was reported.

In the present work a method to reconstruct the frequency dependence of CDP of soils under laboratory conditions is discussed with the use of coaxial-waveguide sections developed according to the approaches described in [3, 4]. An investigation is carried out of the frequency spectrum of CDP of real soils using a Rohde-Schwarz ZVK vector network analyzer. An inclusion of discontinuities of adapter units in the measurement system in the course of reconstruction of CDP of sample soils is carried out using a procedure of calibration measurements with two empty containers of different lengths.

An analysis of the experimental data allowed us to obtain physical parameters of the refraction model necessary for the description of the soils under study.

The work was performed within the framework of planned scientific investigations in collaboration with the Kirensky Institute of Physics of the SB, RAS in the town of Krasnoyarsk and the Russian Academy of Sciences following a contract under the topical program of research "Procedures for advanced highly informative methods and facilities of microwave radiometry for the purposes of monitoring of biochemical cycles in polar regions of Siberia".

1. MEASUREMENT PROCEDURE

When selecting a measurement procedure, we took into account the necessity to obtain CDP in a wide range of frequencies. For this purpose, a coaxial container was manufactured which was attached to a Rohde-Schwarz ZVK vector network analyzer. The vector network analyzer allows for the measurement of the frequency spectrum of the elements of the *S*-scattering matrix of the attached device in a wide frequency range. The measuring containers represent sections of a coaxial waveguide whose dielectric filling is the soil sample under study. The container dimensions ensure a single-mode regime, i. e., the conditions of the ground wave propagation of a TEM type and suppression of higher-order modes.

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[1] Altai State University, e-mail: komarov@phys.asu.ru; [2] Kirensky Institute of Physics of the Siberian Branch of the Russian Academy of Sciences, e-mail: rsdvm@ksc.krasn.ru, yura_lu@mail.ru. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 9, pp. 29–34, September, 2006.

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The measuring system consists of two main component parts: the section containing the sample soil under study and adaptor units ensuring a match to the connectors of the vector network analyzer. Now we can write for the entire waiveguide system a transmission matrix in terms of transmission matrices of the measurement sections [3, 5]

$$\boldsymbol{T} = \boldsymbol{T}_1 \boldsymbol{T}_x \boldsymbol{T}_2 , \tag{1}$$

where $\boldsymbol{T}_1$, $\boldsymbol{T}_2$ are the transmission matrices of the adaptor units located before and after the container with a sample soil, respectively, which is described by matrix $\boldsymbol{T}_x$. The matrix elements entering Eq. (1) are related to the elements of the scattering matrices S as follows [5]:

$$\boldsymbol{T}_i = \begin{pmatrix} \dfrac{1}{S_{21}^i} & -\dfrac{S_{22}^i}{S_{21}^i} \\ \dfrac{S_{11}^i}{S_{21}^i} & \dfrac{S_{21}^i S_{12}^i - S_{11}^i S_{22}^i}{S_{21}^i} \end{pmatrix}, \; i = 1, x, 2 . \tag{2}$$

If the container is not filled with any material, then for the condition of a single mode regime fulfilled the matrix equality (1) can be written in terms of relations of their elements

$$\begin{cases} t_{11} = t_{11}^1 t_{11}^2 e^{-ik_0 d} + t_{12}^1 t_{21}^2 e^{ik_0 d} , \\ t_{12} = t_{11}^1 t_{12}^2 e^{-ik_0 d} + t_{12}^1 t_{22}^2 e^{ik_0 d} , \\ t_{21} = t_{21}^1 t_{11}^2 e^{-ik_0 d} + t_{22}^1 t_{21}^2 e^{ik_0 d} , \\ t_{22} = t_{21}^1 t_{12}^2 e^{-ik_0 d} + t_{22}^1 t_{22}^2 e^{ik_0 d} , \end{cases} \tag{3}$$

where $k_0 = 2\pi f / c$ is the wave number in free space, d is the container length, and f is the signal frequency.

The system of equations (3) could be considered in terms of eight unknown quantities: $t_{11}^1 t_{11}^2$, $t_{12}^1 t_{21}^2$, $t_{11}^1 t_{12}^2$, $t_{12}^1 t_{22}^2$, $t_{21}^1 t_{11}^2$, $t_{22}^1 t_{21}^2$, $t_{21}^1 t_{12}^2$, $t_{22}^1 t_{22}^2$, which are the characteristics of the adaptor units.

In order to solve Eq. (3), we need two empty calibration containers of different lengths d_1 and d_2.

From the system of equations (1) we can find t_{11}^x and t_{22}^x for the known adaptor unit characteristics: $t_{11}^1 t_{11}^2$, $t_{12}^1 t_{21}^2$, $t_{11}^1 t_{12}^2$, $t_{12}^1 t_{22}^2$, $t_{21}^1 t_{11}^2$, $t_{22}^1 t_{21}^2$, $t_{21}^1 t_{12}^2$, $t_{22}^1 t_{22}^2$. Elements t_{11}^x and t_{22}^x are related to the wave number k and the soil sample length d in the following way [4]:

$$\cos(kd) = \frac{1 + \left(S_{21}^x\right)^2 - \left(S_{22}^x\right)^2}{2 S_{21}^x} = \frac{t_{11}^x + t_{22}^x}{2} . \tag{4}$$

From Eq. (4) we can readily derive the value of complex dielectric permittivity ε of soil

$$\varepsilon = \left(\frac{ck}{2\pi f} \right)^2 , \tag{5}$$

where

$$k = \frac{\arccos\left(\frac{t_{11}^{x} + t_{22}^{x}}{2}\right)}{d}. \tag{6}$$

Clearly, the measurements assume two stages. The first stage consists in the calibration procedure using two empty containers. In the second stage one container is filled with the soil sample and, using calibration relations, scattering parameters of the filled section are found, from which CDP of the soil under study is derived by Eqs. (4)–(6).

2. REFRACTIVE MIXING DIELECTRIC MODEL OF SOILS

It is convenient to write the refractive mixing dielectric model (RMDM) of soils [1] in terms of the refraction coefficient n and the reduced absorption coefficient κ, which are related to CDP as $\sqrt{\varepsilon} = n + i\kappa$. According to [1], RMDM for n and κ of soils is written in the following form:

$$n = \begin{cases} n_d + (n_b - 1)W, & W \le W_t, \\ n_d + (n_b - 1)W_t + (n_f - 1)(W - W_t), & W > W_t, \end{cases} \tag{7}$$

$$\kappa = \begin{cases} \kappa_d + (\kappa_b - 1)W, & W \le W_t, \\ \kappa_d + (\kappa_b - 1)W_t + (\kappa_f - 1)(W - W_t), & W > W_t, \end{cases} \tag{8}$$

where W_t is the maximum bound water fraction in this type soil, indices d, b, and f correspond to a dry mixture, bound and free water, respectively. The values of n_d and κ_d are related to the dry mixture density as follows:

$$n_d = 1 + \frac{\rho}{\rho_m}(n_m - 1), \tag{9}$$

$$\kappa_d = \frac{\rho}{\rho_m}\kappa_m, \tag{10}$$

where ρ and ρ_m are the densities of the dry mixture and monolith, respectively, and n_m and κ_m are the refraction and absorption coefficients of the monolith, respectively.

Dielectric properties of bound and free water are well described by the Debye formula

$$\varepsilon_{b,f} = \varepsilon_\infty + \frac{\varepsilon_{sb,f} - \varepsilon_\infty}{1 - i2\pi f \tau_{b,f}} + i\frac{\sigma_{b,f}}{2\pi f \varepsilon_0}. \tag{11}$$

Here ε_∞ is the "optical" dielectric permittivity determined by the atomic and electronic polarizations that do not depend on the signal frequency f, $\varepsilon_{sb,f}$ is the "static" dielectric permittivity, $\tau_{b,f}$ is the effective time of molecular relaxation, $\sigma_{b,f}$ is the ionic conductivity of a water solution, and $\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m is the dielectric permittivity of vacuum. The indices b and f correspond to bound and free water, respectively. The values of Debye parameters for free water ε_{sf}, τ_f, σ_f as a function of temperature and content of soluble salts were found empirically [6].

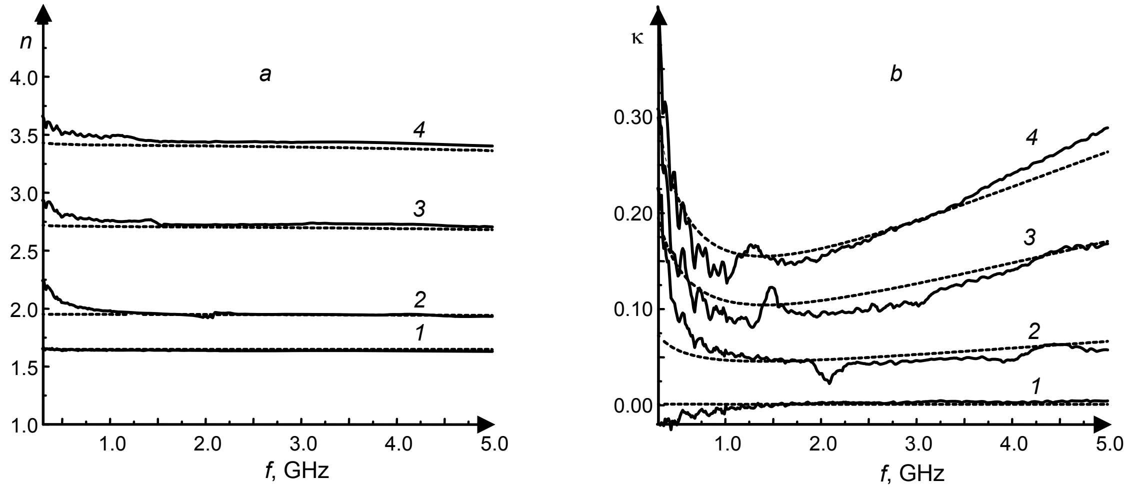

Fig. 1. Measured and model (dotted line) refraction n (*a*) and absorption κ (*b*) coefficients for moistened sand: $W = 0$ (curve *1*), 0.04 (curve *2*), 0.14 (curve *3*), and 0.21 (curve *4*).

3. TEST MEASURMENTS

In order to test the procedure, two samples were selected: air and moistened sand. The choice of sand was dictated by the fact that dielectric properties of coarse-grained sand moistened with water have been extensively studied [1]. The results are presented as refraction coefficients and reduced coefficient of absorption of the samples. When reconstructing CDP of air, a discrepancy in the solution of the problem was found out at the frequencies below 500 MHz. In the frequency range from 500 MHz to 5 GHz, the relative reconstruction error for n did not exceed 1%. Since the theoretical value of κ is zero, in this case it is possible to consider only the absolute error. For κ in the frequency range from 500 MHz to 5 GHz it does not exceed 0.006. The discrepancy in the reconstruction algorithm at low frequencies is associated with the fact that the wavelength becomes too long compared to the container length, thus making this procedure non-applicable.

Figure 1 depicts the reconstructed and model curves of the frequency spectra of n and κ of sand for different moisture contents. For spectroscopic parameters of water in the refraction model of sand use was made of an empirical Stogryn formula [6]. The relative measurement error n did not exceed 6%. The absolute error for κ did not exceed 0.04.

4. SOIL MEASUREMENTS

Within the framework of a joint research project with the Krasnoyarsk Kirensky Institute of Physics, it was planned to measure the spectra of refraction n and absorption κ coefficients and to construct a physical model of soil taken from the test site near the settlement Bor of the Krasnoyarsk territory for further use of the model in the solution of an inverse problem of remote radiometric and radar sounding.

Figure 2 shows the dependences of n and κ of soil on moisture content for different electromagnetic field frequencies.

From the graphs in Fig. 2 it is evident that with decrease in frequency there is a noticeable deviation from the linear dependence of n and κ versus the relative volumetric water content. This is associated with the soluble salts contained in the soil. Indeed, as the volumetric moisture content is increased the concentration S of salts in the soil solution decreases. This gives rise to a dependence of S on moisture W, and also on the Debye parameters of water (ε_s, τ, σ) [3]. Due to the appearance of this dependence the linear character of the refraction formulas is distorted, though earlier it was shown that

TABLE 1. Refraction Parameters

Soil parameters	Value	Water parameters	Value
$(n_m - 1)/\rho_m$	0.44	ε_0	79
κ_d	0.011	τ, ps	9.45
W_t	0		
Z, ‰	0.4		

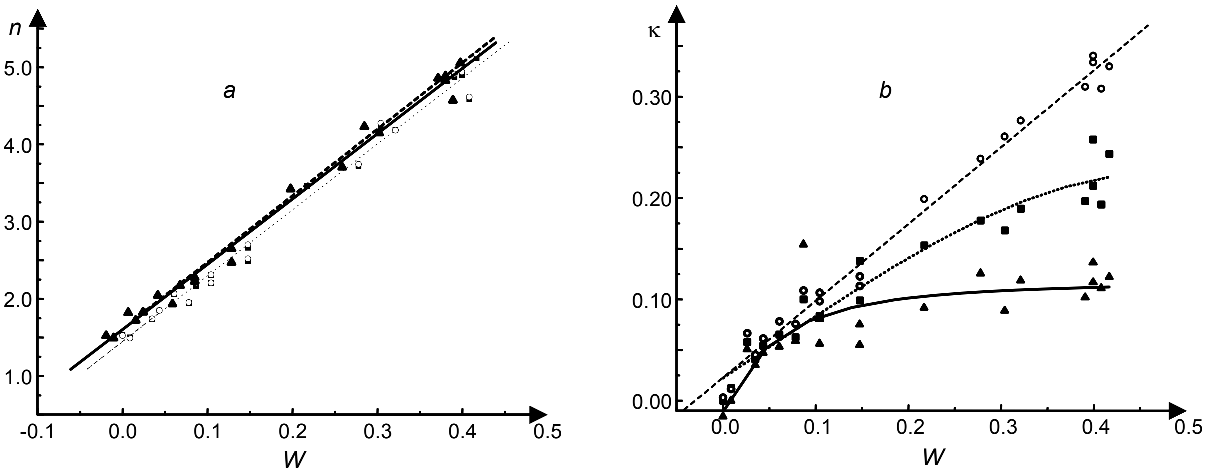

Fig. 2. Dependence of the refraction n (a) and absorption κ (b) coefficients of soil on the volumetric moisture content: f = 5.0 (○), 1.5 (■) and 0.5 GHz (▲).

these formulas had been applicable [3]. It should be noted that there is no chain function in Fig. 2. This implies that there is practically no bound water in the soil under study.

In this case the refraction model parameters were determined via approximation of the reconstructed values of n and κ of soil versus the volumetric water content W using the functions Eqs. (7) and (8) with the Debye parameters non-linearly depending on moisture and described by the experimental Stogryn formulas [6]. Taking advantage of the fact that in the Stogryn formulas it is possible to single out relaxation parameters of non-saline water that is used to moisten the soil, the Debye parameters of this water and soil salinity Z were found. The $(n_m - 1)/\rho_m$ parameter, characterizing the properties of the monolith, was found from the values of n and κ for a dry mixture using the formula (9). The dependence of the absorption coefficient of a dry mixture κ_d on density was not considered due to the smallness of this quantity. Table 1 lists the reconstruction parameters for RMDM and the Debye parameters of non-saline water used to moisten the soil.

Shown in Fig. 3 are the measured and model curves of the frequency spectra of n and κ of sand for different moisture content. The relative measurement error n does not exceed 4%. The absolute error for κ does not exceed 0.04.

SUMMARY

Measurements of complex dielectric permittivity of moist soils have been performed in the frequency range 0.5–5.0 GHz. Using the relation for discontinuous transmission lines, the scattering characteristics of adaptor units of the container in the microwave guide were taken into consideration during solution of the problems of reconstruction of CDP of the material under study.

The testing procedure was performed by measuring CDP of a mixture of sand and distilled water. The maximum relative error of the refraction coefficient was found to be 6%, and the maximum absolute error of the absorption coefficient – 0.04.

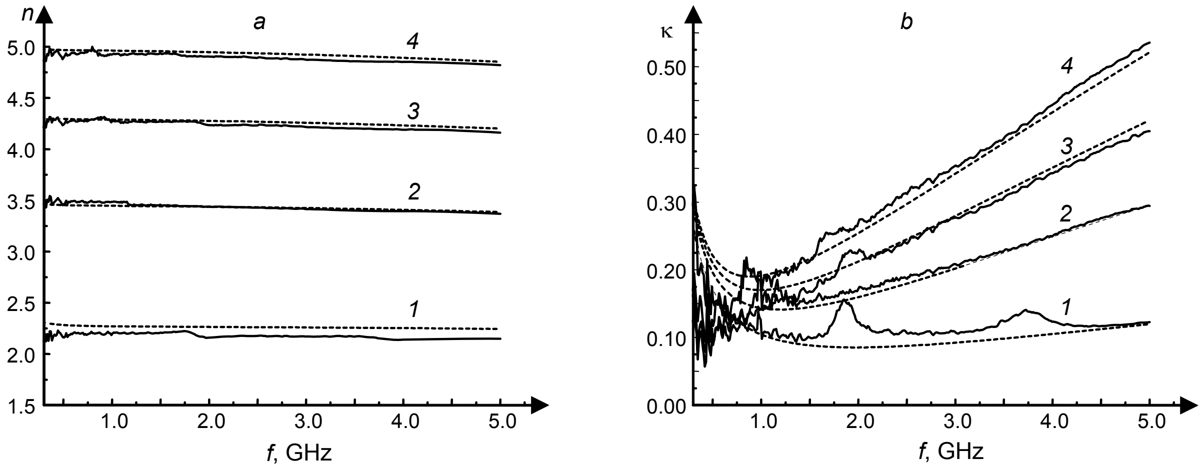

Fig. 3. Measured and model (dotted lines) refraction n (*a*) and absorption κ (*b*) coefficients for moist soil: $W = 0.08$ (curve *1*), 0.22 (curve *2*), 0.32 (curve *3*) and 0.43 (curve *4*).

Physical parameters of the refraction model of the soil from the test site of the settlement Bor in the Krasnoyarsk territory have been determined.

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