Evaluation of the effective dielectric capacitivity in the near-surface soil

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Abstract. The results of estimate of the effective dielectric permittivity presented. We measured the soil moisture data in a toplayer 2 meters thick. This data used to calculate the view of depth’s dependence of real part of the soil’s complex dielectric permittivity and conductivity. We calculated of soil surface reflectivity at a frequency of 3 and 30 MHz. This data were used to estimate of the soil’s effective dielectric permittivity and conductivity.

1. Introduction

The electromagnetic wave propagation prediction at a high frequency (HF) in a ground-ionosphere waveguide requires knowledge of the radiophysical characteristics of the underlying surface. The results of prediction are necessary for solving practical problems long-distance radio communications and over-the-horizon radar. At now rather large amount of theoretical and experimental studies carried out for development a models of the underlying surface. This models are based on a description of the mid-season conductivity and permittivity for individual geographical areas. The values of permittivity and conductivity are given in the maps obtained as a result of the analysis of the propagation of electromagnetic waves near the underlying surface [1]. Also, these parameters can be calculated by the known content of physical clay in the soil. When calculating the radio propagation paths, it is considered that the parameters of conductivity and permittivity either remain constant or change slightly when the seasons change [2]. However, the dielectric characteristics of soils can change very quickly; for example, in the process of precipitation, infiltration, and evaporation of soil moisture, and during freezing/thawing processes. Moreover, the difference in the values of the complex dielectric permittivity (CDP) before the process and at its end can reach very noticeable values. Also, the dielectric characteristics of soils also noticeably change with depth. These facts determine the relevance of the problem of short-term and operational forecasting of the propagation conditions of decameter radio waves on radio lines for the adaptation of the model description of the underlying surface to the real situation.

The soils on the natural conditions at frequencies above 1 GHz can be considered as a dispersed mixture (a set of components that do not enter into a chemical reaction with each other) of the following components: fragments of minerals, organic matter, air, water and/or ice. The magnetic permeability of these soil components is close to unity. For this reason, the interaction of the electromagnetic field with such a structure depends on the value of its CDP. The CDP of the soil depends on the volume fraction and CDP of each of the components that make up the soil [3]. Currently known that the soil’s CDP mixing dielectric model are empirical and semi-empirical. A theory of dielectric mixtures has not been developed. A relaxation processes strongly affect CDP at frequencies below 1 GHz due to the polarization of interphase boundaries, especially in clay soils with a large specific surface. This leads to an increase in the real and imaginary parts of the CDP with decreasing frequency. However, the International Telecommunication Union has recommended the use of the Dobson model for calculating soil’s CDP (Recommendations ITU-R P.527-4 [4]). This
model is develop on the basis of experimental measurements of the dielectric constant of five soils at frequencies from 1.4 to 18 GHz [5]. The measurements of CDP were carried out under laboratory conditions. The authors [5] have recognized the unsuitability of this model for frequencies below 1 GHz. Later, they published the results of measurements of the CDP of four soils in the frequency range 0.3-1.3 GHz and a new dielectric model [6]. The input parameters of the model are the specific content of the three particle fractions (sand, clay and silt), the density of the dry additive, the volumetric moisture, and the frequency. The Dobson model was widely used in the Earth remote sensing data processing at frequencies above 1 GHz until the beginning of the 21st century [7]. Analytical expressions describing the Dobson model allow calculating CDP values only at relatively high frequencies. Its use at low frequencies is associated with noticeable errors [8]. For this reason, reliable data on CDP at frequencies corresponding to the ranges of HF and VHF waves can be obtained only in the process of nature or laboratory measurements.

So, the currently known approaches to assessing the CDP of the underlying surface in the HF range do not take into account the seasonal variability of the radiophysical characteristics. The underlying surface is considered in the approximation of a homogeneous dielectric medium with losses with a constant CDP value throughout the season. The change in values of CDP with depth is not taken into account.

2. Description of models and approximations

Soil moisture sampling was carried out in the layer thick of 2 meters. The moisture sampling point was located in the south-west of the Omsk region near the Gvozdyovka village. The coordinates of the moisture sampling site were 54° 35' 25'' N and 71° 53' 17'' E. The extraction of soil samples was carried out using a Kachinsky drill. Soil moisture was retrieved by the thermostat-weight method. The complex permittivity and conductivity were measured in laboratory state using the original method developed by one of the co-authors of this paper [9]. The reflectivity was estimated using the model valid for a two-layer medium (see Fig. 1a) [10]:

\[
R_p = \left| r_p \right|^2 = \frac{r_1 + r_1 \exp(-2 j k_2 \Delta Z_2)}{1 + r_1 r_2 \exp(-2 j k_2 \Delta Z_2)}; \tag{1a}
\]

where \( R_p \) is reflection coefficient by power, \( r_p \) is complex amplitude reflection coefficient, \( r_2 \) is Fresnel reflection coefficient at the upper boundary, \( r_1 \) is reflection coefficient from a semi-infinite medium below the first layer; \( k_2 = k_0 (\varepsilon_2 \sin^2 \theta)^{1/2} \), \( \Delta Z_1 \), \( \varepsilon_1 \) is characteristics of the first layer - the projection of the wave number on the vertical axis, the thickness and the CDP of the first layer, respectively; \( k_0 = 2 \pi / \lambda \) wave number in a vacuum, \( \theta \) is the angle of the wave incidence. However, this model is applicable for calculating the reflectivity of soil with an arbitrary type of dependence of the dielectric constant with depth. So, the topsoil is divided into \( N \) layers, within which the dielectric characteristics were considered constant. The reflection characteristics from such a structure were estimated during iterative use of the species (see Fig. 1b):

\[
R_p = \left| r'_n \right|^2 = \frac{r'_{n} + r'_{n-1} \exp(-2 j k_{2n} \Delta Z_{2n})}{1 + r'_{n} r'_{n-1} \exp(-2 j k_{2n} \Delta Z_{2n})}; \tag{1a}
\]

where \( r'_{n} \) is Fresnel reflection coefficient at the upper boundary \( n \), \( r'_{n-1} \) is reflection coefficient from a layered medium lying below layer \( n \).
Figure 1. The representation of the surface soil layer as a layered structure: (a) a two-layer medium, (b) a multilayer medium.

3. Model results
The view of soil moisture profiles are shown in Fig. 2. The real part of CDP and conductivity on the depth were calculated with relationship between CDP and soil moisture measured in laboratory. The view of depth's dependence of real part of CDP and conductivity shown on the Fig. 3-5.

Figure 2. The view of the depth's dependence of volumetric soil moisture in a layer of 2 meters. (1) is measurements 05/12/2018, (2) is measurements 04/06/2018, (3) is measurements 07/19/2018.
Figure 3. The view of depth's dependence (a) real part of the CDP and (b) conductivity in a 2-meter layer, measurements from 05/12/2018. (1) is frequency at 30 MHz, (2) is frequency at 3 MHz.

Figure 4. The view of depth's dependence (a) real part of the CDP and (b) conductivity in a 2-meter layer, measurements from 06/04/2018. (1) is frequency at 30 MHz, (2) is frequency at 3 MHz.

Figure 5. The view of depth's dependence (a) real part of the CDP and (b) conductivity in a 2-meter layer, measurements from 07/19/2018. (1) is frequency at 30 MHz, (2) is frequency at 3 MHz.
It is noticeable that as the soil moisture evaporates, the shape of the moisture profile noticeably changes. The values of the reflection coefficient from such a structure were determined using expression (1b). Subsequently, the found values of the reflection coefficient were used to search for the effective values of the dielectric constant and conductivity. To do this, we searched for such values of the real part of the CDP and the conductivity of a homogeneous medium for which the value of $R_p$ from its surface was equal to $R_p$ from the layered medium. The values found in this way are shown in table 1.

| Date          | 3 MHz  | 30 MHz  |
|---------------|--------|---------|
| 05/12/2018    | 0.207  | 0.242   |
| 06/04/2018    | 0.206  | 0.290   |
| 07/19/2018    | 0.110  | 0.105   |

As can be seen from the above data, the effective values of permittivity and humidity vary markedly. Moreover, the temporal variability of these parameters at a frequency of 3 MHz is manifested to a lesser extent than at 30 MHz. This is explained by the greater thickness of the skin layer at a frequency of 3 MHz and the lower variability of soil moisture at depths of more than 1 meter.

4. Conclusion
The measurements showed that changes of soil moisture in the top layer during the period of intensive evaporation can reach significant values. The effective values of the radiophysical characteristics also undergo noticeable changes. The temporal variability of the effective values of the real part of the CDP and conductivity at a frequency of 3 MHz is less than 30 MHz. It is explained by the peculiarity of changes in the values of soil moisture and the difference in the thickness of the skin layer at different frequencies.

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