

A Large-Size Coaxial Waveguide Time Domain Reflectometry Unit for Field Use

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Abstract—A large-diameter open-ended coaxial waveguide has been interfaced with a commercially available time domain reflectometry (TDR) unit for field measurements of the dielectric properties of frozen and thawed soils and ice. A core barrel developed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and modified for use in frozen soil was used to agger an annular slot around which the waveguide fits. Time domain traces of waveforms reflected from the sample-air interface and from a metal short are recorded in the field and later analyzed to give complex dielectric permittivity between 0.05 and 1.0 GHz.

Introduction

Time domain reflectometry (TDR) is used for measuring the complex dielectric permittivity as a function of frequency [1]-[5]. The use of fast rise time (<35 ps) tunnel diodes will commonly enable calculations at frequencies as high as 4 GHz and up to 14 GHz under special circumstances [1]. Measurements previously have been performed in precision coaxial waveguides on liquids and fine-grain soils because they can maintain complete contact with the waveguide. However, the small size of these waveguides requires repacking of the soil and, therefore, loss of the original soil structure. In this paper we report the extension of this technique to the field whereby frozen or thawed samples may be prepared in situ or removed and prepared for immediate testing with a modified (CRREL) core barrel and the use of 3-in coaxial waveguide.

Principles of TDR

In TDR the quantity sought is the frequency (f) dependent complex relative dielectric permittivity \( K^*(f) \) expressed as

\[
K^*(f) = K'(f) - jK^*(f)
\]

where \( j = \sqrt{-1} \). The quantity \( K' \) is known as the dielectric constant when it is much greater than \( K^* \). The quantity \( K^* \) is known as the dielectric loss factor under the same condition.

In TDR, \( K^*(f) \) of a material sample is determined from the time dependent waveforms of the incident and sample reflected pulses propagating along a coaxial transmission line. At any particular frequency the ratio of the Fourier transformations of these pulses is the reflection coefficient \( \rho(f) \), which is determined by the change in transmission line impedance caused by the insertion of a test sample. In an air-filled line containing a sample at the end, \( K^*(f) \) is related to \( \rho(f) \) through the relation

\[
K^*(f) = \left| \frac{1 - \rho(f)}{1 + \rho(f)} \right|^2.
\]

Since \( \rho(f) \) is complex, the relative time delay between incident and reflected pulses must be correctly determined to avoid errors in computing the reflection coefficient.

In the TDR system (Fig. 1), a tunnel diode generates step waveforms in a coaxial waveguide. A sampling oscilloscope displays the reflections from the sample interface and then from a short circuit at the end of the line with the sample removed. The latter reflection gives the incident waveform. The waveforms are positioned relatively in the time domain using the manual procedure described in [1] and then Fourier-analyzed using a modification of the Shannon sampling theorem [6] to give the incident and reflected amplitudes at discrete frequencies. The processed data are then converted to relative complex dielectric permittivities.

TDR System

We used a Tektronix 1502A TDR unit which produces a pulse with a rise time of about 140 ps. The pulse travels from the unit through a 7-mm coaxial line. This line is directly mated to the type N adapter of a second (commercially available) 50-Ω line (7.62-cm O.D.) which contains the sample (Fig. 2). Both lines also have the same wave impedance (377 Ω) below about 1.7 GHz so that the two

Fig. 1. TDR system consisting of a Tektronix 1502 cable tester, standard-type N coaxial cable, and a larger size coaxial sample holder. The plastic stock is inserted into the sample. The ring is a short circuit used for generating reference waveforms.
waveguides are theoretically well matched below this frequency. Higher order TE and TM modes propagate in the air-filled larger waveguide above about 1.7 GHz [7] preventing a good match. Practically, transmission through the waveguide junction both before and after reflection from a short circuit within the larger waveguide produces insignificant distortion of the original 140-ps pulse. This reflection from a short circuit is used to record the reference (incident) waveform and is shown in Fig. 3.

Samples are inserted in the large waveguide 25 cm from the transition to avoid interference between the pulse and the weak ringing from the transition. The overall sample lengths were at least 20 cm to prevent rear reflections from interfering with the decay of the sample relaxation. The line was terminated with an open circuit.

To prepare a sample, an annular slot is augered in the desired material with a modified CRREL core barrel. The hole for the center conductor is drilled with a special fixture slipped over the sample as a guide. The sample is faced off while in the ground or the entire sample may be broken off, faced off at one end, and immediately inserted in the coaxial waveguide. This latter procedure is possible with a dielectric constant of 3.2 with a sample machined to fit the coaxial adaptor interface between the two different size waveguides.

Fig. 2. Illustrative detail of the coaxial lines, inserted sample, and short circuit.

![Diagram of coaxial lines, inserted sample, and short circuit.](attachment:image.png)

Fig. 3. Pulse response of the short circuit. The small ripple is due to the coaxial adaptor interface between the two different size waveguides.

![Diagram of pulse response of the short circuit.](attachment:image.png)

RESULTS AND DISCUSSION

The validity of the large-diameter coaxial waveguide TDR technique was first confirmed by laboratory testing of materials with known dielectric properties. The first test was performed on Delrin plastic stock for which the dielectric constant is listed between 3.0 and 3.4 [8]. We measured a dielectric constant of 3.2 with a sample machined to fit the inner and outer lines perfectly (Fig. 4). Several Delrin samples were then machined with incorrect inner and outer radii to determine the effects of poor sample fit. Our results were only qualitative at best as we could not maintain a uniform air gap between sample and waveguide as is typical in practice. An error of 3 percent in the sample outside radius resulted in a 9-percent decrease in $K'$. An error of 5 percent in the radius of the sample center hole resulted in a 6-percent decrease in $K'$. Theory [10] predicts an 8- and 13-percent error, respectively, for these two cases and our disagreement is probably due to our nonuniform contact between sample and waveguide. Westphal's formula [10] may possibly predict the worst case possible. Machining the sample face so that its normal was tilted 5° with respect to the waveguide axis caused a 2-percent decrease in $K'$.

Butyl alcohol was selected for testing because it is a dispersive liquid with a relaxation frequency around 400 MHz [3], well within our operating bandwidth. The coaxial sample line was inserted into a glass beaker filled with the alcohol. Fig. 5 shows the reflected traces from the alcohol-air interface and from the reference shorting plate placed at the end of the sample cell. The traces have been properly positioned relatively in time. Fig. 6 shows the dielectric permittivity as a function of frequency as processed from the traces. The values agree extremely well with the previously published data [3] up to 1.5 GHz. Above 1.5 GHz, however, the values no longer agree as predicted by the multimoding argument discussed earlier.

Fig. 4. Complex relative dielectric permittivity of Delrin.

![Diagram of complex relative dielectric permittivity of Delrin.](attachment:image.png)

Fig. 5. Reflected pulses from a short circuit and from butyl alcohol.

![Diagram of reflected pulses from a short circuit and from butyl alcohol.](attachment:image.png)
Inaccuracies in determining the correct permittivity values may be caused by sample inhomogeneity as well as poor mechanical fitting. Inhomogeneity within the body of the sample may cause secondary reflections that interfere with the primary front-face reflection. Inhomogeneities should be much smaller than the shortest in situ wavelength corresponding to the highest frequency necessary to maintain the pulse shape. For example, at 140-ps rise time this frequency is about 7 GHz so that for $K' = 4$, the wavelength in the sample is about 2 cm. The dimension of the inhomogeneity in the cross sectional plane of the waveguide should therefore be no larger than say, about 0.5 mm.

As stated earlier, the upper frequency limit is determined by the waveguide dimension which determines the onset of multimoding. The lower frequency limit is mainly determined by the sample length. With long homogeneous samples, pulse reflection decays may be observed well beyond the time sweeps we used without any interference from rear end reflection. Thus the influence of low-frequency conduction may be added to the behavior of the complex permittivity.

**CONCLUSIONS**

Field dielectric testing of cored samples is an easily accomplished procedure using a readily available TDR system and waveguide components. Data quality depends mainly on the fit of the sample to the waveguide and this generally would not be a problem for unfrozen soils and carefully machined frozen samples. The TDR data is easily processed to give permittivity over a frequency range broad enough to cover the bandwidth of most ground penetrating radars (50–500 MHz), and thus be used to facilitate echo interpretation.

**REFERENCES**


