Effects of temperature on soil dielectric permittivity measured in time and frequency domains

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Abstract

Measuring the electrical permittivity of soil is currently the basic method of determining its water content using commercially available sensors and meters. However, the relationship between permittivity and soil water content is also determined by other factors including soil texture, salinity, and temperature. The paper presents the electrical permittivity of various soil samples at different temperatures measured by using two techniques: Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR). In the first one, the apparent electrical permittivity is determined from the propagation time of an electric pulse along a metallic and parallel transmission line placed in the soil. The applied frequencies are not exactly defined as the measured material acts as a filter. Therefore, the TDR-measured soil dielectric permittivity is named as bulk soil dielectric permittivity ε_b. The FDR technique measures the soil complex electrical permittivity for each frequency from the range 20 MHz - 3 GHz using a setup with a coaxial cell filled with soil.

The results showed complicated temperature behavior of soil dielectric spectrum, depending on water content, salinity, frequency, and texture. Also, the parameters of a permittivity/moisture conversion function were established at various temperatures and frequencies.

1. Introduction

Most of the physical, chemical, and biological properties of porous materials, including soil, are determined by water content θ and temperature T that condition almost all processes occurring in the natural environment. Temperature sensors of various accuracy and sizes are readily available and, along with the necessary electronics, can be easily accommodated in the sensor housing of your choice. Soil moisture sensors pose more problems because they do not directly measure soil water content, but its dielectric permittivity, as the most used moisture indicator. Dielectric measurements enable rapid, non-destructive, and easily automated soil moisture measurements. Dielectric sensors typically fall into one of two groups: (i) time-domain devices, which are accurate but can be expensive, or (ii) frequency-domain devices, which are usually more cost-effective, but primarily for instruments operating at frequencies of several dozen megahertz, may not be accurate enough due to dielectric dispersion caused by factors such as texture, salinity, or temperature [1].

The study is aimed to present the effect of temperature on the soil apparent dielectric permittivity measured by TDR technique in the temperature range from 5°C to 55°C and the effect of temperature on the soil complex dielectric permittivity measured by FDR technique in the temperature range from 0.5 to 40°C and in the frequency range from 20 MHz to 3 GHz, which covers the operating frequencies of many popular soil moisture sensors. Data obtained in this area could also be used to improve algorithms for collecting moisture from soil using remote sensing operating in the microwave L-band. Also, knowing the actual impact of temperature on the complex dielectric permittivity of the soil could improve the calibration functions and measurement accuracy of time and frequency-domain devices. The more detailed description of the applied TDR and FDR equipment can be found in [2] and [1], respectively.

2. Material and Methods

2.1 TDR Technique Measurements

TDR measurements were performed in laboratory on 19 various mineral soils collected from local area mainly from the topsoil layer.

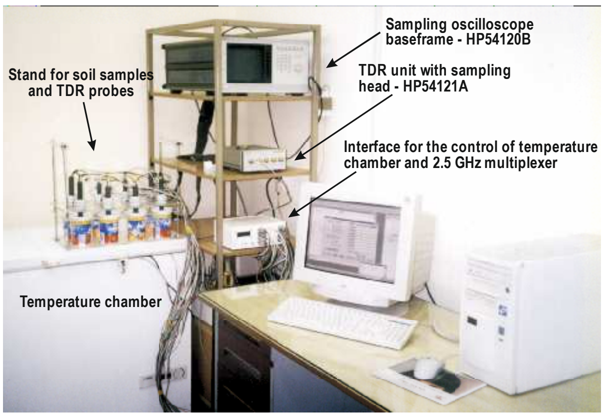

Figure 1. Picture of the TDR measurement setup.

Soil density and specific surface area S of the tested soil samples varied from 1.04 to 1.70 g/cm^3 and 9 to 83 m^2/g, respectively. Sand, silt, and clay in tested soils differed from 52, 5, 1 to 97, 34, 83 (in %), respectively.
The measurement unit was an oscilloscope frame HP54120 with the TDR unit HP54121T of 12 ps electric pulse risetime. The TDR probe was made of two parallel stainless-steel rods with length, diameter, and distance between the centers of the bars of 100, 2 and 16 mm, respectively [3]. The temperature chamber consisted of a freezer, a fan-heater inside it, and an additional fan to minimize temperature gradients inside the chamber. The picture of the TDR measurement setup is presented in Figure 1.

2.2 FDR Technique Measurements

Complex dielectric permittivity spectra of soil samples were measured with the use of a six-channel version of a coaxial cell transmission-line system [1]. The six-cell configuration was chosen to shorten the time necessary for the experiment while maintaining the system compact enough to fit inside a thermal enclosure. A single port reflectometer R60 (Copper Mountain Technologies, USA) was connected via a switch and Type-N/EIA 1 5/8" adapters to six sample holding cells, which were terminated on the other ends by an electronic calibration unit (ECUs) with four states (open, short, offset short and a matched load). The schematic overview of the system is presented in Figure 2.

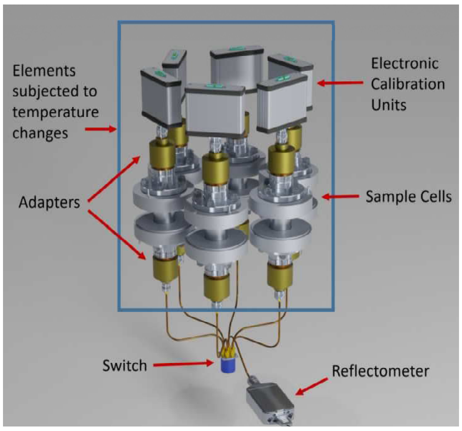

Figure 2. Schematic overview of the system. Blue frame indicates the elements around which a thermally insulated enclosure was constructed and connected to the temperature chamber.

Measurements of reflection coefficients of the cell terminated with those four states enabled the recovery of the scattering matrix and subsequent calculation of complex dielectric permittivity spectrum of the sample under test with the use of a nonlinear least-squares algorithm. The sample was held in a fragment of a coaxial transmission line with the use of plastic supports equipped with rubber orings to prevent any leakage or evaporation. The position of the supports was adjustable, enabling measurement of samples of various volumes, which in the present experiment varied from 26.3 to 40.3 cm^3.
Samples of three types of soil were tested: silt loam, sandy loam, and loamy sand. Density of the samples varied from 1.29 to 1.91 gcm^{-3} with an average of 1.65 gcm^{-3}, which corresponded to dry bulk density range from 1.17 to 1.65 gcm^{-3} with an average value of 1.42 gcm^{-3}. The inner diameter of the sample cells was equal to 3.88 cm. The quality of the calibration was examined before each sweep by measuring a cell filled with a polycarbonate sample in each channel. The samples under test, the six-cell system was placed in an insulated enclosure connected to a temperature chamber.
To decrease the impact of complex dielectric permittivity ε^* measurement errors at respective frequencies and to determine direct current bulk electrical conductivity of the samples σ_{dc}, the three-pole Debye model with σ_{dc} term:

$$\varepsilon^* = \varepsilon_\infty + \sum_{i=1}^{3} \frac{\Delta\varepsilon_i}{1 + j\omega\tau_i} - j\frac{\sigma_{dc}}{\omega\varepsilon_0} \qquad (1).$$

was fitted to all spectra with the use of the nonlinear-least-squares algorithm implemented in the Matlab software environment. In Equation (1) ε_∞ stands for high-frequency real permittivity limit, $\omega = 2\pi f$ where f is the frequency of the electric field, τ_i and $\Delta\varepsilon_i$ are relaxation time and amplitude of an i-th pole, respectively, ε_0 is the vacuum permittivity and j is the imaginary unit.

3. Results

3.1 TDR Measurement Results

The tested soils were divided into groups with the soil specific surfaces below 12 m^{2}g^{-1}, between 20 and 35 m^{2}g^{-1} and above 37 m^{2}g^{-1}. The calibration curves taken for the tested soils are trend lines of 2nd degree polynomials fitted to the data pairs [θ, $\varepsilon_b(T)$] collected experimentally at six applied temperatures from 5°C to 55°C with 10°C steps. The first group of soils had TDR calibration curves close to the Topp equation [4], while with the increase of the soil specific surface, S, as well as the decrease of bulk density, ρ, the ε_b values were below it. This agrees with other reports [5] showing the influence of S and ρ on the soil moisture calibration of the TDR method. The highest difference in ε_b in the analyzed temperature increase was observed in the highest moisture of brown soil marked as 569 and was equal to -3.49. This soil was characterized by low density ρ = 1.33 gcm^{-3} and high sand content (73%). The temperature decrease of ε_b corresponds to the decrease of calculated $\theta = 0.037$.
The calibration curves for each soil taken for different soil temperatures meet at a characteristic point, named for the purpose of this study - the equilibrium water content, θ_{eq}, where the physical phenomena responsible for the temperature effect of soil dielectric permittivity equalize as shown in Figure 3.

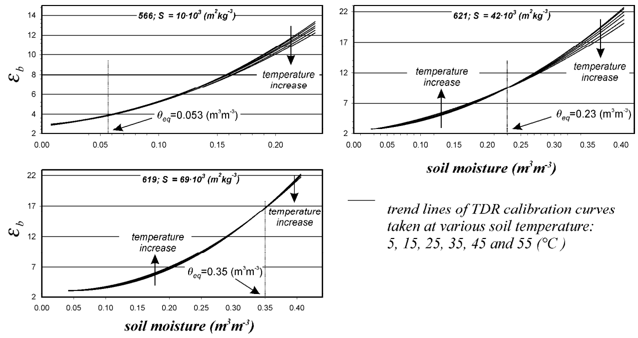

Figure 3. TDR calibration curves for three tested soils at different temperatures.

For water contents below θ_{eq}, the soil ε_b measured at 5°C is smaller than the one measured at 55°C and for water contents above θ_{eq} the change of ε_b with temperature is opposite. The observed temperature effect of soil dielectric permittivity confirms the theory given in [6] as the effect of two opposite phenomena:

- the increase of soil temperature causes the release of free water molecules from the soil solid phase and consequently the increase of ε_b,
- the increase of soil temperature causes the decrease of dielectric permittivity of free water molecules and consequently the decrease of ε_b.

The value of ε_b for air-dry soils does not depend on temperature. With the increase of soil moisture from air dry, there is an increase of ε_b with temperature. All soils except one (soil 562) have higher values of ε_b for 5°C than 55°C at high water contents, and the biggest difference is observed for the soils having medium values of *S*. For the soil 562, there was no equilibrium water content observed in the analyzed temperature range, although this soil does not have the highest value of specific surface area from all the tested soils. The bulk dielectric permittivity for this soil was higher at 55°C than for 5°C from air dry state to almost saturation. The abnormal behavior of ε_b of the soil 562 can be explained as the result of:

- the increase of conductivity with temperature and consequently decrease of velocity of propagation of EM in the soil, or
- the temperature determined release of bound water from the solid phase of this soil was present even for the very wet, almost saturated soil.

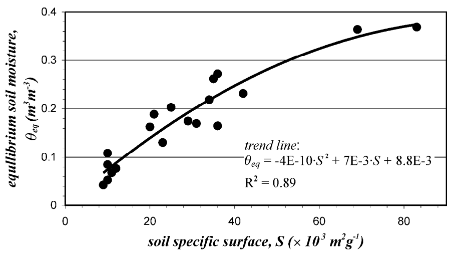

Figure 4. Empirical relation between the equilibrium water content, θ_{eq}, and soil specific surface *S* for the tested soils.

The value of soil moisture at the equilibrium point, θ_{eq}, depends on the amount of bound water attracted by the soil, that is described by equation (1). The relation between the equilibrium water content, θ_{eq}, and the specific surface for the tested 19 soils, except the soil 562, is presented in Figure 4.

The good correlation between *S* and θ_{eq} confirms the assumed physical description of the processes involving the temperature effect of soil dielectric permittivity.

3.2 FDR Measurement Results

The dielectric spectra of two silt-loam soil samples were measured at different temperatures represented by point series and lines corresponding to the model from equation (1) fitted to the spectra are shown in Figure 5. Both samples were prepared with a KCl solution of σ_{KCl} = 1.0 Sm^{-1}.

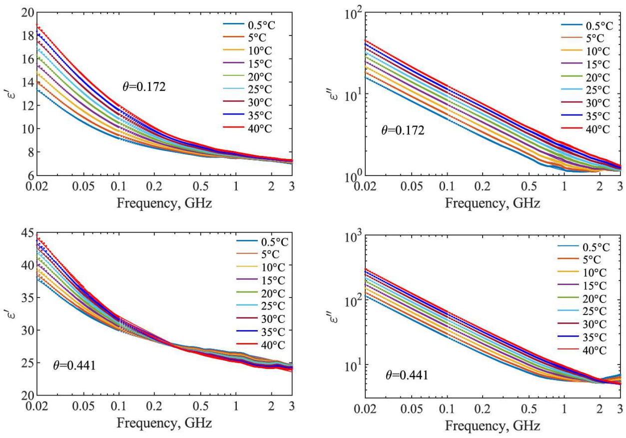

Figure 5. Real *ε'* and imaginary *ε''* parts of complex dielectric permittivity as functions of frequency at various temperatures for two samples of silt loam soil of two levels of volumetric water content *θ* given in the graphs.

In the case of a drier sample, the real part of dielectric permittivity increased with increasing temperature in the entire frequency range tested. The increase in *ε*′ with increasing temperature may be caused by an increase in dielectric dispersion due to an increase in bulk electrical conductivity, affecting interfacial phenomena and/or the release of bound water to the free water state. However, in the case of the second presented sample with a higher water content, *ε*′ increased with increasing temperature only at frequencies below about 300 MHz, and the effect of temperature changes was minimal. At higher frequencies, *ε*′ decreased with increasing temperature, which corresponds to the effect of temperature on the permittivity of free water.

The imaginary part of the dielectric permittivity increased with increasing temperature of both samples due to the increase in bulk electrical conductivity. For the sample with higher moisture content, at frequencies higher than approximately 2 GHz, the opposite behavior occurred, which may have been due to the increase in the relaxation frequency of free water with increasing temperature. The influence of temperature on the modeled spectra *ε*′ of samples of various *θ* and σ_{KCl} of the moistening solution for the three tested soils is presented further in Figure 6.

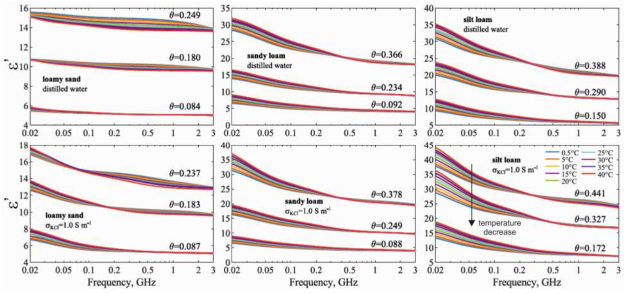

Figure 6. Real part of complex dielectric permittivity at various temperatures for samples of three tested soils of various θ and σ_{KCl} of moistening solutions.

The results showed that the effect of temperature on ε' depends on frequency, soil texture, water content and electrical conductivity of the liquid used to prepare the sample.

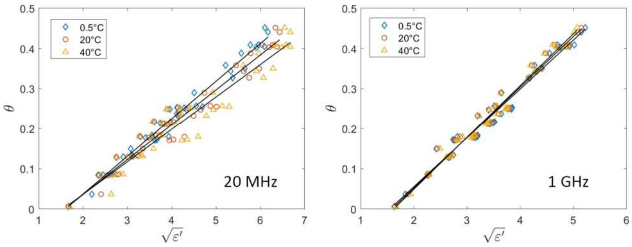

Figure 7. Relations between θ and $\sqrt{\varepsilon'}$ for all samples of all tested soils at selected frequencies and temperatures given in the graphs. Lines represent the fitted model according to the applied linear model at respective temperatures.

Linear model for all tested temperatures and frequencies $\theta = a\sqrt{\varepsilon'} + b$ was fit to the data using Matlab's *fitlm* function. Figure 7 shows graphs for selected frequencies and temperatures along with lines corresponding to this linear model. As expected, the greatest impact of temperature on the $\theta\left(\sqrt{\varepsilon'}\right)$ relationship occurred at the lowest tested frequency.

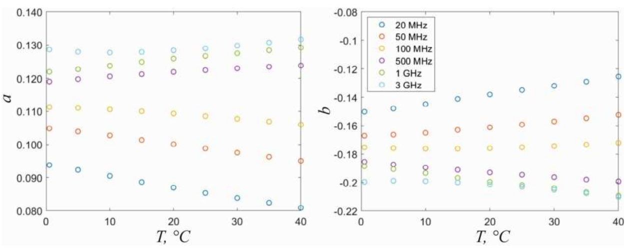

Figure 8. Temperature dependence of the a and b parameters of the linear model fitted to data obtained from all measured samples and at selected frequencies given in the legend.

The values of a and b varied with temperature at different frequencies (see Figure 8), i.e. the parameter a increased with increasing temperature at higher frequencies and decreased at lower frequencies, and the parameter b decreased with increasing temperature at higher frequencies, while its values increased or remained relatively stable at lower frequencies.

4. Conclusions

The influence of temperature on the dielectric spectrum of loamy sand, sandy loam and silt loam soils was studied at temperatures from 0.5 to 40°C in the frequency range from 20 MHz to 3 GHz. The results confirmed the complex dependence of dielectric permittivity on temperature, resulting from several competing mechanisms. This relationship varied between the tested soils. Parameters influencing this behavior included water content, salinity, texture, specific surface area, and frequency. For practical purposes, it can be argued that the output of dielectric soil moisture devices operating at lower frequencies, such as tens of MHz, may be much more temperature dependent than that of high frequency devices, especially if the low frequency device is placed in soil characterized by high dielectric dispersion resulting from interfacial phenomena with relatively low water content. The parameters of the linear conversion function between soil moisture and the square root of dielectric permittivity were determined at different frequencies and temperatures. Accurate quantification of the different dielectric mechanisms and their temperature dependence requires testing of many different soils under different moisture, salinity, and temperature conditions, as well as further research in dielectric modeling. Work is underway on a new version of the coaxial cell system with an extended frequency range and a set of sample placement tools.

5. Acknowledgements

This work was supported by the Polish National Centre for Research and Development (NCBR), Agreement No. TANGO-V-C/0007/2021-00.

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