Radiophysical methods for modelling frozen soils dielectric permittivity in the southern Vitim plateau (Eastern Siberia, Russia)

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Abstract. The article presents the results of applying the radiophysical method for modelling the dielectric permittivity on the example of Haplic Chernozem Molliglossic soils in the south of the Vitim plateau, depending on VHF and UHF wavelengths, temperature, and soil moisture. Depending on the heterogeneity of moisture reserves and heat content, the soil is considered as a three-layer medium with different soil characteristics. A difference in the frequency dispersion of the complex dielectric permittivity over the entire soil profile in the VHF and UHF ranges has been established.

1. Introduction
Russia is a country where 65\% of the territory is located in the permafrost zone. Most of the territory of Transbaikalia is characterized by soil formation in constant or prolonged contact with ice strata, in conditions of negative mean annual temperatures, high continentality and annual heat turnover [1, 2]. The southern border of the permafrost passes through the south of the Vitim plateau and the north of the Selenga midlands in Transbaikalia [3]. It is here, in the transition zone from continuous permafrost to island one, that the dynamics of temperature, water, and permafrost soils regimes, caused by global and regional climate changes, are most clearly manifested. Therefore, the purpose of this communication is to introduce new approaches to be used to study the regime characteristics of soils in permafrost spreading conditions. Due to the ability of centimetre and decimetre radio waves to penetrate deep into the soil, microwave sensing makes it possible to remotely determine physical characteristics of soils, such as mechanical composition, temperature and humidity conditions [4, 5]. In this context, the soil’s effective dielectric permittivity is a main variable for quantifying the properties of the ground’s surface [6, 7]. Such measurements enable non-destructive diagnostics and highly accurate estimates of soil physical properties [8]. To date, significant progress has been made in the field of radiometry and ground-penetrating radiolocation, opening up the possibility of wide application of microwave sensing techniques to diagnose the physical condition of soils. In order to solve the problems of soil physical parameters recovery it is necessary to obtain dependences between the complex dielectric permittivity and the required parameters. For this purpose, the present work investigates the influence of soil parameters on the dielectric and, respectively, radiative characteristics of soils.
2. Objects and methods
Radiophysical methods of studying the properties of material media based on the interaction of electromagnetic waves of ultrahigh frequency range with matter can be used to analyse the dielectric properties of soils [4]. The character of interaction of radio waves with them is determined by the value of the complex dielectric permittivity (CDP) of soils under study.

The study object is the Haplic Chernozem Molliglossic of the Yeravninskaya depression (south of the Vitim plateau), which occupies the lakeside and plain meadow-steppe landscapes of the Yeravninsky district of the Republic of Buryatia. These soils have high potential fertility, the realization of which in the form of bioproduction of cultivated plants is inhibited by insufficient heat supply and poor moisture in the upper root-containing layers [9].

The studies were carried out at the Yeravninsky forest-steppe permafrost ecological station (52°31’ N, 111°32’ E). The geographic position of the object of research is shown in figure 1, where these soils are formed in the transition zone from continuous permafrost to island permafrost.

Figure 1. Map of the distribution of permafrost types [3] and the scheme of the atmosphere and soil measurement complex (ASMC).

Haplic Chernozem Molliglossic is characterized by a loamy dark humus horizon with high humus content, a neutral reaction, and a fine-lumpy structure with elements of nut structure. Yellow-brown moist heavy-loamy carbonate horizon with a lumpy-nutty structure appears from 53 (65) cm. Frost cracks and cryoturbations, inclusions of cartilage, and gravel are found throughout the soil profile. Soil moisture increases with depth. Permafrost is permanent at a depth of 275-280 (300) cm.

In terms of physical and chemical properties, Haplic Chernozem Molliglossic soils are agronomically favourable. In the accumulative horizons, the humus content is 5.6-12.4%, the exchange capacity is large (12-17 mmol (eq)/100 g of soil) [9]. Calcium and magnesium predominate.
in the composition of exchangeable cations. The reaction of the media is close to neutral; with the transition to carbonate horizons, it is replaced by a slightly alkaline one.

Low air temperature and the absence of snow cover causes strong cooling of the soil, which also promotes an increase in the thermal conductivity coefficient and a decrease in the volumetric heat capacity of the soil in a frozen state. The accumulation of heat in soils is slow. The lower layers are constantly cold and therefore abiogenic.

The investigated soils can be considered as compound dielectric with losses. This dielectric includes dry soil and water with salts dissolved in them [10]. Further, the permittivity of dry soil, in this case, can be considered purely material and independent of the frequency of electromagnetic radiation. The dielectric properties of water can be described by the Debye formula, taking into account the ionic conductivity of salts dissolved in water. In this article, the soil profile, depending on the heterogeneity of moisture reserves and heat content, is considered in the form of a three-layer model [1] at depths of 0-50 cm, 50-100 cm, 100-200 cm. Expressions (1–3) for these soil layers were obtained from the ratios given in [10, 11]:

\[
\varepsilon_{\Pi}(f) = 1 + 0.7d_1 \left(5 + \frac{83 - 0.4t + 8 \times 10^{-4} t^2}{1 + i[19 - 0.026 t + 1.45 e^{-0.063}]} - i 60 \frac{c}{f} \sigma_0 (1 + 0.04 t^2) \right) W_1 + 1
\]

\[
\varepsilon_{\Pi}(f) = 1 + 0.7d_2 \left(5 + \frac{83 - 0.4t + 8 \times 10^{-4} t^2}{1 + i[19 - 0.026 t + 1.45 e^{-0.063}]} - i 60 \frac{c}{f} \sigma_0 (1 + 0.04 t^2) \right) W_2 + 1
\]

\[
\varepsilon_{\Pi}(f) = 1 + 0.7d_3 \left(5 + \frac{83 - 0.4t + 8 \times 10^{-4} t^2}{1 + i[19 - 0.026 t + 1.45 e^{-0.063}]} - i 60 \frac{c}{f} \sigma_0 (1 + 0.04 t^2) \right) W_3 + 1
\]

where $\varepsilon_{\Pi}$, $\varepsilon_{\Pi}$, $\varepsilon_{\Pi}$ – are the complex dielectric permittivity or layers 0-50, 50-100, and 100-200 cm of soil, respectively,

\(d\) – is the specific gravity of dry soil (the bulk density in [2]),

\(t\) – is the temperature of the soil,

\(W\) – is soil moisture (% of soil mass),

\(\sigma_c\) – is specific conductivity of the electrolytic solution at \(t = 0^\circ C\), and for chernozem soils \(\sigma_c = 0.05 \text{ S/m}\).

Expressions (1–3) are applicable for the temperature range from 0 to 50°C. The lowest thawing depth, when all values along with the temperature profile from the zero levels to a depth of 200 cm, become above 0°C, falls in September. The parameters \(d\), \(W\), and \(t\) for modelling were calculated from the values from [9] for this period. All nature parameters are averaging over depth, i.e. each parameter for the entire thickness of a given layer has one value. The calculated parameters are presented in table 1.

| Table 1. Parameters of Haplic Chernozem Molliglossic. |
|----------------|------|--------|---|
| Depth, cm      | \(d\), g/cm³ | \(W\), % | \(t\), °C |
| 0 – 50         | 1.28  | 22     | 10.5 |
| 50 – 100       | 1.52  | 44     | 8    |
| 100 – 200      | 1.72  | 48     | 4    |

3. Results and Discussion

When performing remote sensing tasks, it is necessary to interpret the results obtained. Figure 2 shows the calculated frequency dependences of the real (a) and imaginary (b) parts of the CD for the considered soils.
Figure 2. Frequency dispersion of the real (a) and imaginary (b) components of the CDP for investigated soils.

The above curves show the presence of frequency dispersion of the dielectric constant in the microwave range for the given soil characteristics. It can be seen that with changes in frequency the values of the permittivity vary within a wide range and the imaginary part takes on quite large values. At frequencies above 1000 MHz, both the real and imaginary parts of the CDP decrease for all soil horizons, it merges practically into one line. The frequency dispersion of soils is mainly determined by the presence of water, the relative quantitative content of which has the greatest effect on the dielectric properties of soils [12-14]. The modelling of the dielectric permittivity of soils is an important element of physical algorithms for obtaining soil moisture parameters using remote sensing data from modern radiometric and radar satellites [15].

The frequency dispersion of the CDP appears in all layers of the investigated soil. At the lower boundary of the frequencies of the microwave range, the values of the real and imaginary components of the CDP in the upper soil horizon (0-50 cm) are significantly lower than in the underlying horizons. This is due to its significantly lower moisture content.

Moisture from the upper soil layers is used by plants, partly evaporates or flows downwards, where it is retained by the denser (50-100 cm) and colder (100-200 cm) lower layers, as well as with the presence of groundwater during permafrost thawing.

4. Conclusion
The study of the complex dielectric permittivity, made for Haplic Chernozem Molliglossic, demonstrates the frequency dispersion in all layers, a decrease in both the real and imaginary parts of the CDP from the low-frequency to the high-frequency region. The lowest CDP value is observed in the upper soil layer; with the depth, the CDP increases by more than two times in the range from 30 MHz to 1 GHz and higher. This is associated with the influence of soil moisture on the CDP at the parameters considered.

Acknowledgments
The work was carried out with financial support of the research projects No. 0270-2021-0004, No. 121030100228-4, RFBR grant No. 19-29-05250 mk.
References
[1] Kulikov A, Dugarov V and Korsunov V 1997 Permafrost Soils: Ecology, Heat Balance Capacity, and Productivity Forecast (Ulan-Ude: BSC SB RAS) p 312
[2] Kulikov A, Badmaev N, Sympilova D and Gyninova A 2019 The use of the value of heat cycle to assess the energy stability of permafrost soils at the change of conditions on the surface *Geosciences* **9**(3) 112
[3] Badmaev N and Bazarov A 2019 Monitoring network for atmospheric and soil parameters measurements in permafrost area of Buryatia, Russian Federation *Geosciences* **9**(1) 6
[4] Komarov S and Mironov V, 2000 *Microwave Sounding of Soils* (Novosibirsk: Nauka) p 289
[5] Mironov V, Kerr Y H, Wigneron J-P, Kosolapova L and Demontoux F 2013 Temperature and texture dependent dielectric model for moist soils at 1.4 GHz *IEEE Geosci. Remote Sens. Lett.* **10**(3) 419–23
[6] Park C H, Behrendt A, LeDrew E, and Wulfmeyer V 2017 New approach for calculating the effective dielectric constant of the moist soil for microwaves *Remote Sensing* **7**(9) 732
[7] Wu Y, Wang W, Zhao S and Liu S 2015 Dielectric properties of saline soils and an improved dielectric model in C-band *IEEE Trans. Geosci. Remote Sens.* **53**(1) 440–52
[8] Shamir O, Goldshleger N, Basson U and Reshef M 2018 Laboratory measurements of subsurface spatial moisture content by ground-penetrating radar (GPR) diffraction and reflection imaging of agricultural soils *Remote Sensing* **10**(10) 1667
[9] Kulikov A, Panfilov V and Dugarov V 1986 *Physical Properties and Regimes of Meadow-Chernozemic Permafrost Soils in Buryatia* (Novosibirsk: Nauka) p 137
[10] Redkin B, Klochko V, Khokhlachev V and Babushkin V 1975 Theoretical and experimental studies of the complex dielectric permittivity of soils in the VHF range *Radio Eng. Electron. Phys.* **20**(1) 164–5
[11] Tsydypov C, Tsydenov V and Bashkuev Y 1979 *Study of the Electrical Properties of the Underlying Environment* (Novosibirsk: Nauka) p 176
[12] González-Teruel J D, Jones S B, Soto-Valles F, Torres-Sánchez R, Lebrón I, Friedman S P and Robinson D A 2020 Dielectric spectroscopy and application of mixing models describing dielectric dispersion in clay minerals and clayey soils *Sensors* **22**(20) 1–18
[13] Jin X, Yang W, Gao X and Li Z 2020 Analysis and modeling of the complex dielectric constant of bound water with application in soil microwave remote sensing *Remote Sensing* **21**(12) 3544
[14] Liu J and Liu Q 2020 Soil moisture estimate uncertainties from the effect of soil texture on dielectric semiempirical models *Remote Sensing* **12**(14) 2343
[15] Savin I, Mironov V, Muzalevskiy K, Fomin S, Karavayskiy A, Ruzicka Z and Lukin Y 2020 Dielectric database of organic Arctic soils (DDOAS) *Earth System Science Data* **4**(12) 3481–7