Measurement of Soil Dielectric Permittivity Spectra at Various Temperatures

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***Abstract*—Dielectric sensors are a popular choice for soil moisture measurement. However, soil dielectric permittivity depends not only on moisture content but also on several other properties, including temperature. The aim of this research is to examine the impact of temperature on soil complex dielectric permittivity spectra in the 0.02-3 GHz frequency range. Soil samples were measured in coaxial cells connected to a vector-network-analyzer. The results indicated that the influence of temperature on dielectric permittivity depended on frequency and moisture content.**

Keywords—dielectric permittivity, coaxial cells, VNA, soil moisture, temperature

I. Introduction

Among soil moisture determination methods, dielectric techniques enable fast, nondestructive and easy-to-automate measurements. Dielectric sensors usually belong to one of the two groups: (i) devices operating in the time domain, which are accurate but may be expensive, or (ii) devices operating in the frequency domain, which are usually more cost-effective, but, especially in the case of instruments operating at frequencies of tens of megahertz, may not be accurate enough due to dielectric dispersion caused by the influence of factors such as texture, salinity or temperature [1,2]. Therefore, knowledge of the actual impact of these factors on soil complex dielectric permittivity could improve calibration functions and measurement accuracy of the devices operating in the frequency domain.

The aim of the presented research was to examine the influence of temperature in the range from 0.5 to 40°C on the complex dielectric permittivity of samples of a sandy loam soil in the frequency range from 20 MHz to 3 GHz, which covers frequencies of operation of many popular soil moisture sensors. The data obtained in this range could also be used for improvement of soil moisture retrieval algorithms using remote sensing working in the microwave L-band.

II. Materials and Methods

A. Experimental System

Complex dielectric permittivity ε* was measured with the use of coaxial transmission line cells connected to a one-port vector-network-analyzer (R60, Copper Mountain Technologies). The inner diameter of the outer conductor was about 39 mm and the soil samples were held in the cell by two plastic supports sealed by rubber o-rings. The S-parameter matrix of a sample under test was retrieved from one-port measurements of the sample cell terminated on the other port by an electronic calibration unit (ECU) equipped with four states (short, open, load and offset short). The system was calibrated using measurements of an empty cell connected to the ECU. The values of ε* at each frequency in the specified range were retrieved with the use of a nonlinear-least-squares algorithm. The details of the hardware, calibration and permittivity extraction procedures were presented in [3]. In the configuration used in the presented experiment, a six-channel version of the system was used, in which six separate cells were connected to the VNA by an RF switch.

In order to perform the temperature sweep, the cells along with their ECUs were enclosed in a thermal insulation and connected to a climatic chamber. The whole setup, including the ECU states, were characterized at the temperatures of interest before the experiment.

B. Preparation and Measurement of Samples

Samples of a silt loam soil of moisture in the range from air-dry to saturation were prepared with the use of distilled water and three KCl solutions of electrical conductivity of 0.52, 1.02 and 1.5 S m^{-1}. For each of these four liquids, five moisture content levels were achieved, giving a total of 21 samples, including the air-dry one. On each measurement day, the system was calibrated at room temperature, then the samples were placed in the cells, the thermal insulation was sealed and the temperature sweep was started. Temperature was changed in 5°C increments and each step lasted at least 75 minutes in order to ensure that the samples reached the target temperature. Only the spectra measured after the samples achieved stable temperature were taken for analysis.

III. Results and Discussion

Selected spectra of the real (ε') and imaginary (ε'') parts of soil complex dielectric permittivity obtained at various temperatures for samples of volumetric water content of 9% and 38% are presented in Figs. 1 and 2, respectively. Both ε' and ε'' were sensitive to temperature. In the case of samples with low moisture content, both parts increased with the increase in temperature. However, when moisture content rose, a specific frequency was observed at which there were

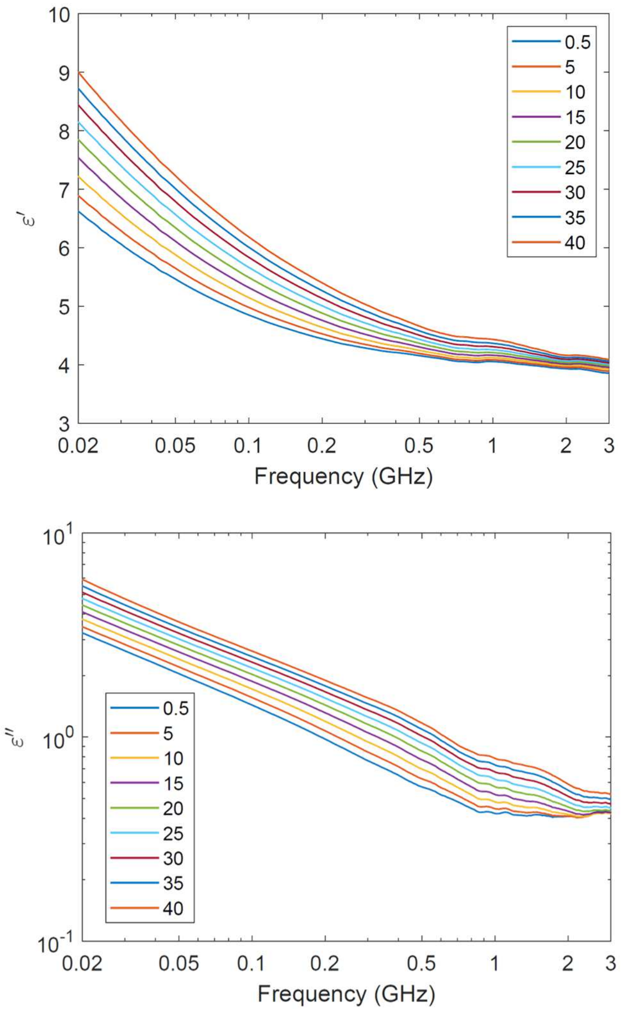

Fig. 1. Real (top) and imaginary (bottom) parts of complex dielectric permittivity of soil of 9% moisture content at various temperatures given in the legend in °C.

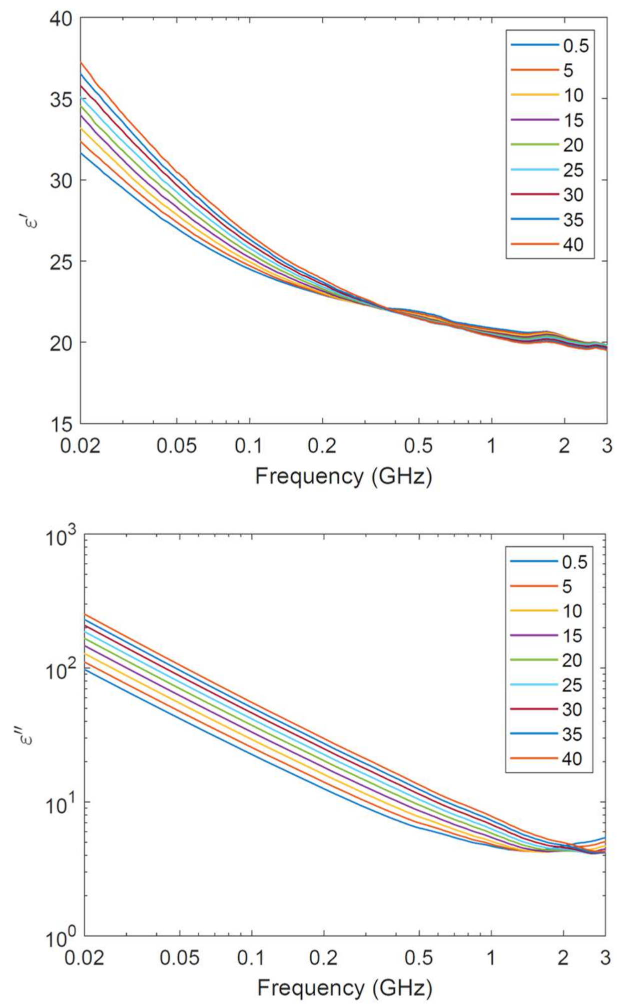

Fig. 2. Real (top) and imaginary (bottom) parts of complex dielectric permittivity of soil of 38% moisture content at various temperatures given in the legend in °C.

virtually no temperature-induced changes. At frequencies above that point, the dependence of permittivity on temperature became opposite, i.e. ε' and ε'' decreased with the increase in temperature. This characteristic frequency depended on moisture content, and in the case of ε'' it was more diffuse than in the case of ε'. Moreover, this frequency differed for ε' and ε'' even for the same soil sample.

Temperature dependence of apparent dielectric permittivity of soil measured by the TDR technique was examined in [4]. It was found that this dependence was complicated and resulted from two competing phenomena: (i) releasing of bound water into the free water state with an increase in temperature, causing an increase in soil permittivity, and (ii) decreasing of soil permittivity with an increase in temperature due to the temperature dependence of free water dielectric permittivity. These combined effects caused an increase in apparent permittivity with an increase in temperature for samples of low moisture content and a decrease in apparent permittivity with an increase in temperature for samples of high water content. Since the value of apparent permittivity measured by TDR devices depends mainly on ε' at high frequencies (several hundred MHz or greater) because of the shape of the TDR needle pulse, the findings of the current study are consistent with the results of [4]. In drier samples, which possess more bound than free water, releasing bound water is the most prominent mechanism of dielectric permittivity temperature dependence while for samples of higher moisture content both of these phenomena can be observed, with the dominance of bound water release at low frequencies and temperature dependence of free water permittivity at high frequencies.

IV. Conclusions

The influence of temperature on soil complex dielectric permittivity in the 0.02–3 GHz frequency range depended on frequency and moisture content of the soil. The increase in permittivity with the increase in temperature could be attributed to the release of bound water into the free water state. For samples of higher moisture content, above certain characteristic frequency, permittivity decreased with an increase in temperature, which was probably caused by the temperature dependence of free water dielectric permittivity. Further research will focus on examination of more soils and analysis of the temperature dependence of relaxation mechanisms present in soil in this frequency range.

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