Microwave Dielectric Spectroscopy of Moist Soils for a Forest-tundra Region

V. L. Mironov, P. P. Bobrov
Radiophysics of Remote Sensing Laboratory
Kirensky Institute of Physics, SB RAS
Krasnoyarsk, Russia
rsdvm@ksc.krasn.ru

A. P. Bobrov, V. N. Mandrygina, V. D.Stasuk
Department of Physics
Omsk State Pedagogical University
Omsk, Russia
bobrov@omgpu.omsk.edu

Abstract − **In this paper, the measured microwave dielectric data are presented for some soils collected in the forest-tundra area located at 64° N and 100° E, which is near the city of Tura in East Siberia. The measurements were developed in the range from 0.3 to 12.5 GHz at the temperature of 24°C. The Debye spectroscopic parameters related to the bound soil water (BSW) and free soil water (FSW) were derived with the use of the generalized refractive mixing dielectric model (GRMDM) [1], [2]. The forest-tundra soils analyzed were found to contain the smaller percentage of bound water, with its complex dielectric constant (CDC) being less than that of the soils in the agricultural zones of Siberia [3]-[5], in spite of the fact that the forest-tundra soils demonstrated smaller clay and humus percentage as compared to the agricultural soils. The results obtained can be considered as a substantial contribution to the soil dielectric data base for the northern circumpolar region, which is a compulsory element of physically based both the remote sensing models and retrieving algorithms.**

Keywords - dielectric properties; microwave spectroscopy, soil bound and free water

I. INTRODUCTION

Radar remote sensing of the forested area in Siberia has recently become an issue of interest for some large scale international research programs. At the same time, the dielectric characteristics of soils, particularly in the northern forest-tundra part of Siberia, are still a matter that has not been studied enough to become available for creating both the radar scattering models and radar remote sensing retrieval algorithms [6]. To fill this gap, there was measured the complex permittivity for some soils collected in the forest-tundra area located at 64˚ N and 100˚ E, which is near the city of Tura in East Siberia. Using these data, the spectral dielectric parameters for each soil were derived on the basis of the generalized refractive mixing dielectric model (GRMDM) [1], [2]. The latter are represented by the dielectric constants and loss factors for dry soils, maximum bound water fractions, static dielectric constants, relaxation times, and conductivities for both the bound and free soil water components.

II. EXPERIMENT DESCRIPTION

In order to obtain the experimental data to be processed for deriving bound and free soil water spectroscopic parameters, the soil CDCs were measured as a function of volumetric moisture. In these studies, the following types of soil, having contrasting mineral and organic contents, were selected: 1) the thixotropic kryozem sample, containing 24.0% of clay and 3.25% of humus; 2) the thixotropic kryozem sample, containing 15.9 % of clay and 1.16 % of humus; 3) the homogeneous kryozem soil, containing 13.8 % of clay and 2.27 % of humus; 4) the granuzem soil, containing 4.0 % of clay and 0.28 % of humus. All the samples measured were classified as weakly saline soils. The measurements were conducted at the frequencies from 0.8 to 12.5 GHz at the temperature of 24°C.

Using the coaxial line and rectangular waveguide, the module of the reflection and transmission coefficients were measured, with the soil sample being placed into the waveguide. To reach higher accuracy, soil containers of different length were used to perform measurements at different moistures, in order to ensure that the waves reflected from both the front and rear boundaries of soil sample equally contributed in the values of complex reflectance and transmittance. The results measured for the refractive index (RI), $n=Re\sqrt{\varepsilon}$, here ε stands for the CDC, and normalized attenuation coefficient (NAC), $k=Im\sqrt{\varepsilon}$, are shown in Fig. 1 as a function of volumetric moisture at the frequency of 7,5 GHz.

III. METHODOLOGY FOR SPECTROSCOPIC PARAMETERS ESTIMATION

The dielectric parameters of bound and free water and its volumetric fraction in a given type of soil were evaluated using the GRMDM proposed in [1], [2]. To take into account soil density variations with moisture, which have impact on the measured soil water CDC values, we applied the modified refractive mixing dielectric model (RMDM) suggested in [3]:

$$\left(\sqrt{\varepsilon_s(W)}-\sqrt{\varepsilon_a}\right)D(W)=\left(\sqrt{\varepsilon_m}-\sqrt{\varepsilon_a}\right)\rho_{cd}(W)/\rho_m+\left(\sqrt{\varepsilon_b}-\sqrt{\varepsilon_a}\right)W \qquad W\le W_t \qquad (1)$$

$$\left(\sqrt{\varepsilon_s(W)}-\sqrt{\varepsilon_a}\right)D(W)=\left(\sqrt{\varepsilon_m}-\sqrt{\varepsilon_a}\right)\rho_{cd}(W)/\rho_m+\left(\sqrt{\varepsilon_b}-\sqrt{\varepsilon_a}\right)W_t+\left(\sqrt{\varepsilon_u}-\sqrt{\varepsilon_a}\right)(W-W_t) \qquad W\ge W_t \qquad (2)$$

The work was supported by the Siberian Branch of the Russian Academy of Sciences in the frame of the Integrated Research Program, Projects 13, 13.1, and by the RFBR grant no. 05-02-97712-r-yenisei-a.

0-7803-9050-4/05/$20.00 ©2005 IEEE.

Here and henceforth, subscripts *s, a, m, b, u* attached to symbols ε, *n*, and *k* should be related to the moist soil, air, soil mineral, bound and free soil water fractions, respectively. Index *W* is used to denote a volumetric part of bulk soil water, while W_t designates the maximum bound water fraction (MBWF) related to a given type of soil. CDCs of dry samples were calculated with the use of Bruggeman's formula [7]. Function *D(W)* is determined with the following equation [3]:

$$D(W) = (1 + W\rho_W / \rho_{cd}(W)) \cdot (\rho_{cd}(W) / \rho_{cw}(W)) \qquad (3)$$

The values ρ_w, $\rho_{cw}(W)$ and $\rho_{cd}(W)$ stand for the mass densities of water, moist soil, and dried soil, having moisture of *W* before drying, respectively.

Before applying the model (1) – (3) for processing measured soil dielectric data, we have compared the measured CDCs with those evaluated through the empirical model proposed in [8]. For soils 1), 2) and 3), the empirical model appeared to provide for inflated estimates. It was only soil 4) for which the semi empirical model provided for the CDCs to be in good agreement with the measured ones. Therefore, we made an attempt to apply the RMDM as represented by formulas (1) – (3) to improve the agreement between the modeled and measured dielectric data regarding the soils mentioned above.

The methodology proposed in [2], [3] makes possible to derive from dielectric data similar to those given in Fig. 1, the values of dielectric constant, ε', and loss factor ε'' relating to the soil mineral, bound and free soil water, as well as the maximum bound water fraction W_t.

Thus calculated values are shown in Table I for each type of soil, having been averaged on the basis of frequencies 0.8, 1.0, 1.5, 1.8, 2.5, 3.0, 3.2, 3.4, 4.3, and 4.5 GHz. Here H and C designate the percentage of humus and clay in the soil, respectively. As expected, according to Table I, the dielectric constant, ε'_m, and loss factor, ε''_m, of soil mineral component were found to undergo only minor variations. At the same time, those concerning the soil bound water appeared to be dependent on soil type to a large extent, in spite of averaging over frequencies.

Unlike formulas (1) – (3), the maximum bound water fraction, W'_t, in Table I is given in terms of the ratio of water mass to bulk soil mass, which is related to the volumetric maximum bound water fraction in (1)-(3) with the formula $W'_t = W_t / \rho$ where ρ designates the dry soil density.

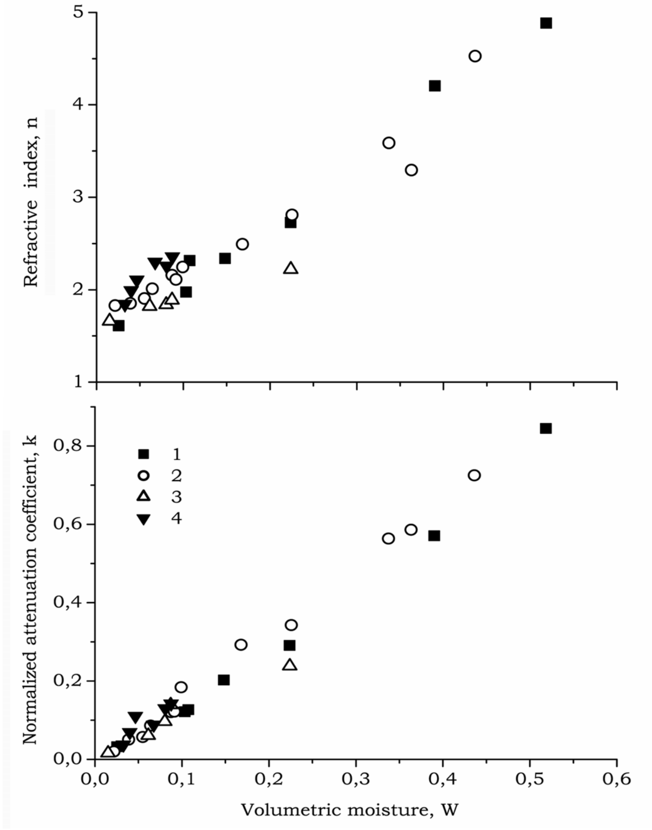

Fig 1. Refractive index and normalized attenuation coefficient for different types of soil as a function of volumetric moisture at 7.5 GHz. 1- thixotropic kryozem with 24,0% of clay and 3,25% of humus; 2 – thixotropic kryozem with 15,9% of clay and 1,16% of humus; 3 - homogeneous kryozem with 13,8 % of clay and 2,27 % of humus; 4 - straw-colored granuzem with 4.0 % of clay and 0.28 % of humus.

The maximum bound water fraction value in Table I varies from 0.02 to 0.12 *g/g*. The limits of this range are characteristic [5] for the sand and sandy loam agricultural soils, respectively. It is worth noticing that the bound water dielectric constant in Table I showed tendency to decrease with an increase in maximum bound water fraction.

In [9], based on the dielectric data for the agricultural soils in West Siberia, there was proposed an empirical formula for evaluating the values of maximum bound water fraction, *W′*$_t$, as a function of humus and clay percentage:

TABLE I. GRANULOMETRIC AND DIELECTRIC PARAMETERS OF MEASURED SOIL TYPES

	ρ_{cd}	ρ_m	ε'_m	ε''_m	ε'_b	ε''_b	W_t, g/g	ε'_u	ε''_u	H, %	C,%
1	1,31	2,50	4,97	0,02	30,24	19,27	0,12	66,71	35,20	3,25	23,97
2	1,43	2,25	5,22	0,22	20,88	15,33	0,06	59,00	30,11	1,16	15,94
3	1,20	2,52	4,82	0,40	16,95	8,55	0,07	77,10	22,44	2,27	13,80
4	1,53	2,60	5,05	0,41	69,42	3,05	0,02	85,65	22,95	0,28	4,01

$$W'_t = (0,22 \pm 0,03)\cdot C+(1,25 \pm 0,21)\cdot H \quad (4)$$

The error in calculating maximum bound water fraction with formula (4), as compared to those given in Table I, appeared to be less than 10% in the range $W'_t \geq 0,06$, being increased up to 30% for the smaller values of W'_t.

In order to study frequency dispersion of moist soil permittivity, the methodology proposed in [2], [3] was applied to derive the Debye relaxation parameters for both the bound and free soil water in terms of conductivity, σ, relaxation time, τ, and static dielectric constant, ε_0, with the optical dielectric constant being of 4.9 as in [2]. For this purpose the dielectric data similar to those in Fig. 1 were used, as measured at 0.8; 2.5, 3.4, 4.5, 7.6, 10.0, and 12.5 GHz. The results of these calculations are shown in Table II.

Given the data in Table II, the dielectric constants and loss factors for soil bound water were obtained as a function of frequency, using the Debye relaxation formulas as in [2]. The results of these calculations are shown in Fig. 2, being referred to as model. The values of dielectric constants and loss factors obtained directly via fitting formulas (1) and (2) to the measured RIs and NACs, are also shown in Fig.2, to demonstrate the error arising for soil water dielectric predictions in the case of tundra soils, if using the GRMDM methodology. These are referred to in Fig. 2 as experiment.

From the analyses of the data in Table II, it follows that the Debye relaxation parameters of both the bound and free soil water are noticeably dependent on soil mineralogy.

TABLE II. CONDUCTIVITIES, RELAXATION TIMES AND STATIC DIELECTRIC CONSTANTS OF BOUND AND FREE WATER FOR MEASURED SOIL TYPES

Soil Type	**Bound Water**			**Free Water**		
	σ (S/m)	***τ (ps)***	ε_0	***σ (S/m)***	***τ (ps)***	ε_0
1	1,43	12,55	28,09	2,05	7,82	76,63
2	0,96	11,89	24,49	1,91	7,69	64,08
3	1,37	12,97	23,55	0,82	-----	82,52
4	1,25	14,99	77,08	1,59	7,11	93,42

IV. CONCLUSION

The results of this paper can be estimated as the first example of the soil water spectroscopic analyses in a specific Northern circumpolar region and a substantial contribution to the soil dielectric spectroscopic data base, which is a compulsory element of the physical basis for developing both the remote sensing models and retrieving algorithms.

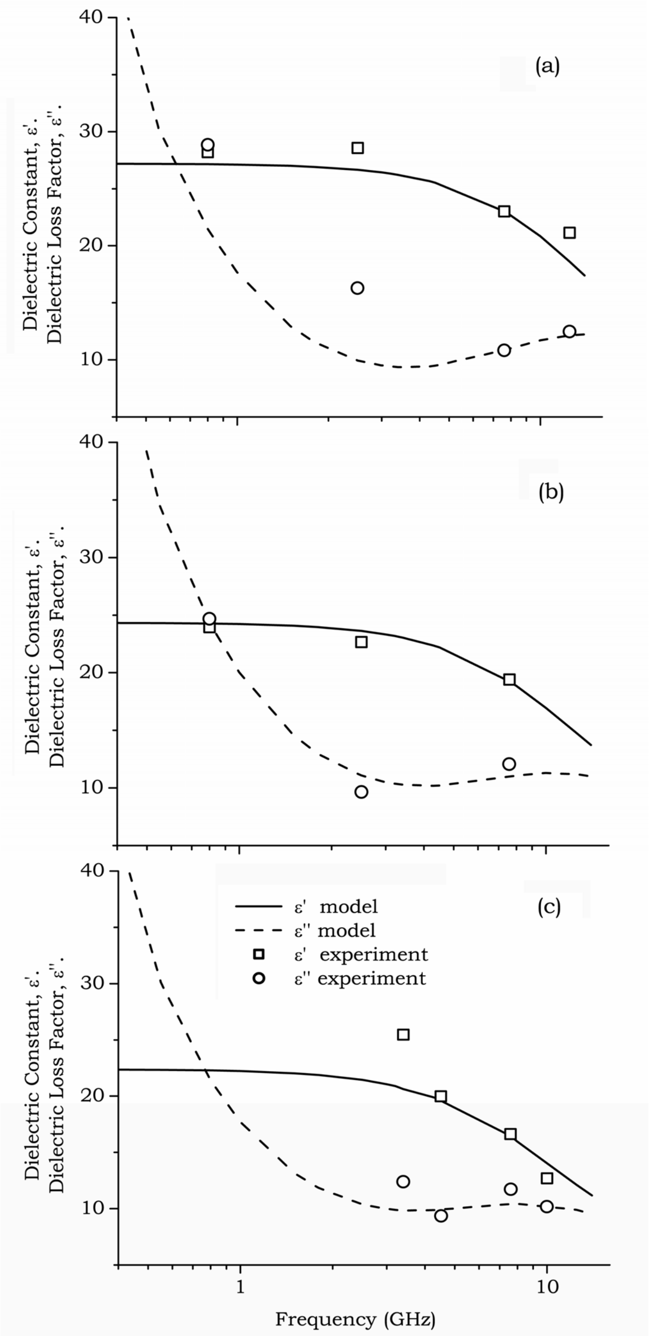

Figure 2. Measured and modeled values of dielectric constant and loss factor of soil bound water as a function of frequency for different types of soil. (a) - soil type 1; (b) – soil type 2; (c) – soil type 3.

REFERANCES

[1] V. L. Mironov, M. C. Dobson, V. H. Kaupp, S. A. Komarov, and V. N Kleshchenko, "Generalized refractive mixing dielectric model for moist soils," in Proc. IGARSS'02, Toronto, Canada, vol.VI, 2002, pp. 3556-3558.

[2] V. L. Mironov, M. C. Dobson, V. H. Kaupp, S. A. Komarov, and V. N. Kleshchenko, "Generalized refractive mixing dielectric model for moist soils," IEEE Trans. Geosci. Remote Sensing, vol. 42, no. 4, pp. 773 – 785, 2004.

[3] V. L. Mironov, and P. P. Bobrov, “Soil Dielectric Spectroscopic Parameters Dependence on Humus Content,” in Proc. IGARSS’03, Toulouse, France, vol. II, 2003, pp. 1106-1108.

[4] V. L. Mironov, P. P. Bobrov, and V. N. Mandrygina, “Bound Water Spectroscopy for the Soils with Varying Mineralogy,” in Proc. IGARSS'04, Anchorage, USA, vol. V, 2004, pp. 3478 - 3480.

[5] V. L. Mironov, “Spectral Dielectric Properties of Moist Soils in The Microwave Band,” in Proc. IGARSS'04, Anchorage, USA, vol. V, 2004, pp. 3474 - 3477.

[6] J. L’Hermitte, , T. Le Toan, M. Grippa and A. Bouvet, “Monitoring the Siberian Boreal Forest Using ENVISAT/ASAR Data: First Analysis Results,” in Proc. IGARSS'04, Anchorage, USA, vol. VII, 2004, pp. 4586 – 4589.

[7] A. H. Shivola, E. Alanen, “Studies of mixing formulae in the complex plane,” in IEEE Trans. Geosci. Remote Sensing, vol. 29, no. 4, 1991, pp. 679-687.

[8] M. C. Dobson, F. T. Ulaby, M. T. Hallikainen and M. A. El-Rayes "Microwave dielectric behavior of wet soil. Part II: dielectric mixing models," in IEEE Trans. Geosci. Remote Sensing, vol. GE-23, no.1, 1985, pp. 35-45.

[9] T. A.Beljaeva, A. P. Bobrov, P. P. Bobrov, O. V. Galjeev and V. N. Mandrygina “Determination of soil dielectric models parameters at various density and humus content using experimental measurement data at frequency band 0,1-20 GHz,” in Earth Obs. Rem. Sens. vol. 18, no.5, 2003, pp. 28-34, (in Russian).