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# Comparison of Open-Ended Coax and TDR sensors for the measurement of soil dielectric permittivity in microwave frequencies

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A b s t r a c t. The study presents a comparison of two sensors for the determination of the complex permittivity of soil: a three-rod TDR probe and an Open-Ended Coax probe. The measurements were performed using a TDR system working with a 20 ps rise-time step pulse and a Vector Network Analyzer (VNA) operating in the frequency range from 20 kHz to 8 GHz. The sensors were calibrated on liquids of known dielectrical properties and were used to measure the complex permittivity of three types of soil at various moisture levels. The real part of the complex permittivity calculated from $S_{11}$ parameters measured by VNA for frequencies near 1 GHz is in agreement with the values measured by TDR method using three-rod probes. The values of the imaginary part of the complex permittivity of the soil samples measured by the probes applied also show a good correlation. The comparison of the hardware differences between the systems for the measurement of the complex permittivity of porous materials working in time and frequency domains is also discussed.

K e y w o r d s: TDR, Open-Ended Coax sensor, soil permittivity

## INRTODUCTION

Real-time and non-invasive monitoring of the physical and chemical properties of agrophysical objects *ie* food products and agricultural materials, as well as the environment of their growth, storage and transportation, is necessary to improve quality as well as quantity of agricultural production and to minimize losses. The development of technology in recent years has increased the number of methods and decreased the price of monitoring tools for application in agriculture. Data transmission facilities, accurate and battery operated converters of physical and chemical properties into electrical signals and measurements in high frequency range are a few examples of the progress observed.

An important parameter for soil monitoring is moisture because water directly influences the other physical and chemical parameters of soil as a porous body. Indirect measurement of moisture using its dielectrical properties seems to be the right direction for the researchers. The objectives of the study are:

a) description of the main features of the two methods of determination of $\varepsilon^*$: Open-Ended Coax Probe and Time Domain Reflectometry (TDR) methods,

b) comparison of real and imaginary parts of $\varepsilon^*$ determined from the measurement of three mineral soils using the measurement methods discussed,

c) discussion of the hardware differences of the meters working in the frequency domain (Open-Ended Coax Probe) and time domain (TDR),

d) long term objective is to design and build a prototype of a portable and inexpensive meter for the measurement of $\varepsilon^*$ of porous materials, working in the frequency domain.

The presented methods for the determination of the complex dielectric permittivity of materials are applications of dielectric spectroscopy, the branch of science aimed at identifying relationships between dielectric properties of materials and their important quality characteristics and at developing scientific principles for measuring these characteristics through interaction of radio frequency and microwave electromagnetic fields with the agricultural materials and products.

Dielectric spectroscopy has some advantages over other physicochemical measurements: sample preparation is relatively simple, a variety of sample sizes and shapes can be measured, measurement conditions can be varied under a wide range of temperatures, humidity, pressure, *etc*, the technique is extremely broad band (mHz - GHz) thus

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enabling the investigation of diverse processes over wide ranges of time and scale. Moreover, the construction of an inexpensive and reliable meter working in the frequency range adjusted to the material under study can be a significant step towards the standardization of the measurement of the dielectric properties of agricultural materials and products.

## THEORY

As the wave enters from one medium *eg* free space or a coaxial cable, to another *eg* soil or another agricultural material, a part of its energy is reflected from the material and the rest is transmitted through it. This is due to the difference of the velocity of travel of electromagnetic waves in different media. When the material is lossy, it will attenuate the electric signal or introduce the insertion loss.

The fundamental electrical property describing the interactions between the electric field applied and the material described is the complex relative permittivity of the material $\varepsilon^*$ (Topp *et al*., 1980; Kraszewski, 2001):

$$\varepsilon^* = \varepsilon' - j\varepsilon'', \tag{1}$$

where: $\varepsilon'$ is its real part, often called the dielectric constant, and $\varepsilon''$ is its imaginary part, $j$ is an imaginary unit.

Dielectric material has an arrangement of electric charge carriers that can be displaced or polarized in an external electric field. There are different polarization mechanisms in a material and each has a characteristic resonant frequency or relaxation frequency. As the frequency increases the slower mechanisms do not contribute to the overall $\varepsilon'$. The imaginary part, $\varepsilon''$, will correspondingly have a local maximum at each critical frequency (Fig. 1).

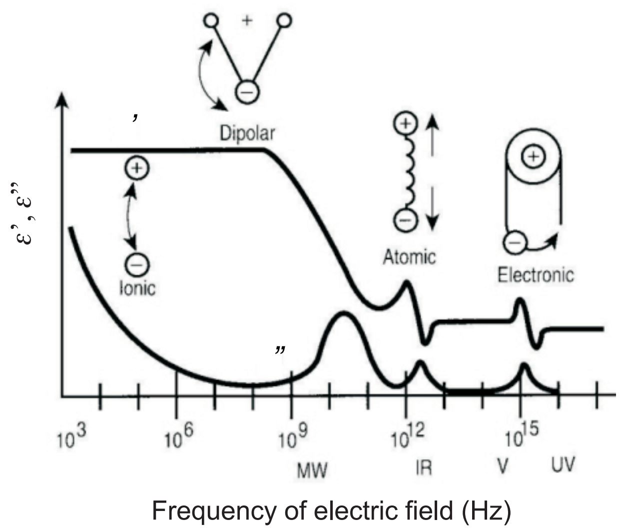


**Fig. 1.** Frequency response of dielectric mechanisms: MW, IR, V and UV are the microwave, infrared, visible and ultraviolet spectra respectively (HP AN 1217-1, 1992).

There are different mechanisms of polarization of charge carriers in a material: electronic polarization, atomic, orientation and ionic polarizations. Water is an example of a substance with strong orientation polarization. Ionic conductivity, $\sigma$ (S m$^{-1}$), present at low frequencies, only introduces losses into a material and the measured loss of material can be expressed as a function loss due to the dielectric polarization of the particles in the alternating electric field, $\varepsilon_d''$, and conductivity, $\sigma$ (Topp *et al*., 1980):

$$\varepsilon'' = \varepsilon_d'' + \frac{\sigma}{2\pi f \varepsilon_0} \tag{2}$$

where: $f$ is the frequency of the electric field applied, $\varepsilon_0$ is the dielectric permittivity of free space.

Because water is present in all agricultural materials and its influence on the majority of agricultural properties is dominant, the specific property of water causing the orientation polarization is of primary area of interest of dielectric spectroscopy (Kraszewski, 2001).

### Time Domain Reflectometry method

The Time Domain Reflectometry method for the determination of dielectric permittivity is widely accepted, especially for soil moisture determination (Topp *et al*., 1980; Malicki and Skierucha, 1989; Malicki and Walczak, 1999), for its advantages: simplicity of operation, accuracy and fast response, usually does not need calibration, it is non-destructive, portable systems are available, it is capable of automation, and can accept multiplex probes. The construction of a TDR meter for the determination of the velocity of propagation of electromagnetic pulse in the material is much simpler than that of a frequency domain reflectometer. The basic elements of the meter are: two pulse generators, a delay unit, a sampling head with data conversion facilities, a TDR probe (sometimes several multiplexed probes) and a micro-controller (Fig. 2). The construction of the TDR meter needs a lot of skills and professional instrumentation (Malicki and Skierucha, 1989) to maintain stable parameters in field applications. The pulse travel times along the parallel waveguide in the measured media must be determined with the resolution of picoseconds. The measurement error of the pulse travel time along the probe rods equal to 10 ps will give the error of soil moisture measurement of about 0.2%.

The frequency applied in Time Domain Reflectometry (TDR) method is not as exactly defined as it can be done for Frequency Domain Reflectometry (FDR) represented by the Open-Ended Coax probe method. The application of a step pulse or a needle pulse of very short rise time, $t_r$, corresponds to the frequency range with the upper limit, $f_{\max}$, that can be calculated by the following engineering formula (Strickland, 1970):

$$t_r = 0.35 f_{\max}^{-1}\ . \tag{3}$$

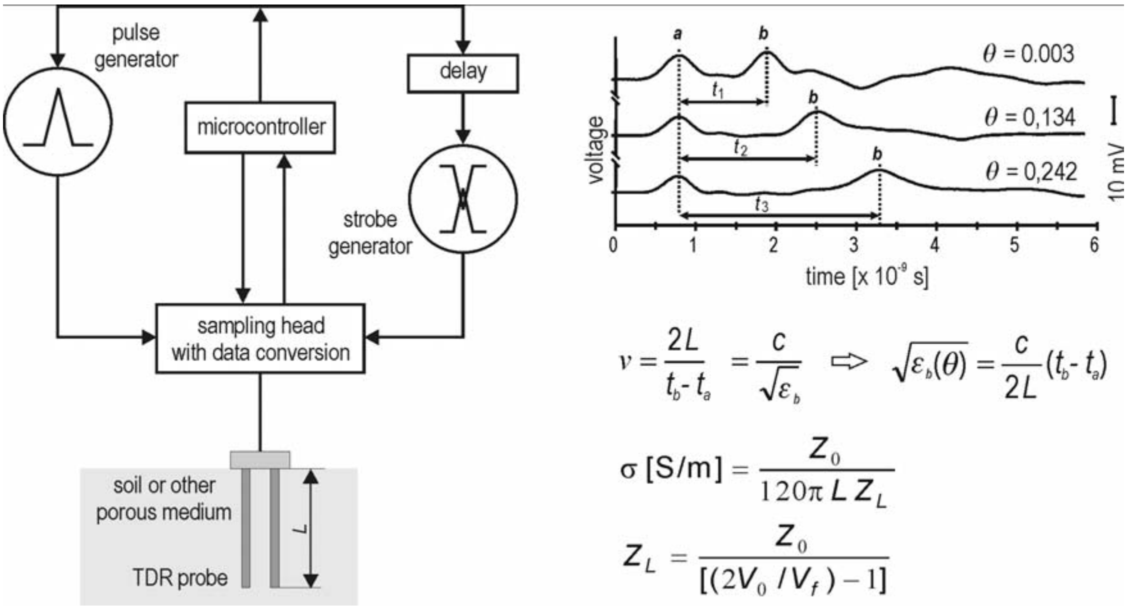


**Fig. 2.** Basic elements of the time domain reflectometer for determination of velocity of propagation of electromagnetic waves in porous media.

The probe in the TDR method is a waveguide consisting of two or three parallel metal rods inserted into the tested medium. The velocity of propagation of the pulse in this waveguide, $v$, is modified by the dielectric permittivity of the waveguide surroundings. In calculations it is usually assumed that the dielectric loss of the material does not influence the velocity of propagation of the pulse (Topp *et al*., 1980). The real part of the medium complex dielectric permittivity, the dielectric constant, is the indicator of its moisture, $\theta$. For the probe length $L$, the bulk dielectric constant of the material, $\varepsilon_b$, and indirectly its moisture, can be calculated (Malicki and Skierucha, 1989) using the formula in , where: ($t_b$-$t_a$) is the measured time the pulse covers the distance $2L$, $c$ is the velocity of light in free space.

Most commonly used σ determination is based on Giese and Tiemann (1975) approach:

$$\sigma = \frac{Z_0}{120\pi L Z_L}, \tag{4}$$

where: $Z_0$ is probe impedance, $L$ is probe length, and $Z_L$ is the measured resistive load impedance across the probe embedded into the soil:

$$Z_L = \frac{Z_0}{[(2V_0 / V_f) - 1]}, \tag{5}$$

where: $V_0$ is the voltage amplitude of the incident step and $V_f$ is at large distance along the TDR time axis.

Lossy media attenuate the TDR reflected pulse and this makes the method practically useless for electrical permittivity of materials exceeding 4 dS m$^{-1}$, which is a high value for arable soils (Marshall and Holmes, 1979). In saline soils the signal reflected from the end of the probe rods is completely attenuated (no amplitude at point $b$ in ). The measurement of the amplitude of the pulse reflected from the end of the probe, taken simultaneously to the pulse travel time, enables the determination of the electrical conductivity of the soil, $\sigma$, and its salinity defined as the electrical conductivity of the extract of a saturated soil paste (Rhoades and Ingvalson, 1971).

### Open-Ended Coaxial probe method

The measurement of dielectric properties of materials in frequency domain, with the application of microwave frequencies, needs expensive instrumentation. The basic elements of a simplified Vector Network Analyzer (VNA), working only in reflection mode, for the determination of reflection parameter $S_{11}$ is presented in Fig. 3. The device consists of a very stable frequency synthesizer generating sinusoidal waveforms of variable frequency feeding a sensor – Open-Ened Coax probe – connected to the output/ input port of the VNA. For a defined frequency, the directional couplers sense the amplitudes and the phases of the waveforms produced by the generator and reflected from the probe. The detected difference in amplitude and phase depends on the dielectric properties of the tested material at the end of the open-ended coaxial probe. The signals from the directional couplers are mixed with the signals from another generator, heterodyne, the frequency of which is

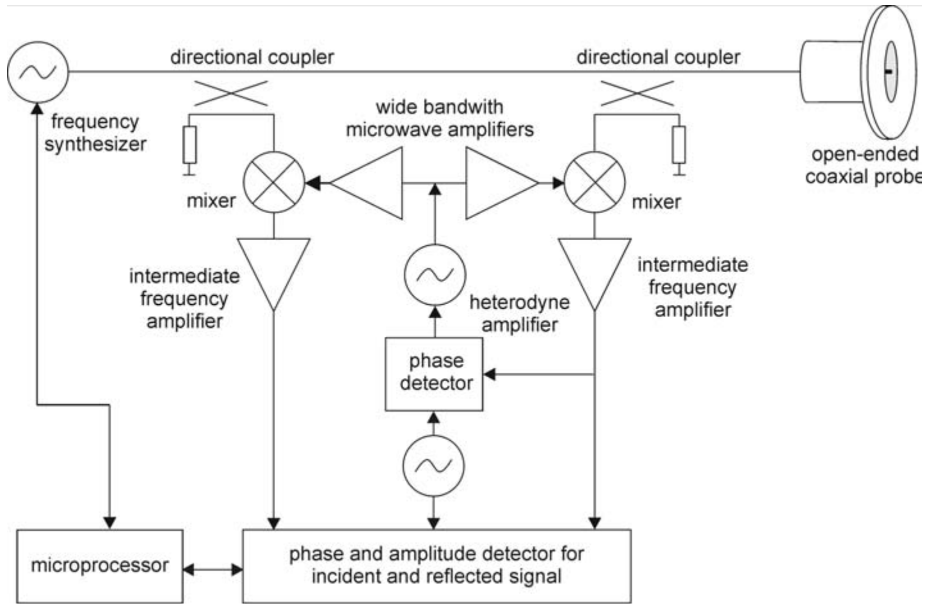


**Fig. 3.** Basic elements of the frequency domain reflectometer for determination of complex dielectric permittivity of porous media.

adjusted by the phase detector. The reason for this frequency conversion is to have constant frequency, not dependent on the synthesized frequency, of the signals reaching the measuring detector. The signals detected are characterized by constant frequency but their amplitudes and phase shifts do not change. The whole process of waveform generation and detection is controlled by a microprocessor that changes the frequency of the synthesizer and registers the signals detected. All the elements used in the presented system work in a broad frequency range, from kHz to GHz, and they must have linear characteristics. Moreover, the measuring system accomplishes continuous recalibration to maintain parameters stable in time and temperature.

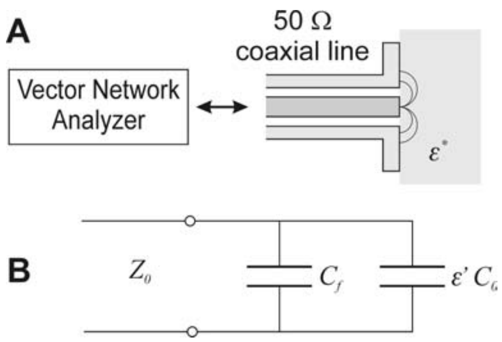


**Fig. 4.** A - Open-ended coaxial probe in the form of coaxial line open to the space with material of unknown dielectric permittivity $\varepsilon^*$, B - modelling the discontinuity of electromagnetic field by lumped capacitances $C_f$ and $C_0$.

Fundamental to use the Open-Ended Coax probe (Fig. 4) is an accurate model relating the reflection coefficient at its end to the permittivity of the material contacting with the probe. The lumped capacitance circuit model (Stuchly and Stuchly, 1980) is applied in the example presented here.

The lumped capacitance model of the probe applied assumes the presence of capacitance at the end of the probe. Its value depends on the complex dielectric permittivity of the material the probe was pressed into (Fig. 4). The complex value of the admittance of the probe end, $Y_L^*$, is:

$$Y_L^* = j\omega Cf + j\omega C_0 \varepsilon^* = j\omega(Cf + C_0\varepsilon') + \omega C_0 \varepsilon'', \quad (6)$$

where: $C_f$ represents the part of admittance that is independent from the dielectric sample, $C_0$ is a part of admittance for air as dielectric.

Before performing measurements on unknown materials, the Open-Ended Coax probe should be calibrated on media with known dielectrical properties, usually distilled water, methanol or air, to find the values of $C_f$ and $C_0$. The measurement method and the lumped capacitance model described were verified by measuring the dielectric permittivity of teflon. It was found that the $C_f$ value is negligible and $C_0$ calculated from Eq. (6) to the $C_0$ coefficient of the correction polynomial obtained during calibration. Consequently, the model may be simplified to:

$$Y_L^* = \omega C_0 \varepsilon^* = j\omega C_0 \varepsilon' + \omega C_0 \varepsilon'' \quad (7)$$

The value of $C_0$ describes the geometry of the probe and the frequency range of its application. The larger the dimensions of the probe, the bigger its value and the better accuracy in applications for materials of small values of dielectric permittivity, and simultaneously the high frequency range of measurement is limited. This limitation comes from the fact that in the case of materials of high dielectric permittivity and at high frequencies, changes in the dielectric permittivity of the material cause very small changes of the phase shift of the reflection coefficient. This drastically decreases the accuracy of measurement and creates the need to apply calibration media of small value of dielectric permittivity.

## MATERIALS AND METHODS USED

Dielectric permittivity of three soils was compared. Table 1 presents the basic physical parameters of the soils tested. Dry soils were mixed with an appropriate amount of distilled water to achieve four samples for each soil analyzed with different moisture values and taking care to obtain homogeneous distribution of water in the soil samples. Twelve containers with soil samples, covered with plastic foil (to minimize evaporation), were left for 24 h at room temperature for water distribution in the samples in the natural way. Gravimetric moisture, $\theta$, and bulk density, $\rho$, were determined (ISO 16586, 2003) for each soil sample directly after the dielectric permittivity measurements were completed. The values of $\rho$ in Table 1 are the mean values for all applied moistures for each soil tested. Soil texture was determined by standard Bouyoucos method (Turski, 1993). The values of soil specific surface, $S$, were determined with the water vapour adsorption method (Ościk, 1983).

The Time Domain Reflectometry (TDR) and Open-Ended Coax Probe methods of determination of the complex dielectric permittivity of porous materials were applied.

TDR measurements were performed using the oscilloscope frame HP54120 with the TDR unit HP54121T, featured by 20 ps rise-time step pulse. The TDR probe was based on the standard coaxial connector (type N jack) with three stainless steel wires soldered to the centre contact and two others symmetrically to the connector flange (Fig. 5A). The diameter of the rods was 2 mm, the distance to the central rod - 13 mm and the length of the rods - 114 mm. The characteristic impedance, $Z_0$, of the parallel waveguide measured from the reflection coefficient by the TDR unit was 165 ohm (Agilent, 2002).

The data from the Open-Ended Coax probe were collected by the 20 kHz – 8 GHz Rohde&Schwarz ZVCE Vector Network Analyzer (Stuchly and Stuchly, 1980; Blackham and Pollard, 1997). It enabled the calculation, on the basis of the measured $S_{11}$ parameter, the complex reflection coefficient and the complex admittance at the end of the probe. The probe was constructed on the basis of type N coaxial connector machined flat at the side where it contacts with the material tested (Fig. 5B).

**T a b l e 1.** Localization and selected physical parameters of tested soil samples

| Soil type | Density (g cm$^{-3}$) | Granulometric composition (%) (dia in mm) | | | Specific surface (m$^2$ g$^{-1}$) |
|---|---|---|---|---|---|
| | | sand | silt | clay | |
| | | 2-0.02 | 0.02-0.002 | <0.002 | |
| Eutric Cambisol (611*) | 1.59 | 94 | 5 | 1 | 9 |
| Eutric Histosol (606*) | 1.42 | 97 | 2 | 1 | 23 |
| Haplic Phaeozem (619*) | 1.16 | 87 | 12 | 1 | 69 |

*According to Gliński *et al*., 1991.

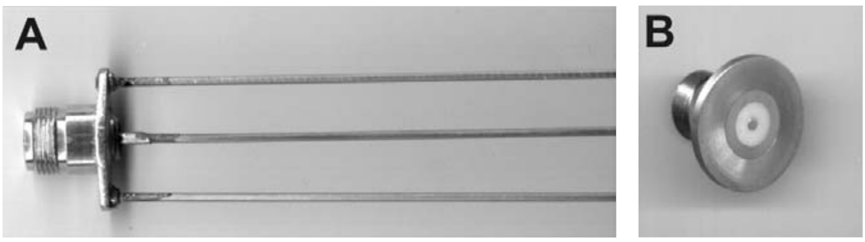


**Fig. 5.** A three-rod TDR probe (A), and an Open-Ended Coax probe (B) used in the measurement of dielectric permittivity of soils.

The Open-Ended Coax Probe method was verified by comparing the measured data to the Cole-Cole model (Blackham and Pollard, 1997). The Cole-Cole equation models the permittivity of free water and other polar substances:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau_{rel})^{1-\alpha}}, \tag{8}$$

where: $\varepsilon_\infty$ is the relative high frequency permittivity, $\varepsilon_s$ is the relative static permittivity and $\tau_{rel} = 1/f_{rel}$ is the relaxation time (inverse of relaxation frequency $f_{rel}$) of orientation polarization defined as the time at which the permittivity equals $(\varepsilon_s + \varepsilon_\infty)/2$, $\alpha$ is an experimental correction. The Cole-Cole model values of $\varepsilon_\infty$, $\varepsilon_s$, $\tau_{rel}$ and $\alpha$ are 4.45, 33.7, 4.95 $10^{-11}$ s and 0.036, respectively.

## RESULTS AND DISCUSSION

The comparison of the measured and the modeled data, using the Cole-Cole model of complex dielectric permittivity of methanol is presented in Fig. 6. The measured and modeled data are very close to each other proving the measurement procedure applied to be adequate.

show higher values than the time domain measurements. More differences between the measurements from both probes can be found for the imaginary parts of the $\varepsilon^*$, where the values from TDR measurements were much lower than for frequency domain. This inconsistency may result from two reasons:

1) problems during the calibration of the Open-Ended Coax probe (the Vector Network Analyser calibration kit was not fitted for the performed measurements),

2) the assumption that the dielectric loss, $\varepsilon''$ in Eq. (2), was negligible in the TDR measurements is false.

Both of the two methods for the determination of the dielectric permittivity of porous materials have advantages

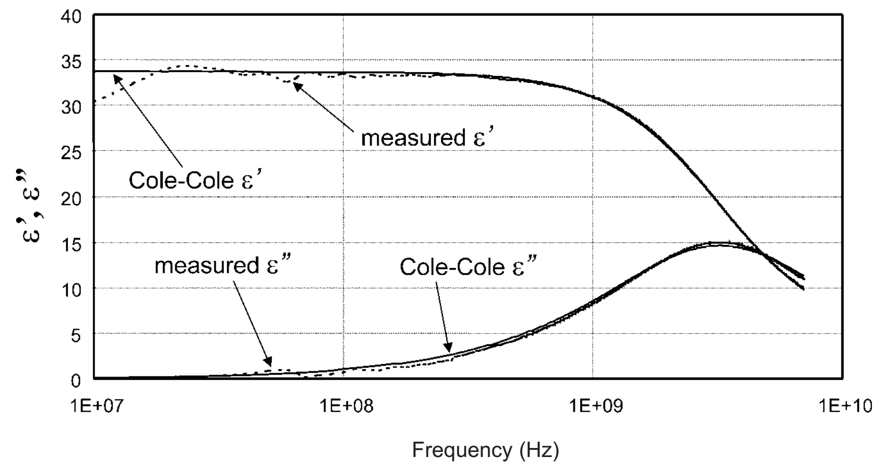


**Fig. 6.** Frequency change of real and imaginary parts of the complex dielectric permittivity of methanol for Cole-Cole modelled data and measured using Open-Ended Coaxial probe.

The comparison of the measured real and imaginary parts of the complex dielectrical permittivity of the analyzed soils is presented in Fig. 7.

The curves representing the relation $\varepsilon'(f)$ for soils of different moisture, $\theta$, determined by gravimetric method, are collected by the Open-Ended Coax probe. In the lower frequency limit of 10 MHz, the real part of the complex dielectric permittivity is relatively high. This is attributed to the influence of ionic double layers associated with colloidal soil particles. This effect is often referred to as the 'Maxwell-Wagner' effect (Hilhorst and Dirksen, 1994). There was no orientation relaxation found in the measured frequency range from 10 MHz to 7 GHz because the soils tested have very small clay content. There is a slight decrease of the measured $\varepsilon'$ with the frequency increase.

The real part of dielectric permittivity of the soils tested, $\varepsilon'_{\text{Open-Coax}}$, taken for the comparison with the soil bulk dielectric constant determined by TDR method, $\varepsilon_{b\text{-TDR}}$, are values for 1 GHz frequency. There is a high correlation between the $\varepsilon'_{\text{Open-Coax}}$ and $\varepsilon_{b\text{-TDR}}$, except for high water content, where the measurements in the frequency domain

and drawbacks. The parallel waveguide can have lengths ranging from 5 to 50 cm or more and the material tested constitutes its propagation medium, therefore, as opposite to the Open-Ended Coax method, the propagation velocity is an average along the probe rods and the volume of measurement is much larger. For small samples of material, or in cases when it is not possible to insert the rods into it, the Open-Ended Coax method is more suitable. The frequency of the TDR measured $\varepsilon_b$ is not precisely defined, as it is a superposition of sinusoidal waves making the final step or needle pulse. Also, for the frequencies in the range 0.5-1.5 GHz, the real and imaginary parts of the dielectric permittivity do not change for the majority of agricultural materials. In the case of the Open-Ended Coax probe, the user has the whole frequency spectrum for analysis.

The meters for the TDR and Open-Ended Coax measurements must work in high frequency to cover the physical phenomena associated with dipolar polarization of water molecules. The TDR meter working in time domain (Fig. 2) is much simpler to construct as compared to the meter working in frequency domain (Fig. 3), although both

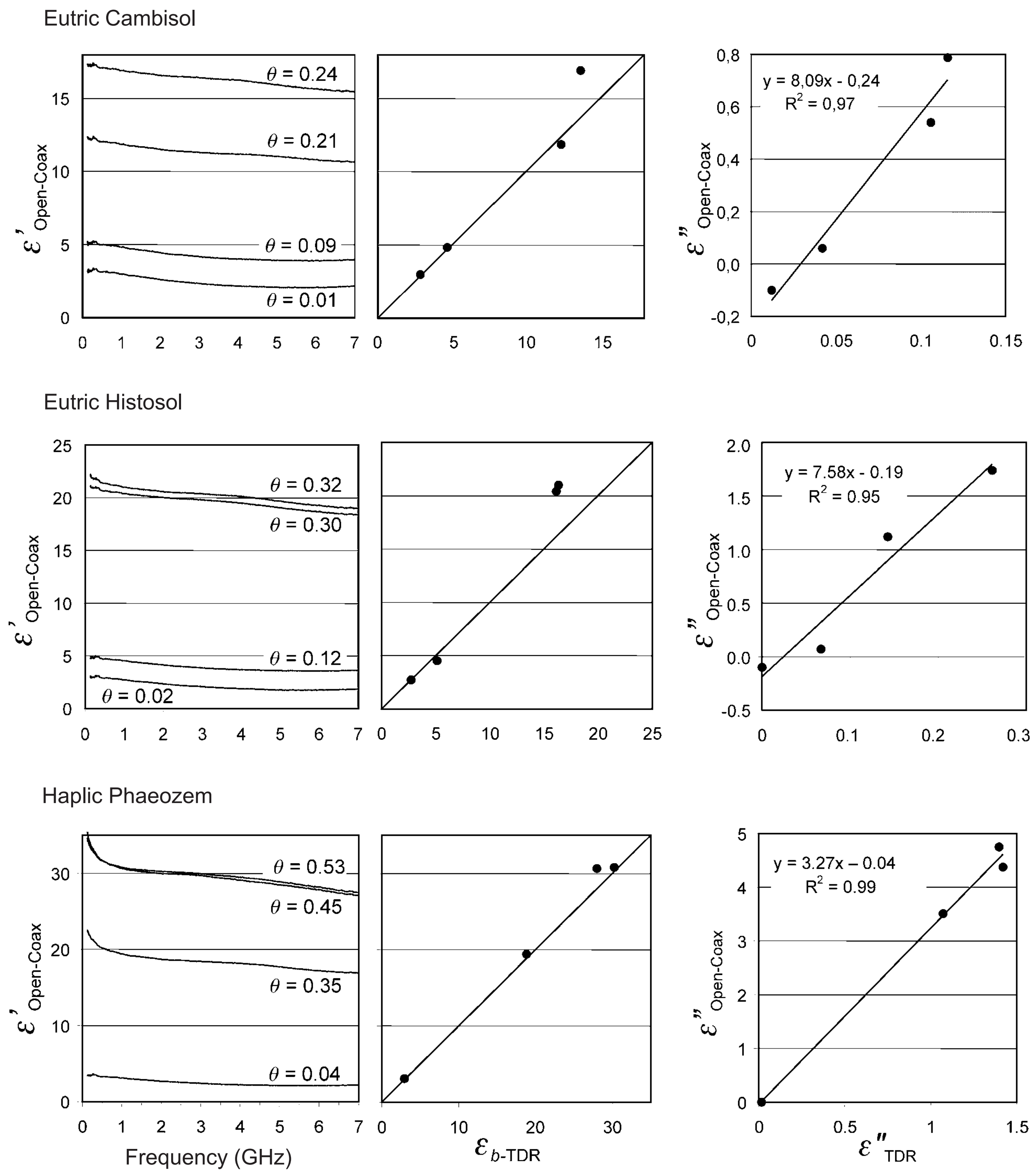


**Fig. 7.** Comparison of real, ε', and imaginary, ε", parts of the complex dielectric permittivity for the selected soils, calculated from the TDR and Open-Ended Coax probe measurements; $\varepsilon_{b\text{-TDR}}$ is the bulk dielectric constant measured by TDR.

require much effort and test instrumentation. The temperature and long-term stable frequency conversion in the required range of change, from kHz to GHz, need careful selection of electronic elements, which needs time and investment. However for the selected material only one frequency can be applied. The choice of this frequency can be determined by preliminary tests with the use of a professional VNA.

## CONCLUSIONS

1. Real parts of $\varepsilon^*$ of the soils tested, determined by both measurement methods, are highly correlated and the measured values are close to each other. However, for soil of high moistures, the values of the real part $\varepsilon^*$ determined by the Open-Ended Coax probe are higher than those determined by the TDR method. The imaginary parts are highly correlated but differ significantly.

2. The difference of the imaginary parts of $\varepsilon^*$ of the soils tested needs additional research for explanation; it may result from the inadequate calibration tools applied.

3. The Open-Ended Coax and Time-Domain Reflectometry methods need further development in the field of modeling (to provide models of tested media and identify the measured quantities with indicators of material properties) and hardware (to select appropriate geometry of applied sensors for different porous materials and to decrease the price of the meters).

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