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Optimum Frequency Range for Remote Sensing of Soil Moisture with Various Texture, Density and Organic Matter Content

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***Abstract*—In this article, the frequency range, within which the dependence of reflectivity on soil moisture is invariant respect to changes in soils texture, dry bulk density and organic matter content, has been established. The analysis is based on dielectric measurements of 16 natural mineral nonsaline soils in the frequency range from 45-100 MHz to 2 GHz. The moisture of soils varied from air dry to the field capacity. The clay, silt and sand content in the soil samples are ranging from 0% to 76%, from 1% to 93%, and from 0 to 100%, respectively. The dry bulk density and organic matter content in soil samples are ranging from 0.7 g/cm^3 to 1.8g/cm^3, and from 0.6% to 69%, respectively. As a result, it is shown, that the variations in texture, dry bulk density, and organic matter content of soils have the least effect in the frequency range from 125 MHz to 820 MHz (with minimum at a frequency of 350 MHz) on the dispersion of the dependence of refractive index on volumetric moisture. As an example, the case of smooth bare soil surface remote sensing at a frequency of 435 MHz is considered. It is shown that for the entire set of soils, a single calibration curve for conversion of reflectivity to volumetric soil moisture is sufficient to retrieve soil moisture with a root-mean square error of 2.1% and a determination coefficient of 0.981. The established frequency range can be recommended for microwave remote sensing methods of soil moisture measurement, not depended on soils texture.**

Keywords*—Microwave remote sensing, radiolocation, unmanned aerial vehicle, soil permittivity, soil moisture

I. INTRODUCTION

Currently, electromagnetic methods based on permittivity measurement [1], [2] are widely used to measure soil moisture. Time (TDR) and frequency (FDR) domain reflectometry are contact measurement methods. Ground penetrating radar (GPR) technique, microwave radar and radiometric sensing methods realized on as an unmanned aerial vehicle (UAV), as satellite platforms are remote sensing methods. The TDR and GPR systems use impulses, the frequency spectrum of which is in the range less than ~3 GHz. Industrially produced impedance (HydraProbe, Delta-T ML3) [3], [4] and capacitance (Decagon GS3) [5] FDR probing tools use a single frequency signal with oscillation of about 20-100 MHz [2]. The developed remote sensing methods of soil moisture with using radiometric data from satellites Soil Moisture Active Passive (SMAP) and Soil Moisture and Ocean Salinity (SMOS) [6], passive radar Global navigation satellite system (GNSS), GNSS-reflectometry [7] mainly use the L-frequency band (1.2-1.6 GHz).

TDR and FDR systems measurements are converted to soil moisture based on the widely used Topp's [8] calibration curve: $W = -5.3\ 10^{-2} + 2.92\ 10^{-2}\varepsilon_s\ - 5.510^{-4}\varepsilon_s^2\ + 4.310^{-6}\varepsilon_s^3$. Here ε_s is the real part of complex permittivity of soil. This calibration formula was derived by Topp, based on TDR measurements with using step impulse generator with rise time about 25ps. In this case, as shown in [9], the effective frequency of registered step pulses (commonly used in TDR) lies in the range lower 0.7–1.0 GHz. Moreover, it can be below 0.6 GHz for heavy clay soils. The decrease of the effective frequency of sensing pulse is explained by the frequency dispersion of soils complex permittivity in the frequency range below ~1 GHz. In this frequency range, the frequency dispersion of soils complex permittivity is due to the Maxwell-Wagner (MW) relaxation processes [10], which depending on the soil texture can have different scales both in the strength and in the relaxation frequency [11]. As a result, the TDR and FDR sensors need to be calibrated for each individual soils type in order to perform precise soil moisture measurements. The frequency dependence of soils complex permittivity at frequencies above ~1GHz is determined by the dielectric relaxation of caused by the dipole polarization of bounds and free water molecules. In this frequency range, the complex permittivity of soils is described by dielectric mixing models of Bruggeman [12], de Loor [13], Birchak [14], Dobson [15], Wang, and Schmugge [16], Boyarskii [17], Park [18], Mironov [19]. For soil moisture retrievals in the algorithms of the radiometric SMAP and SMOS satellites (operated on a frequency of 1.4 GHz), the refractive dielectric mixing model [19] is used. This dielectric model [19] describes the soil's permittivity of wide texture variety with accuracy suitable for practical use.

In recent years, new perspectives have been opened in the development of ultrawideband remote sensing radar systems mounted on platforms of small UAV [20]-[22]. This technology allows to combine as a large area and a high spatial resolution of satellite remote sensing methods, as a wide band of sensing impulse used in GPR and TDR systems. However, in the literature, the question of optimal frequency band to soil

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moisture sensing, in the range of which the soil texture and density would minimally impact on the measured permittivity, is poorly studied. In this work, on the basis of an extensive dielectric database of 16 soil samples, the possibility of finding such an optimal frequency range is investigated, for applications to the monostatic radar remote sensing of soils.

II. SOILS DESCRIPTION AND METHODOLOGY OF ANALYSIS

A. *Soil Samples*

The soils dielectric data were selected to cover a wide spectrum of soils texture from sands to heavy clays, with varying density and content of organic matter. The complex permittivity values of soil samples were taken from literature [23]-[25]. The complex permittivity of soil samples was measured by the coaxial-waveguide method at a temperature of 20°C. Characteristics of soil samples are shown in Table I.

TABLE I. SOIL CHARACTERISTICS

No	**Percent (by weight)**				**Density (g/cm^3)**	**Class^1 (USDA)**	***f*(GHz)**	**Ref.**
	Clay	***Silt***	***Sand***	***Organic matter***				
A	76	22	2	-	from <1.4 to 1.7>	C	0.045-25	[23]
B	0	2	98	-		Sa		
C	4	8	88	-		Sa		
D	14	9	77	-		SaL		
E	7	93	0	-		Si		
F	51	48	1	-		SiC		
G	13	32	55	-		SaL		
H	34	64	2	-		SiCL		
I	0	0	100	-		Sa		
J	54	46	0	-		SiC		
K	7	89	4	-		Si		
L	0	1	99	-		Sa		
Wa	30	50	20	0.6	0.7-1.8	SiCL	0.1-10	[24]
Mo	41	57	2	2.3	1.1-1.4	SiC	0.045-15	[25]
Fb	40	41	19	4.2	1.2-1.6	SiC	0.045-15	SA^2
Ro	39	35	26	6.9	1.2-1.5	CL	0.045-15	SA^2

^{1}C-Clay, Sa-Sand, Si-Silt, SaL-Sandy Loam, SiC- Silty Clay, SiCL- Silty Clay Loam, CL-Clay Loam; ^{2}Submitted article (SA).

Soil samples of A-L were taken by the Geotechnical Laboratory at Waterways Experiment Station (U.S.). Wa sample was taken near the river Unstrut in Thuringia, Germany. Mo sample was collected from the mineral soil horizon on the Yamal Peninsula, Russia in the area of Vaskiny dachas. Ro (field 1) and Fb (field 2) samples were taken from the top layer of agrosoil (horizon A_{arable}) in the area of the Minino village, Krasnoyarsk Region.

B. *Simulation Model*

The reflectivity of electromagnetic wave with plane front from soil surface is contained as a function in many radar-backscattering models [26]-[28]. In this regard, the assessment of the frequency range is relevant, within which the reflectivity dependence on soil moisture is invariant for a wide variety of soils texture and density. In the case of nadir-looking monostatic radar sensing of a dielectric-homogeneous half-space of bare soil with smooth boundary, the expression for reflectivity can be written as:

$$\Gamma_0 = \left|\frac{1-\sqrt{\varepsilon_s}}{1+\sqrt{\varepsilon_s}}\right|^2, \qquad (1)$$

where ε_s is the complex permittivity of soil. Further analysis will be carried out for the refraction index $n_s = Re\sqrt{\varepsilon_s}$, which makes the main contribution to the reflectivity value.

C. *Method of Analysis*

At a frequency of 435 MHz, the dependence refractive index on volumetric soil moisture, calculated from the soils complex permittivity database (see Table I) is depicted on Fig. 1. As can be seen from Fig. 1, at a fixed frequency, the dependence of refractive index on volumetric soil moisture has a dispersion relative to some average fitted curve. At a fixed frequency and at a given soil moisture, the dispersion of refractive index are due to different soil texture, density and organic matter content in the soil samples (see Table I).

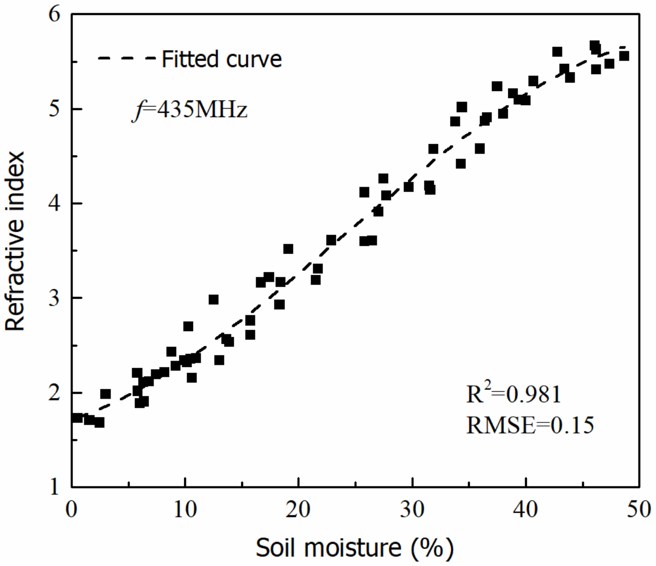

Fig. 1. Refraction index dependence on volumetric soil moisture. Calculation done for a frequency of 435 MHz, based on complex permittivity soil database, see Table I.

The main task of the study is to find such a frequency range within which the observed dispersion of the refractive index (see Fig. 1) would be minimal. For this purpose, at each in the frequencies in the range from 100 MHz to 2 GHz with a step of 25 MHz, the refractive index dependence on volumetric soil moisture was fitted with a polynomial of the third degree. Then, at each frequency, the root-mean-square error ($RMSE_{ns}$) of such fitting was estimated. As an example, the result of third-degree polynomial fitting of the refractive index dependence on volumetric moisture at a frequency of 435 MHz is shown in Fig. 1 by dash line. Known dielectric models for fitting the refractive index dependence on volumetric soil moisture (Fig. 1) were deliberately not used in order to eliminate the influence of dielectric models themselves on the analysis of soils (see Table I) complex permittivity experimental data.

III. RESULT AND DISCUSSION

In accordance with the method described above, the $RMSE_{ns}$ values depending on frequency were found (see Fig. 2). Fig. 2 shows, in the frequency range from 125 MHz to 820 MHz (at a level of 20% of the minimum value at a frequency of about 350 MHz), the minimum values of RMSE are clearly observed. The formation of this local minimum can be explained as follows. At frequencies above ~1 GHz, the complex permittivity of wet soils is determined by the dielectric relaxation caused by the dipole polarization of a bound and free water molecules.

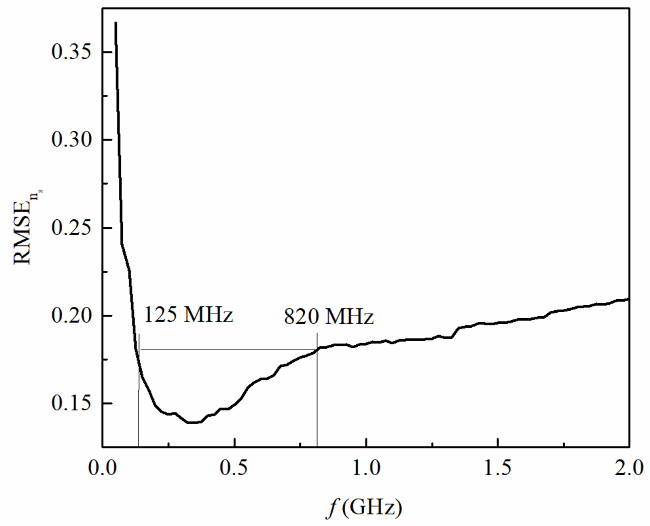

Fig. 2. Root-mean square error dependence on frequency as the result of the third-degree polynomial fitting of experimental data such as depicted on Fig. 1.

At the same time, at a fixed frequency, the complex permittivity of wet soil decreases (increases) with an increase (decrease) in the clay content. The phenomenon occurs due to an increase (decrease) in the content of bound water, the complex permittivity of which is less than that for free soil water. This causes a smooth change in RMSE dependence on frequency for the entire set of soils under consideration (see Fig. 2, frequencies more than ~350 MHz). At frequencies below ~1 GHz, the Maxwell-Wagner relaxation processes are added to the dipole relaxation, due to the polarization of the water-mineral and water-air interfaces, which leads to a sharp increase in the complex permittivity of wet soils. MW relaxation processes are determined by soil microstructure, particle size and surface specific area of water-mineral and water-air interphase boundaries, electrical conductivity of soil solution, and can have different scales both in frequency and intensity of relaxations [10], [11]. In our opinion, the competition between the two relaxation processes of dipole and MW relaxation leads to the formation of this frequency region (see Fig. 2). In this frequency region, the dispersion of refractive index has minimum respect to the variations of soil texture, density and organic matter.

A frequency of 435 MHz from the optimal frequency range (see Fig. 2) was chosen. At a given frequency, the reflectivity according to formula (1) was calculated using soils (see Table I) complex permittivity database values for all available moisture variations. The calculated reflectivities value dependence on volumetric soil moisture are shown in Fig. 3. As can be seen (from Fig. 3), the exponential fitted curve (see a caption to Fig. 3) describes the reflectivity dependence on volumetric soil moisture (W) from 0% to 50%, with RMSE equal of 0.45dB. (For different type, density and organic matter content of soils.) Note that as the volumetric soil moisture increases from 0% to 50%, the reflectivity changes by only ~9 dB from about -12 dB to about -3 dB.

It is noticeable that with an increase in soil moisture, the dispersion of reflectivity decreases respect to the fitting curve. This is due to the fact that with the decreasing of total soil moisture, the percentage of bound water increases, but as bound water content as its complex permittivity depends on clay content.

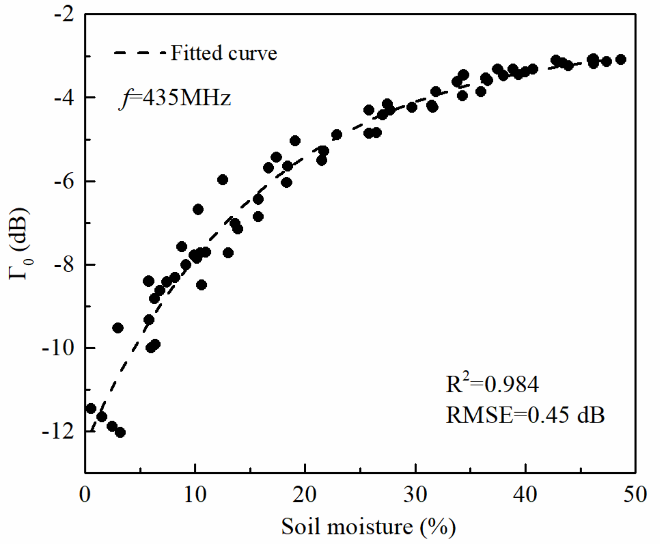

Fig. 3. Reflectivity dependence on volumetric soil moisture at a frequency of 435 MHz. Fitted curve: Γ_0=-2.57-9.77exp(-W/16.18).

The established exponential dependence (see the caption to Fig. 3) between Γ_0 and W makes it possible to analytically express the volumetric soil moisture in terms of reflectivity:

$$W = -16.18 \ln \frac{\Gamma_0 + 2.57}{-9.7}. \tag{2}$$

Using reflectivity values (see Fig. 3, dots), soil moisture values were calculated based on expression (2). The correlation between the retrieved and original values of volumetric soil moisture is shown in Fig. 4.

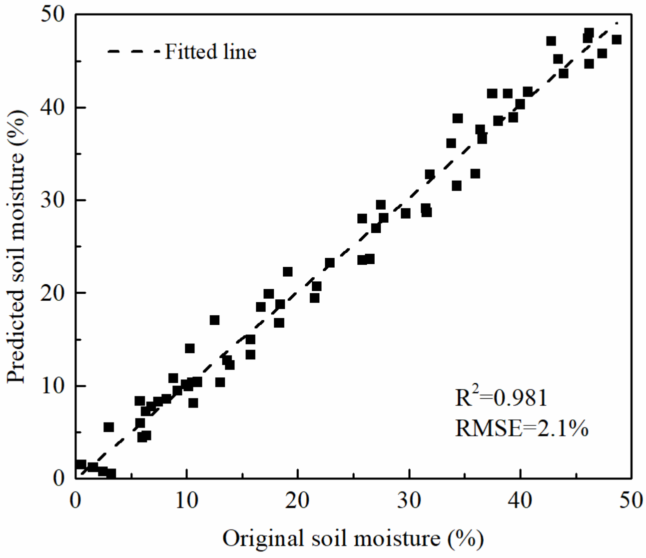

Fig. 4. Predicted vs original values of soil moisture.

From the data presented in Fig. 4, it can be seen that the RMSE in soil moisture determination based on nadir-looking radar remote sensing at a frequency of 435 MHz can be equal of 2.1% for soils with different texture, density and organic matter content.

IV. CONCLUSION

In this work, the frequency range from 125 MHz to 820 MHz was found, within which it is possible to measure soil moisture by dielectric-reflectometry methods with a minimal impact of variations in the texture, density, and organic matter content of natural mineral nonsaline soils. At the same time, for various natural soils, only one calibration curve of reflectivity (or refractive index) dependence on volumetric soil moisture is required for the characteristic frequency of probing tool.

The established MHz-frequency range can be recommended for the development of wideband remote sensing methods to soil moisture retrieval. Compared to the L-band, the MHz-frequency waves are less scattering on soil surface roughness and elements of vegetation canopy, and it penetrates deeper into the soil. For multifrequency or broadband impulse methods of remote sensing soil moisture in the established MHz-frequency range, it is required to create frequency-dependent dielectric models that take into account both dipole and MW relaxation for soil with various textures, density and organic matter content. The development of new dielectric models and radar scattering models in the MHz-frequency range opens up prospects for remote sensing of moisture profiles in topsoil at various soil texture, density and organic matter content in depth.

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